UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO
POSGRADO EN GEOGRAFÍA

ANÁLISIS DE LA GANADERÍA BOVINA TROPICAL DESDE EL ENFOQUE DE SISTEMAS SOCIOECOLÓGICOS Y SOSTENIBILIDAD

TESIS

QUE PARA OPTAR POR EL GRADO DE:
DOCTORA EN GEOGRAFÍA

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CIUDAD UNIVERSITARIA, CIUDAD DE MÉXICO
OCTUBRE 2023

A mi mamá, mi papá y mi hermana por su amor y apoyo incondicional.

AGRADECIMIENTOS

A mi tutor principal el Dr. Leopoldo Galicia Sarmiento por guiarme y permitirme desarrollar todas mis ideas a cada paso del doctorado. Gracias Polo, has creído en mi proceso y me has impulsado a seguir creciendo como investigadora.

A mi comité tutor integrado por la Dra. Sophie Ávila Foucat y el Dr. Guillermo Jiménez Ferrer por el seguimiento y evaluación que hicieron que cada semestre aprendiera y afinara el proyecto.

A los miembros del jurado conformado por la Dra. María Perevochtchikova, Dra. Patricia Balvanera, Dra. Elisa Oteros Rozas, Dra. Sophie Ávila Foucat y Dr. Guillermo Murray Tortarolo por los aportes que hicieron que este documento reflejara de mejor manera el trabajo realizado.

A la Red de Organizaciones Agropecuarias Silvopastoriles del Estado de Chiapas S.A. de C.V que me proporcionó gran parte de los datos que hicieron posible esta investigación. Gracias Benito Díaz Morales por abrirme la puerta a entender lo que implica hacer ganadería desde el sur de México.

Al Consejo Nacional de Humanidades, Ciencias y Tecnologías (CONAHCYT) por la beca doctoral (750544) y la Universidad Nacional Autónoma de México (UNAM) por poner a mi disposición las herramientas necesarias para realizar el posgrado. Espero que esta investigación regrese al pueblo de México un poco de todo lo que me ha dado.

Al Programa de Apoyo a Proyectos de Investigación e Innovación Tecnológica (PAPIIT) No. 302421—Proyecto: Provisión de servicios ecosistémicos en sistemas socio-ecológicos agrícolas, ganaderos y forestales: Transición hacia la sostenibilidad de sistemas productivos, por el financiamiento de publicaciones, congresos y otros eventos académicos.

A mi mamá por ser el soporte fundamental sobre el cual he construido y deconstruido cada día de mi vida. Gracias mami, esta tesis es el resultado del sacrificio de las dos.

A Mauricio y Mila por el amor, la compañía y recorrer conmigo la montaña rusa que fue hacer el doctorado en pandemia. Gracias Mau por sostener mi mano en cada reto que trajo la cotidianidad y esforzarte en entender lo que siento y pienso para ayudarme a continuar.

A mis amigos, Antonio, Issa, Marisol, Laura Alicia y Raiza por los abrazos, enseñanzas, consejos y muchos momentos vividos estos últimos cuatro años.

ÍNDICE

Acrónimos Frecuentes (español e inglés)

AC/CA: Acción colectiva

AL/LA: América Latina

MF: Multifuncionalidad

MFA: Multifuncionalidad del agroecosistema

SE/ES: Servicios Ecosistémicos

SSE/SES: Sistemas Socioecológicos

SSP/SPS: Sistemas Silvopastoriles

SM: Supplementary Material

Índice de Figuras

Figure 3. Proportions (blocks) and percentages (values) of mentions and measurements of critical approaches and concepts in the study of cattle ranching in LA.

Figure 4. Ecological (green box) and socioeconomic components (purple box) integrate the cattle ranching SES in LA in interaction with external factors (blue box) identified in the papers re-viewed. In addition, it shows the spatial and temporal scales at which these components and fac-tors are usually analyzed.

Figure 5. Levels of analysis reported in studies on livestock in Latin America and ecological/socioeconomic components and external factors identified within different levels in constant interaction. The color indicates the types of levels (institutional or ecological), and the size of the bubble indicates the number of studies reported for each year of analysis.

3. A social-ecological systems framework for studying tropical cattle ranching sustainability in Latin America

Figure 1. Approaches and concepts underlying the proposed framework.

Figure 2. Conceptual framework for the analysis of cattle ranching SES in Latin America.

Figure 3. The Silvopastoral Network's bovine SES, Chiapas, Mexico. Solid arrows indicate relationships, and the dotted arrows indicate feedback.

Figure 4. Range of progress in sustainability (1, 2, and 3) for the 12 descriptors by the nine-member associations (A1 – A9) in the Silvopastoral Network. The purple radars represent socio-economic descriptors, and the blue radars represent ecosystem services descriptors.

4. Assessing sustainable intensification for the planning and management of cattle ranching in the tropics: A case study in southern Mexico

Figure 1. Location of ranches in The Silvopastoral Network, and three regions described in Chiapas, Mexico.

Índice de Tablas:

3. A social-ecological systems framework for studying tropical cattle ranching sustainability in Latin America

Table 1. Application of the SALSA framework.

Table 2. Relationships and feedback in cattle ranching SES on land in Latin America.

Table 3. Descriptors, ranges of progress, and cattle ranching sustainability categories for the Silvopastoral Network. Colors and numbers indicate the sustainability category: 1-low, 2-medium, and 3-high.

4. Assessing sustainable intensification for the planning and management of cattle ranching in the tropics: A case study in southern Mexico

Table 1. Characterization of the Silvopastoral Network by production regions.

Table 2. Ecosystem services assessed.

Table 3. Management strategies, economic characteristics and location of cattle ranches.

Table 4. Standardized maximum likelihood coefficients relating the variables describing management strategies, economic characteristics, and ecosystem services with the sustainability of cattle ranches.

Material Suplementario

3. A social-ecological systems framework for studying tropical cattle ranching sustainability in Latin America

SM 1. Literature Review Excel Matrix

SM 1. Table 1. The questionnaire that guided the semi-structured interviews of the Silvopastoral Network.

SM 2. Table 1. Location of the Silvopastoral Network's nine cattle ranching member associations (A1-A9).

SM 2. Figure 1. Spatial distribution of the products produced by the Silvopastoral Network's cattle ranching members in the six socioeconomic regions in Chiapas, Mexico.

SM 2. Figure 2. Percentage of Producers per Association of the Silvopastoral Network

SM 2. Table 2. List of vegetation species.

SM 3. Table 1. Characterization of the ecological subsystem of the Silvopastoral Network's SES

SM 3. Table 2. Characterization of the Silvopastoral Network's social subsystem.

SM 3. Table 3. Characterization of the Silvopastoral Network's economic subsystem.

4. Assessing sustainable intensification for the planning and management of cattle ranching in the tropics: A case study in southern Mexico

SM1. Table 1. The questionnaire that guided the semi-structured interviews of the Silvopastoral Network (see supplementary information in the previous chapter).

SM2. Table 1. Eigenvalues of multiple factor analysis

SM2. Figure 1. Contribution of variables. Variables that contribute the most to Dim.1 and Dim.2 are the most important in explaining the variability in the data set.

SM2. Figure 2. Cluster plot showing the three clusters (outcome of the hierarchical cluster analysis) in the MFA component 1and 2 plane.

SM2. Table 2. Means and Kruskal-Wallis statistic values for the groups (types of cattle ranches) obtained in the hierarchical cluster analysis.

SM2. Table 3. Distribution in percent of the zones within the types of cattle ranches.

SM2. Table 4. Standardized maximum likelihood path coefficients linking location to management strategies and economic characteristics of cattle ranches.

SM2. Table 5. Standardized maximum likelihood path coefficients linking economic characteristics to management strategies and ecosystem services of cattle ranches.

SM2. Table 6. Standardized maximum likelihood path coefficients linking management strategies to economic characteristics and ecosystem services of cattle ranches.

Resumen

Los sistemas de producción de bovinos son sistemas socioecológicos (SSE) que otorgan a las personas y a las comunidades beneficios que pueden utilizar como parte fundamental de sus medios de vida y como un seguro para cubrir la alimentación en las zonas rurales. En los trópicos los sistemas de producción extensiva generan importantes impactos ambientales, entre los que destaca la expansión de las tierras de cultivo de forrajes y pastoreo como uno de los principales conductores de deforestación. La intensificación sostenible que consiste en producir más productos con un uso más eficiente de todos los insumos biofísicos y socioeconómicos involucrados en la producción (por ejemplo, mano de obra, recursos alimentarios o capital financiero) - de manera duradera en el tiempo – y a la vez reducir los daños ambientales y fortalecer el flujo de servicios ecosistémicos (SE), se presenta como una alternativa de gestión de las tierras agropecuarias en un mundo que exige aumentar la producción de alimentos. Sin embargo, para los trópicos de América Latina (AL) representa sobre todo una estrategia para conservar los bosques y sostener la provisión de SE esenciales para las poblaciones humanas. Como modelo de intensificación sostenible, los sistemas silvopastoriles (SSP) - sistemas de producción animal que incluyen árboles y arbustos asociados con gramíneas que forman un paisaje forrajero diverso de varios estratos de vegetación - son uno de los enfoques más prometedores para la planeación sostenible de la ganadería que usa tierra en los trópicos de AL.

El término “Intensificación Sostenible” ha sido objeto de profundos debates y confusión en cuanto a su significado y las características que determinan que existe sostenibilidad en sistemas de producción de pastoreo, manejados dentro de esquemas intensivos en contextos socioeconómicos y ecológicos diferenciales. Se ha argumentado que las prácticas agropecuarias han estado impulsadas principalmente por la "intensificación" y no tanto por la "sostenibilidad" que implicaría mejoras ambientales, económicas y sociales, por lo que delimitar las propiedades que impulsan y limitan la intensificación sostenibilidad de la ganadería bovina de pastoreo desde una visión integral ayudaría a posicionar a los SSP como una alternativa viable a la producción extensiva y representa un tema prioritario de

investigación. En México, la dominancia espacial de la ganadería extensiva y su expansión plantea retos de sostenibilidad (p. ej., degradación ambiental, deforestación y pobreza); y como sexto productor mundial de carne de bovino, la ganadería vacuna tiene un papel protagónico en el país. Los vacunos ocupan el 56% del territorio (109,8 millones de hectáreas) y 881.000 personas dependen de ganado de pastoreo para subsistir. Aunque los bovinos se distribuyen en las distintas regiones de México, un tercio de la producción se concentra en regiones tropicales en donde se maneja al ganado principalmente en sistemas extensivos con importantes implicaciones ambientales, sociales y económicas. El estado de Chiapas destaca como un modelo de estudio de avance en el establecimiento de SSP en contextos desafiantes que incluyen los más altos niveles de marginación del país, que se contraponen con los costos iniciales de inversión y el conocimiento técnico necesario para el silvopastoreo. En este proyecto de investigación se planteó como objetivo general identificar los principales componentes de la ganadería bovina en los trópicos de AL y la relación entre dichos componentes que podría influir en la transición hacia la intensificación sostenible. Para alcanzar dicho objetivo se propusieron cuatro objetivos particulares:

1. Identificar los abordajes teórico-conceptuales y analíticos y sus principales componentes para el estudio de la ganadería bovina en América Latina que permiten una visión integrada.

2. Identificar los componentes (ecológicos, sociales y económicos) que influyen en la intensificación sostenible de ranchos bovinos del trópico de América Latina desde el marco de sistemas socioecológicos en un caso de estudio de Chiapas, México.

3. Analizar las relaciones existentes entre los componentes ecológicos, sociales y económicos del sistema socioecológico ganadero bovino presentes en distintos niveles de intensificación y su influencia en la sostenibilidad de ranchos silvopastoriles en Chiapas, México.

4. Discutir sobre la comprensión de la ganadería bovina con menor costo ambiental como un desafío entre lo personal y lo político en el contexto del trópico mexicano.

Partiendo de una revisión sistemática de literatura, se identificó que el marco teórico de los SSE que implica una visión integrada ha sido incluido de manera incipiente (16%) en la investigación ganadera en AL. Además, se rastreó una desconexión entre el reconocimiento y la medición de la sostenibilidad y los SE como marcos holísticos de análisis. Aunque el 83% y 48% de los estudios mencionaron los conceptos, sólo 4% y 5% aplicaron un método para cuantificar la sostenibilidad y los SE, respectivamente (Objetivo 1). Sumado a la revisión sistemática de literatura, 350 entrevistas a productores de la Red Silvopastoril de Chiapas y un taller participativo permitieron proponer un marco conceptual de SSE para la ganadería tropical de la región. Los componentes del subsistema ecológico incluyen factores bióticos y abióticos entre los que destacan el suelo, la vegetación y el ganado que se gestionan a escala local mediante estrategias que emergen del SSE del que forman parte. Los productores, asociaciones ganaderas, reglas e instituciones son los componentes determinantes en el subsistema social. El subsistema económico se compone de la infraestructura, empleos, cadenas de comercialización, e ingresos generados en el SSE. El marco de SSE también propone una zona de interfaz con tres elementos clave de diagnosticar (multifuncionalidad, SE y acción colectiva) para promover transiciones hacia sistemas de producción de bovinos más sostenibles como los SSP (Objetivo 2).

Retomando la información que se obtuvo en las entrevistas, se tipificaron los ranchos silvopastoriles en un gradiente de intensificación, se analizó cómo se relacionan sus componentes y cómo contribuyen a la sostenibilidad ganadera en ranchos silvopastoriles. Los pequeños y medianos ranchos silvopastoriles mostraron provisiones intermedias y altas de SE que plantean un escenario más sostenible para la ganadería de pastoreo. En contraste, los grandes ranchos silvopastoriles mantienen una producción enfocada en maximizar la producción de bovinos y tienen una menor disponibilidad de vegetación, similar a lo que ocurre en las lógicas de producción extensiva en los trópicos. A través de un modelo de ecuaciones estructurales se evaluó la relación entre los principales componentes ecológicos, sociales y económicos, y se comprobó que comprende una cadena causal de forma que los componentes económicos (características económicas) influyen sobre los componentes sociales (estrategias de manejo) dificultando el silvopastoreo y causando afectaciones sobre los componentes ecológicos (provisión de SE). La consolidación de las cadenas de comercialización haciéndolas competitivas para los productores, la diversificación de los ranchos, la mejora de los ingresos, el aumento de la mano de obra con empleos más dignos y la frecuencia de la rotación del ganado son estrategias indispensables que apoyan la provisión de SE y la sostenibilidad en ranchos ganaderos (Objetivo 3).

El modelo de ecuaciones estructurales también mostró que minimizar el área ganadera y el énfasis productivo que tienen los SE de provisión (en este caso la producción de bovinos), al tiempo que se incremente la provisión de hábitat, sombra para el ganado, alimento para el ganado y conocimiento tradicional son aspectos que contribuyen directa y positivamente a la sostenibilidad de los ranchos. Esta configuración de estrategias implica reconocer que la producción ganadera tropical debe integrar prácticas agroforestales y contemplar un límite de oferta de carne y forraje para continuar sosteniéndose en el tiempo. En ese sentido, la intensificación sostenible a través del silvopastoreo es una alternativa para la ganadería extensiva siempre que garantice la provisión de todos los tipos de SE, contenga la deforestación y represente suficientes ganancias económicas para los productores (Objetivo 3).

Finalmente, a partir de la revisión se discutió sobre la ganadería como un tema personal/individual (intervenciones sociales) y político (intervenciones institucionales) para aportar evidencia teórica sobre las acciones que instituciones gubernamentales y la sociedad en general pueden sumar para promover sostenibilidad en la ganadería de pastoreo del trópico de México. Entre las acciones políticas destaca la formulación de leyes que concreten condiciones justas de compra y venta de ganado para los pequeños y medianos productores que suelen tener poco poder negociador, estrategias que promuevan la diversificación productiva, campañas informativas que visualicen una dieta balanceada con menores consumos de carnes y disminución del desperdicio, y apoyo técnico y financiero a los SSP. Las acciones personales pueden incluir la disminución de los consumos de carne y leche, producir con menor impacto ambiental, y reclamar acciones políticas encaminadas en la protección del medio ambiente y el mejoramiento de las condiciones sociales y económicas de los productores y sus familias (Objetivo 4).

Abstract

Cattle production systems are social-ecological systems (SES) that provide people and communities with benefits they can use as a fundamental part of their livelihoods and as insurance to cover food in rural areas. In the tropics, extensive production systems generate significant environmental impacts, among which the expansion of fodder crops and grazing lands stands out as one of the main drivers of deforestation. Sustainable intensification, which consists of producing more products with a more efficient use of all biophysical and socioeconomic inputs involved in production - in a lasting manner over time - while reducing environmental damage and strengthening the flow of ecosystem services (ES), is presented as an alternative for managing agricultural and cattle land in a world that demands increased food production. However, for the Latin American (LA) tropics, it represents a strategy for conserving forests and sustaining the provision of essential ES for human populations. As a sustainable intensification model, the silvopastoral systems (SPS) - animal production systems that include trees and shrubs associated with grasses that form a diverse forage landscape of various vegetation strata - are one of the most promising approaches to sustainable planning of cattle ranching in the tropical regions of LA.

The term "sustainable intensification" has been the subject of much debate and confusion regarding its meaning and the characteristics that determine sustainability in grazing cattle systems managed within intensive schemes in differential socioeconomic and ecological contexts. It has been argued that agricultural practices have been driven mainly by "intensification" and not so much by "sustainability," which would imply environmental, economic, and social improvements, so delimiting the properties that drive and limit the sustainability intensification of cattle grazing from an integral vision would help to position SPS as a viable alternative to extensive production and represents a priority research topic. In Mexico, the spatial dominance of extensive cattle ranching and its expansion pose sustainability challenges (e.g., environmental degradation, deforestation, and poverty); as the world's sixth largest beef producer, cattle ranching plays a leading role in the country.

Cattle occupy 56% of the territory (109.8 million hectares), and 881,000 people depend on grazing cattle for their livelihood. Although cattle ranching is distributed in different regions of Mexico, one-third of production is concentrated in tropical regions where cattle are managed in extensive systems with significant environmental, social, and economic implications. The state of Chiapas stands out as an exciting case of progress in establishing SPS in challenging contexts, including the highest levels of marginalization in the country, contrasted with the initial investment costs and the technical knowledge necessary for silvopastoralism. The general objective of this research project was to identify the main components of cattle ranching in the LA tropics and the relationship between these components that could influence the transition to sustainable intensification. To achieve the general objective, four specific objectives were proposed:

1. Identify the theoretical-conceptual and analytical approaches and their main components for studying cattle ranching in Latin America that allow an integrated vision.

2. To identify the components (ecological, social, and economic) that influence the sustainable intensification of cattle ranches in the Latin American tropics within the socio-ecological systems framework in a case study of Chiapas, Mexico.

3. To analyze the existing relationships among the ecological, social, and economic components of the socioecological cattle ranching system present in different levels of intensification and their influence on the sustainability of silvopastoral ranches in Chiapas, Mexico.

4. To discuss understanding cattle ranching with lower environmental costs as a challenge between the personal and the political in the context of the Mexican tropics.

Based on a systematic literature review, it was identified that the theoretical framework of SES implying an integrated vision has been incipiently included (16%) in livestock research in LA. Furthermore, a disconnect was observed between the recognition and measurement of sustainability and ES as holistic analysis frameworks. Although 83% and

48% of the studies mentioned the concepts, only 4% and 5% applied a method to quantify sustainability and ES, respectively (Objective 1). In addition to the systematic literature review, 350 interviews with producers of the Silvopastoral Network of Chiapas and a participatory workshop made it possible to propose a conceptual framework of ES for tropical cattle ranching in the region. The components of the ecological subsystem include biotic and abiotic factors, including soil, vegetation, and cattle, which are managed at the local scale through strategies that emerge from the SES of which they are a part. Producers, cattle associations, rules, and institutions are the determining components in the social subsystem. The economic subsystem comprises the infrastructure, jobs, marketing chains, and income generated in the SES. The SES framework also proposes an interface zone with three key elements to diagnose (multifunctionality, SE, and collective action) to promote transitions to more sustainable cattle production systems such as SPS (Objective 2).

Based on the information obtained in the interviews, the silvopastoral ranches were typified in a gradient of intensification, how their components are related, and how they contribute to cattle ranches sustainability were analyzed. Small and medium silvopastoral ranches showed intermediate and high supplies of ES that pose a more sustainable scenario for grazing livestock. In contrast, large silvopastoral ranches maintain production focused on maximizing cattle production and have lower vegetation availability, similar to the extensive production logics in the tropics. A structural equation model was used to evaluate the relationship between the main ecological, social, and economic components. It was found that it comprises a causal chain in such a way that the economic components (economic characteristics) influence the social components (management strategies), making silvopastoralism difficult and affecting the ecological components (provision of ES). Consolidating commercialization chains, making them competitive for producers, diversification of ranches, improvement of income, increase of labor with more dignified jobs, and frequency of livestock rotation are indispensable strategies that support the provision of ES and sustainability in cattle ranches (Objective 3).

The structural equation model also showed that minimizing cattle area and the productive emphasis of the SE provision (in this case, bovines) while increasing the provision of habitat, shade for cattle, feed for cattle, and traditional knowledge are aspects that contribute directly and positively to the sustainability of the ranches. This configuration of strategies implies recognizing that tropical livestock production must integrate agroforestry practices and contemplate a limit of meat and forage supply to continue sustaining itself over time. In this sense, sustainable intensification through silvopastoral systems is an alternative for extensive livestock production if it guarantees the provision of all types of ES, contains deforestation, and represents sufficient economic gains for producers (Objective 3).

Finally, based on the review, cattle ranching was discussed as an personal/individual and political issue to provide theoretical evidence on government institutions and society's actions to promote sustainability in pastoral cattle ranching in Mexico's tropics. Among the political actions (institutional interventions) are the formulation of laws that establish fair conditions for the purchase and sale of cattle for small and medium producers who usually have little negotiating power, strategies that promote productive diversification, information campaigns that visualize a balanced diet with lower meat consumption and reduced waste, and technical and financial support to the SPS. Personal actions (social interventions) should reduce meat and milk consumption, produce with less environmental impact, and call for political actions to protect the environment and improve the social and economic conditions of producers and their families (Objective 4).

Introducción

La actividad ganadera y sus impactos

Los sistemas pecuarios a escala global vienen en todas las formas y tamaños, desde pequeños agricultores que cortan la hierba para alimentar los animales en corrales, pasando por sistemas donde la vegetación nativa ha sido convertida en especies agronómicas y el alimento y el agua son suministrados durante todo el año o en ciertas épocas de escasez en sistemas estabulados o de pastoreo; hasta sistemas extensivos en los que los insumos son bajos, el ganado deambula por grandes áreas, se alimenta de la vegetación nativa y en gran medida se las arregla por sí solo (Gordon, 2018). Sin embargo, a nivel mundial, el 45% de la leche de vaca y cerca del 37% de la carne de bovinos se produce en sistemas extensivos de < 20 hectáreas manejadas por pequeños y medianos ganaderos que suelen tener poco apoyo institucional (Herrero et al., 2017). La problemática en torno a la ganadería es particularmente compleja por su naturaleza multiescalar, multitemporal y multisectorial. El alcance del sector ganadero como usuario de recursos naturales, fuente de sustento y motor del crecimiento económico ha sido objeto de una atención significativa en la última década (Steinfeld et al., 2006; Thornton, 2010; Herrero et al., 2010; 2013; 2016; 2018); y su relevancia en la provisión de alimentos, ingresos y empleos a la sociedad es ampliamente reconocida (Herrero et al., 2009; 2018; Mottet et al., 2017; Henry et al., 2018).

Las implicaciones económicas y sociales del sector se vislumbran al entender su papel como proveedor de servicios ecosistémicos (SE) indispensables en la dinámica diaria de los humanos, su impacto en términos territoriales y de consumo de recursos (Schneider et al., 2011). El sector pecuario proporciona sustento directo y beneficios económicos a 1,300 millones de productores y minoristas, y es la base de los medios de subsistencia para 1,000 millones de pobres en todo el mundo (Herrero et al., 2016). Los productos de la ganadería suministran un tercio del consumo mundial de proteínas y de la misma manera que contribuyen a la obesidad, son una posible solución a la desnutrición. Los productos ganaderos son la base para la alimentación de 800 millones de personas en condición de inseguridad alimentaria (Herrero et al., 2013), y aportan el 17% al balance global de la dieta de los humanos (Herrero et al., 2009). Como actividad económica, la ganadería contribuye en 40 - 50% al PIB agrícola a escala mundial (Steinfeld et al., 2006; Herrero et al., 2016). Las implicaciones económicas y sociales también se evidencian en la velocidad del crecimiento del sector, ya que el consumo mundial per cápita de productos ganaderos se ha más que duplicado en los últimos 40 años (Herrero et al., 2018).

Aunque la demanda global de carne está aumentando, esto ocurre a distintos ritmos y en regiones diferentes. En los Estados Unidos la tendencia del consumo per cápita está subiendo lentamente o incluso se están estancando, al tiempo que en Europa la tendencia muestra una disminución en la demanda de carne de vacuno en más de 10 millones de toneladas métricas desde 1990 (Herrerto et al., 2018). Por su parte, la tendencia de mayor crecimiento está ocurriendo en China, Brasil y la India como resultado de una clase media emergente e incentivos políticos (Ramankutty et al., 2018). A pesar de las tendencias, el promedio del consumo de China no se acerca ni a un tercio del promedio actual del consumo per cápita europeo. Las proyecciones de aumento de la población humana, de los ingresos y de la urbanización impulsarán aumentos en el consumo de leche y carne en los próximos años globalmente. Aunque hay poca claridad respecto a la ubicación puntual del aumento de la demanda per cápita de vacuno, se reconoce que la mayor parte del crecimiento de la producción ocurrirá en países tropicales en desarrollo que son actualmente los mayores proveedores de forrajes y en donde las tendencias de consumo per cápita van al alta (Herrero et al., 2018).

La ganadería impacta negativamente en prácticamente todos los aspectos del medio ambiente, incluyendo el cambio del uso de la tierra, la fertilidad del suelo, el agua, la biodiversidad, la multifuncionalidad y la contaminación atmosférica a través de las emisiones de gases de efecto invernadero (GEI) (Herrero et al., 2013; 2016; 2018; Gordon, 2018; Solorio et al., 2017). Las actividades pecuarias han sido incluidas en la mayoría de los ecosistemas del planeta, y su amplia distribución respalda la magnitud de gravedad de las afectaciones. El sector ganadero da forma a la agricultura de cultivo a través de su demanda de forrajes y piensos; de los casi 3,000 millones de hectáreas de tierras aptas para la producción de cultivos, se usan 1,500 millones de hectáreas para alimentar al mundo, y un tercio de esta superficie se destina a la producción de forrajes para el ganado (FAOSTAT, 2018). Además, aproximadamente 20 mil millones de animales hacen uso del 30% de la superficie terrestre libre de hielo para el pastoreo (Herrero et al., 2016), por lo que se reconoce que la ganadería ocupa alrededor del 70% del total de la superficie agrícola (Van Zanten et al., 2018), y usa una gran cantidad de agua dulce en los procesos de producción (~8% del agua mundial) (Eshel et al., 2014). La estructura y funcionamiento de los suelos, incluida la porosidad, la química, la microbiología, los ciclos de nutrientes, la productividad y las tasas de erosión también son impactados por la ganadería (Smith et al., 2014).

El pisoteo del ganado aumenta la compactación y la erosión, y tras la pérdida de los primeros horizontes del suelo se reducen los almacenes de nutrientes y los niveles de materia orgánica a largo plazo. Estas afectaciones en conjunto han reducido el potencial productivo global de la ganadería en un 19%, y sumadas a las prácticas de producción predominantemente extensivas y a los patrones de consumo globales, han hecho que los suelos se encuentren bajo una creciente presión de deterioro (Smith et al., 2014). La relación entre la ganadería y la atmósfera ha sido abordada desde la problemática de las emisiones de GEI por representar una amenaza para la producción futura de alimentos (IPCC, 2013; Springmann et al., 2018). La producción de alimento es responsable del ~26% de las emisiones globales de GEI. De ese porcentaje, la ganadería de vacuno (por gestión del estiércol y pastos) representa el 31% de las emisiones de GEI asociadas a la producción. Otro 6% de las emisiones proviene de la producción de forrajes, y 16% resultan del uso de la tierra para la ganadería, sin contar el papel de los gases que se emiten en las cadenas de suministro (~18%) (Ritchie, 2019).

La sostenibilidad de la ganadería tropical

En los países tropicales de economias emergentes, para los productores de bajos ingresos la mejora de los rendimientos e ingresos son prioridades que con frecuencia se ven obstaculizadas por el capital económico insuficiente que minimiza las capacidades humanas y de infraestructura, y el constante abandono institucional. Además, los esquemas de producción predominantemente extensiva plantean desafios en las tres dimensiones de la sostenibilidad: ambiental, social, económica. En el contexto ganadero, la sostenibilidad implica que los sistemas sean respetuosos con el medio ambiente, económicamente viables para los ganaderos y socialmente aceptados (Lebacq et al., 2013; Broom, 2016). Sin embargo, la sostenibilidad suele ser compleja de definir y medir, y por tanto de gestionar en la realidad. Por el contrario, la insostenibilidad de la ganadería ha sido ampliamente reconocida y aunque sus particularidades varían espacialmente, las nociones de mejoras socioecológicas han sido generalizadas a escala global y las opciones propuestas han sido planteadas desde el norte global (Herrero et al., 2018). En ese sentido, el abordaje de la ganadería tropical, y en concreto de su sostenibilidad, requiere un análisis integrador y localizado que permita caracterizar cuestiones ecológicas, sociales, económicas y espaciales clave que orienten la producción y comercialización de bovinos sobre vías que permitan tendencias más sostenibles; y que contribuyan a la resolución de problemáticas propias de la región latinoamericana. El enfoque teórico de los sistemas socioecológicos puede ser útil en la medida en que se reconozca a la sostenibilidad como una propiedad que emerge de la interacción entre los componentes de un sistema y sus interrelaciones con el entorno que terminan por definir procesos y retos a diferentes escalas territoriales (Ruggerio, 2021). De esa manera, se puede lograr evaluar sistemáticamente opciones futuras, asignar valores para las opciones a través de la construcción de indicadores, y personalizar estrategias para fabricar opciones específicas a cada contexto (Redman, 2014).

Los trópicos y subtrópicos son el hogar de gran parte de las tierras de pastoreo del mundo y de algunos de los pueblos más pobres que dependen de esas tierras para su seguridad alimentaria y para cubrir sus medios de vida (Gordon, 2018). El ganado bovino es fundamental para satisfacer las necesidades nutricionales de estas regiones, en donde los factores socioeconómicos, incluida la dependencia de la producción local de alimentos y la vulnerabilidad a la degradación de las tierras, aumentan el riesgo de inseguridad alimentaria (Henry et al., 2018). El pastoreo en sistemas extensivos (Figura 1) es el principal modo de producción en el trópico. Los sistemas ganaderos extensivos de doble propósito (producción de carne y leche) predominan en las regiones tropicales y están basados en monocultivos de pastos inducidos (pasturas) que suelen tener baja productividad (Bacab et al., 2013). El establecimiento de grandes áreas despejadas en los trópicos en las que sólo se cultivan plantas herbáceas como forraje, se suma infraestructura básica para alojar a los animales o materiales relacionados con la producción implican superficies de bosques y selvas deforestadas (Quero et al., 2007; Steinfeld et al., 2006; Bacab et al., 2013). La expansión de las pasturas ganaderas incluye remoción de árboles y arbustos, e introducción de plantas no-nativas que comprende una o un número muy pequeño de especies (Arroyo-Rodríguez et al., 2017). Para mantener las pasturas tropicales, los herbicidas son utilizados frecuentemente y con ellos la biodiversidad disminuye (Bacab et al., 2013). La producción ganadera en grandes extensiones ocupaba más del 27% de los paisajes rurales de América Latina (AL) en 2010 (Murgueitio et al., 2011) y sigue ampliándose (Herrero et al., 2018).

La ganadería tropical en América Latina

La forma de producir, transformar, distribuir, y consumir carne y leche de vacunos es un tema prioritario de investigación (Ellis et al., 2019), especialmente para las zonas tropicales de AL. A escala planetaria, el sector ganadero sigue creciendo velozmente por el aumento en la demanda mundial de productos ganaderos a consecuencia del incremento de los ingresos, el crecimiento demográfico y la urbanización (Alexandratos & Bruinsman, 2012). Se prevé que la producción de carne de rumiantes, especialmente de carne de vacuno en AL crezca un 125% en 2050 en comparación con la producción reportada en el año 2000 (Herrero et al., 2018); y que el abasto se cubra desde el sur global donde la producción vacuna ya es significativa (Lerner et al., 2017; Arango et al., 2020). El crecimiento del sector ganadero en las zonas tropicales se ha debido al establecimiento de extensas zonas de pastoreo para aumentar el número de animales (Herrero et al., 2018); sin embargo, la ganadería no siempre se concibió a través de grandes extensiones de pastos.

El ganado vacuno llegó a AL junto con los colonos europeos; la primera especie introducida fue el *Bos taurus* con mínimos requerimientos de extensión de pastos, por lo que los SSP predominaron el paisaje durante más de 400 años hasta la introducción del ganado cebú (*Bos indicus*) (Guevara & Lira-Noriega, 2011), es decir, los SSP son en AL la manera más antigua de producir ganado y no las pasturas extensivas como se suele pensar. La sustitución del tipo de ganado junto con la revolución verde (disponibilidad de máquinas y fertilizantes) condujeron a la apertura masiva de pastos en detrimento de la vegetación natural, y favorecieron la deforestación de grandes extensiones del territorio. Desde entonces, la ganadería ha transformado los ecosistemas y promovido la plantación de especies exóticas de pastos procedentes de África y Asia (Hernández, 2001; Herrero et al., 2016). Los problemas ambientales causados por la ganadería en AL son en parte el resultado de la transformación de ecosistemas naturales en pastizales con gramíneas exóticas, algunas de ellas invasoras o potencialmente invasoras (D'Antonio & Vitousek, 1992).

La región latinoamericana destaca por haber presentado una de las mayores expansiones de la frontera agropecuaria en los últimos 50 años (78%) concentrada en las zonas tropicales (Herrero et al., 2018) para satisfacer la demanda de alimentos de origen animal y apoyar la seguridad alimentaria regional y mundial (FAO, 2017). Aunque AL representa sólo el 16% de la población total del mundo y el 34% de la población rural, posee el 67% de las cabezas de ganado para producción de carne y el 76% para producción de leche. Con ello, genera el 30% de la carne y el 28% de la leche bovina del planeta (FAO, 2019). En las regiones tropicales de AL, la vulnerabilidad socioeconómica, la degradación del suelo, el uso extensivo de la tierra y la variabilidad climática crean importantes retos de sostenibilidad para el sector ganadero (Figueroa et al., 2022).

Las alternativas de manejo en los trópicos

Las principales alternativas a la producción extensiva incluyen los enfoques de ganadería sostenible que integra la dimensión ambiental, social y económica y dentro de la cual se anida el marco de intensificación sostenible (Rademaker et al., 2017), la ganadería climáticamente inteligente que busca establecer sinergias entre la productividad, la mitigación de emisiones GEI y adaptación al cambio climático, y la ganadería regenerativa enfocada en reestablecer procesos ecológicos (Germer et al., 2023). El término "intensificación sostenible" se originó a partir de esfuerzos que apuntaban a aumentar la productividad de la agricultura subsahariana en la década de 1990 (Pretty, 1997). Se utilizó en el contexto de aumentar la producción de tierras agrícolas existentes de manera que se redujera el impacto ambiental y se detuviera la conversión de tierras o pérdida de ecosistemas (Campbell et al., 2014). La intensificación sostenible consiste en producir más productos con un uso más eficiente de todos los insumos biofísicos y socioeconómicos (por ejemplo, mano de obra, recursos alimentarios o capital financiero) - de manera duradera en el tiempo – y a la vez reducir los daños ambientales y fortalecer la capacidad de recuperación y el flujo de SE (The Montpellier

Panel, 2013). Esto significa que se intensifican la producción real, o el rendimiento por unidad de superficie y también la provisión de los SE, lo que conlleva al aumento de los beneficios por unidad de superficie (Lerner et al., 2017). Rao et al. (2015) discutieron que la intensificación sostenible de los sistemas ganaderos de pastoreo incluye varios procesos de intensificación, dentro de ellos el despliegue de razas ganaderas productivas, y el desarrollo y uso de gramíneas y leguminosas de mayor producción de biomasa, valor nutritivo y persistencia en relación con los pastos.

En los trópicos una clave para la intensificación sostenible exitosa de los sistemas de pastoreo es la selección adecuada de especies forrajeras, por ejemplo, *Leucaena leucocephala*, Lam., un fijador de nitrógeno ampliamente usado dentro de sistemas silvopastoriles (SSP) de AL (Dumont et al., 2018). Los SSP destacan por ser sistemas de producción animal que incluyen árboles y arbustos asociados con gramíneas que forman un paisaje forrajero de varios estratos de vegetación (Murgueitio et al., 2011) (Figura 1).

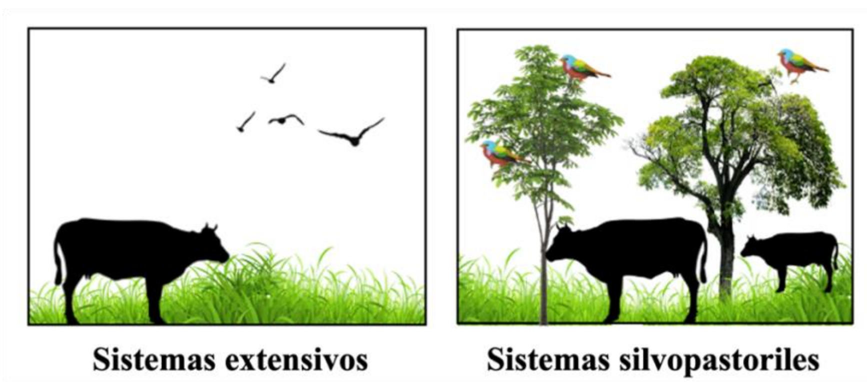

Figura 1. Principales sistemas de producción de pastoreo en los trópicos.
Fuente: Elaboración propia.

Los SSP se extienden desde los menos intensivos (SSP tradicionales) desarrollados localmente con los recursos disponibles e incluyen árboles y arbustos dispersos, hasta los más intensivos (SSP mejorados) que contienen pastos, alta densidad de arbustos y árboles altamente nutritivo (>10.000 plantas ha^{-1}), que proporcionan forraje, sombra, y fijación de nitrógeno atmosférico (Murgueitio et al., 2011; Broom et al., 2013); bancos de forraje que reducen la necesidad de concentrados de granos, y cercas vivas que delimitan potreros, proporcionan madera y forrajes adicionales (Fuentealba & González-Esquivel, 2016). Los

SSP tradicionales y los SSP mejorados se conciben como sistemas multifuncionales que resultan de la coevolución histórica entre las comunidades locales y su entorno (Plieninger & Huntsinger, 2018), conformando una configuración paisajística diversificada que fomenta el suministro de SE (Venturi et al., 2021). Como esquema de producción modelo de intensificación sostenible en los trópicos de AL, los SSP podrían ser una alternativa a los sistemas extensivos, pero esto sigue siendo objeto de debate debido a la necesidad de establecer umbrales locales y hacer frente a la incertidumbre sobre la gestión de posibles incentivos perversos y disyuntivas (Lerner et al., 2017).

Aunque actualmente no es discutible que es prioritario "producir alimentos con menos impactos ambientales" mediante una ganadería que no se expanda, utilice mejor y cada vez menos insumos y minimice los impactos en los ecosistemas (Lal, 2023). Sigue siendo necesario visualizar límites de producción para los trópicos y de consumo de ganadería a escala planetaria; y desarrollar indicadores de intensificación sostenible en función de tipos y escalas específicas (Mahon et al., 2017). Además, es importante entender que aunque la intensificación sostenible logre el cierre de las brechas de rendimientos, contenga la deforestación y sostenga la provisión de diversos tipos de SE (Dumont et al., 2018), será insuficiente porque satisfacer las demandas proyectadas del crecimiento demográfico requerirá mejorar la distribución y el acceso a los alimentos, así como la infraestructura del mercado, lo que implicará cambios en las políticas y los mecanismos globales que rigen el sistema alimentario (Foley et al., 2011).

Los beneficios ecológicos, sociales y económicos de los SSP han sido documentados (p.ej. tienen la capacidad de reducir emisiones GEI, conservan la cubierta vegetal evitando la deforestación, aumentan los rendimientos que generan ingresos complementarios) (Chará et al., 2019; Calle, 2020), han tenido bajas tasas de adopción principalmente porque los pequeños productores no pueden hacer frente a los costos iniciales de inversión, tienen pocas capacidades técnicas y presentan arraigo cultural a los sistemas extensivos (Calle, 2020; Van Loon et al., 2020). En general, los productores en zonas tropicales a menudo tienen un capital financiero y social limitado, infraestructura modesta, pocas opciones para diversificar los medios de subsistencia más allá del pastoreo de ganado, y están aislados de los principales centros urbanos e instituciones gubernamentales, lo cual los segrega del acceso a rutas comerciales y a subsidios que pudieran permitir el cambio de práctica de producción hacia algunas que conserven a los ecosistemas (Sayre et al., 2013). En ese sentido, existe un diálogo global que enfrenta el dilema de aumentar la producción de alimentos sin destruir el medio ambiente, y se ha planteado que para minimizar el impacto ambiental hay que centrarse en la intensificación sostenible (Foley et al., 2011).

La definición de sostenibilidad dentro del marco de la intensificación sostenible aborda en gran medida la reducción de los efectos nocivos, y presta menor atención a producir resultados ambientales positivos (Dumont et al., 2018). La intensificación sostenible se ha convertido en un concepto controvertido con respecto a su significado preciso, medios de implementación y resultados deseados (Mahon et al., 2017). Algunos autores sostienen que la intensificación sostenible podría favorecer a los grandes productores en detrimento de los pequeños agricultores y del público en general (Cook et al., 2015) y otros afirman que la intensificación no es compatible con la sostenibilidad (Lewis-Brown & Lymberry, 2012). A pesar de las preocupaciones asociadas, la intensificación sostenible en el contexto de los trópicos apunta a reservar tierra para los ecosistemas, ya que la mayor parte de los suelos cultivables disponibles se encuentran debajo de bosques tropicales, en donde la conversión a la agricultura y ganadería es altamente indeseable (Dumont et al., 2018). Respecto a ello, los SSP son el enfoque más prometedor para la planeación sostenible de las regiones tropicales, y representan el modelo de intensificación sostenible en los trópicos de AL en donde podrían permitir la producción ganadera en el largo plazo (Lerner et al., 2017).

La ganadería en México

México destaca como el sexto productor mundial de carne de bovino, con 35 millones de cabezas de ganado que ocupaban en 2020 el 56% de su territorio para pastoreo (109,8 millones de hectáreas) y en donde 881.000 personas dependen del pastoreo de bovinos para su subsistencia (SIAP-SADER, 2020). En el trópico mexicano se concentra un tercio del hato ganadero del país (SIAP, 2018), manejado principalmente dentro de sistemas extensivos. En estos sistemas pastan en promedio 0.5 bovinos por hectárea (FAOSTAT, 2018), con implicaciones significativas para la sostenibilidad ambiental y social del país (Rivera-Huerta et al., 2016; 2019; Figueroa et al., 2020). Sin embargo, algunos esfuerzos campesinos han logrado establecer SSP tradicionales, principalmente por el fortalecimiento de la gobernanza a través de alianzas entre diferentes sectores sociales (p. ej., productores, agencias de desarrollo, academia y gobierno) resultante de acciones colectivas impulsadas por la necesidad de aprovechar la vegetación disponible, y la existencia de una economía menos orientada al mercado y, por lo tanto, con menos recursos disponibles para la compra de insumos (Jiménez-Ferrer et al., 2008; Apan-Salcedo et al., 2021).

El establecimiento de SSP en el trópico mexicano ha permitido a pequeños y medianos productores hacer frente a las altas temperaturas y a los cambios en la frecuencia y magnitud de las lluvias la mayor parte del año (Figueroa et al., 2020). Sin embargo, en México, como en el resto de los países tropicales de AL, las políticas públicas no han apoyado acciones que promuevan el establecimiento generalizado de SSP (Figueroa et al., 2020; 2022). Un caso interesante de avance en el escalamiento de SSP se localiza en Chiapas (Apan-Salcedo et al., 2021), un estado del sur de México que ubicado entre los paralelos 14 y 17 N, y los meridianos 90 y 94 W; entre las planicies de Tabasco al norte y el océano Pacífico al sur. Limita al este con los ríos Usumacinta y Suchiate y la cordillera de Montes Cuchumatanes, y al oeste con los estados de Veracruz y Oaxaca. El territorio chiapaneco posee 75,634 km^2 en los que presenta una morfología compleja, formada por extensas zonas montañosas que soportan diversos climas y suelos (INEGI, 2016). El 54% de Chiapas tiene un clima cálido húmedo, el 40% tiene un clima cálido subhúmedo y el 6% restante tiene un clima templado húmedo. La temperatura media anual varía según la región entre 17ºC y 30ºC. Las comunidades vegetales integran 17 tipos de vegetación e incluyen 1,516 especies de árboles (INEGI, 2016).

Chiapas tiene 5.464.136 habitantes, de los cuales el 76,4 % se encuentran en alguna categoría de pobreza (CONEVAL, 2018). La ganadería es la actividad primaria más importante en el estado (Orantes-Zebadúa et al., 2014) y se enmarcan en una economía de subsistencia, en la que predomina el autoconsumo y el empleo parcelario con una notable participación de la fuerza de trabajo familiar. Cada integrante de la familia tiene un rol importante en las unidades de producción (p. ej., pastoreo, ordeña, limpieza, preparación del suelo, cercado, etc.) (Jiménez-Trujillo et al., 2018). El estado ocupa el cuarto lugar en volumen de producción de carne en canal de bovino a nivel nacional (105,521 toneladas)

(SIAP, 2018), y la comercialización se realiza en los centros de acopio donde convergen todos los agentes de la cadena productiva de carne de bovino (Zebadúa & Nández, 2016). El 59% de las transacciones de venta de ganado se realiza a intermediaros locales o regionales que retienen entre el 10 y el 30 % de la ganancia en cada venta (Calderón et al., 2012), el 39% del ganado se vende directamente al consumidor local y el 2% de las ventas restantes se hacen a otro tipo de comprador (e.g., rastros, carnicerías regionales, etc.) (INEGI, 2017).

La Red Silvopastoril (Red de Organizaciones Agropecuarias Silvopastoriles del Estado de Chiapas S.A. de C.V) fue creada como una iniciativa sin fines de lucro en 2014. Agremia 350 productores de bovino que pertenecen a 9 asociaciones ganaderas - *agrupaciones de productores legalmente constituidas* - distribuidas en 6 regiones socioeconómicas y municipios de Chiapas (Tabla 1 y Figura 2).

Tabla 1. Localización de las asociaciones agremiadas en la Red Silvopastoril.

Municipio	**Región socioeconómica**	**Asociaciones**	**Localización y altitud**
Ocosingo	Selva Lacandona	AGL Frontera Corozal; SG Lekil wakax; SG Santa Helena-Taniperla; AGL Cuenca Rio Jatate	16°54'26" Latitud Norte 92°05'46" Longitud Oeste **888 m.s.n.m**
Maravilla Tenejapa	Meseta Comiteca	AGL Frontera Sur Maravilla Tenejapa	16°08'21" Latitud Norte 91°17'44" Longitud Oeste **400 m.s.n.m**
Marqués de Comillas	Maya	AGL Río Lacantún	16°19'56" Latitud Norte 90°45'55" Longitud Oeste **133 m.s.n.m**
Tecpatán	Norte	SG La Pomarrosa	17°08'10" Latitud Norte 93°18'40" Longitud Oeste **311 m.s.n.m**
Mezcalapa	Mezcalapa	SG Grupo Malpaso	17°11'18" Latitude Norte 93°36'21" Longitud Oeste, **136 m.s.n.m**
Pijijiapan	Istmo Costa	SG Las Cañas	15°41'12" Latitude Norte 93°12'33" Longitud Oeste **57 m.s.n.m**

Notas: AGL: Asociación ganadera local; **SG:** sociedad ganadera.

La Red silvopastoril pretende hacer frente al exceso de intermediarios encontrando espacios y formas de comercialización de productos que se generan en SSP y promover escenarios ganaderos más sostenibles en el sur de México. Estas motivaciones de agregación ya han sido documentadas, de hecho las iniciativas iniciales de asociación de los productores agrícolas y pecuarios comprenden acciones colectivas para combatir las condiciones asimétricas del mercado (Grashuis & Skevas, 2023). Debido a las enormes diferencias de escala con los grandes compradores y vendedores, los productores agrícolas suelen unirse a organizaciones para mejorar el acceso a los mercados de insumos y productos y obtener precios justos, especialmente en los países con economías emergentes (Grashuis & Su, 2019). El efecto positivo de la organización de los productores es especialmente notable a nivel de rancho, ya que fortalece la inversión en suelo orgánico y vegetación (Ma et al., 2018), mejora los ingresos (Bachke, 2019), la productividad (Chagwiza et al., 2016), la adopción de tecnologías (Manda et al., 2020) y la eficiencia de la producción (Olagunju et al., 2021).

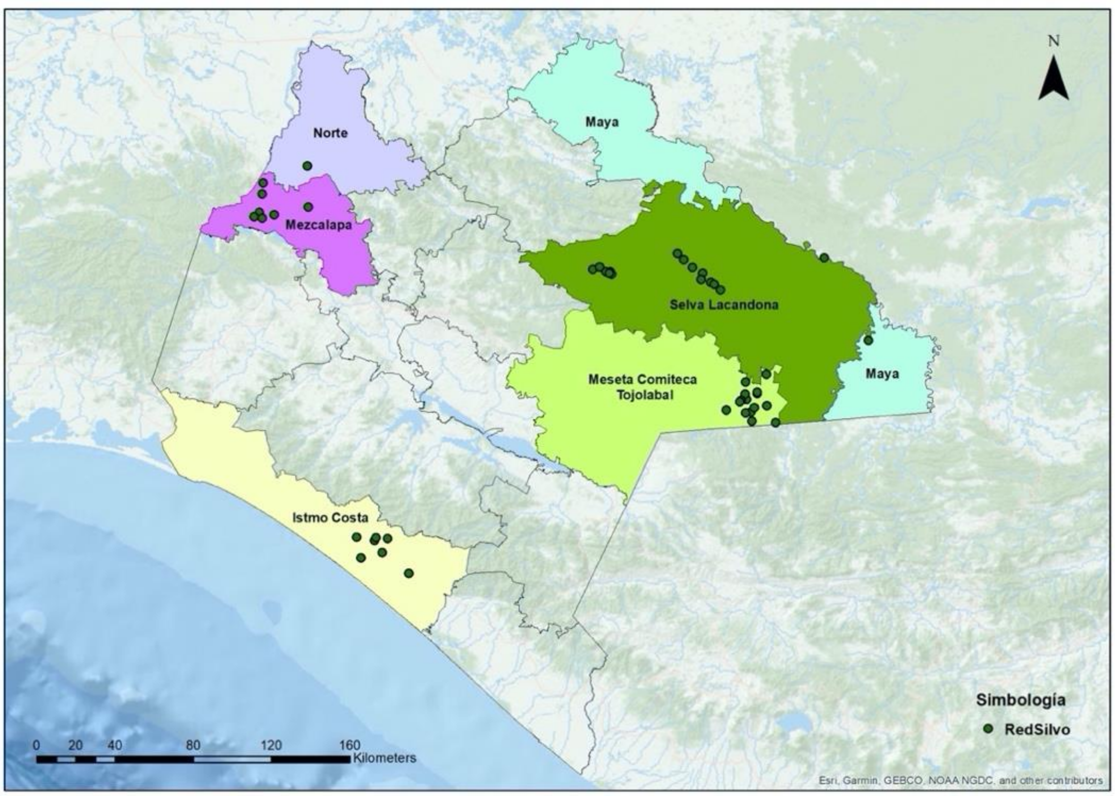

Figura 2. Localización de la Red Silvopastoril de Chiapas.

Fuente: Elaboración propia.

Las discusiones sobre lo que podría ser sostenible e implicar la sostenibilidad de la intensificación han sido principalmente de arriba hacia abajo, lo cual ha reflejado una multitud de opiniones individuales. De hecho, los intentos de contextualizar tales debates basándose en las opiniones de múltiples partes interesadas son raros (Dumont et al., 2018), a pesar de que se reconoce que la ausencia de una visión compartida entre las partes puede obstaculizar transiciones exitosas hacia la sostenibilidad (Mahon et al., 2021). En ese sentido, trabajar con asociaciones y redes de productores como la Red Silvopastoril, permite dimensionar lo que significa la sostenibilidad en contextos locales, y delimitar con quienes tienen experiencia en el manejo de los SSP (de abajo hacia arriba) aquellas cuestiones que promueven e impiden el establecimiento de estrategias de producción y comercialización de bovinos más sostenibles en el trópico de México.

Retos de investigación

En la teoría la intensificación sostenible busca la conciliación de la gestión de los recursos naturales y la producción de alimentos a largo plazo y en condiciones de incertidumbre climática (Dumont et al., 2018). Sin embargo, existe confusión en cuanto a las características de los sistemas de producción que son indicadores de intensificación sostenible en contextos diferenciales (Mahon et al., 2017), lo cual hace imprescindible reconocer dentro de los diferentes tipos de SSP niveles de intensificación que promueven en menor y mayor medida beneficios socioecológicos. Además, sabiendo que el análisis de la sostenibilidad debe abordar los conductores biofísicos y socioeconómicos de cambio que suelen ser mediados por las decisiones humanas, dinámicas institucionales y esfuerzos de acción colectiva en los territorios (Redman, 2014), hace falta identificar los principales componentes ecológicos, económicos y sociales inherentes a los sistemas socioecológicos que se retroalimentan a través de las escalas espaciales. Esto representaría evidencia teórica sobre las condiciones sociales, ambientales y económicas concretas que hacen posible y limitan transiciones hacia escenarios más sostenibles dentro de manejos intensivos del ganado de pastoreo, con las cuales se podrían demandar cambios políticos en los territorios y delimitar nuevos retos de investigación (Milán & González, 2022).

Lograr visibilizar la importancia del establecimiento de SSP insertos en paisajes multifuncionales en los trópicos y promover un debate ascendente y sensible a los diversos actores involucrados también representa un desafío (Mahon et al., 2021). Reconocer la importancia que tiene el compromiso del sector privado y las acciones políticas (intervenciones institucionales) y las acciones individuales/personales (intervenciones sociales) son cuestiones esenciales para impulsar escenarios agropecuarios más sostenibles (Godfray & Garnett, 2014; Escribano et al., 2016). En ese sentido, como reto de investigación, sigue haciendo falta abordar la intensificación sostenible de la ganadería bovina desde una visión integral y ascendente para posicionar a los SSP como una alternativa viable a la producción extensiva en ranchos tropicales de América Latina. Por lo anterior se proponen las siguientes preguntas y objetivos de investigación.

Preguntas y objetivos

- **Pregunta general**

¿Cuáles son los principales componentes de la ganadería bovina en los trópicos de América Latina y la relación entre ellos que podría influir en la transición hacia la intensificación sostenible?

- **Preguntas particulares**

1. ¿Cuáles han sido los abordajes teórico-conceptuales y analíticos y sus principales componentes para el estudio de la ganadería bovina en América Latina que permiten una visión integrada?

2. ¿Qué componentes influyen en la intensificación sostenible de ranchos bovinos del trópico de América Latina desde el marco de sistemas socioecológicos?

3. ¿Cómo son las relaciones entre los componentes ecológicos, sociales y económicos del sistema socioecológico ganadero bovino presentes en distintos niveles de intensificación y cómo influyen en la sostenibilidad de ranchos silvopastoriles en Chiapas, México?

4. ¿De qué manera se puede comprender a la ganadería bovina con menor costo ambiental como un desafío entre lo personal y lo político en el contexto del trópico mexicano?

Como **hipótesis de investigación**, se plantea que los principales componentes de la ganadería bovina en los trópicos de América Latina que influyen en la transición hacia la intensificación sostenible son los ecológicos, sociales y económicos. La relación entre ellos comprende una cadena causal de forma que, los componentes económicos influyen sobre los componentes sociales dificultando la intensificación sostenible y causando afectaciones sobre los componentes ecológicos. A partir de este planteamiento se deriva como **objetivo general** del trabajo identificar los principales componentes de la ganadería bovina en los trópicos de América Latina y la relación entre ellos que podría influir en la transición hacia la intensificación sostenible.

- **Objetivos particulares**

1. Identificar los abordajes teórico-conceptuales y analíticos y sus principales componentes para el estudio de la ganadería bovina en América Latina que permiten una visión integrada.

2. Identificar los componentes (ecológicos, sociales y económicos) que influyen en la intensificación sostenible de ranchos bovinos del trópico de América Latina desde el marco de sistemas socioecológicos en un caso de estudio de Chiapas, México.

3. Analizar las relaciones existentes entre los componentes ecológicos, sociales y económicos del sistema socioecológico ganadero bovino presentes en distintos niveles de intensificación y su influencia en la sostenibilidad de ranchos silvopastoriles en Chiapas, México.

4. Discutir sobre la comprensión de la ganadería bovina con menor costo ambiental como un desafío entre lo personal y lo político en el contexto del trópico mexicano.

A continuación se describe brevemente el contenido de los cinco capítulos de la tesis y su relación con los cuatro objetivos particulares de la investigación (Figura 3).

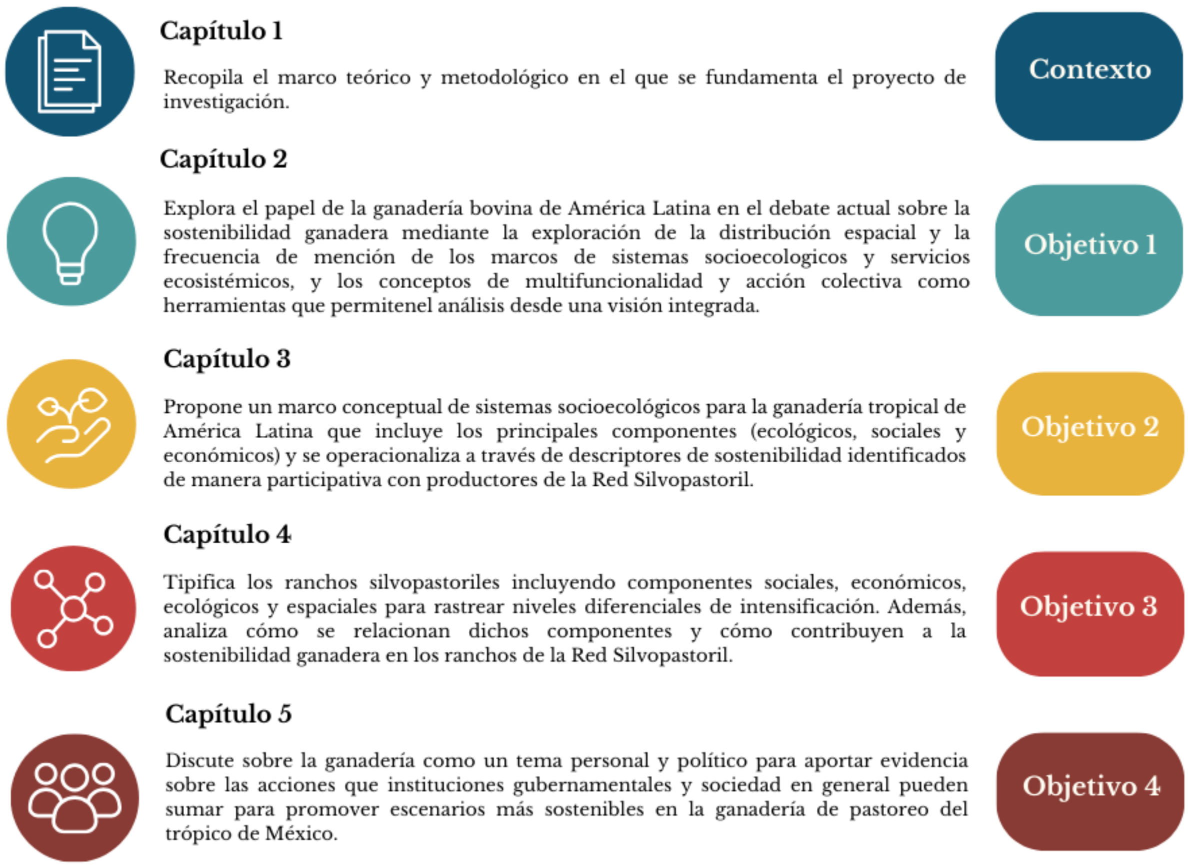

Figura 3. Síntesis capitular de la tesis.

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Capítulo 1

Marco Teórico y Metodológico

1. Abordajes Teóricos de la Intensificación Sostenible

La intensificación sostenible abarca la investigación disciplinaria específica en temas que van desde la ciencia de los cultivos hasta la agronomía, la ecología, la economía, los estudios rurales y más (Thomson et al., 2019). Sin embargo, las prácticas agrícolas y pecuarias parecen seguir estando impulsadas principalmente por la "intensificación" y no tanto por la "sostenibilidad" que suele quedar relegada a una posición discursiva (Norton, 2016; Perevochtchikova et al., 2019), por lo que evaluar la intensificación sostenible desde su impacto en la sostenibilidad a diversas escalas espaciales representa un reto actual de investigación que requiere de una visión integral (Thomson et al., 2019). Existen pocas sugerencias en la literatura sobre lo que debería comprender un abordaje holístico y de base amplia para la intensificación sostenible (Mahon et al., 2018). Sin embargo, se reconoce que la aplicación de enfoques integrados plantea desafíos teóricos y metodológicos a nivel científico, así como otras cuestiones a nivel social y político (Perevochtchikova et al., 2019). En ese sentido, el marco conceptual de los sistemas socioecológicos (SSE) hace frente a dichos desafíos en la medida en que conduce al análisis de las condiciones sociales, ambientales y económicas presentes en distintos sistemas de producción, y podría permitir el ajuste de estrategias de intensificación que sean compatibles con la sostenibilidad ambiental, social y económica (Rudel, 2020).

1.1 Sistemas Socioecológicos (SSE)

Los ecosistemas y los sistemas sociales son redes complejas de componentes vinculados por procesos dinámicos y están abiertos a intercambios a través de sus fronteras por conectividad (Limburg et al., 2002). A pesar de estas similitudes, los seres humanos y los ecosistemas han sido abordados históricamente por separado, generalmente bajo una perspectiva de desarrollo contra conservación; sin embargo, dicha separación es arbitraria cuando se analiza el uso sostenible y el disfrute de los beneficios que obtiene la sociedad de los ecosistemas (Berkes & Folke, 1998). Existen varias formas de articular la noción de lo que es entendido como un SSE: relaciones naturaleza-sociedad, sistemas naturales-humanos acoplados, relaciones humano-ambientes; sistemas socioambientales, entre otros (Ávila-Foucat & Perevochtchikova, 2019). Los SSE se caracterizan en un sentido básico por contener: (1)

componentes (que en su conjunto constituyen la estructura de un sistema), (2) interacciones entre ellos, que generan procesos del sistema (funcionamiento), y (3) al ser sistemas abiertos generan flujos que cruzan las fronteras del sistema. Entre estas características, las interacciones (de componentes, procesos o sistemas con otros sistemas) son responsables de la aparición de comportamientos intrincados.

En un sentido básico los SSE son sistemas adaptativos complejos de humanos (subsistema social) y naturaleza (subsistema ecológico), que se componen de módulos individuales heterogéneos que interactúan localmente y evolucionan (física, conductual o espacialmente) como resultado de esas interacciones (Figura 1) (Martín-López, et al., 2009; Colding & Barthel, 2019). Sin embargo, poseen características en un sentido más amplio: 1) procesos biogeofísicos y socioculturales integrados, 2) autoorganización, 3) dinámicas no lineales e impredecibles, 4) retroalimentación entre procesos sociales y ecológicos, 5) comportamiento cambiante en el espacio y en el tiempo (umbrales espacio-temporales), 6) efectos de comportamiento heredado con resultados en escalas temporales diferentes, 7) propiedades emergentes, y 8) la imposibilidad de extrapolar la totalidad de información de un SSE a otro por ser contexto-específico (Delgado-Serrano & Ramos, 2015).

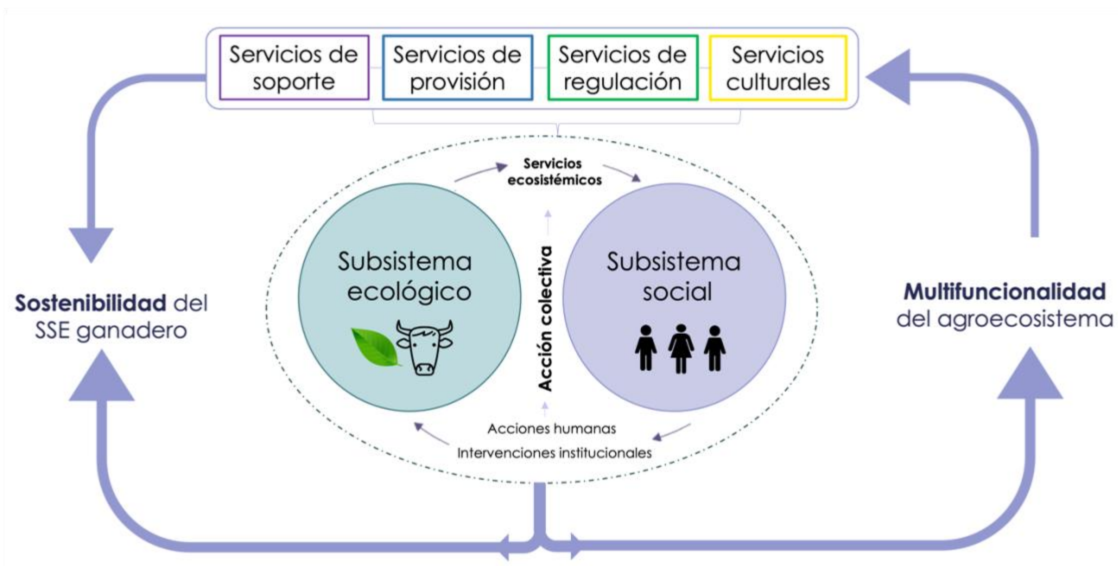

Figura 1. SSE en el contexto de la ganadería de pastoreo. Los subsistemas ecológico y social (SSE) se retroalimentan: las acciones humanas e institucionales impactan en cascada sobre la multifuncionalidad y el flujo de servicios ecosistémicos que se proveen desde el subsistema ecológico, desembocando en escenarios más o menos sostenibles para el SSE.

El subsistema social está compuesto por los individuos, grupos locales, instituciones a mayor escala, así como por las relaciones que se establecen entre ellos (Martín-López et al., 2009). Las personas incluidas en el subsistema social se benefician de los servicios ecosistémicos generados por el subsistema ecológico, en la medida en que el flujo entre estos tenga influencia sobre el bienestar humano (p. ej.,, productos agrícolas y ganaderos), o en las intervenciones humanas (p. ej., acciones colectivas) o institucionales sobre el territorio (p. ej., restauración, conservación, manejo adaptativo) (Figura 1). Dichos flujos generan un impacto sobre la estructura, patrones, procesos y multifuncionalidad de los agroecosistemas que pueden o no alterar la integridad ecológica, con un consecuente impacto en el flujo de los servicios ecosistémicos y representar un escenario más o menos sostenible (Rincón-Ruíz et al., 2014). Otros cambios impredecibles en el sistema son causados por factores indirectos, que son fuerzas externas que operan a mayor escala espacial, organizacional o institucional y que influyen en la dinámica del SSE (Dearing et al., 2010).

La noción de SSE surge en los 70s (Ratzlaff, 1970), desde entonces el concepto ha sido ampliamente utilizado tanto en las ciencias ambientales y sociales, como en economía, y en campos de conocimiento tan diversos como medicina, psicología, artes y humanidades (Colding & Barthel, 2019). El análisis de los SSE puede utilizar herramientas conceptuales y metodológicas extraídas de las teorías de sistemas, complejidad o grafos, basadas en una definición matemática del término "sistema" (Becker, 2012). Este término puede abordarse desde la definición de sistemas duros y blandos que se diferencian por cómo se considera el mundo externo. Desde el enfoque de los sistemas duros, un sistema puede ser diseñado y constituido por la interacción del observador con el complejo mundo real. El enfoque de los sistemas blandos asume que los sistemas, incluidas las personas, no pueden diseñarse para alcanzar un estado ideal (Cundill et al., 2012). Los SSE se sitúan en el ámbito de la ciencia de los sistemas blandos, sus marcos de análisis están diseñado para sintetizar información cualitativa y cuantitativa que conduzca a la comprensión de algunos procesos del sistema en contextos sociales, ecológicos y económicos variables que nunca tendrán un estado ideal debido a la variedad de intereses y realidades (Becker, 2012) pero que si pueden transitar hacia escenarios más sostenibles.

1.1.1 La sostenibilidad de los SSE

La adopción del término sostenibilidad por diferentes áreas del conocimiento ha generado heterogeneidad en los trabajos que abordan su conceptualización y análisis. Aunque no existe una única definición de sostenibilidad aceptada de manera generalizada en la comunidad científica, hay corrientes teóricas que han aportado ideas sobre lo que es e incluso estructuras metodológicas para medirla (Ruggerio, 2021). Desde la teoría de la resiliencia, los cambios experimentados por los SSE o su entorno podrían provocar diferentes cambios en su estado, estas transiciones repentinas entre estados pueden representar un mayor o menor grado de estabilidad. La aplicación del concepto de resiliencia a los SSE ha dado lugar a una nueva línea de investigación centrada en debatir cómo la sociedad fortalece su capacidad para prevenir y 'adaptarse' a las perturbaciones ambientales, y que define a la sostenibilidad como la resiliencia de los SSE (Ahern, 2013).

Partiendo de la teoría de los sistemas, la sostenibilidad es una construcción conceptual que puede ser aplicada a sistemas reales que son sistemas abiertos, y por lo tanto intercambian materia, energía e información con su entorno. Dichos intercambios pueden representarse como insumos o variables de entrada y productos o variables de salida (Ruggerio, 2021). Recientemente se ha evaluado la relación entre la capacidad de carga de un sistema y su dinámica demográfica interna, y desde allí se describió la sostenibilidad de un sistema como un equilibrio dinámico en el proceso de interacción entre una población y la capacidad de carga de su entorno, tal que la población se desarrolla para expresar todo su potencial sin producir efectos adversos irreversibles sobre la capacidad de carga del entorno del que depende (Ben-Eli, 2018). En este proyecto de investigación la sostenibilidad se describe como una propiedad emergente de los SSE que supone un estado de mejoría en el espacio y el tiempo en tres dimensiones base: ambiental, social y económica, e incluso en la dimensión geográfica que puede ser incluida para comprender las diferencias regionales de transiciones hacia estados más sostenibles (Liu, 2009).

La cuestión de la sostenibilidad de los SSE puede abordarse desde dos enfoques: sostenibilidad débil y sostenibilidad fuerte. La sostenibilidad débil supone que el sistema económico es el sujeto y su objetivo principal es lograr un crecimiento económico sostenido o, como se suele denominar, el desarrollo sostenible. Por su parte, la sostenibilidad fuerte asume que algunos atributos de la naturaleza no pueden ser reemplazados y debido al grado de incertidumbre asociado con los SSE, el 'principio de precaución' debe predominar sobre la lógica economista de la teoría neoclásica del crecimiento económico sostenido. Esto no significa adoptar un punto de vista conservacionista de la naturaleza, sino asumir que la persistencia de los SSE depende de revertir la creciente tendencia a deteriorar el medio ambiente, proponer estrategias de manejo compatibles con el sostenimiento a niveles altos de funciones y servicios ecosistémicos, y apoyar a las poblaciones para que obtengan alternativas de medios de vida a través del fortalecimiento de capacidades y acompañamiento institucional. En ese sentido, esta tesis se apega al enfoque de sostenibilidad fuerte. Es importante mencionar que: 1) los resultados de los análisis de sostenibilidad serán únicamente indicadores de la sostenibilidad o insostenibilidad del sistema de interés (sistema focal), y 2) dada la variabilidad e incertidumbre intrínseca a los SSE, sólo se podrán identificar tendencias hacia la sostenibilidad, por lo que un SSE no podrá ser definido por completo como sostenible o insostenible (Ruggerio, 2021).

La evaluación de la sostenibilidad es un paso clave para apoyar el desarrollo de sistemas agrícolas y pecuarios más sostenibles (Sadok et al., 2008). En la práctica, implica dividir las tres dimensiones de la sostenibilidad antes mencionadas en varias cuestiones de atención (Gómez-Limón & Sánchez-Fernández, 2010) y evaluarlas mediante la construcción de indicadores. Un indicador se define como “una variable que proporciona información sobre otras variables de difícil acceso y que puede utilizarse como punto de referencia para tomar una decisión” (Gras, 1989). Aunque se han desarrollado muchos indicadores y métodos (p.ej., la Evaluación de Sistemas de Manejo de Recursos Naturales incorporando Indicadores de Sostenibilidad (MESMIS) (Astier et al., 2012) para analizar la sostenibilidad, el principal desafío ha sido utilizar un proceso de selección transparente para evitar la manipulación de intereses en la evaluación e incluir a los actores clave (p.ej., productores, academia, sector gobierno). En ese sentido, sigue siendo un reto de investigación delimitar indicadores de sostenibilidad ganadera a escalas locales partiendo de realidades específicas y contemplando las visiones de la mayor parte de los involucrados (Lebacq et al., 2013).

1.1.2 El SSE de la ganadería bovina de pastoreo

El subsistema ecológico del SSE ganadero incluyen factores bióticos y abióticos de los ecosistemas que se gestionan a escala local mediante estrategias de manejo. Los factores abióticos son componentes físicos y químicos no vivos (p. ej., suelos, agua, rocas). Por el contrario, los factores bióticos son los componentes vivos de un ecosistema (fauna, flora y sus interacciones). El subsistema social se compone de cuatro elementos: i) “productores”, categoría que incluye a propietarios, administradores y trabajadores de los sistemas de producción, es decir, actores internos no gubernamentales que desempeñan un papel crucial al ser responsables de las estrategias de gestión y decisiones de comercialización; ii) “asociaciones ganaderas”, a través de las cuales se realizan acuerdos entre los productores y las comunidades del área espacial de influencia (local y regional) de las asociaciones ganaderas; iii) “reglas”, establecidas para prohibir, exigir, determinar, definir e incluso limitar el comportamiento humano en una situación determinada, en este caso, actividades de producción y comercialización relacionadas con el ganado. Las reglas pueden estar relacionadas con la acción constitucional, operativa y colectiva (Ostrom, 2009a); y iv) “instituciones”, que están compuestas por actores gubernamentales que participan y promueven el desarrollo de actividades productivas, e instituciones de investigación que realizan un trabajo social y ecológico que contribuye al conocimiento sobre la ganadería.

El subsistema económico está compuesto por cuatro elementos: i) la “infraestructura” que los productores y asociaciones ganaderas utilizan para las actividades agropecuarias, entre las que destacan las capacidades estructurales (p. ej., establos, sistemas de refrigeración, mataderos), maquinaria y equipos (p. ej., trituradoras, motobombas, camiones de transporte), y estrategias de reproducción artificial y complementos alimenticios; ii) los “empleos” generados que pueden ser internos (familiares) o externos (jornaleros); iii) las "cadenas de comercialización" que se definen por el tipo de comercialización (directa o indirecta) y están compuestas por actores externos no gubernamentales (por ejemplo, intermediarios, supermercados, carniceros, productores industriales) y los productos que se venden; y iv) “ingresos”, que incluye las ganancias totales obtenidas por los “productores”, los ingresos anuales de las “Asociaciones Ganaderas” e incluso los precios de los diferentes productos, los cuales pueden reflejar oportunidades de asociación con otros productores, vendedores o transformadores de bovinos.

El SSE ganadero interactúa con factores externos a mayores escalas, a saber: "cambio global", "globalización" y "dinámicas demográficas y de consumo de la sociedad". Como característica inherente de los SSE, sus subsistemas y elementos se relacionan y retroalimentan constantemente a través de las escalas espaciales y temporales. Una *relación* dentro del SSE puede ser definida como la influencia positiva [+] o negativa [-] de un sistema o elemento sobre otro sistema o elemento, mientras que una *retroalimentación* se describe cuando la interacción de un sistema con otro sistema dentro o fuera del SSE permite la reinyección de información que puede tener un efecto acumulativo o creciente (retroalimentación positiva [+]) o un efecto sustractivo o decreciente (retroalimentación negativa [-]) (Synes et al., 2019) dentro del SSE.

1.2 Marcos de análisis de los SSE

Los marcos desarrollados para el estudio de los SSE (Tabla 1) proporcionan un lenguaje meta-teórico usado para comparar teorías e identificar los elementos universales que cualquier teoría relevante para el mismo tipo de fenómenos tendría que incluir (Redman, 1999; Gallopín et al., 2001; Holling & Allen, 2002; Newell et al., 2005; Ostrom, 2007; 2009a; Pahl-Wostl, 2010; Scholz et al., 2011; McGinnis & Ostrom, 2014). Aunque difieren en el objetivo, los antecedentes disciplinarios, la aplicabilidad, la escala temporal y espacial, y la conceptualización de los componentes internos y externos proveen un lenguaje común para la comunicación entre disciplinas, organizan la investigación y el análisis, y explican las relaciones de un SSE (McGinnis & Ostrom, 2014; Leslie et al., 2015). A modo de síntesis, existen diez principales marcos para el análisis de los sistemas socioecológicos (Tabla 1).

Tabla 1. Propósitos de los diferentes marcos para el análisis de los SSE.

Marco analítico	Propósito
Conductor, Presión, Estado, Impacto, Respuesta (DPSIR)	Comprender los impactos de las actividades humanas en el medio ambiente, así como de los indicadores y las respuestas

	adecuadas a los mismos, a lo largo de la cadena causal - conductores de la presión - estado - impacto - respuestas.
Análisis de los sistemas terrestres (ESA)	Comprender las interacciones globales y la dinámica del sistema terrestre, así como sus evoluciones sostenibles.
Servicios de los Ecosistemas (ES)	Analizar las interacciones integrales, dinámicas y complejas de los componentes bióticos y abióticos de un ecosistema en relación con el suministro de los servicios que este sistema proporciona para apoyar la vida en la Tierra.
Marco de Sistemas del Medio Ambiente - Humano (HES)	Proporcionar una guía metodológica para analizar la estructura de los sistemas socioecológicos y comprender los procesos y dinámicas entre los sistemas sociales y ecológicos, así como dentro de las diferentes escalas del sistema social.
Análisis del flujo de materiales y energía (MEFA)	Analizar los perfiles metabólicos de las sociedades. Analizar los flujos de material y energía como representación del metabolismo de una sociedad, región o nación.
Marco de gestión y transición (MTF)	Apoyar la comprensión de los sistemas hídricos, los regímenes de ordenación y los procesos de transición hacia una ordenación más adaptable; permitir el análisis comparativo de una amplia gama de diversos estudios de casos; y facilitar la elaboración de modelos de simulación basados en pruebas empíricas.
Marco de Sistemas Socioecológicos (SESF)	Proporcionar un lenguaje común para la comparación de casos a fin de organizar las numerosas variables pertinentes en el análisis del SES en una jerarquía de múltiples niveles que pueda desplegarse cuando sea necesario, y para facilitar la selección de variables en un estudio de casos.
Medios de vida sostenibles (SLA)	Analizar qué combinación de activos permite mezclar estrategias de medios de vida con resultados sostenibles.
El paso natural (TNS)	Proporcionar un marco para la planificación hacia la sostenibilidad basado en: principios constitucionales (cómo se constituye el sistema); resultado (principios para la

	sostenibilidad); y proceso para dicho resultado (principios para el desarrollo sostenible).
Marco de vulnerabilidad (TVUL)	Analiza quién y qué es vulnerable a los múltiples cambios ambientales y humanos, y qué se puede hacer para reducir estas vulnerabilidades.

Fuente: (Binder et al., 2013).

Nota: Los acrónimos se mantuvieron del nombre original de los marcos en inglés.

Independientemente del enfoque, no existe un marco único para analizar todas las cuestiones de investigación derivadas de los SSE, por lo que adaptar marcos de referencia a contextos socioecológicos específicos permite construir nuevas propuestas de conceptualización y análisis (Binder et al., 2013). La importancia del entendimiento de los sistemas ganaderos como SSE, recae sobre la idea de que estos proveen a las personas diversos SE, generan disyuntivas que retornan como impactos negativos, y son impactados por factores internos y externos que pueden aumentar o disminuir su funcionamiento, y con ello beneficiar o perjudicar los medios de vida (Hendrickson & Sanderson, 2017). En ese sentido, de los marcos existentes, el marco de los SE resulta de particular utilidad, porque los múltiples SE que proporciona la ganadería (especialmente los de regulación, soporte y culturales) suelen pasarse por alto y pocas veces se han cuantificado (Dumont et al., 2019).

1.2.1 Marco de los Servicios Ecosistémicos

El marco analítico de los SE establece explícitamente las complejas relaciones y retroalimentaciones que existen entre los ecosistemas y los sistemas humanos. El concepto de SE ha atraído atención como una forma de comunicar la dependencia social a los sistemas ecológicos que soportan la vida, y en conjunto son definidos como los beneficios que las personas obtienen de los ecosistemas (Wallace, 2007; de Groot et al., 2010; García-Nieto et al., 2019). Los orígenes de la historia moderna de los SE surgen a finales de la década de 1970 con el encuadre utilitario de las funciones beneficiosas de los ecosistemas como servicios para aumentar el interés público en la conservación de la biodiversidad (Westman, 1977; Ehrlich & Ehrlich, 1981). En la década de 1990 surge la incorporación de los SE en la literatura (Costanza & Daly, 1992) con un mayor interés en los métodos para estimar su valor económico (Costanza et al., 1997).

La Evaluación de los Ecosistemas del Milenio (MEA, 2005) contribuyó en gran medida a que los SE ocuparan un lugar destacado en la agenda política, y desde su publicación, la literatura sobre los SE creció exponencialmente (Fisher et al., 2009). Dicha evaluación propuso cuatro categorías: servicios de provisión que abarcan todos los productos obtenidos de los ecosistemas; servicios de regulación incluyendo todos los beneficios obtenidos de la regulación de procesos ecosistémicos, un "popurrí de beneficios intangibles" denominados servicios culturales que involucran los beneficios no materiales como el enriquecimiento espiritual, el desarrollo cognitivo, la reflexión, la recreación y las experiencias estéticas; y finalmente los servicios de soporte que son necesarios para la producción de todos los demás SE (MEA, 2005). El término “SE” ha sido controversial por su habitual relación con la mercantilización de la naturaleza, y por la complejidad de la implementación en el trabajo con las ciencias sociales o con los profesionales locales, incluidos los pueblos indígenas. Esto generó preocupación por la equidad social, y se manifestó la necesidad de proponer un enfoque inclusivo, tanto en términos de las líneas de conocimiento incorporadas como de la representación de cosmovisiones, intereses y valores (Lele et al., 2013).

En respuesta a ello, recientemente la plataforma intergubernamental científico-normativa sobre diversidad biológica y servicios de los ecosistemas (IPBES, por sus siglas en inglés) propuso el concepto “Contribuciones de la naturaleza a las personas” (NCP, por sus siglas en inglés), para agrupar a todas las contribuciones, tanto positivas como negativas de la naturaleza viva (diversidad de organismos, ecosistemas y los procesos ecológicos-evolutivos asociados) a la calidad de vida de las personas. En una primera inspección, la noción de las NCPs no parece diferir demasiado de la definición original de SE, sin embargo, el enfoque de NCP reconoce el papel central y omnipresente que desempeña la cultura en la definición de todos los vínculos entre las personas y la naturaleza. Además, el uso de las NCPs eleva, enfatiza y operativiza el papel del conocimiento indígena y local en la comprensión de las NCPs (Díaz et al., 2018). Es decir, la cultura atraviesa a través de los tres grandes grupos de NCPs en lugar de estar confinada en una categoría aislada ("servicios culturales" en el marco de la MEA). En este trabajo se reconoce el valor de integración y comunicación del enfoque emergente de las NCPs, sin embargo, mantiene el enfoque de los SE porque, aunque se ha incluido algún método participativo con ganaderos, la esencia de este proyecto escapa del énfasis cultural e incidencia que debería incluirse y pretender alcanzar el uso de las NCPs.

La importancia de los sistemas ganaderos en los trópicos varía según la dependencia de las partes interesadas (p. ej., productores, procesadores, comercializadores, consumidores) a los SE obtenidos de los sistemas (Rao et al., 2015). Los principales SE de apoyo que provee la ganadería incluyen el hábitat, la protección del acervo genético, la retención de humedad del suelo y la productividad de los pastos (Murgueitio et al., 2011; Figueroa et al., 2020). Los SE de aprovisionamiento incluyen todos los productos obtenidos de los ecosistemas y el ganado (p. ej., pastos, forrajes, madera, alimentos, fibra y agua) (Tauto et al., 2018). Los SE de regulación incluye recarga de aguas subterráneas, fertilidad del suelo, secuestro de carbono, fijación de nitrógeno y regulación microclimática derivada de la sombra para el ganado (Accatino et al., 2019; Figueroa et al., 2020). Los SE culturales incluyen la apreciación estética de la naturaleza y el paisaje, la protección del ecosistema, las actividades recreativas, la espiritualidad, los valores educativos y la salvaguarda de las cosmovisiones (Tauro et al., 2018; Dumont et al., 2019). Más allá de los SE individuales, existen porciones del territorio con capacidad de suministrar múltiples SE (paquetes de SE) en el espacio y/o tiempo (Raudsepp-Hearne et al., 2010), dadas las coberturas y usos de suelo derivadas de las prácticas de manejo incluyendo el manejo ganadero (Burkhard & Maes, 2017).

1.2.1.1 Acción colectiva para la gestión de los SE

La acción colectiva (AC) se ha definido en términos generales como "una acción llevada a cabo por un grupo [...] para favorecer los intereses compartidos percibidos de sus miembros" (Scott & Marshall, 2009). La AC representa un proceso voluntario de cooperación entre diversos interesados, usuarios y administradores que abordan un problema común de gestión de los SE en un territorio determinado. Puede ser especialmente útil para dilucidar los desafíos (sociales, económicos y ecológicos) que implica la gestión de los SE que no se basan necesariamente en recursos de uso común (p. ej., los SE de sistemas ganaderos dentro de esquemas privados de tenencia de la tierra) (Barnaud et al., 2018). La noción de interdependencia social y ecológica de los SE es fundamental para la aplicación de la AC. En efecto, si las personas no se sienten mutuamente interdependientes y parte del entorno que las rodea, es poco probable que inviertan tiempo y energía en colaborar. Además, se requiere aprendizaje social, fomento de la confianza y comprensión mutua (Pahl-Wostl et al., 2007). El concepto de SE, ha sido utilizado para poner de relieve las interdependencias sociales ocultas, por lo tanto, contribuye a dilucidar la AC potencial y fortalecer la AC existente (Barnaud et al., 2018). A pesar de que la AC incluye procesos de toma de decisiones de las partes interesadas, transmite valores emancipadores de equidad y justicia social (Rawls, 1997), tiene riesgos inherentes (p. ej., exclusión social, comportamientos individuales estratégicos, asimetrías de poder), y costos de transacción y vigilancia (Ostrom, 2009b) que no siempre pueden ser gestionados en territorios con altos índices de pobreza pero que deben ser contemplados dentro de los análisis que la aborden.

1.2.1.2 Multifuncionalidad de los SE

La multifuncionalidad (MF) es un concepto simple y con muchas aplicaciones potenciales. Se estudia cada vez más en la ciencia fundamental de la biodiversidad y de los ecosistemas, a la vez que se convierte en un objetivo común de la gestión de los ecosistemas y de las políticas a múltiples escalas (Manning et al., 2018). Aunque no existe una única definición aceptada de MF, ni medios acordados de manera generalizada para medirla, es definida como "la capacidad de los ecosistemas de realizar simultáneamente múltiples funciones que podrían ser capaces de proporcionar SE o paquetes de SE particulares” (Berry et al., 2016). La MF en agroecosistemas surgió como concepto en el decenio de 1980 y se difundió a raíz de la Comisión Mundial sobre el Medio Ambiente y el Desarrollo como una forma de reconectar la función económica de la agricultura con sus raíces ecológicas y sociales (Caron et al., 2008). La **MF en los agroecosistemas** (MFA) reconoce que estos sistemas más allá de su función de producción de alimentos y fibras tienen otras funciones potencialmente esenciales para el SSE del que forman parte (Hodbod et al., 2016).

Existen dos formas de abordar la MF: la multifuncionalidad de la función de los ecosistemas (Multifuncionalidad-FE) y **multifuncionalidad de los SE** (Multifuncionalidad-

SE) (Manning et al., 2018), esta última exige no perder de vista que, aunque la MF está estrechamente relacionada con los paquetes de SE, no son lo mismo (Berry et al., 2016). La multifuncionalidad–FE constituye una medida del rendimiento global de un ecosistema que intenta representar funcionamiento sin ningún juicio de valor sobre el nivel deseado o los tipos de función, definido idealmente sólo en tasas de procesos ecológicos. La multifuncionalidad – SE hace referencia a una medida que se define y valora desde una perspectiva humana (Mouchet et al., 2017; Manning et al., 2018). La cuantificación de los paquetes de SE suele hacerse a través de indicadores localmente relevantes y finalmente el cálculo de la MF, multiplicando el valor normalizado del indicador por las ponderaciones o pesos de importancia derivadas de los actores involucrados en el proceso.

La MFA cobra relevancia en el estudio de la intensificación sostenible de la ganadería, porque con ella se hace explicita la importancia del establecimiento de paisajes multifuncionales que mantengan paquetes de SE dentro de la misma unidad espacial o delimitación social (Stürck & Verburg, 2017). En ese sentido, en este proyecto la investigación se delimita teóricamente a partir del estudio de los SSE y el acoplamiento de los conceptos de SE, MFA, AC y sostenibilidad (Figura 1). Es decir, reconoce que los sistemas ganaderos tropicales son SSE en los que suele haber una influencia y un control desproporcionados por parte de los impulsores sociales y económicos sobre los elementos ecológicos, los cuales determinan en gran parte la MFA y con ella la provisión de SE individuales y paquetes de SE (Hodbod et al., 2016) que pueden ser gestionados través de la AC y que conducen a escenarios más sostenible para la ganadería.

1.3 Metodología

La metodología asociada a los cuatro objetivos del proyecto de investigación se dividió en tres etapas asociadas a las fuentes de obtención de datos: revisión sistemática de literatura, entrevistas semiestructuradas y un taller participativo (Figura 2). En general, las revisiones sistemáticas publicadas sobre la aplicación del marco SSE: i) discuten los conceptos y capacidad teórica de interrelación (Herrero-Jáuregui et al., 2018), ii) exploran la diversidad de metodologías y retos empíricos a los que se enfrenta (de Vos et al., 2019), e iii) identifican la red de colaboración científica para la operacionalización del marco SSE y el estado de la interdisciplinariedad en los estudios relacionados vistos a través de los métodos desarrollados (Gómez-Santiz et al., 2021).

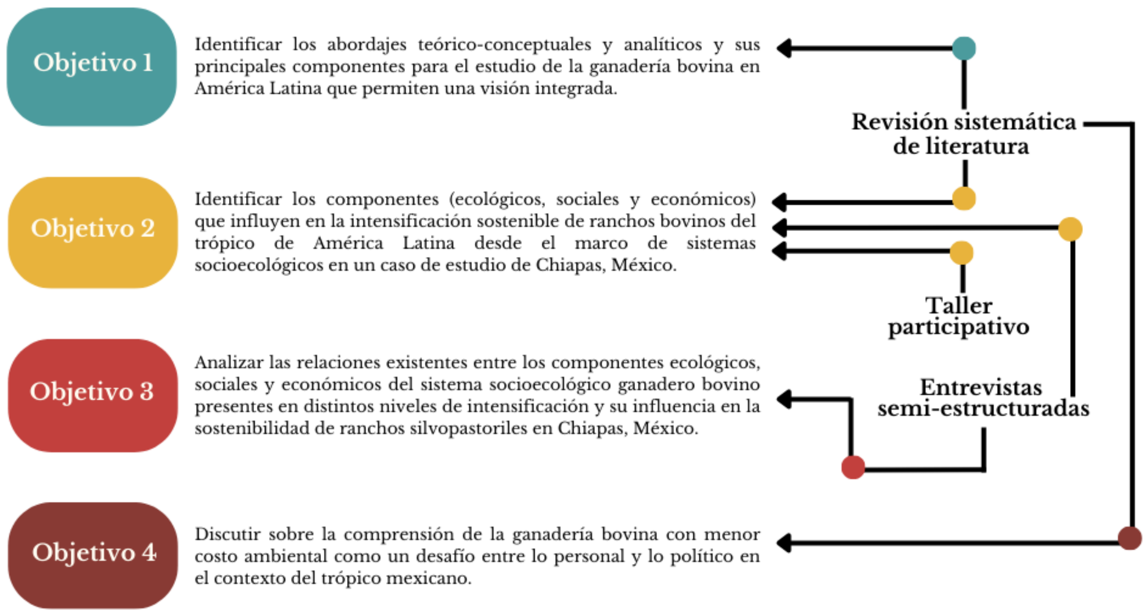

Figura 2. Relación de las fuentes de datos con los cuatro objetivos de investigación.

La segunda fuente de obtención de datos fueron las entrevistas, que suelen ser definidas como "una conversación que se propone con un fin determinado distinto al simple hecho de conversar." Las entrevistas semiestructuradas presentan gran flexibilidad debido a que parten de preguntas planeadas y estructuradas dentro de cuestionarios, que pueden motivar al interlocutor y ajustarse a los entrevistados (Díaz-Bravo et al., 2013). Finalmente, los talleres participativos facilitan la toma de decisiones, la generación de consensos y el encuadre de proyectos en una atmósfera de negociación informada, que motiva la apropiación de conceptos, metodologías, actitudes y actuaciones necesarias para la gestión local y la sostenibilidad en territorios (Poggi, 2016).

1.3.1 Obtención de datos

- **Revisión sistemática de literatura**

La revisión sistemática de literatura fue estructurada a través del Marco SALSA que consta de cuatro fases: Búsqueda, Evaluación, Análisis y Síntesis (Grant & Booth, 2009). Las dos primeras fases (Búsqueda y Evaluación) se rigen de los principios de la sistematización, a través de ellas se garantiza la identificación de un conjunto completo de conocimientos sobre el tema elegido. Las aproximaciones metodológicas adoptadas para abordar las otras dos fases (Análisis y Síntesis) van en función de las características y los objetivos del trabajo en el que se integren, o de las características de la revisión (Codina, 2018). La búsqueda se basó en la literatura publicada en inglés y español a lo largo de 20 años (2000-2020); y se realizó el 12 de enero de 2021 en las bases de datos Scopus, Web of Science y Google Scholar en tres etapas: título, título y resumen, y texto completo (Mengist et al., 2020). Se establecieron criterios de selección. Se seleccionaron 170 artículos, de ellos 120 artículos se localizaban espacialmente en el trópico de AL, y los 50 artículos restantes relacionaban la ganadería con los conceptos de SSE, MF, SE y AC, muchos de ellos en contextos tropicales de otras regiones del mundo. El análisis de la información que se obtuvo de la revisión sistemática de literatura varío dependiendo del objetivo (ver la sección de métodos del capítulo 2 y 3 para profundizar).

- **Entrevistas semi-estructuradas**

Se realizaron entrevistas semi-estructuradas entre julio y octubre de 2018 a 350 productores miembros de la Red Silvopastoril. El cuestionario que guio las entrevistas (ver capítulo 3, SM 1. Table 1) fue diseñado para capturar valores asociados con elementos ecológicos, sociales y económicos organizados en 10 bloques temáticos que caracterizaron el SSE ganadero, como parte del proyecto "Sistemas de producción sostenible y biodiversidad" de la Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), la Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT), y el Fondo para el Medio Ambiente Mundial (GEF, por sus siglas en inglés). La aplicación de las 350 entrevistas en campo duró en promedio entre 1:30 y 2:00 horas cada una, y fueron realizadas por técnicos pertenecientes a cada asociación ganadera, quienes recibieron capacitación previa para tal fin. Los técnicos locales devolvieron la información y las pruebas fotográficas a la oficina de administración de la Red Silvopastoril. La información cualitativa de las entrevistas se organizó y analizó en matrices de datos de Excel, y los datos se desagregaron a nivel de productor, cada uno representando un rancho ganadero distinto (N = 350 ranchos). El análisis de la información derivada de las entrevistas varío dependiendo de los objetivos (ver la sección de métodos del capítulo 3 y 4 para profundizar).

- **Taller participativo**

Se realizó un taller participativo con 23 productores de la Red Silvopastoril en febrero de 2019 para obtener los datos que permitieran analizar la sostenibilidad del SSE ganadero. Cuatro facilitadores académicos encabezaron una discusión abierta con los productores sobre los temas productivos/organizativos y ambientales (descriptores) más relevantes para avanzar hacia escenarios más sostenibles en la ganadería. Los **12 descriptores de sostenibilidad** resultantes fueron socializados y validados en plenaria con la ayuda de un pizarrón. Siete descriptores de sostenibilidad estuvieron relacionados con temas socioeconómicos (generación de empleo, infraestructura, mercadeo, densidad ganadera, frecuencia de rotación del ganado, diversificación y participación familiar), y cinco con SE. Finalmente, se pidió a los participantes que definieran los descriptores y propusieran tres rangos de progreso en sostenibilidad para cada descriptor. Los rangos de progreso debían incluir un escenario de sostenibilidad baja (valor =1), media (valor=2) y alta (valor=3). Para profundizar en el método asociado al taller, ver sección de métodos del capítulo 3.

1.3.2 Análisis general de datos

- **Identificación de componentes y escalas de los SSE ganaderos**

A partir de la revisión de literatura, se registró la frecuencia con la que se mencionaban y medían los enfoques y conceptos que desde esta investigación se consideran clave para el abordaje integral de los SSE ganaderos: SE, MF, AC y Sostenibilidad. Además se dentificaron los componentes ecológicos, sociales y económicos que se abordaban en los artículos de investigación relacionados con ganadería en AL y las escalas a las que se analizaban dichos componentes. Como las escalas espaciales se solían confundir con los niveles de agregación, se combinaron dos enfoques conceptuales para visualizar los componentes identificados en una jerarquía.

Las escalas espaciales y los niveles de agregación reportados en los estudios se agruparon en dos niveles de análisis distintos siguiendo la lógica de las jerarquías ecológicas e institucionales basadas en las propuestas de Ruiz-Rivera & Galicia (2016) y Hein et al (2006).

La primera propuesta incluye el **concepto de escala** y los diferentes elementos y dimensiones que la componen: extensión, resolución, nivel y jerarquía (Ruiz-Rivera y Galicia, 2016). La segunda propuesta entremezcla escalas espaciales y **niveles de agregación en dos clasificaciones:** (1) *escalas ecológicas* (la escala del proceso que se gestiona) y (2) *escalas institucionales* (la escala de gestión) en interacción por el acoplamiento entre los humanos y el medio ambiente (Hein et al., 2006).

- **Tipología de ranchos ganaderos**

Se construyó una tipología sabiendo que los productores de la Red Silvopastoril tienen avances diferenciados en el establecimiento de SSP. Se propuso rastrear los diferentes tipos de ranchos ganaderos existentes en función de la oferta de SE ofrecida, las características económicas de los productores, las estrategias de manejo utilizadas y la ubicación espacial. Para ello, se realizó un Análisis Factorial Múltiple (AFM), - un método de análisis de datos multivariado para resumir y visualizar un conjunto de datos complejo en la que los individuos son descritos por varios conjuntos de variables (cuantitativas y cualitativas) estructuradas en grupos- (Abdi et al., 2013). Así, a partir de un pequeño número de variables, se obtienen síntesis de similitudes entre individuos, vínculos entre variables y vínculos entre grupos de variables. Los datos se agruparon en cuatro categorías: características económicas, SE, estrategias de manejo y ubicación.

Posteriormente, se realizó un Análisis de Conglomerados Jerárquico (HCA, por sus siglas en inglés) -un enfoque general del análisis de conglomerados en el que el objetivo es agrupar objetos o registros que están "cercanos" entre sí- (Köhn & Hubert, 2014) utilizando el método de Ward para inferir el número más apropiado de clusters (partición inicial). Luego se utilizó la distancia de Manhattan para trazar todos los caminos posibles y determinar la cercanía entre las variables y el método K-medias para la partición final. Finalmente, se aplicó la prueba de Kruskal-Wallis (un análisis de varianza no paramétrico para más de 60 datos) para ver si había diferencias estadísticamente significativas entre los grupos encontrados para las variables incluidas en el análisis. Se usó la prueba de Tukey como método de comparación post hoc. Se escalaron las medias a valores de 0 a 10 para construir gráficos de radar donde se pudieran observar diferencias entre los tipos de ranchos para todas las variables incluidas.

- **Modelo de Ecuaciones Estructurales**

El modelo de ecuaciones estructurales (SEM, por sus siglas en inglés) representa un método multivariante que permite descifrar las relaciones entre variables, determinar las relaciones más relevantes y comprender en qué medida influyen en un fenómeno complejo como variable latente -una variable no medida que se construye a partir de la relación entre variables medidas- (Kline, 2015). El SEM combina el análisis factorial con la regresión lineal para probar el grado de ajuste de los datos observados a un modelo hipotetizado expresado mediante un diagrama o mapa mental (Hair et al., 2017). El SEM utiliza la información disponible, incluido el conocimiento previo de los especialistas, para proponer relaciones potenciales a probar en un mapa mental. En este caso, se plantearon relaciones directas e indirectas entre las características económicas, SE, estrategias de manejo y ubicación geográfica con la sostenibilidad de los ranchos de la Red Silvopastoril (Figura 3).

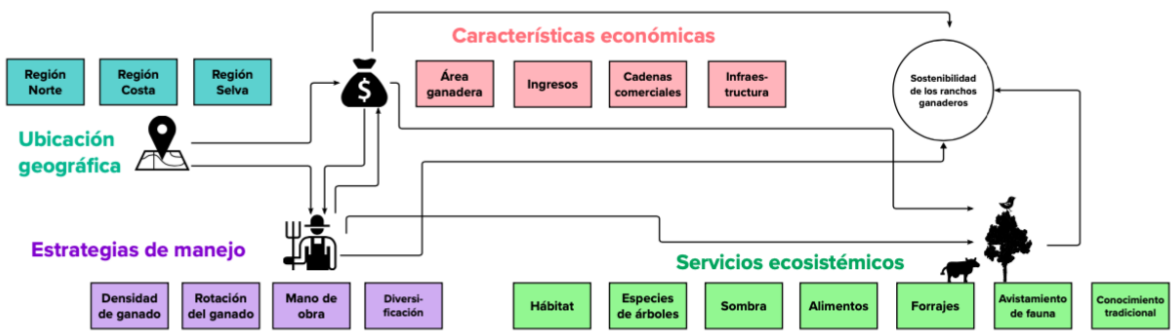

Figura 3. Mapa mental con las relaciones probadas en el SEM.

La identificación de los parámetros del SEM inicia estimando las covarianzas (Kline, 2015). Posteriormente se calculan los coeficientes estandarizados y no estandarizados que indican las relaciones entre variables a través del método de máxima verosimilitud (ML). Finalmente se calculan las medidas de ajuste del modelo a través del índice de bondad de ajuste comparativo (CFI) y la raíz del residuo cuadrático promedio de aproximación (RMSEA), dos métricas ampliamente documentadas para la evaluación de los SEM (Lai & Green, 2016). La metodologia general del proyecto y la relación con cada uno de los objetivos de investigación se muestran en la figura 4

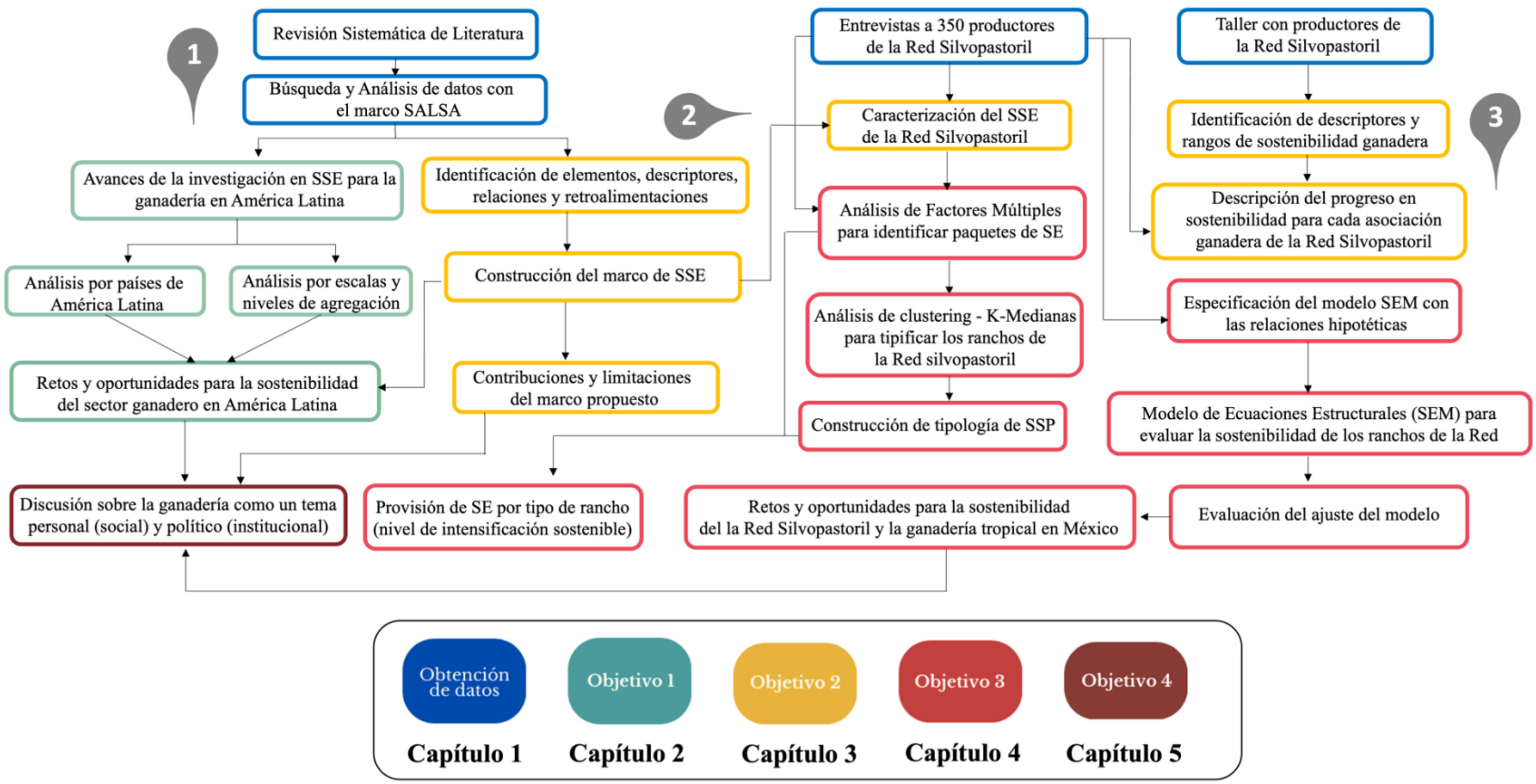

Figura 4. Metodología general. El color de las cajas indica la ruta metodológica asociada a cada objetivo de investigación y capítulo de la tesis.

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Capítulo 2

Latin American Cattle Ranching Sustainability Debate: An Approach to Social-Ecological Systems and Spatial-Temporal Scales

sustainability

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https://doi.org/10.3390/su14148924

Abstract

The significance of Latin America (LA) in the global food supply is large and prominent. The livestock sector at this time faces social-ecological challenges that will be accentuated in the future and will be incredibly challenging for small and medium producers. We conducted a systematic literature review to understand the role of LA cattle ranching in the current sustainability debate. In addition, we identified the main components of cattle ranching social-ecological systems and evaluated the institutional and ecological interactions of livestock studies by identifying spatial and temporal scales. Our results show a broad debate on livestock sustainability in LA; nevertheless, efforts to measure sustainability and analyze cattle ranching systemically are scarce. The study of LA cattle ranching in the 21st century was geographically concentrated on the main producing countries (Mexico, Colombia, Brazil, and Argentina) and was consistently promoted by government and academic institutions aiming to understand management strategies that improve yields. However, it less often focused on analyzing their impacts on ecosystems and climate. The complexity and dynamism of cattle ranching in LA make it necessary to address sustainable planning from a systemic approach to guide viable transformations through spatial scales.

Keywords: livestock; ecosystem services; multifunctionality; collective action; scales

1. Introduction

Cattle ranching has been studied in recent decades from the perspectives of global change and sustainability (Thornton, 2010; Springmann et al., 2018). Within the economic dimension, livestock provides financial income to 1.3 billion producers and retailers. It is the basis of the livelihoods of 1 billion poor and 200 million smallholder families worldwide

(Herrero et al., 2016; Engler & von Wehrden, 2018). As part of the social dimension, livestock products supply one-third of the global protein consumption and are essential components of the diet of 800 million food-insecure persons (Herrero et al., 2013). The environmental dimension of sustainability has been approached from the biophysical implications of cattle ranching. Cattle have been introduced into most world ecosystems, and their extensive spatial distribution has led to changes in land use, soil fertility, water quality, water use, biodiversity, multifunctionality, and climate change (Herrero et al., 2016; Gordon, 2018). Despite the ensuing environmental costs, production and consumption of livestock products continue to rise. The global demand for food of animal origin is expected to be at least 50% higher in 2030 than in the year 2000 (Alexandratos and Bruinsma, 2012), and it will be supplied mainly by the global south, where livestock production is already significant (Lerner et al., 2017; Arango et al., 2020). LA will increase beef production by 125% by 2050 to sustain meat demand with significant planetary implications. The spatial predominance of cattle ranching in LA underpins one of the most significant expansions of the agricultural frontier in the last 50 years on a global scale (Herrero et al., 2018). It can be understood by exploring the historical context.

Cattle arrived in the LA along with the European settlers; the first species introduced was the *Bos taurus* with minimal requirements for pasture extension, so silvopastoral systems, a form of production using the forage provided by the trees and shrubs of forests and tropical forests, were maintained predominantly for more than 400 years until the introduction of zebu cattle (*Bos indicus*) (Guevara & Lira-Noriega, 2011). The substitution of this type of cattle led to the massive opening of pastures at the expense of natural vegetation and favored the deforestation of large extensions of the territory. Since then, cattle ranching has led to significant transformations of ecosystems and the establishment of exotic pasture species from Africa and Asia (Hernández, 2001). The environmental problems caused by cattle ranching in LA are partly the result of the transformation of natural ecosystems into pastures with exotic grasses, some of which are invasive or potentially invasive (D'Antonio & Vitousek, 1992).

Starting from the history of the extensification domain, currently, the LA region contributes to meeting the growing demand for food of animal origin and supports regional and global food security (FAO, 2017). While LA represents only 16% of the world's total population and 34% of its rural population, it possesses 67% of the heads of cattle for meat production and 76% for milk production. This region generates 30% of the planet's meat and 28% of its bovine milk (FAO, 2019). Therefore, the LA livestock sector contributes to 46% of the agricultural GDP, which is increasing by 3.7% annually; this exceeds the average global GDP growth rate (3.4%) (FAO, 2017; Word Bank, 2019). The growth of the livestock sector has been mainly due to an increase in the number of animals and extensive areas that promoted deforestation of forests for cattle grazing. Moreover, agricultural frontiers, used to grow cattle feed, shifted to the tropics with new frontiers established in LA and promoted deforestation (Herrero et al., 2018).

The role of LA in the regional and global food supply is broad and leading. The livestock sector currently faces social-ecological challenges that will be accentuated in the future and will be incredibly challenging for small and medium producers who raise and market cattle, for whom extensive practices will possibly cease to be viable as the primary source of income and livelihood (Springmann et al., 2018). In general, there is concern about managing the sector's growth so that these benefits can be attained at a lower environmental cost and to address the inefficient use of resources in cattle ranching systems (Herrero et al., 2013). The sustainability debate of cattle ranching systems in emerging regions such as LA often occurs within the theory of sustainable intensification, through which the market orientation of production systems is contemplated, combined with appropriate incentive policies that achieve the establishment of systems that remain within sustainability thresholds and increase not only production per unit area but also the provision of benefits in the same land area (Herrero et al., 2013; Arango et al., 2020).

However, attempts at planning for sustainability in the livestock sector have been criticized for not handling growing conflicts caused, among other reasons, by a mismatch between the scale of management and the scale of the process being managed and poor understanding of ecological and social scales in geographic space (Cumming et al., 2006; Marshall, 2015).

Moreover, it has been neglected because of the importance of a systems perspective, which allows tracing the main elements that make up social-ecological systems (SES) (Sandström et al., 2013). It is recognized that place- based planning can help evaluate more sustainable alternative futures for SES (Oteros-Rozas et al., 2015). The different components of livestock systems involve complex interactions at multiple scales, making a systemic approach necessary to trace possible solutions in favor of the social and ecological logic of the sector (van Zanten et al., 2018). Therefore, exploring and driving comprehensive studies can help to understand and plan for sector sustainability tailored to the unique attributes of the contexts (Marshall, 2015). In that sense, we propose as objectives from a systematic literature review:

(1) to understand the role of LA cattle ranching in the current sustainability debate, considering the conceptual frameworks for SES and ecosystem services (ES), and the concepts of multifunctionality (MF) and collective action (CA) as critical tools for a comprehensive analysis;
(2) to identify the main ecological, social, and economic components frequently studied in livestock research in LA;
(3) to assess the institutional (the scale of management) and ecological (the scale of the process being managed) interactions of livestock studies by identifying spatial and temporal scales at which research is conducted, and cattle ranching components are developed.

1.1 Approaches and Concepts

The concept of SES has proven itself the strongest and most convincing candidate in the contest for a boundary object relevant both to sustainability science and to the study of the manifold of interdependencies among natural and social processes along different temporal and spatial scales (Becker, 2012). SES are cohesive, integrated systems characterized by strong connections and feedbacks within and between social and ecological components that determine their overall dynamics. The SES framework recognizes that society benefits from ecosystems to meet its needs and that the utilization of these ecosystems modifies them, thereby creating a continuously changing dynamic (Oteros-Rozas et al., 2015).

SES analysis can use conceptual and methodological tools drawn from systems, complexity, or graph theories based on a mathematically oriented definition of the term “system” (Becker, 2012). This term can be approached from the definition of hard and soft systems. The difference between hard and soft systems approaches is given by how the external world is considered. From the hard systems approach, a system can be designed and constituted by the observer’s interaction with the complex real world. The soft systems approach assumes that systems, including people, cannot be designed to achieve an ideal condition (Cundill et al., 2012). The SES framework is situated in the realm of soft systems science because it is designed to synthesize qualitative information leading to an understanding of some system processes in varying social, ecological, and economic contexts that will never have an ideal state because of the variety of interests and realities (Becker, 2012).

The structure of the SES is transformed due to changing interactions at all scales. Hierarchies and adaptive cycles comprise the basis of SES across scales; together they form a panarchy. An adaptive cycle, proposed as a unit for understanding complex systems, can lie between long periods of aggregation and transformation of resources and short periods of innovation (Figure 1). Fast-moving cycles at small scales are more prone to innovations, whereas slow-moving cycles of larger scales stabilize and preserve the memory of successful events (Resilience Alliance). The adaptive cycle analyzes degrees of stability in complex systems over time and looks at how a complex system reacts to certain shocks and represents four phases: the growth (exploitation) phase (r phase), conservation phase (K phase), release phase (omega; Ω-phase, corresponding to the end), and reorganization phase (alfa; α-phase, corresponding to the beginning) (Resilience Alliance). The panarchy describes how a healthy system can invent and experiment, benefiting from inventions that create opportunity while being kept safe from those that destabilize because of their nature or excessive exuberance (Holling, 2001; Gunderson & Holling, 2002) (Figure 1). The concepts of resilience, vulnerability, transformation, and sustainability are needed to understand the dynamics of an intertwined SES through the adaptive cycle. Resilience is the capacity of a system to absorb disturbance and reorganize during the change to retain essentially the same function, structure, and feedback, and therefore identity. Typically, the resilience of a system is high in the r phase, declines in the advanced K phase, and increases in the transition from the Ω to α phase (Walker, 2012).

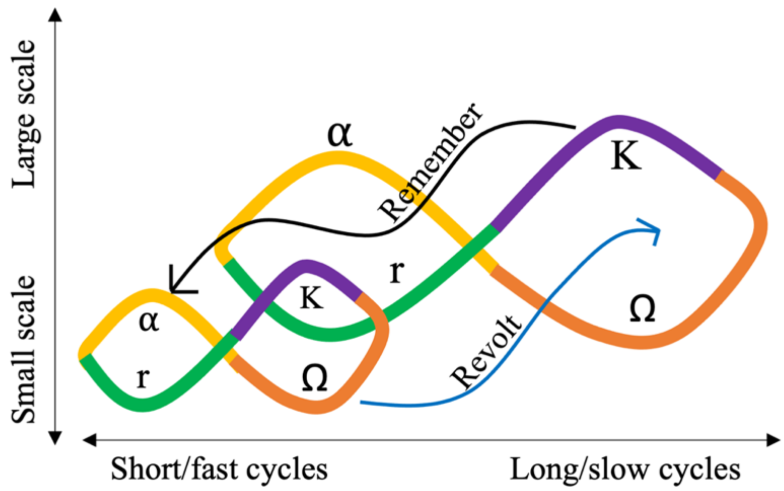

Figure 1. Panarchy of interconnected adaptive cycles at different spatial and temporal scales. A heuristic of nested adaptive cycles is observed that can be connected through re-member and re revolt across multiple temporal and spatial scales interactions simultaneously (Adapted from Gunderson & Holling, 2002 - Island Press).

The concept of vulnerability has its roots in the study of natural hazards and poverty. Vulnerability includes the attributes of persons or groups that enable them to cope with the impact of disturbances. Transformation is presented as adaptive possibilities enabled by organizations or individuals, may be forced by system failures, or chosen in anticipation of collapse and movement to a new state of the SES (Folke et al., 2010; Walker, 2012; Duru & Therond, 2015). On the other hand, sustainability promotes changes aimed at guaranteeing human well-being and environmental integrity (Duru & Therond, 2015). Production systems are complex adaptive or self-organizing systems, such that their behavior changes over time due to internal processes of development and interactions of system components. The way the social and ecological systems of a SES interact causes the system to go through adaptive cycles (Antoni et al., 2019).

A cattle ranching system is a local SES embedded in a complex system of multiple interactions across different levels and scales (Torralba et al., 2018). The aggregation level is a categorization used by a geographic observer to locate and classify a phenomenon within a hierarchy (e.g., home, ecosystem, landscape) (Ruiz-Rivera & Galicia, 2016). Therefore, it can be arbitrary and have different meanings in different contexts. In contrast, spatial scales denote the size or spatial extent of a process, phenomenon, or study (e.g., local, regional, and global) (Lloyd, 2014). However, SES operate across various spatial and temporal scales and aggregation levels that mix ecological and institutional hierarchies (Hein et al., 2006) that complicate their analysis.

In this sense, several analytical frameworks for approaching the SES facilitate their interpretation. The ES analytical framework helps reveal the interaction between ecosystems and humans (Binder et al., 2013) and integrate environmental and cultural values according to the local context (Torralba et al., 2018). Social-ecological dynamics in livestock landscapes supply ES bundles; some parts of livestock territories can supply complete sets of ES (Raudsepp-Hearne et al., 2010) associated with the management strategies in place (Burkhard & Maes, 2017) under the prevailing ecological conditions. The maximization of ES in cattle production systems can be promoted from the MF (Manning et al., 2018) or CA approach. The MF of agroecosystems implies that, beyond their function in producing food and fiber, they perform other essential functions for the SES of which they are a part (Hodbod et al., 2016). However, the recognition of ES provided by livestock should not obscure the need to weigh these services against their adverse effects (trade-offs) nor obscure the importance of promoting research and policies that ensure viable multifunctional landscapes (Dumont et al., 2019).

Although the CA theory was put forward to evidence challenges in the management of common property resources (Ostrom, 1990), it can also be helpful to improve the provision and governance of ES in systems that are not based on common property resources (Barnaud et al., 2018). Cattle ranching systems in LA are not only part of communities (Apan-Salcedo et al., 2021). There are also private land tenure schemes in which producers often make decisions collectively for expected benefits in the localities. The organized, cooperative management of cattle production can deliver human and ecological well-being in other territories through social, economic, and environmental impacts, since production and trade activities are connected at various spatial scales (Reed et al., 2009). In synthesis, the concepts and approaches for managing sustainability through systemic analysis to ensure that livestock systems are economically viable for farmers, environmentally friendly, and socially acceptable (Ten Napel et al., 2011) are described below.

• **Social-ecological systems (SES)** are complex adaptive systems formed by humans and nature. They comprise heterogeneous individual modules that interact and are physically, behaviorally, and even spatially transformed over time (Martín-López et al., 2009).

• **Ecosystem services (ES)** are the benefits that people obtain from the environment (support, provision, regulation, and culture) to satisfy their needs (MA, 2005).

• **Multifunctionality (MF)** is the ability of ecosystems or agroecosystems to carry out multiple functions simultaneously that can potentially supply ES packages, providing ecological, social, and economic benefits to multiple actors (Manning et al., 2018; Berry et al., 2016).

• **Collective action (CA)** is the voluntary cooperation of various stakeholders to address a common ES management issue in each territory (Barnaud et al., 2018).

2. Materials and Methods

The systematic literature review is aimed at understanding the role of the LA live-stock sector in the ongoing discussion on sustainability, considering the SES and ES framework and the MF and CA concepts as essential tools. In addition, the purposes are to identify ecological, social, and economic components emerging from cattle ranching SES in LA and to assess the institutional and ecological importance of livestock research in LA. We apply the SALSA (Search, Appraisal, Synthesis, and Analysis) framework to realize the systematic literature review as described below:

• Search

We searched for peer-reviewed scientific papers, whether conceptual or empirical. Conceptual studies present a theoretical characterization, develop a common language, or propose guidelines and frameworks for assessing the sustainability of cattle ranching. In contrast, empirical studies are based on analyzing actual observations or measurements. The search was based on literature that was published in English and Spanish over 20 years (2000–2020) to examine the advances made by livestock research in the first two decades of the 21st century and evaluate the advances made by livestock research following the recognition of the livestock revolution in 1999 (Delgado et al., 1999). We searched the Scopus and Web of Science databases and the Google Scholar search engine. The search used combinations of keywords: Livestock, Latin America, Sustainability, Social-ecological systems, Multifunctionality, Ecosystem Services, and Collective Action.

• Appraisal

Included was every study that met at least one of the following four selection criteria in any of the search stages (title and abstract, and full text):

- It characterized cattle management in a LA country.
- It analyzed livestock systems using the SES approach.
- It analyzed the ES or trade-offs of cattle ranching.
- It examined or mentioned the MF or CA concepts in livestock systems.

• Synthesis

Examination of the 120 selected is presented in an Excel spreadsheet for analysis (Table S1). Data included document citation, title, author(s), year of publication, type of publication, journal name, the method used, keywords, issues addressed, study site, spatial scale or aggregation level, and temporal scale of analysis whenever this could be discerned.

• Analysis

Within the analytical phase, we identify the countries where the livestock research mentions the framework of SES and ES, sustainability, and the concepts of MF and CA. Additionally, we recorded the frequency with which these approaches and concepts were mentioned and measured; we identified the ecological, social, and economic components that were addressed within the selected articles, and the scales at which these components were analyzed. As spatial scales were often conflated with aggregation levels, we coupled two conceptual approaches to visualize the identified components in a hierarchy.

The spatial scales and aggregation levels reported in the studies were grouped into two distinct analysis levels following the logic of ecological and institutional hierarchies based on the proposals of Ruiz-Rivera and Galicia (2016) and Hein et al (2006). The first proposal includes the concept of the scale and the different elements and dimensions that compose it: extension, resolution, level, and hierarchy (Ruiz-Rivera and Galicia, 2016). The second proposal inter-mixes spatial scales and levels of aggregation in two classifications: (1) ecological scales (the scale of the process being managed) and (2) institutional scales (the scale of management) in interaction by the coupling between humans and the environment (Hein et al., 2006). The resulting categorization reflects the aggregation levels and scales at which decisions are made, institutions and stakeholders that participate, and ecological processes reported in the literature on cattle ranching in LA.

3. Results and Perspectives

3.1. Trends in Livestock Research in Latin America

Livestock research in LA increased during the 21st century. In the review, livestock included ruminant species, namely cattle (*Bos taurus* and *Bos indicus*), sheep (*Ovis aries*), goats (*Capra hircus*), and buffalo (*Bubalus bubalis*), and non-ruminant species, namely pigs (*Sus scrofa domesticus*) and chickens (*Gallus domesticus*). However, 95% of the livestock studies analyzed address cattle production, processing, sale, distribution, or consumption issues—the remaining 5% study represented other livestock species. The current debate mainly focuses on cattle ranching systems; therefore, we will use the words livestock and cattle ranching as synonyms. Studies in just four countries accounted for 50% of all the articles reviewed: Mexico (17%), Colombia (12%), Brazil (12%), and Argentina (9%) (Figure 2a). These countries account for 70–80% of the production of the principal livestock species in LA (ECLAC, 2017), so it is not surprising that they are the countries where livestock research is strengthened. We identified a disconnection between recognizing and measuring the approaches and concepts that are key to encouraging sustainability and the notion and quantification of sustainability in formal livestock research. Although cattle research mentioned sustainability in most LA countries (Figure 2a), its measurement was weakly explored. In this regard, the significant conceptual advance was recognizing the sustainability (83% of the studies mentioned the concept); however, only 4% of the studies applied a method to quantify sustainability, most of them in Mexico (Figure 3).

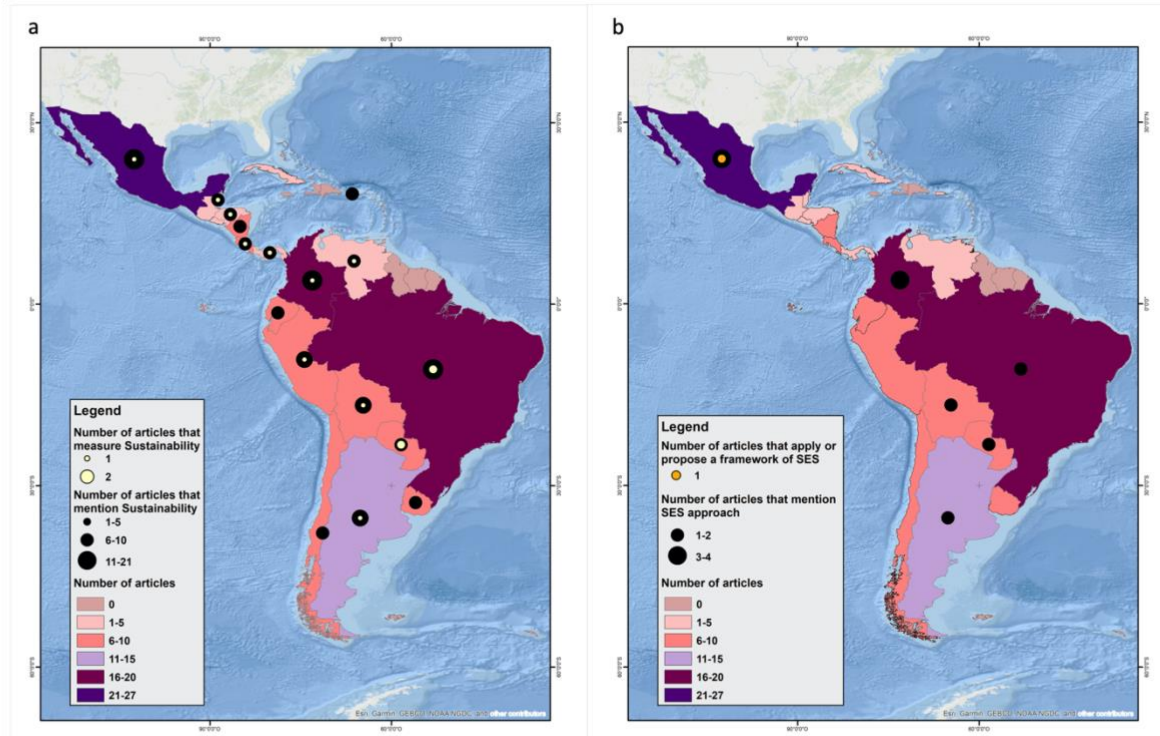

Figure 2. (a) Spatial distribution of livestock research in Latin America between 2000 and 2020 where sustainability is mentioned and measured; **(b)** Spatial distribution of livestock research in Latin America between 2000 and 2020 where a conceptual framework of SES is mentioned and applied.

Research from Mexico, Colombia, Brazil, Bolivia, Paraguay, and Argentina mentioned the integrative SES approach and recognized its usefulness for systematically studying cattle ranching (Figure 2b). The SES concept was mentioned in 16% of the studies. However, less than 1% of them (only one study) applied SSE theory to examine through a framework the relationship between local social-ecological components and livestock management (Figures 2b and 3) (Sánchez-Romero et al., 2021). The inclusion of the SES framework in livestock research was incipient, possibly because the diversity of people, interests, and power asymmetries involved throughout the agri-food system in LA (production, processing, marketing, and consumption) make it challenging to plan the sector holistically, as is the case with the study of soft systems (Cundill et al., 2012). MF was mentioned in 8% of the documents but was explicitly measured in less than 1% of papers (Figure 3). Lack of understanding of MF has already been reported for SES research, just as a comprehensive treatment of multi-scale systems containing closely interdependent components within SES is still lacking (Mao et al., 2021). ES were mentioned in 48% of the reviewed studies but were quantified or mapped in only 5% (Figure 3).

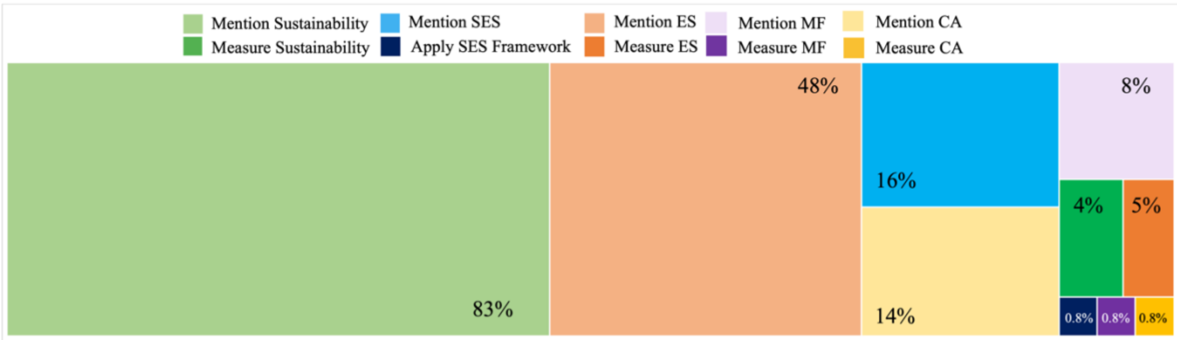

Figure 3. Proportions (blocks) and percentages (values) of mentions and measurements of critical approaches and concepts in the study of cattle ranching in LA.

Our results support that livestock is an essential driver of most rural landscapes and economies in emerging countries (Broom, 2016), where certain benefits derived from cattle ranching are recognized. On the other hand, the various ES that livestock systems provide to society, beyond food production, are often overlooked and rarely quantified or mapped (Dumont et al., 2019). Steering livestock towards sustainability involves improving the provision and quantification of all types of ES, as well as ensuring communication of their importance for improving ecosystem conservation, making the existing cultural and spiritual relationships visible, and moving towards profitable and productive management with less environmental impact (Idem).

CA was recognized in 14% of the documents reviewed but was included in a conceptual framework in only 1% of them (Figure 3). The scarce mention and measurement of CA processes in LA livestock contexts visualize a primary challenge for cattle breeding and marketing in the region, as CA has the potential to strengthen governance and improve the livelihoods of farmers living from livestock production (Barnaud et al., 2018). This is essential, as the fragility that results from poor governance and weak cooperation and organization among people is compounded throughout the supply chain and amplified across scales, problems that hinder the development of the sector and that have been reported in other poor regions of the world (Barrett et al., 2017; Gwaka et al., 2020). The inequities in power relationships based on the governance of the supply chain highlighted potential points of entry and exclusion for smallholders (Rich et al., 2009). Moreover, along with inequalities, systemic traps that maintain the status quo in the hands of the powerful undermine sustainability (Meadows, 2008)). An improvement to one part of the supply chain, say for instance production, without concomitant interventions in better processing and marketing capacity, could lead to higher production without an adequate market outlet, further depressing prices for smallholders (Rich et al., 2009).

Including CA in community and private livestock management would promote the sector's sustainability. Specific strategies of organization and cooperation between producers and institutions can orient cattle production and trade towards sustainability (Barnaud et al., 2018). Current strategies (e.g., the market orientation of production systems, combined with appropriate incentive policies that achieve the establishment of systems with less environmental impact) (Lerner et al., 2017) and future strategies must consider the many market failures in the form of high transaction costs, information and power asymmetries, limited organizational capacity, externalities, regulatory deficiencies in LA where smallholders often have little bargaining power (Rich et al., 2009). About 43% of the documents used qualitative methods; 26% used quantitative methods; and the remaining 31% combined qualitative and quantitative approaches, thus reflecting and supporting the predominance of studies at levels of institutional analysis so far this century. Among the documents reviewed, 66% were research articles; 27% were review articles; and 7% were book chapters (Table S1).

3.2. The Components of Cattle Ranching in LA

Understanding the sustainability debate depends on the interactions between internal components (e.g., social, ecological, or economic) and external factors (e.g., global environmental problems, political conflicts) (Holling, 2001; Gunderson & Holling, 2002). Livestock systems represent a potential pathway out of poverty for many smallholder farmers in the developing world; however, understanding their social, economic, and ecological components in a disaggregated manner can help identify opportunities for real-life environmental and social justice improvements. The identified components are part of cattle ranching systems that use land in LA. They are managed by small and medium producers who face problems of unsustainability (e.g., degradation of pastures, soil fertility and erosion problems, loss of biodiversity, etc.) in contexts of high vulnerability (Gordon, 2018; Gallo & Tadich, 2018; González-Quintero et al., 2020).

Ecosystems establish the biophysical conditions necessary to maintain MF at high levels, ensure ES, and sustain livestock management strategies as viable livelihoods over time (Peri et al., 2016; Boillat et al., 2017; Coppock et al., 2017; Hölting et al., 2019). The ecological components identified include biotic and abiotic factors of ecosystems. Abiotic factors are non-living physical and chemical components (e.g., soils, water, rocks). In contrast, biotic factors are the living components of an ecosystem (fauna, flora, and their interactions). Ecological components within cattle ranching SES are analyzed on local-regional spatial scales over days and months of studies, usually in experimental designs (Figure 4). However, many ecosystem processes occur over hundreds and thousands of years (e.g., soil formation, altered climatic regimes) and change within long/slow adaptive cycles (Figure 1), often overlooked in livestock research. These components shape two primary management practices used in LA to produce beef, milk, or both: extensive pastures (EP) and silvopastoral systems (SPS) (Figure 4). EP uses ex-tensive areas of natural vegetation where only herbaceous plants are grown for use as forage, along with rudimentary facilities to house cattle and store production-related materials (Quero et al., 2007; Bacab et al., 2013).

In the EP, the removal of tree cover and low density of cattle per unit area highlights the inefficient conversion of energy into animal products typical of production in tropical regions of LA. In contrast, SPS includes trees and shrubs associated with grasses to form a landscape of multi-layered vegetation for forage (Murgueitio et al., 2011); they also include forage banks and living fences to delimit individual pastures and provide additional wood and forage (Calle et al., 2013). SPS also retains or includes shrubs and trees that increase the capacity of the system to convert solar energy into biomass and enhance the complexity of the habitat (Chará et al., 2019). There is broad academic support for SPS in terms of environmental benefits. However, there has been little exploration of their role in the household economy in LA, where there are no differentiated value chains to commercialize what is produced in lower environmental impact livestock management systems (Rich et al., 2009).

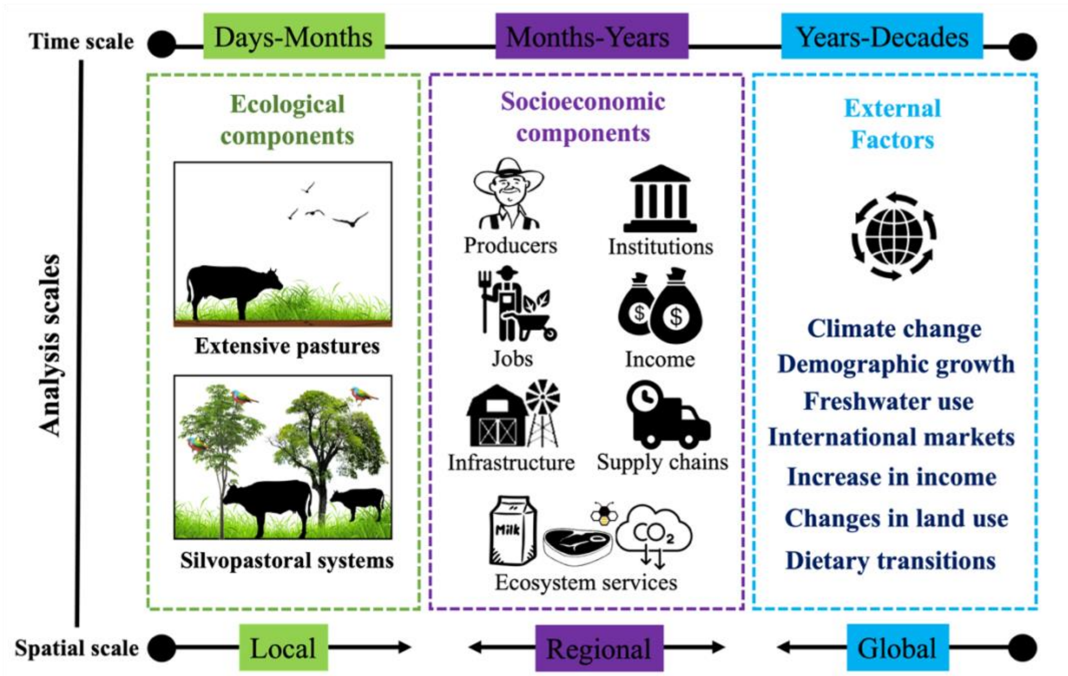

Figure 4. Ecological (green box) and socioeconomic components (purple box) integrate the cattle ranching SES in LA in interaction with external factors (blue box) identified in the papers re-viewed. In addition, it shows the spatial and temporal scales at which these components and fac-tors are usually analyzed.

We also recognized through the review critical socioeconomic components that are most frequently analyzed in livestock research in LA at local and regional spatial and temporal scales that include months and years: producers, supply chains (shorts and longs), income, institutions (governmental and non-governmental institutions), infra-structure, jobs generated, and the ecosystem services they provide (Figure 4), but which change within short/fast adaptive cycles (Figure 1). The current way of trading cattle means that producers remain dependent on conventional channels based on intermediaries and are monopolized by large companies that control the distribution of meat and milk. In this sense, the value chain approach thus provides a framework to analyze the nature and determinants of competitiveness in value chains where small farmers can participate. It also provides the basic understanding needed for designing and implementing appropriate development programs and policies to support market participation (Rich et al., 2009).

Beyond the value chain approach, it is necessary to consider the socio-ecological interactions arising from the injustice in which livestock buyers and consumers develop the sector and the severe consequences for long-term sustainability. However, tracking the components and understanding their relationships alone will not achieve the changes needed to move toward sustainability. Working with organizations—people who are persuaded to undertake some activity or change some operation—can help. Organizations might be considered "political cauldrons" where different and shifting coalitions emerge to get things accomplished. Understanding who has power (in its different forms) is key to making changes (Reynolds & Holwell, 2010).

A short food supply chain can be any marketing strategy based on a maximum of one intermediary between a producer and a final consumer. In contrast, a long supply chain involves more than one intermediary (Dragicevic, 2021). Cattle producers frequently use EP with limited financial and social capital, modest infrastructure, and few opportunities to diversify their livelihoods beyond cattle ranching. They are isolated from urban centers and government institutions, often segregating them from trade routes, subsidies, and other incentives (Sayre et al., 2013). In general, the lack of financial capacity to access technological improvements, scarce government support, little training on alternative production strategies, non-existence of special competitive supply chains, and excess of intermediaries that retain a percentage of the profit and poor governance (Gaudin & Padilla-Pérez, 2020; Romano-Armada et al., 2014) hinder the sustainability of livestock in LA. Although it is not possible to establish a single profit threshold for intermediaries along livestock product supply chains, it is known that the percentage they retain depends on three factors: (i) the contribution of intermediaries to the generation of total value added in the chain (which sometimes damages product quality), (ii) the value-added captured by the intermediary as a percentage of total value added in the chain, and (iii) whether or not the intermediary's income is generated to the detriment of producers' income and capacity building (Gaudin & Padilla-Pérez, 2020). The cattle ranching systems are characterized by long supply chains featuring great distances, numerous phases of weight gain and feeding regimes, many levels of traders and transactions, a multitude of steps and stages of processing, and various employment-creating services and expense generators (Rich et al., 2009).

Despite commercial constraints, the trade and consumption of animal products reduce the vulnerability of households to seasonal shortages of food and income for producers, workers, intermediaries, and butchers and improve food security and the nutritional status of the most vulnerable population [FAO, 2017; Gallo & Tadich, 2018; Galeana-Pizaña et al., 2021). It is essential to increase jobs in the agricultural sector and improve hiring conditions and the income of producers and workers in livestock production systems to reduce the vulnerability of rural families in LA (Rivera-Huerta et al., 2019). In addition, it is a priority to guarantee from government institutions that farmers have access to inputs, capital, infrastructure, technological improvements, technical information, and awareness to sustain management strategies with less environmental impact over time (Marinidou et al., 2018) associated with higher investment costs (Astier et al., 2011; van Loon et al., 2020).

The cattle ranching in the LA region is related to factors external to bovine SES analyzed predominantly on a global scale and time scales of years and decades: international markets, global increase in income, demographic growth, use of freshwater, changes in land use, dietary transitions with more significant preferences for livestock products and the contributions to climate change, primarily associated with the deforestation of forests (IPCC, 2013; Solorio et al., 2017; Galeana-Pizaña et al., 2018; 2021; Figueroa et al., 2021) (Figure 4). Some of these factors change within short/rapid cycles (e.g., changes in land use, dietary transitions) and others within long/slow adaptive cycles (e.g., climate change) (Figure 1). Other critical features include the changes in land use and freshwater use, as livestock production takes up about 70% of the total agricultural area (farmland and EP) worldwide (van Zanten et al., 2018), and its processes consume large volumes of freshwater (~8% of the global water supply) (Eshel et al., 2014). International markets (especially meat) are external factors stemming from a telecoupled world that maintains long-distance social, economic, and environmental interconnections among livestock production, processing, trade, and consumption (Liu et al., 2015; Zimmerer et al., 2018; Chung & Liu, 2019). On the other hand, population growth, increases in income, dietary transitions, and climate change (Ibarrola-Rivas et al., 2017; Tello et al., 2020) can trigger changes at regional and local scales and affect social and economic systems.

3.3. Institutional and Ecological Interactions across Spatial Scales

Despite the broad range of spatial scales and aggregation levels of livestock research in Latin America, 76% of the studies analyzed it at the institutional level, and 24% reported ecological analyses. However, the number of studies on cattle ranching and the number of documents, including ecological analyses, increased since 2015 (Figure 5), thus reflecting a growing concern about the environmental implications of cattle production and commercialization from LA. Institution-level studies focused on understanding yield improvements and the export potential of LA to meet the growing demand in other continents (ECLAC, 2017). Studies including ecological analyses characterized production systems [González-Quinter et al., 2020; Webster et al., 2019) and the impacts of livestock on ecosystems, particularly about climate change (greenhouse gas (GHG) emissions and land-use change), soil degradation (nutrient depletion, soil erosion), and pollution caused by the use of fertilizers supplying nitrogen and phosphates [Astier et al., 2011; Romano-Armada et al., 2014; Gerssen-Gondelach et al., 2017; Arango et al., 2020; Figueroa et al., 2020).

Our results reflect that socioeconomic components and external factors were analyzed mainly at institutional levels (producer level, household, municipality, state, region, country, countries, continents, and global) and to a lesser extent at ecological levels (plot, production system, ecosystem, landscape, and biome) for the consideration of ES and the estimation of GHG emissions (Figure 5). For their part, ecological components (biotic and abiotic) were studied almost strictly within ecological levels of analysis (animals, species, plots, production systems, ecosystems, landscapes, and biomes) (Figure 5). This approach to livestock from a purely disciplinary view highlighted the socio-ecological disconnect within biological studies with potential implications for sustainability management. In other words, the evaluated ecological studies on cattle ranching in LA were predominantly reductionist because they did not connect the social and economic dimensions that largely shape ecosystems. The study of cattle in LA during the first two decades of the 21ST century was consistently promoted by government and academic institutions to understand management strategies that improve yields and animal welfare (Vargas-Bello-Pérez et al., 2017).

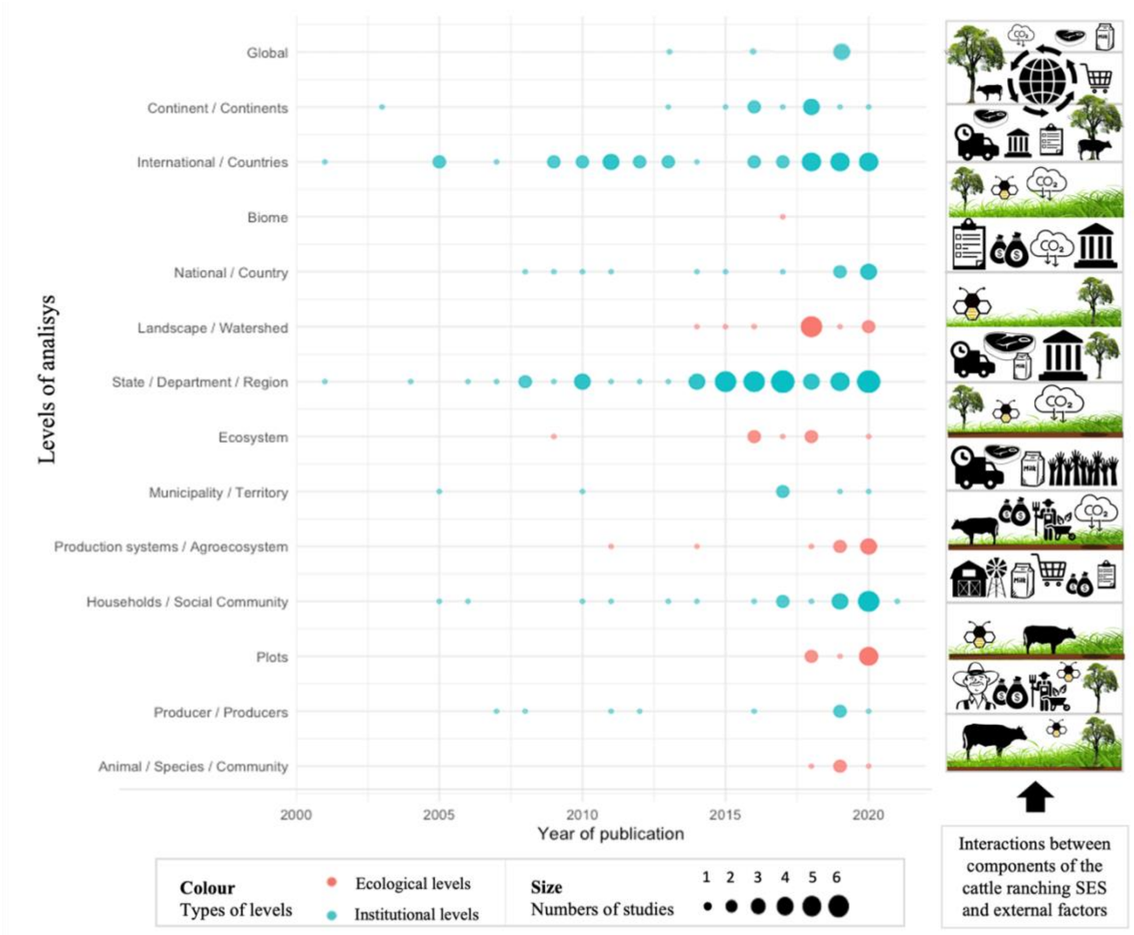

Figure 5. Levels of analysis reported in studies on livestock in Latin America and ecological/socioeconomic components and external factors identified within different levels in constant interaction. The color indicates the types of levels (institutional or ecological), and the size of the bubble indicates the number of studies reported for each year of analysis.

Nevertheless, it rarely focused on analyzing its impact on ecosystems, landscapes, and climate, which makes the lack of a holistic perspective explicit. The complexity and socioeconomic and environmental dynamism of the cattle ranching SES in LA make it necessary to address sustainable planning from a systemic approach to guide viable transformations. Insight into the scales and their interactions in space and time remains a challenge for SES management and for informing policy (Magliocca et al., 2018). The primary role of humans in the configuration of ecosystems implies that the interpretation of sustainability in SES depends on the environments created by humans (Zurlini et al., 2006). Although agriculture and livestock have radically altered natural landscapes with multiple social-ecological effects [Herrero et al., 2016; Rivera-Huerta et al., 2016; Uwizeye et al., 2018; Arango et al., 2020; Figueroa et al., 2020), the issue of spatial scales in the SES theory has been little explored (Zurlini et al., 2006; Ávila Foucat & Perevochtchikova, 2019). The poor understanding of the linkages between the processes of social-ecological change at different scales leads to errors in estimating impacts and the design of public policies for land-use planning and adaptation (Berrouet et al., 2018). Therefore, this research contributes to reducing the scalar gap. Considering the current trend in livestock production and consumption, we are facing an unprecedented challenge in sustainability throughout the agri-food system (Reyes et al., 2017), so exploring the viability of SPS within the ecological, social, and economic dimensions represents a priority for the region. Sustainable solutions will have to be constructed by combining personal and political actions that guide the transformation and ensure ecological, social, and economic benefits that can last over time (Figueroa & Galicia, 2021) and strategically amplify across space and sustained over time.

4. Conclusions

Livestock research in Latin America so far in the 21st century has been geographically concentrated in Mexico, Colombia, Brazil, and Argentina, mainly due to the leading role of these countries in the production and commercialization of cattle on the local, regional, and global scale. In addition, it shows a decoupling between institutional interests associated with the amplification of production (ecological and socioeconomic components) and the possible planetary consequences (external factors) associated with maximizing yields in extensive systems and opening markets every time more distant and demanding. The inclusion of the SES framework in livestock research has been incipient, possibly due to the difficulty of sizing and integrating the diversity of capacities, worldviews, interests, and power asymmetries in LA agri-food systems. However, the complexity and socioeconomic and environmental dynamism of LA's cattle ranching SES make it necessary to address sustainable planning from a systemic approach to guide viable transformations that address unsustainability. Promoting sustainability implies, on the one hand, improving its measurement to assess the current state of SES and, on the other hand, improving the provision and quantification of all types of ES, as well as ensuring the communication of its importance to improve the conservation of ecosystems, make visible the existing cultural and spiritual relationships, and move towards profitable and productive management with less environmental impact.

The scarce mention and measurement of CA processes in LA contexts visualize a primary challenge for cattle ranching production and commercialization in the region, as CA has the potential to strengthen governance and improve the livelihoods of producers who make their living from cattle management. The consolidation of organizations within which organizational processes are strengthened can be a strategy through which different and shifting coalitions emerge to get things accomplished. Working with organizations is indispensable to understanding the forms of power; they are crucial to leveraging changes and establishing cooperation with institutions.

The lack of financial capacity to access technological improvements, limited government support, poor training on alternative production strategies, the absence of special and competitive supply chains, an excess of intermediaries who keep a percentage of the profits, and poor governance hinder the sustainability of livestock farming in LA. These issues must be addressed systemically, recognizing their multi-scale, multi-temporal, and multi-sectoral dimensions. Livestock studies in institutional levels of analysis in LA include predominantly socio-economic components and external factors to the local SES but also integrate environmental issues, which show better social-ecological integration. However, studies conducted at ecological levels of analysis maintained a strictly environmental focus, and most of them ignored the social and economic dimensions that shape ecosystems and are indispensable for improving sustainability. Knowing the scales and their interactions in space and time remains challenging for SES management and informing policy. In that sense, this research contributes to reducing the scalar understanding gap.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1. Table S1: Data matrix derived from systemic review.

Author Contributions: Conceptualization, D.F. and L.G.; methodology, D.F.; formal analysis, D.F.; writing—original draft preparation, D.F.; writing—review and editing, D.F., L.G. and M.S.L.; supervision, L.G.; project administration, M.S.L.; funding acquisition, L.G and M.S.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Consejo Nacional de Ciencia y Tecnología (CONACYT) through the doctoral grant (750544/CVU: 723924) awarded to Daniela Figueroa. In addition, we received funding for data analysis from Universidad Nacional Autónoma de México (UNAM), through the Programa de Apoyo a Proyectos de Investigación e Innovación Tecnológica (PAPIIT) No. 302421—Project: Provisión de servicios ecosistémicos en sistemas socio-ecológicos agrícolas, ganaderos y forestales: Transición hacia la sostenibilidad de sistemas productivos.

Acknowledgments: We thank Ann Grant for the English Language editing and her valuable editorial contributions to the manuscript.

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Capítulo 3

A social-ecological systems framework for studying tropical cattle ranching sustainability in Latin America

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Manuscript status: submitted to ***Environmental Management***

ABSTRACT

The social-ecological systems (SES) approach has been used recently to redirect resource management practices toward sustainability. Based on a systematic literature review, we created a conceptual framework of SES agri-food systems for tropical regions in Latin America (LA) that use the land for grazing bovines. In addition, a case study from the Mexican tropics was also used to operationalize the framework through a participatory approach with smallholders. The main theoretical and practical contributions include a disaggregated presentation of the SES and subsystems, their elements and descriptors, the relationship between spatial scales, and identifying factors that inhibit the development of tropical cattle ranching in the region. Identifying local sustainability thresholds generalizable to other bovine SES in LA was also possible. The framework helps to characterize an agri-food system based on grazing bovines, identify social-ecological impacts, and promote sustainable management strategies for tropical cattle ranching.

Keywords: Cattle ranching; Collective action; Ecosystem services; Multifunctionality; Sustainability; Tropical regions

1. Introduction

Cattle production in the tropics of Latin America (LA) is a crucial source of income for smallholders and part of production and consumption traditions that involve significant natural resource reserves (Murgueitio et al., 2011; Springmann et al., 2018). Exploring the sustainability of cattle ranching is a relevant topic, especially in the tropics, where native forests continue to be pressured by cattle pasture expansion (Lerner et al., 2017). Addressing the cattle ranching sustainability dilemma requires a thorough understanding of this agri-food system. The social-ecological systems (SES) approach facilitates the integration of the social, ecological, and economic components involved in the problem and potential solutions. SES are cross-disciplinary frameworks that enable understanding human-nature systems transformed over time and space (Martín-López et al., 2009). A cattle agri-food system is a local SES embedded in a complex network of multiple interactions at different scales (Duru et al., 2015). The SES approach has been used to understand the interactions between humans and ecosystems derived from harnessing ecosystem services (ES). Insight into what happens within an SES and its relationship with the environment has the potential to guide agri-food systems toward more sustainable scenarios. Nevertheless, few SES frameworks exist to address the problems involved in cattle ranching (Duru et al., 2015; Marshall, 2015; Torralba et al., 2018; Ryschawy et al., 2019), and to our knowledge, there are none for LA, where there is a significant amount of cattle ranching activities (Arango et al., 2020).

The LA region generates 30% of the planet's meat and 28% of its bovine milk (FAOSTAT, 2019), this has provided a large portion of the supply that is needed to meet the growing demand (Alexandratos and Bruinsma, 2012), and it is crucial for ensuring food security regionally and worldwide (FAO, 2017a). However, it will be challenging to maintain the supply of meat and milk over time if the sustainability challenges posed by the production (Herrero et al., 2018) and commercialization of bovine (Broom, 2016) are not addressed. The environmental dimension of sustainability in LA has been approached from the biophysical implications of cattle ranching production (Figueroa et al., 2022). Cattle ranching have led to changes in land use, soil fertility, water use, biodiversity, climate change, and multifunctionality (Herrero et al., 2016; Gordon, 2018). Abrupt changes in the multifunctionality of agroecosystems (MFA) imply losses in the co-supply of multiple ES relative to their human demand. The spatial predominance of extensive cattle ranching in LA reflects one of the most significant expansions of the agricultural frontier in the last 50 years on a global scale (Herrero et al., 2018) being a major cause of tropical forest deforestation (Lerner et al., 2017) with consequent loss of MFA and ES.

Socio-economic unsustainability has been related to the need for more access to financing, information, technological innovations, inputs, and differentiated value chains needed to increase productivity without substituting tropical ecosystems for cattle grazing (Lerner et al., 2017; Figueroa et al., 2022) In the tropics of LA, very small (1 to 30 bovines) and small

(31 to 50 bovines) ranches dominate the landscape (González-Quintero et al., 2020), and they are managed primarily in two grazing production systems (Gallo and Tadich, 2018; González-Quintero et al., 2020). One system is extensive pastures (EP), the most expansive and characterized by clearings where the only plants grown are herbaceous plants for feed (Herrero et al., 2016). The other is silvopastoral systems (SPS), where bovine is produced in grazing areas containing native and planted trees and shrubs along with various vegetation strata (Murgueitio et al., 2011). The SPS have been recognized as a critical agenda item for the sustainable intensification of cattle ranching in the tropics (Boval et al., 2017), particularly in tropical regions in LA (Lerner et al., 2017), where the adoption of SPS by smallholders can foster biodiversity and habitat conservation within agroecological landscapes (Tscharntke et al., 2012).

Mexico is the world's sixth-largest producer of bovine meat, with 35 million heads of cattle occupying 55.9% of its land (109.8 million hectares), from which 881,000 people earn a living (SIAP-SADER, 2020). While cattle ranching activities occur throughout Mexico, the tropical region is notable for containing one-third of the nation's total cattle (SIAP, 2018). The ecological, social, and economic benefits of SPS have been documented (Chará et al., 2019; Calle, 2020). Nonetheless, in Mexico, as in other tropical forested regions in LA, EP continues to be the main form of production on which an average of 0.5 bovines graze per hectare (FAOSTAT, 2018), and they have significant implications for the environmental and social sustainability (Rivera-Huerta et al., 2016; 2019). Despite them, an interesting case in the advancement of SPS in tropical regions in LA is Chiapas, a state in southern Mexico where SPS have been amply established (Apan-Salcedo et al., 2021).

The construction of a framework of SES cattle ranching needs to consider the gaps in the theory: the disaggregation of the economic dimension (Colding and Barthel, 2019) and the exploration of spatial scales (Ávila Foucat and Perevochtchikova, 2019). It is also crucial to apply conceptual proposals to local contexts to identify appropriate strategies for management and commercialization (Figueroa et al., 2022). In fact, only 14% of SES research that proposes a conceptual framework operationalizes it in a local context (De Vos et al., 2019). The integration of conceptual and practical issues can present an opportunity for promoting the adoption and use of more sustainable scenarios for the region, as well as for establishing actions based on diverse types of knowledge, e.g., inherited, empirical, external, or combination of all types (local knowledge) (Sánchez-Romero et al., 2021) and proposing precise and generalizable thresholds for addressing agricultural sustainability (Gil et al., 2019). Given the growing uncertainty about the future viability of EP as the primary economic support for thousands of rural families in the Mexican tropics (Rivera-Huerta et al., 2019), systemic planning of cattle ranching on multiple scales is indispensable (Figueroa and Galicia, 2021). In this sense, we propose the following:

- To construct a conceptual framework of SES to analyze social, economic, and ecological characteristics of cattle ranching food systems in the tropics of LA; and identify opportunities for improvement in their management and marketing practices.

- To operationalize the SES framework with a series of quantitative descriptors of sustainable cattle ranching applicable to LA tropical regions; tested locally through a participatory approach with smallholders in Chiapas, Mexico.

2. Theoretical Background

The SES approach has emerged as a fundamental conceptual and analytical framework for understanding social and environmental connections and feedback in real-world systems (Colding and Barthel, 2019). Ecosystems provide society with supporting, provisioning, regulating, and cultural ES to satisfy their needs (MA, 2005). Consequently, human actions and institutional activities, directly and indirectly, affect ecosystems as they are using them (Fig. 1). Integrating the ES framework as an element within SES can facilitate decision-making and improve management strategies (Binder et al., 2013). The cattle ranching SES consists of ES that integrate environmental, cultural, and economic values, the latter through the income producers earn using private and common land (Torralba et al., 2018). The ES classification distinguishes all the ecosystem functionalities supporting social benefits. Specifically, for cattle systems, supporting services are habitat, food for wildlife, soil moisture retention, and fertility. Provisioning services include all products obtained from ecosystems and cattle (e.g., pasture for cattle, feeds, wood, food derived from ranching, fiber, and water). Regulating services include recharging groundwater, soil fertility, carbon sequestration, nitrogen fixation, and microclimatic conditions derived from shade for cattle. Finally, cultural services include the aesthetic appreciation of nature and the landscape, protection of nature, recreation activities in nature, spirituality, educational values, and safeguarding of worldviews (Tauro et al., 2018; Dumont et al., 2019). This conceptualization of ES includes a wide range of values from economic or local knowledge or cultural uses that can be captured in a SES.

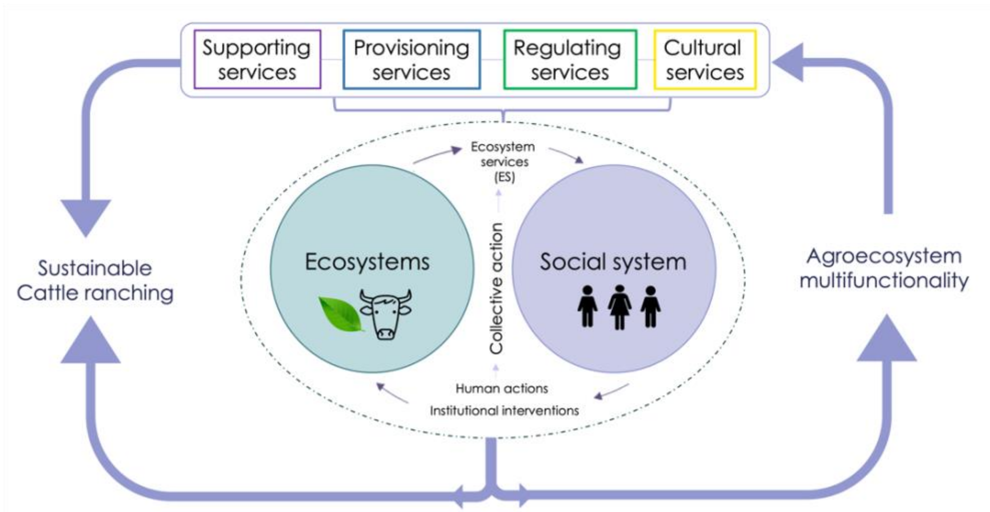


Fig 1. Approaches and concepts underlying the proposed framework.

ES provision directly depends on the ecological qualities ("functions/stocks") existing in an ecosystem. MFA describes the capacity of an agroecosystem to provide several ES simultaneously and is particularly relevant to applied research where stakeholders have definable management objectives (Manning et al., 2018). MFA recognizes, in the case of cattle systems, that they have other essential functions for SES beyond SE provisioning (Figueroa et al., 2022). However, integrating the multiple functions of agri-food systems within sector planning must simultaneously be accompanied by mitigating trade-offs associated with grazing and food production (Hodbod et al., 2016; Dumont et al., 2019).

In cattle production systems, managing ES and promoting sustainable trajectories can be optimized through collective action (CA) - a cooperative strategy representing governance, production, and marketing advantages for organized smallholders (Barnaud et al., 2018;

Figueroa et al., 2022). Power asymmetries and conflicts of interest, blunt in LA's widely unequal social structures (ECLAC, 2017), can impede CA, which requires social learning, trust-building, and mutual understanding. Further, negotiation and conflict resolution processes (Ostrom, 2009a). In that sense, there is still a need to strengthen social capacities and governance in tropical regions to move cattle ranching SES toward more sustainable scenarios (Barnaud et al., 2018; Figueroa et al., 2022).

3. Methods

3.1 Conceptualization of the SES Framework

A systematic literature review (SLR) was performed to construct a conceptual framework of SES that steers tropical agri-food bovine systems toward sustainability by identifying relevant social, economic, and environmental components and using the ES framework and MFA and CA concepts as tools for this approach. The Search, Appraisal, Synthesis, and Analysis (SALSA) is a methodology proposing a search protocol for a SLR (Grant and Booth 2009), and it has been used to ensure accuracy, systematization, exhaustiveness and reproducibility (e.g., Perevochtchikova et al., 2019). The description of each phase of the SALSA framework is shown in Table 1.

3.2 Operationalization of the SES framework

After developing the framework of SES for tropical cattle ranching in LA, it was applied to a case in the Mexican tropics (Chiapas), where a quantifiable set of descriptors and associated sustainability thresholds was identified by adopting a general method proposed by Leslie et al. (2015), to translate the SES framework into quantitative measurements of the potential for social-ecological sustainability. The operationalization of the conceptual framework of SES involved interconnecting actors (producers and academics). It included diverse knowledge and analyses (Gomez-Santis et al., 2021) to understand the SES under study.

Table 1. Application of the SALSA framework.

Phase	Description
Search	The search was based on literature that has been published in English and Spanish over 20 years (2000-2020). It was aimed at capturing the characteristics of cattle activities during what has transpired in this century after the recognition of the cattle revolution (Delgado et al., 1999). The search was conducted on January 12, 2021 in Scopus, Web of Science and Google Scholar databases in three stages: title, title and abstract, and full text (Mengist et al., 2020). The search used combinations (+ = plus) of keywords such as: Cattle ranching + Latin America + Tropics; Cattle ranching + Socio-ecological Systems; Cattle ranching + Multifunctionality; Cattle ranching + Ecosystem Services; Cattle ranching + Collective Action, and Cattle ranching + Tropics.
Appraisal	All the studies that met at least one of the following four selection criteria were included: i) characterization of tropical cattle ranching management in one LA country; ii) analysis of cattle ranching systems based on the SES approach in a tropical context; iii) incorporation of the ES framework and/or trade-offs involved in cattle ranching; and iv) evaluation or mention of the concept of MFA and or CA in the analysis of cattle ranching systems.
Synthesis	A total of 368 retrievals were obtained from the search. However, 170 articles were selected based on the criteria described above. These were organized using an Excel matrix that included the documents' citations, titles, authors, years of publication, types of publication, journal names, keywords, methodologies, problems addressed, study sites, and spatial scales (see SM 1. Matrix). Of the selection, 120 articles were spatially located in tropical LA, and the remaining 50 articles related cattle ranching to the concepts of SES, MFA, SE, and CA, many of them in tropical contexts in other regions of the world that were included in the SLR to

	strengthen the understanding of frameworks SES in cattle ranching research. However, articles not spatially located in LA were not considered for conceptualizing the cattle ranching SES.
Analysis	The analysis stage involved evaluating the synthesized data (N=122) and extracting the relevant information (Mengist et al., 2020) to build the conceptual framework of SES cattle systems in LA. The mentioned frequency analysis was used to identify and select the cattle ranching characteristics (internal SES elements) and the related global phenomena (elements external to SES). Further, the social, economic, and ecological innovations and problems (one-way interactions [relationships] and two-way interactions [feedback] between systems and elements) in the articles reviewed. A *relationship* within the SES was defined as a system or element having a positive [+] or negative [-] influence on another system or element, whereas *feedback* is described when the interaction of one system with another system within or outside the SES permitted the reinjection of information that can have a cumulative or growing effect (positive feedback [+]) or a subtractive or decreasing effect (negative feedback [-]) (Synes et al., 2019). Knowing that the frequency of mentions can be looked at to understand the weighted importance of individual factors, we identified the elements and descriptors that were most often included as the socio-economic and ecological analyses of cattle systems that use land in LA.

3.2.1 Case Study: Chiapas, Mexico

Cattle ranching is an economic activity on which thousands of producers in Mexico depend (Fuentealba and González-Esquivel, 2016). Particularly in Chiapas, a state located in Southern Mexico (see SM 2. Fig. 1), raising and selling bovine is the most important farming activity for the economics of the region. Already 82,000 producers and their families directly depend on the production and commercialization of cattle for their survival (INEGI, 2017). These production and commercialization activities occur under tropical conditions in systems managed by small and medium producers who commercialize the cattle in a market that mediators have cornered. On average, 59% of bovine in Chiapas is sold to local and regional intermediaries who retain a portion of the income (INEGI, 2017).

The Silvopastoral Network was created in response to the excessiveness of intermediaries and to draw attention to the products that are produced in cattle ranching systems that use regular silvopastoral practices (e.g., increased cattle density and inclusion of trees and shrubs). This network was created as a non-profit initiative in 2014. Its members included nine cattle ranching associations - legally constituted producer groups to manage cattle production and commercialization practices - and 350 bovine producers distributed throughout six socio-economic regions and municipalities in Chiapas (see SM 2. Fig. 1 and SM 2. Table 1). After approaching some producers, the Silvopastoral Network was defined as the SES focal to which the proposed conceptual framework was applied.

3.2.2 Characterization of SES focal

Semi-structured interviews were administered between July and October of 2018 to 350 producer members of the Silvopastoral Network. The questionnaire (see SM 1. Table 1) was designed to capture values associated with ecological (e.g., tree and shrub components, cattle species), social (e.g., ages, schooling, rules), and economic (e.g., machinery, jobs, products sold) issues in 10 thematic blocks that characterized the SES focal, as part of the project "Systems of sustainable production and biodiversity" by National Commission for the Knowledge and Use of Biodiversity (CONABIO in Spanish), Ministry of Environment and

Natural Resources (SEMARNAT in Spanish), and the Global Environment Facility (GEF). The application of the 350 interviews in the field was carried out by technicians belonging to each cattle ranching association, who received prior training for this purpose. The local technicians returned the information and photographic evidence to the Silvopastoral Network at the end of the interviews, which lasted, on average, between 1:30 and 2:00 hours each.

The qualitative information from the interviews was organized and analyzed in Excel data matrix and was associated with each subsystem and element in the proposed SES conceptual framework. In the interviews, we obtained the list of tree, shrub, and grass species from the interviews where common names were reported. Using the national forest and soil inventory (CONAFOR, 2021), we performed the translation to the scientific name after eliminating synonymies and confirming the spatial distribution of the species. Since soil biogeochemical data were not obtained from the pastures, the information about the soil was taken from publications (Soto-Pinto et al., 2010 and Villanueva-López et al., 2015) that have reported on the relationship between cattle ranching and nutrient dynamics in some of the municipalities located around the influence area of the Silvopastoral Network.

3.2.3 Assessing sustainability in the SES

Sustainability was analyzed through contextualized descriptors identified by producers of the Silvopastoral Network (N=23) in a participatory workshop (Herrera-Franco et al., 2018) held in February 2019. To ensure representativeness, the number of participants was estimated from the following equation:

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

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

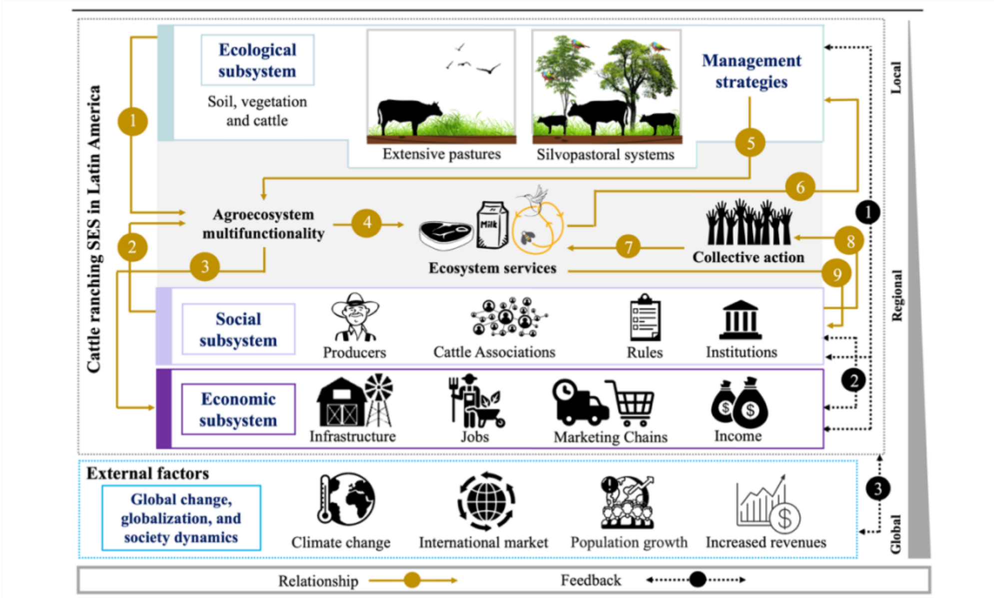
To this end, four academic facilitators led an open discussion with producers on the most relevant productive/organizational and environmental issues (descriptors) for moving towards more sustainable scenarios in cattle ranching. The 12 resulting descriptors were socialized and validated in plenary with the help of a board. Seven sustainability descriptors are related to socioeconomic issues (job creation, infrastructure, marketing, livestock density, rotation frequency, diversification, and family participation), and five to ES. It is essential to mention that we approached regulating ES such (as the shade of cattle), supporting ES (habitat and race diversity), and provisioning ES (cultivated fodder and water availability) using the analysis of some of the ES identified by Tauro et al. (2018) for cattle ranches in the Mexican tropics.

Finally, participants were asked to define the descriptors and proposed three thresholds or progress ranges in sustainability for each descriptor. The progress thresholds were to include a low, medium, and high sustainability scenario. The information associated with the measurements of the proposed descriptors was obtained by analyzing the semi-structured interviews. The values for each descriptor were identified based on the data matrix obtained from the interviews at the producer level. They were standardized by assigning a category of 1, 2, or 3 to each value to associate it with an individual range of progress. To report progress within each association, we calculated the average progress of its producers for each descriptor (see SM 2. Fig. 2). The categories (low 1, medium 2, and high 3) for each cattle ranching association were interpreted as sustainability trends (Leslie et al., 2015) given the thresholds set by producers and were visualized using radar diagrams.

4. Results

4.1 SES for cattle ranching in LA

Agri-food systems include activities involving bovine production and distribution and are structured according to their physical, biotic, economic, and socio-cultural components (FAO, 2017b). The main production models that use land in tropical LA and sell products (EP and SPS) can be analyzed as agri-food systems using the proposed framework of tropical cattle ranching SES (Fig. 2). Three groups of elements in the *ecological subsystem* — soil, vegetation, and bovine— are managed at the local scale through “management strategies,” which are properties that emerge from the SES of which they are part since they result from pre-established social and cultural decisions, economic contexts, and ecological conditions that both facilitate and impact them. The descriptors are related to the soil's physical and chemical properties, species diversity, grazing intensity, and even issues involving animal wellbeing (Fig. 2). It is important to mention that ecological descriptors can be interpreted as ES as long as a group of people within the SES values them as direct or indirect benefits.



Elements	Descriptors	Elements	Descriptors	Elements	Descriptors
Soils	1. Physical and chemical soil properties 2. Total and available nutrient contents 3. Nutrient dynamics 4. Enzymatic activity	Producers	1. Internal non-governmental actors 2. Sex, age, and education level 3. Role in the system	Infrastructure	1. Structural capacities 2. Machinery and equipment 3. Reproduction and feeding
		Cattle Associations	1. Description 2. Spatial influence 3. Membership conditions and structure	Jobs	1. Internal jobs 2. External jobs 3. Job conditions
Vegetation	1. Tree species 2. Shrub species 3. Grass species	Rules	1. Constitutional, operational, and collective action rules 2. Resource management	Marketing Chains	1. External non-governmental actors (intermediaries, direct buyers) 2. Products traded
Cattle	1. Cattle species 2. Animal welfare 3. Grazing intensity	Institutions	1. Government actors 2. Research institutions	Income	1. Income of producers and associations 2. Income of workers 3. Market prices

Fig. 2 Conceptual framework for the analysis of cattle ranching SES in Latin America.

The *social subsystem* is made up of four elements: i) "producers," a category that includes owners, administrators, and workers in the production systems, that is, internal non-governmental actors that perform a crucial role in being responsible for management strategies and commercialization decisions; ii) "cattle associations," through which agreements are made between producers and the communities in the spatial area of influence (local and regional) of the cattle ranching associations; iii) “rules,” defined as prohibiting, requiring, determining, defining and even limiting human behavior in a given situation, in this case, production and commercialization activities related to cattle. Rules can be related to constitutional, operational, and collective action (Ostrom, 2009a); and iv) “institutions,” which are made up of government actors who are involved in and promote the development of production activities, and research institutions that conduct social and ecological work that contributes to knowledge about cattle ranching in LA (Fig. 2). Although associations, rules, and institutions constitute governance systems, these elements can be separated to improve the disaggregated assessment of the relationships and feedback (Ostrom, 2009b) between their descriptors.

The *economic subsystem* is composed of four elements: i) the “infrastructure” that cattle producers and associations use for farming activities, notable among which are structural capacities (e.g., stables, refrigeration systems, slaughterhouses), machinery and equipment (e.g., grinders, motor pumps, transportation trucks), and strategies involving artificial reproduction and feed supplements; ii) the “jobs” that are generated can be internal (families) or external; iii) "marketing chains" are defined by the type of marketing (direct or indirect) and are made up of external non-governmental actors (e.g., intermediaries, supermarkets, butchers, industrial producers) and the products being sold (Fig. 2); and iv) “income,” which includes the total profits earned by the “producers,” the annual income of the “Cattle Associations,” and even the prices of the different products, which can reflect competition or an opportunity to associate with other producers, sellers, or transformers in the agri-food system.

The *interface* (gray zone) is a socio-ecological space resulting from the integration of three elements (MFA, ES, and CA) (Fig. 2). Conceptually, it is similar to the subsystem "Outcomes" proposed by Ostrom (2009b) and should be understood within the analysis of tropical cattle ranching and, given the time scale of each study, as a pre-existing, current, or future social-ecological performance measure. Therefore, operationalizing the interface in the comprehensive analysis of cattle ranching is relevant for diagnosing and promoting transitions toward sustainable agri-food bovine systems in LA.

The MFA reflects the current functional state of the ecological subsystem, resulting from the historical management of agroecosystems. Within a cattle ranching SES, MFA should be enhanced through management that supports a notion of sustainable and finite resource use and, thus, a different relationship with nature, for example, by focusing on adaptive practices that are contextually explicit (Hodbod et al., 2016). Their measurement reveals the ecological viability of production practices over time. Although there is no single way to measure multifunctionality within fundamental ecology, the main methods for quantifying it are the "averaging" (or sum) approach (e.g., Maestre et al., 2012) and the "threshold" approach (e.g., Byrnes et al., 2014). More recently, measures have been incorporated that group ecological functions and social and economic ecosystem attributes into ES categories defined and valued from a human perspective (Manning et al., 2018).

The ES as a central and priority element of our framework, connects the ecological subsystem, its condition (stocks), and the generation of economic and social-ecological benefits (flows) to different actors (social subsystem), outside and inside the SES (households, enterprises, an economic sector, and individuals) (UNSD, 2021). The benefits include other dimensions of well-being than economic benefits (e.g., food security and health, attachment to the territory and identity, livelihood opportunities, Etc.). The cattle ranching systems also generate common/public goods, such as water purification, soil water, nutrient retention, habitat for biodiversity, and soil health (Tauro et al., 2018). These attributes and functions become ES when individuals or groups appreciate them and through their intrinsic value (e.g., the value of a cattle ranch that conserves or includes trees and shrubs, thus maintaining tropical biodiversity, providing shade and improving animal nutrition) (Barton et al., 2016). ES assessment can be approached from biophysical, socio-cultural, economic, and integral/plural perspectives. Integral valuation seeks to include actors without a voice in decision-making, and to analyze power asymmetries as a structural factor in the access and distribution of ES in specific contexts (Rincón-Ruiz et al., 2022). Although biophysical, socio-cultural, and economic approaches contribute to the understanding and valuation of ES, integral/plural valuation may be particularly appropriate in LA, a region where multiple society-nature relationships co-exist with polarized social structures, high levels of corruption, poverty, and inequality (ECLAC, 2017; Rincón-Ruiz et al., 2022). In this sense, it is fundamental to articulate local worldviews in ES assessment and decision-making (Díaz et al., 2018). On the other hand, recognizing that an exclusively monetary valuation could promote a mercantilist discourse (Díaz et al., 2018) among decision-makers and economic sectors, thus increasing the risk of ecosystems in LA, one of the most biodiverse regions in the world.

The interface's third element is CA, which can drive improvements in ES management. Strengthening CA processes and, in general, the governance of livestock SES in the Latin American tropics could increase people's awareness of the importance of managing more sustainable production and consumption scenarios (Barnaud et al., 2018). There are participatory methods that support processes involving CA with ES, such as deliberative appraisal, scenario planning (Palomo et al., 2011; Oteros-Rozas et al., 2015), and participatory mapping (García-Nieto et al., 2019). These methods strengthen social learning and trust relationships between stakeholders with different conceptions, interests, and needs. The characterization of social, economic, and ecological subsystems, combined with the operationalization of the interface of bovine SES, makes it possible to approach the sustainability of tropical cattle ranching at the local scale. Sustainability assessment at larger scales (e.g., LA region) should pay attention to issues external related to local SES. Cattle ranching SES interacts with global *external factors* (Fig. 2), namely: "global change," "globalization," and "society dynamics." This includes four key elements: 1) "climate change," due to which many EP in developing countries will become hotter, drier, and more frequently subject to extreme weather conditions; 2) "international markets," which result from a telecoupled world that maintains long-distance connections throughout the bovine agri-food system (Marshall, 2015; Chung and Liu, 2019); 3) demographic growth, and 4) increased income, which drives food transitions that promote cattle consumption (Alexandratos and Bruinsma, 2012).

4.1.1 SES relationships and feedback

The bovine agri-food system interacts with internal components and external factors. This has implications on multiple scales. It is important to emphasize that, as in the case of the descriptors, the interactions identified by the conceptual framework serve as a robust baseline for the analysis of any cattle ranching SES that uses land in tropical LA. Nonetheless they can be adjusted when operationalizing the framework in local contexts and must be validated by fieldwork (Tenza et al., 2017) and by including multiple actors and disciplines (Gomez-Santiz et al., 2021). All relationships and feedbacks are described in Table 2.

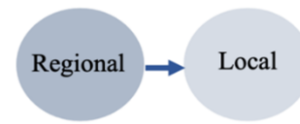
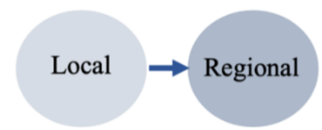
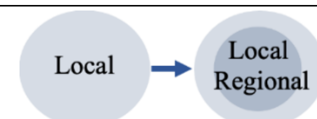
4.2 Application of the framework

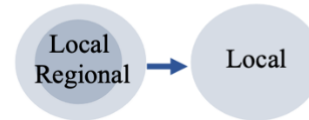
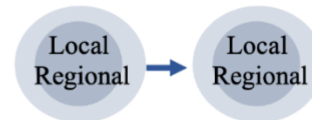
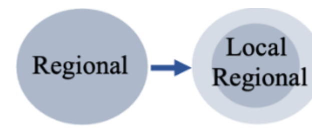
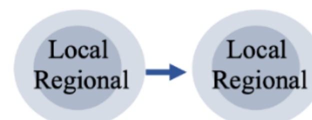
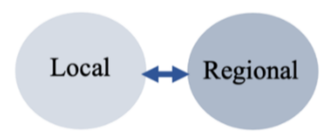
4.2.1 The Silvopastoral SES

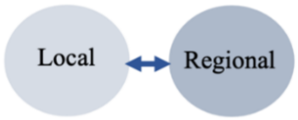
The Silvopastoral Network's agri-food system is based on the production and sale of bovines that graze in EP and SPS under tropical conditions. The ecological subsystem (see SM 3. Table 1) is characterized by the presence of three types of soil: Regosol, Leptosol, and Cambisol (Fig. 3). Although these are not considered to be very suitable for agriculture, in Mexico, they are used for cattle ranching, especially in tropical regions (Relationship 1). The clay and clay-loam soils in the SES expand with the moisture that they receive during the rainy season and contract in the dry season, thereby increasing the risk of erosion which contributes to the loss of nutrients with possible effects on the MFA and on limiting cattle production (Relationships 3 and 4). This dynamic intensifies with the increased occurrence of droughts in the region (Feedback 3).

Carbon and nitrogen contents differ for the different types of cattle management practices. EP (treeless pastures) register more storage of soil organic carbon (SOC) (75.1 Mg C ha-1) than SPS (68.5 Mg C ha-1), while also presenting less total carbon (TC) contents (78.8 Mg C ha-1) (Soto-Pinto et al., 2010) and a lower percentage of total nitrogen (TN) (25 % of N) than SPS (142 Mg C ha-1; 29% of N) (Fig. 3) (Villanueva-López et al., 2015) (Relationship 5). In addition, the ecological subsystem includes 66,318 natural (secondary tropical forest) and planted (leguminous species) trees (~ 190 trees per producer) on 4,674 hectares of pasture, including 106 species of tree and shrubs and 9 species of grass (Fig. 3; SM 2. Table 2). Its herd includes 11,098 bovines representing 6 bovine species (Relationship 2) (SM 3. Table 1).

Table 2. Relationships and feedback in cattle ranching SES on land in Latin America.

Interaction	Description	Spatial scales coupling
Relationships →		
1. Ecological subsystem → MFA	The ecological system establishes the biophysical conditions needed for maintaining high MFA levels (Boillat et al., 2017; Coppock et al., 2017).	
2. Social subsystem → MFA	The management decisions involving EP (monocultures) and SPS (trees and shrubs) and the consumption that arises in the social system can decrease or increase the MFA (Astier et al., 2011; Murgueitio et al., 2011; Amarilla et al., 2019; Chará et al., 2019; Parra-Bracamonte et al., 2021).	
3. MFA → Economic subsystem	The increase or decrease in the MFA affects cattle yields and efficiency, which directly impact jobs and income (Pica-Ciamarra et al., 2011; Hodbod et al., 2016).	
4. MFA → ES	Having high MFA levels ensures the ability of agroecosystems to provide individual and bundles of ES in specific territories (Manning et al., 2018).	
5. Management strategies → MFA	Extensive pastures, monocultures, the inclusion of live fences and trees, and the management of cattle density and grazing intensity impact the MFA (Lerner et al., 2017; Figueroa et al., 2020).	

6. ES → Ecological subsystem	The use of ES can harm ecosystems and decrease long-term social wellbeing (Astier et al., 2011; Arango et al., 2020).	
7. CA → ES	CA manages the ES that are provided by cattle ranching lands. Its inclusion can be an innovation in the design of production networks or associations, commercialization, and the study of cattle ranching systems (Pica-Ciamarra et al., 2011; Barnaud et al., 2018).	
8. Social subsystem → CA	CA is promoted by organizational processes that include decision-making and cooperation through associations, networks, and institutions (Barnaud et al., 2018; Coppock et al., 2017; Westholm and Ostwald, 2019, Apan-Salcedo et al., 2021; Figueroa et al., 2022).	
9. ES → Social subsystem	Cattle ranching ES are often interpreted as final ES. That means they are seen as contributions that ecosystems (in this case, highly modified living systems) make to human well-being. However, cattle ranching provides other benefits such as pollinator support, habitat, protection of the gene pool (intermediate ES) (Tauro et al., 2018; Amarilla et al., 2019; Figueroa et al., 2020).	
Feedback ← →		
1 Connection among the three subsystems in cattle ranching SES	Ecological, social, and economic subsystems provide feedback in terms of ES, agroecosystem management, job preservation, income, infrastructure, and technology (Romano-Armada et al., 2016; Arango et al., 2020).	

2. Socio-economic connections	The social subsystem supports non-governmental actors and institutions that generate environments that favor commercialization and income; in turn, income and jobs favor producers and workers (Rivera-Huerta et al., 2019; Arango et al., 2020; González-Quintero et al., 2020).	
3. Connections between the SES focal and external factors	The local expression of the SES focal can mitigate or promote global external factors (e.g., global warming from high GHG emissions), depending on the management strategy (e.g., SPS mitigates methane emissions). In turn, the global change affects the SES focal in LA (e.g., increased biophysical limitations on production) (Rivera-Huerta et al., 2016; Solorio et al., 2017; Figueroa and Galicia, 2021).	

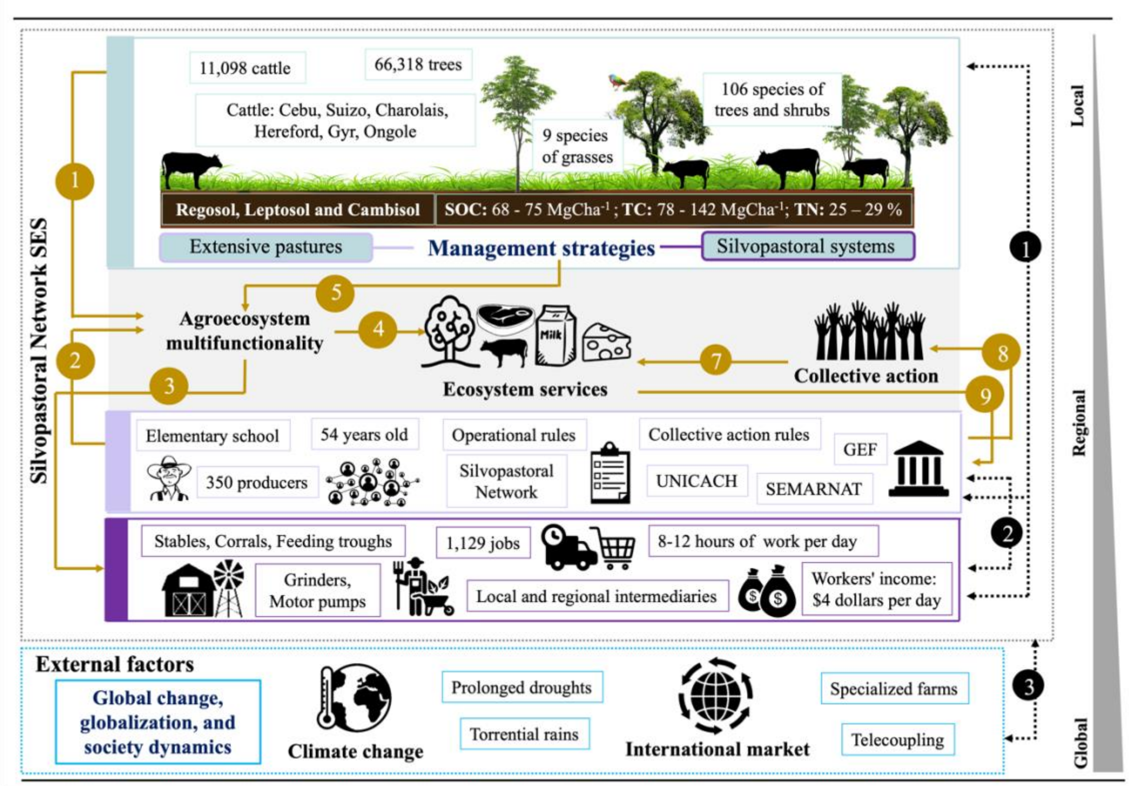


Fig. 3 The Silvopastoral Network's bovine SES, Chiapas, Mexico. Solid arrows indicate relationships, and the dotted arrows indicate feedback.

The social subsystem comprises 350 cattle producers (smallholders who have, on average, 32 bovines) belonging to nine cattle ranching associations whose spatial influence covers six municipalities in Chiapas (see SM 2. Table 1). There are 1,129 workers who perform different activities. The average age of the producers is 54 years old, their average education is a complete elementary school, and 89% of the producers are men. The actors have established operational and CA rules (Relationship 8) for organizing how they function, making collective decisions, communicating, coordinating, and governing the participation of the associates (see SM 3. Table 2). In general, the SES has been in contact with government institutions that are involved in the livestock sector in Mexico (the Secretary of the Environment and Natural Resources (SEMARNAT in Spanish) and with national (the Chiapas University of Arts and Science [UNICACH in Spanish]) and international (Global Environment Facility [GEF]) non-governmental organizations (Fig. 3) that have supported the establishment of model parcels to study SPS under tropical management (Relationship 7) (SM 3. Table 2).

The economic subsystem covers 5,342 hectares of the total area used for cattle ranching, which contains cattle and infrastructure such as stables, pens, feeders, drinkers, and storage of supplies (see SM 3. Table 3). This land also has machinery and equipment for production activities and, to a lesser degree, reproduction capabilities such as artificial insemination. Moreover, feeding capacities such as feed supplements combined with grasses, trees and shrubs to cattle (7% of the total producers in the Silvopastoral Network have sugarcane crops, 4% have corn crops, 25% have protein banks [legumes], and 34% supplement with salts) (Feedback 1). In addition, 750 jobs for the families of producers have produced as well as 379 jobs for external workers (1,129 total jobs), who receive an average of $70 Mexican pesos ($4 dollars) for one day of work (8 to 12 working hours) (Feedback 2) (Fig. 3).

Regarding marketing chains, 90% of the Silvopastoral Network´s cattle are sold indirectly, that is, through intermediaries who retain a percentage of the income. Seventy-eight percent of the producers sell young bulls to local intermediaries retaining a larger percentage of the income from the different products (Feedback 2) (SM 3. Table 3), 12% sell fattening and milk to regional intermediaries, and 10% sell directly beef and milk to butcher and supermarket. The SES focal's dependence on intermediaries for its sales is a response to international telecoupled markets (Feedback 3), which promote specialized meat and dairy production by systems with little diversification, and which are dominated by large producers (Fig. 3). Relationship 6 was not identified by the data from the Silvopastoral Network, and therefore, it was not traced within the SES focal.

4.2.2 Sustainability for cattle ranching in the SES

The sustainability of cattle ranching in the SES was defined by means of thresholds associated with 12 descriptors (Table 3). The economic subsystem supports job creation, infrastructure, and commercialization descriptors. The ES descriptors (shade of cattle, habitat, cultivated fodder, race diversity, and water availability) are based on the ecological subsystem and its multifunctionality (Fig. 2). In turn, the descriptors of cattle density, frequency of rotation, diversification (management strategies), and family participation are shaped by the ecological and social subsystem. The social subsystem was also represented by the nine cattle ranching associations (A1-A9) that participated in the construction of the thresholds (see SM 2. Table 1) that indicate different levels of progress in sustainability: low sustainability with a value of 1, medium sustainability with a value of 2 and high sustainability with a value of 3 (Table 3).

- ***Socio-economic descriptors***

In terms of the cattle density descriptor, progress was low, with an average of the associations having 1 to 2 bovines per hectare. In the descriptor for frequency of rotation, the sustainability value was medium, with bovines remaining in the same pasture for 10 to 20 days, especially for associations A4, A5, and A6 (Fig. 4). The diversification descriptor (a variety of production/economic activities on the same cattle ranch) presented higher sustainability values (medium sustainability) for associations A5 and A6 since their activities included not only cattle grazing but also feed supplements, milking, and cheese production by groups of youth and women (Fig. 4). The job creation descriptor presented low sustainability, except for associations A1, A5, and A6, which had medium sustainability since their member producers generated an average of 2 to 3 external jobs (Fig. 4). However, this was not the case for family participation; that is, the same associations generated more external jobs and had less family participation (low sustainability) (A1, A5, and A6).

The infrastructure descriptor presented low and medium progress in sustainability for nearly all the Silvopastoral Network associations except for association A4 and A5, whose system included tools, stables, grinders, and motor pumps for cattle activities (high sustainability). The commercialization descriptor presented a low sustainability value for most associations (selling young bulls to local intermediaries). Only associations A5 and A6 had progressed to medium and high sustainability, respectively, since their producers, on average, fattened and sold beef, milk, and cheese to butchers and small local markets.

- ***Ecosystem services descriptors***

The descriptor for shade of cattle presented medium sustainability, with associations A1, A5, and A6 having between 11 and 20 trees per hectare, while sustainability values for the other associations were low. Regarding the habitat descriptor, the progress made by most of the associations was low (0 to 30% of the pastures had live fencing), except for associations A5 and A6, which had vegetation in 30 to 50% of their pastures (Table 3, Fig. 4). The progress in sustainability was low for the cultivated fodder, with the systems in the Silvopastoral Network having less than 100 m^2 of forage per bovine, on average, except for associations A1. The progress in sustainability was also low for the race diversity (1 race per system), except for associations A5 and A6, which had 2 and 3 different races, respectively (Table 3, Fig. 4). The water availability descriptor presented high sustainability for nearly all the associations, which indicated that they had water throughout the entire year.

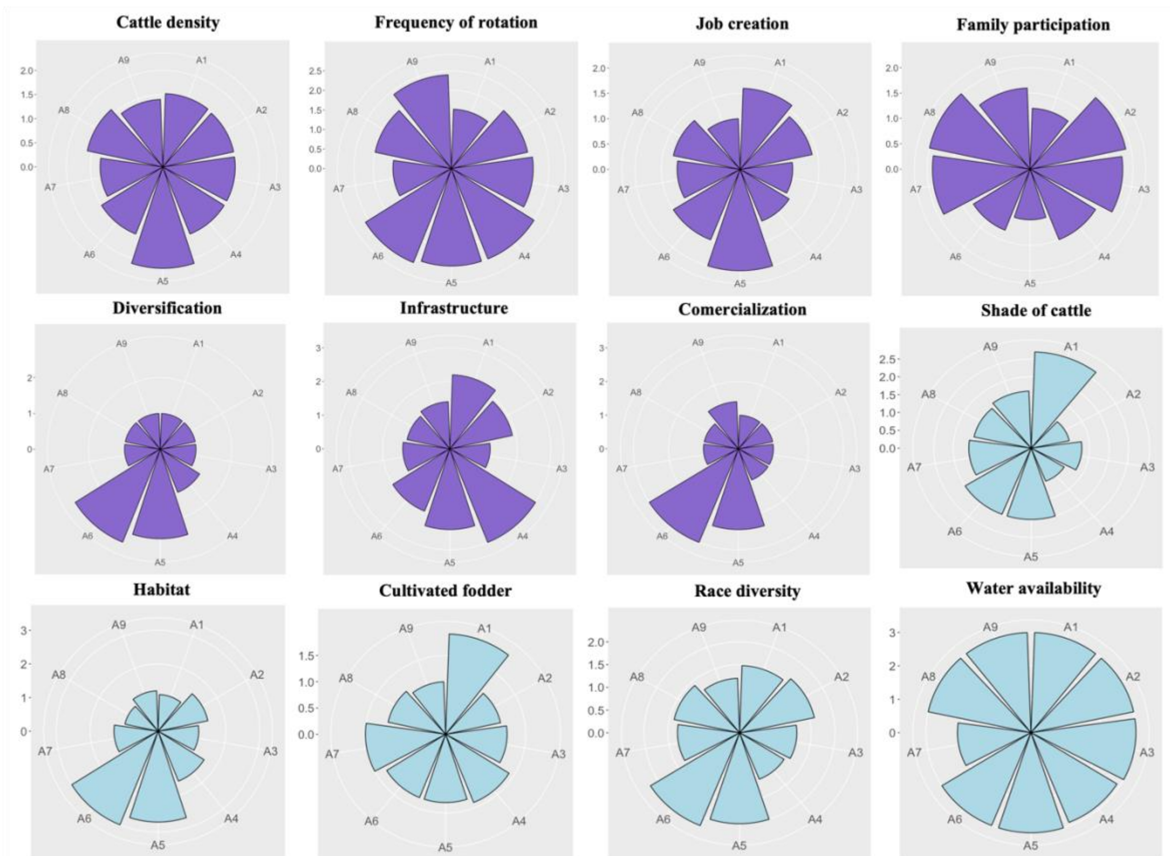


Fig. 4 Range of progress in sustainability (1, 2, and 3) for the 12 descriptors by the nine-member associations (A1 – A9) in the Silvopastoral Network. The purple radars represent socio-economic descriptors, and the blue radars represent ecosystem services descriptors.

Table 3. Descriptors, ranges of progress, and cattle ranching sustainability categories for the Silvopastoral Network. Colors and numbers indicate the sustainability category: 1-low, 2-medium, and 3-high.

Type of descriptors	Descriptors / Unit	Interpretation by producers	Ranges of progress	Sustainability Category
Socio-economic descriptors	**Cattle density** (bovines/hectare)	Increasing the cattle density benefits production and increases income	1-2 bovines/ha	1
			3-5 bovines/ha	2
			> 5 bovines/ha	3
	Frequency of rotation (Days of grazing per pasture/year)	Decreasing the number of days of grazing cattle in the same pasture prevents soil damage	> 20 days	1
			10-20 days	2
			<10 days	3
	Job creation (jobs/ranch)	A sustainable cattle ranch requires and can pay more workers	1 job	1
			2-3 jobs	2
			> 3 jobs	3
	Family participation (family members working/ranch)	New generations and women should participate in cattle production	Only one family member	1
			Parents and children	2
			Parents, children and women	3
	Diversification (Production activities on the ranch)	Including other tasks in addition to grazing helps to sell other types of products and improves their quality	Cattle grazing only	1
			Grazing and feedlot	2
			Grazing, feedlot, sale of milk and cheese making	3
	Infrastructure (Availability of materials and equipment)	Having tools that facilitate production would help to produce in a more sustainable manner	Cattle troughs	1
			Cattle troughs and corrals	2
			Cattle troughs, cattle corrals and grass cutter.	3
	Commercialization (Level of chain consolidation)	Commercializing other products and selling them directly would	Sale of young bulls to local intermediaries	1

		make cattle ranching more sustainable	Sale of fattening and milk to regional intermediaries	2
			Sale of beef and milk to butcher and supermarket	3
Ecosystem services descriptors	**Shade of cattle** (trees/hectare)	Trees in pastures improve soil health and provide shade for the animals	< 10 trees/ha	1
			11-20 trees/ha	2
			> 20 trees/ha	3
	Habitat (% of live fences of the pastures)	Fencing with shrubs prevents ditches that injure animals and provides forage	0-30 % of the pasture	1
			30-50 % of the pasture	2
			> 50 % of the pasture	3
	Cultivated fodder (Square meter)	Having forage banks decreases animals' dependence on pasture vegetation	0-100 m2/animal	1
			100-200 m2/animal	2
			> 200 m2/animal	3
	Race diversity (bovine races/producer)	Including more bovine races and crossbreeding them decreases calf mortality	1 race	1
			2-3 races	2
			> 3 races	3
	Water availability (Seasons during the year with water in the pasture)	Rainwater and nearness to rivers and lakes ensures water for production	Dry all year	1
			Sufficient rainwater	2
			All year	3

5. Discussion

5.1 Conceptual contribution of the framework of bovine SES

The conceptual framework of bovine SES made it possible to systematically analyze the agri-food system and develop strategies that promote more sustainable production and commercialization scenarios. Previous cattle ranching frameworks have conceived of the ecological subsystem in terms of units and systems of resources (McGinnis and Ostrom, 2014), intangibly grouping them along with ecosystems, transformative processes, and products for direct use (Torralba et al., 2018) while excluding the social and economic logic of exploitation and management. The framework herein disaggregates economic, social, and ecological subsystems and brings them into balance by presenting key elements and descriptors with the same level of importance and depth. For example, it explicitly addresses the economic dimension, whereas prior analyses of cattle ranching SES conducted by other studies had mixed with the social and environmental dimensions (e.g., Duru et al., 2015; Torralba et al., 2018; Ryschawy et al., 2019).

The economic dimension was still mixed with social and ecological factors even when Marshall (2015) incorporated first-level attributes (the transformation and producer system) into the proposal by McGinnis and Ostrom (2014), which was a theoretical innovation for food systems research. The disaggregated approach to the economic subsystem in local contexts informs the planning of sustainable cattle ranching, which adds to its viability given that economic motivations that ensure increased profitability are important to making decisions about forms of production that have a less environmental impact in tropical LA (Arango et al., 2020; Calle, 2020). Addressing spatial scales continues to be a challenge for the study and management of SES (Magliocca et al., 2018). A lack of understanding of the scales limits the estimation of impacts and the design of agricultural policies (Berrouet et al., 2018). In this sense, the relationships and feedback that were identified and described result in interconnecting global (factors external to SES), regional (social and economic factors), and local (social, economic, and ecological elements) processes.

The interface, a multi-scale zone within the SES, is conceptualized as a mediator of the relationships among subsystems and an integrator of frameworks/concepts, through which impacts can be measured and more sustainable scenarios can be promoted in the agri-food system. For example, a series of technologies (infrastructure) and agronomic practices (management strategies) exists to improve the efficiency of cattle operations (Rudel et al., 2015; Arango et al., 2020). Nevertheless, there is uncertainty about increasing cattle yields (provisioning ES, mainly pasture for cattle, feeds, wood, food from ranching, fiber, and hides) in LA without increasing GHG emissions (Arango et al., 2020) and deforestation. In addition, there is a lack of clarity on how to increase the technical and financial support (institutions) needed to ensure access to and adoption of new technologies and how to strengthen governance and foster CA among small and medium producers (Lerner et al., 2017; González-Quintero et al., 2020).

Land-sparing theory postulates that intensifying production in one area with higher yields frees up land for conservation in another (Phalan et al., 2011). Land-sharing theory asserts that ES can be encouraged within agricultural landscapes that combine uses within the same production system (Tscharntke et al., 2012). However, both approaches represent potential trade-offs in terms of cattle ranching. For example, releasing land does not necessarily imply its conservation and could lead to the expansion of production. Multifunctional landscapes (high MFA) continue to be challenged by the implicit idea that less food will be produced with them (Lerner et al., 2017). Thus, any strategy guiding the planning of more sustainable scenarios for tropical cattle ranching will need to delve deeper into the associated externalities.

5.2 Contribution of operationalization of the SES

By applying the framework, it was possible to characterize the conditions that intensify social-ecological vulnerability in the Silvopastoral Network and to identify the need to create differentiated and stronger marketing chains to improve the producers' income and their management strategies. This is important for two reasons. One, because their ecological subsystem sustains cattle ranching activities on soil that contains little organic matter, which severely limits the ability of plants to take root (SEMARNAT, 2016), thereby increasing the probability of erosion and degradation. And two, because the social subsystem involves family-based systems that are primarily oriented toward subsistence and the sale of surpluses to intermediaries who retain a portion of the income. These asymmetrical commercial characteristics present disadvantages for small and medium cattle ranchers which have already been reported in Chiapas (Calderón et al. 2012) and other tropical regions in LA (Romano-Armada et al., 2016).

In addition, the climate conditions under which SES production operates represent the possibility of changes in mechanisms that regulate soil fertility, thereby limiting nutrients and impeding the growth of vegetation (impact on regulating and supporting ES). These problems have already been reported in cattle systems operating on clay soils in Mexico's humid and dry tropics, decreasing MFA (Figueroa et al., 2020). The soil's structural and nutritional deficiencies (loss of regulating ES) intensify with the increasingly recurrent droughts in the tropical region (Idem) and with the producers' high dependency on cattle activities for their living, which entails the rural population placing constant pressure on ecosystems (Rudel et al., 2015; Romano-Armada et al., 2016), with repercussions on and from climate change (Arango et al., 2020) (Fig. 3). The identification of this study's SES receiving this feedback from larger-scale external factors (see Table 1, Feedback 3) shows a need for adaptive land planning by the agri-food system in tropical regions.

The evaluation of local descriptors for the SES focal shows that two member associations have made sustainable progress. The associations A5 (10 descriptors) and A6 (8 descriptors) have the highest provision of the evaluated ES and the best socio-economic conditions (medium and high levels of sustainability). This differentiated progress was related to the strength of the organizational processes within both cattle ranching associations, which have fostered the intensification of cattle density, increase in the number of workers, high frequency of rotation, and use of tree vegetation for the shade of cattle and shrubs for habitat. Despite the progress, improving governance, dignifying livelihoods, and increasing the provision of ES beyond provisioning (food and feed) remains a priority challenge for the Silvopastoral Network and the livestock sector in the tropics of AL (Coppock et al., 2017).
The associations A5 and A6 have established real SPS that guarantee socio-ecological improvements. An increased number of employed workers in diversified SPS has previously

been reported as a sustainability descriptor in LA (Astier et al., 2011). The SPS favors biodiversity, hosting richer soil biota and increasing connectivity between forest fragments. In addition, they improve animal welfare, increase animal productivity, and decrease deforestation (Murgueitio et al., 2011). As a land-sparing strategy, the SPS represents an opportunity to move toward more sustainable scenarios if proper management is ensured (Lerner et al., 2017).

Although the A1 association has shown significant progress in the descriptor of cultivated fodder and supplementation with salts and protein banks, the other associations continue with low levels of progress in feeding. The improvements in feeding through supplementation (Murgueitio et al., 2011) favor MFA levels in SPS (Boval et al., 2017). Improved forages incorporating various grass and legume species provide a more nutritious diet (Rudel et al., 2015). They also contribute to increased productivity and reduced greenhouse gas emissions; issues significant for tropical cattle ranching systems (Rao et al., 2015).

5.3 Challenges to the sustainability of the Silvopastoral Network

One of the main challenges for the Silvopastoral Network is employment since, like other production systems in the Mexican tropics, workers are hired informally, with excess hours and low wages that exacerbate extreme poverty (Rivera-Huerta et al., 2019). This is particularly important for rural development in Chiapas, where 76.4% of the population is classified in some category of poverty (CONEVAL, 2018). The smallholders in the SES focal must have access to inputs, capital, infrastructure, technical information, and knowledge about how to sustain alternative management strategies, such as SPS, that have less environmental impact (Marinidou et al., 2018; Arango et al., 2020) and higher investment costs (Calle, 2020; Van Loon et al., 2020).

As in other tropical regions in LA, selling and consuming animal products in Chiapas reduces the vulnerability of households to the seasonal lack of food and income, satisfies their food security needs, and improves the nutritional status of the most vulnerable (Calderón et al., 2012; FAO, 2017a; Gallo and Tadich, 2018). However, incentives are needed to promote diversification in small and medium-sized ranches, through which resource use is optimized, food security is guaranteed (Galeana-Pizaña et al., 2021), and the high rates of deforestation

(Figueroa et al. 2021), which in the country are increasing due to the expansion of extensive pastures for crops and cattle grazing (Galeana-Pizaña et al., 2018; Tello et al., 2020), are decreased. Productive diversification is urgent in tropical LA, as extensive cattle ranching puts the conservation of tropical forests at risk and is in direct conflict with the provision of regulating and supporting ES (Perfecto and Vandermeer, 2010). Finding alternatives to reduce the dependence of smallholders on cattle grazing and produce without deforesting tropical forests should be the planning axis for the region (Murgueitio et al., 2011).

Globally telecoupled markets (Feedback 3) are contributing to the challenge of diversifying production by encouraging producer countries such as Mexico to specialize their production in meat and dairy (Fig. 3), which has potential adverse consequences on the supply of ES (Garrido et al., 2017; Chung and Liu, 2019), especially those associated with tropical forest deforestation. The loss of forests translates directly into the loss of ES essential for human well-being, including climate regulation, nutrient cycling, containment of erosion, landslides and floods, water quality, spiritual qualities, and the safeguarding of worldviews (Balvanera, 2012). These tendencies could be reversed through policies that support local distribution and consumption networks and that contribute to creating local brands that favor multifunctional cattle ranching (Torralba et al., 2018).

Along those lines, solutions will have to be created by combining personal and political actions (Figueroa and Galicia, 2021), including participatory methodologies, the dissemination of knowledge, and raising awareness among producers and consumers (Sánchez-Romero et al., 2021). Agroecological measures will need to be included, such as the diversification of agroecosystems into polycultures, mixed crop-livestock systems, organic soil management, and water conservation and harvesting strategies (Altieri et al., 2015). Moreover, evaluate trade-offs associated with implementing multifunctional landscapes or land use intensification (land sharing or land sparing approaches). With governmental support, the sustainability of the Silvopastoral Network can move in three directions: 1) expand the establishment of SPS; 2) include production and transformation strategies that propel the type of diversification that enables commercializing live cattle, meat, milk, and other products, 3) reactivate the participation of women and youth in production. The lack of participation by women has been documented, and the ability for them to perform new functions and have more resources in diversified systems has been recognized (Westholm and Ostwald, 2019). Strategies that have been less explored in Mexico include consumer preferences (Vargas-Bello-Pérez et al., 2017), changes in eating habits (Ibarrola-Rivas et al., 2017; Tello et al., 2020), perspectives about the quality of meat (Parra-Bracamonte et al., 2021) and purchasing decisions based on the type of production system. Including these approaches in environmental agendas can promote management sustainability throughout the agri-food system considering the current planetary crisis (Läderach et al., 2021).

5.4 Research limitations

Identifying elements, relationships, and feedback allow for understanding an SES. However, promoting sustainability also involves identifying locally relevant descriptors, establishing thresholds, and evaluating the dynamics that emerge from the relationship of the descriptors after elucidating all stakeholder perspectives, needs, incentives, and assets (Van Soest et al., 2019). Although our case study identified locally relevant descriptors and proposed sustainability thresholds for tropical cattle ranching in LA, the application of our framework only identified interactions without making an in-depth assessment of these, an essential requirement to enhance local transformative capacities. Another obstacle presented by the framework is that it does not analyze industrial cattle ranching (cattle restricted to feedlot fattening) or cattle ranching in predominantly non-tropical ecosystems, which also occurs in the region. Thus, understanding that the environmental, social, and economic conditions in industrial systems and non-tropical cattle ranching differ drastically from those observed in EP and SPS in tropical LA, such production systems fall outside the scope of this study's conceptual framework.

6. Conclusions

The conceptual framework of SES helps to characterize an agri-food system based on grazing bovines (EP and SPS), identify social-ecological impacts, and promote more sustainable strategies for cattle ranching in tropical LA. By applying the framework to the SES focal and through sustainability measurement using socio-economic and ES descriptors, it was possible to identify common factors that impede the development of cattle ranching activities and recognize which can be generalized to other Latin American SES. Challenges include vulnerability to soil erosion, soil degradation, and loss of soil fertility, particularly exacerbated by the recurring droughts in the tropical regions of Mexico and the rest of LA. In addition, an excessive number of intermediaries and the need for differentiated and competitive marketing chains for selling what is produced by SPS limit the transformation of the agri-food system under tropical conditions. Given that little product, the low diversification exposes producers to being highly dependent on grazing bovines. It is crucial to improve the sustainability of the Silvopastoral Network by strengthening the livestock sector through government institutions. This improvement in the sustainability of the Network includes creating organizational processes that expand the establishment of SPS, commercialize other products (e.g., milk, cheese, seeds, grains), provide and value other ES (e.g., carbon bonds, fruiting, and timber trees) and reactivate the participation of women and youth in production.

Credit author statement: Daniela Figueroa: conceptualization, methodology, analysis, writing – original draft and review/editing, and visualization data. Leopoldo Galicia and Véronique Sophie Ávila Foucat: conceptualization, review/editing of the original draft, supervision, and funding acquisition. Benito Díaz Morales: methodology and funding acquisition.

Funding: The research on which this work was based has received funds from CONAHCYT through the doctoral grant 750544 (CVU: 723924), and Research Project in Technology and Innovation (PAPIIT) at DGAPA-UNAM: Proyecto PAPIIT 302421. In addition, the project "Systems of sustainable production and biodiversity" by CONABIO, SEMARNAT, and the Global Environment Facility (GEF) funded the semi-structured interviews and the participatory workshop.

Acknowledgments: The authors thank the Silvopastoral Network (Red de Organizaciones Agropecuarias Silvopastoriles del Estado de Chiapas S.A. de C.V.) and the CONAHCYT.

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SUPPLEMENTARY MATERIAL (SM)

SM 1. Literature Review Excel Matrix

SM 1. Table 1. The questionnaire that guided the semi-structured interviews of the Silvopastoral Network.

Block 1. General information:

Location and municipality:			
Region category (mark with (x) as appropriate)	**1. Forest region**	**2. Coastal region**	**3. North region**
Name of the ranching association:			
Name of producer:			
Interview date:			
Total number of hectares (cattle area):		**Total number of pastures:**	
Total property, What percentage is flat? ______ % **What percentage is outstanding?** _____ %			

Block 2. Description of pastures:

- Property name: **- GPS coordinates:**			
Draw a sketch with the measurements of the whole pasture and its divisions. **Area (width x length in meters)**	**No. División**	**Dimensions (width x length)**	**Grazing rotation (Days/year)**

Block 3. Description of the vegetation in the pasture:

Vegetation	Pasture 1	Pasture 2
Pasture grass (square meters per grass type)	Square meters - Species 1.-________ + ______ 2.-________ + ______ 3.-________ + ______ 4.-________ + ______	Square meters - Species 1.-________ + ______ 2.-________ + ______ 3.-________ + ______ 4.-________ + ______
Trees scattered within the pasture (number of trees per species)	No. Total: ____________ Main Species: 1.-________________ 2.-________________ 3.-________________ 4.________________	No. Total: ____________ Main Species: 1.-________________ 2.-________________ 3.-________________ 4.________________
Live fences (linear meters) + list of species	Total linear meters: __________ Meters per species - Species 1.-________ + ______ 2.-________ + ______ 3.-________ + ______ 4.-________ + ______	Total linear meters::__________ Meters per species - Species 1.-________ + ______ 2.-________ + ______ 3.-________ + ______ 4.-________ + ______
Mowing grass (square meters) + species list	Total square meters: ________ Meters per species - Species 1.-________ + ______ 2.-________ + ______ 3.-________ + ______ 4.-________ + ______	Total square meters: ________ Meters per species - Species 1.-________ + ______ 2.-________ + ______ 3.-________ + ______ 4.-________ + ______
Cane and/or maize for feed (square meters)	1.-________________ 2.-________________ Another feed crop: 1.-________________ 2.-________________	11.-________________ 2.-________________ Another feed crop: 1.-________________ 2.-________________
Protein bank (square meters) + Species	Square meters - Species 1.-________ + ______ 2.-________ + ______ 3.-________ + ______ 4.-________ + ______	Square meters - Species 1.-________ + ______ 2.-________ + ______ 3.-________ + ______ 4.-________ + ______

Block 4. Description of infrastructure and equipment for cattle handling:

Infrastructure (e.g., Number of barn, corral, chute, feeding trough, drinking trough, water source)	**Description and condition** (e.g., dimensions, type of material, cleanliness, maintenance)	**How often you use them** (days per week/month/year)
Equipment and machinery (e.g., Number of chopper, brush cutter, motor pump, sprinklers)	**Description and condition** (brand, power, general condition)	**How often you use them** (days per week/month/year)

Block 5. Herd structure (all animals owned for bovine production):

Category	**Quantity**	**Breeds/Crosses**
Stallions		
Fattening bulls (+ 350 kg)		
Bulls		
Cows		
Heifers		
Calves		
Total		

Block 6. Sanitary management and feeding:

Applications	**Dates**	**Inputs and quantity**	**Cost $ (mxn)**
Internal deworming			
External deworming			
Vitamins			
Viral disease prevention			
Commercial supplements			
Purchased food			
Own feed (produced on the ranch)			

Block 7. Work on ranches (Jobs):

Name of employee	Activities in production	No. Workdays per week or per month

Block 8. Diversification issues:

Productive activities (mark with (x) as appropriate)	1. Cattle grazing only	2. Grazing and feedlot	3. Grazing, feedlot, sale of milk and cheese making
What type of products, quantity and weight of each (bulls, cows, milk, cheese)?			
To whom do you sell? Where do you sell? (e.g., local, regional, national intermediaries, feeders, etc.)			
Prices obtained by type of product (in average)			

Block 9. Commercialization data:

Number of intermediaries	Level of consolidation	Category
0	High level	3
1	Medium level	2
>2	Low level	1
Indicate how many intermediaries you have		

Name	Location/municipality	What do you buy?	Price (per kg/lt)

Block 10. Other ecological issues:

- **Fauna sighted:**

Type of fauna observed in the pastures and within the cattle ranches	Sighting season

Types of uses of vegetal species in the cattle production system:

#	Common Name	Uses (According to key*)
1		
2		
3		
4		
5		

*** Key to uses:** 1) edible for human consumption, 2) protein fodder, 3) fiber fodder, 4) construction, 5) manufacture of handicrafts, 6) fuel, 7) medicinal, 8) shade, 9) rubber, 10) colorant, 11) condiment, 12) other uses or services.

Note: If the use is not reflected in the keys, please write it next to it.

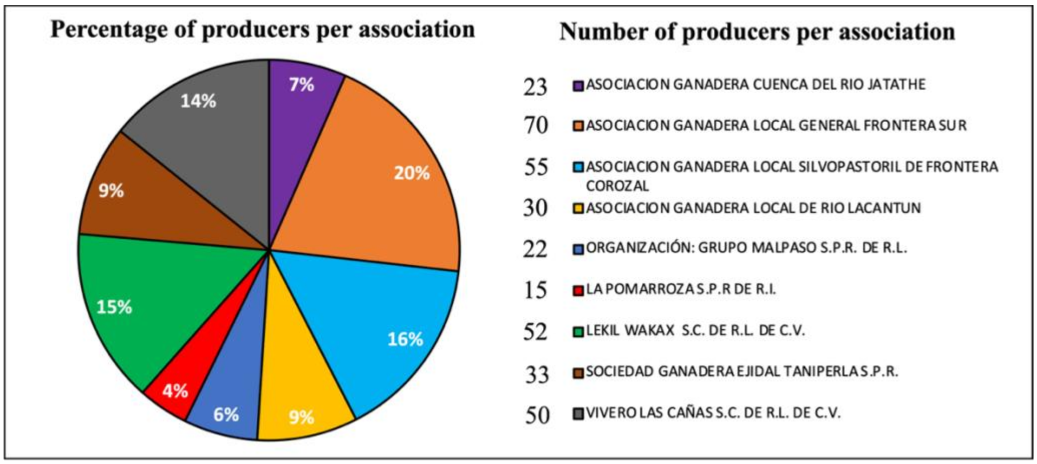
- **General comments:** Please explore and describe issues regarding chemical use, supplemental food, cleanliness of facilities, treatment of animals, availability of shade, and anything else of interest to the producer regarding the production system:

SM 2. Table 1. Location of the Silvopastoral Network's nine cattle ranching member associations (A1-A9).

Municipality	Economic Region	Member Cattle Ranching Associations	Location and Altitude
Ocosingo	Selva Lacandona	**A3:** AGL Frontera Corozal **A7:** SC Lekil wakax **A8:** SPR Santa Helena-Taniperla **A1:** AGL Cuenca Rio Jatate	16°54'26" North Latitude and 92°05'46" West Longitude Altitude 888 masl
Maravilla Tenejapa	Meseta Comiteca	**A2:** AGL Frontera Sur Maravilla Tenejapa	16°08'21" North Latitude and91°17'44" West Longitude Altitude of 400 masl
Marqués de Comillas	Maya	**A4:** AGL Río Lacantún	16°19'56" North Latitude and90°45'55" West Longitude Altitud 133 masl
Tecpatán	Norte	**A6:** SPR La Pomarrosa	17°08'10" North Latitude and 93°18'40" Altitude of 311 masl.

Mezcalapa	Mezcalapa	**A5:** SPR Grupo Malpaso	17°11'18" North Latitude and93°36'21" West Longitude, Altitude of136 masl.
Pijijiapan	Istmo Costa	**A9:** SC Las Cañas	15°41'12" North Latitude and93°12'33" West Longitude Altitude of 57 masl.

SM 2. Fig. 2. Percentage of Producers per Association of the Silvopastoral Network



SM 2. Table 2. List of vegetation species.

Tree and shrub species				
Acacia collinsii	Cecropia obtusifolia	Diphysa americana	Moringa oleifera	Spondias purpurea
Acrocomia aculeata	Cecropia Peltata	Dussia cuscatlanica	Musa paradisiaca	Swietenia macrophylla
Acrocomia vinifera	Cedrela odorata	Enterolobium cyclocarpum	Myroxylon balsamum	Syzygium jambos
Albizia saman	Ceiba aesculifolia	Erythrina chiapasana	Nephelium lappaceum	Tabebuia rosea
Alchornea latifolia	Chrysophyllum mexicanum	Ficus aurea	Oecopetalum greenmanii	Tradescantia spathacea
Alvaradoa amorphoides	Citrus limon	Ficus crocata	Pachira aquatica	Trema micrantha
Andira inermis	Citrus maxima	Ficus insipida	Parmentiera aculeata	Vatairea lundellii
Annona glabra	Citrus medica	Frangula discolor	Persea americana	Vernonanthura phosphorica
Annona muricata L.	Citrus nobilis	Fraxinus uhdei	Persea schiedeana	Zanthoxylum monophyllum
Astrocaryum mexicanum	Coccoloba acapulcensis	Genipa americana	Pinus ayacahuite	Zanthoxylum rhoifolium
Ateleia pterocarpa	Coccoloba barbadensis	Gliricidia Sepium	Platanus mexicana	
Attalea butyracea	Cocos nucifera	Guaiacum sanctum	Platymiscium dimorphandrum	
Bernoullia flammea	Cochlospermum vitifolium	Guarea glabra	Pouteria campechiana	***Species of grasses***
Bixa orellana	Cojoba arborea	Guazuma ulmifolia	Pouteria sapota	
Blepharidium guatemalense	Cordia alliodora	Haematoxylum campechianum	Psidium guajava	Cynodon nlemfuensis
Brosimum alicastrum	Cornus disciflora	Inga belizensis	Psychotria erythrocarpa	Brachiaria decumbens
Bursera bipinnata	Croton glabellus	Inga edulis	Roseodendron donnell-smithii	Hyparrhenia rufa
Bursera excelsa	Cryosophila stauracantha	Inga punctata	Roystonea regia	Panicum maximum cv. Tanzania
Bursera simaruba	Cucurbita argyrosperma	Leucaena leucocephala	Salix humboldtiana	Brachiaria brizantha cv. Marandú.
Byrsonima bucidifolia	Cupania dentata	Licania platypus	Saurauia yasicae	Echynochloa polystachya
Caesalpinia pulcherrima	Dialium guianense	Lysiloma acapulcense	Schizolobium parahyba	Brachiaria humidicola
Calycophyllum candidissimum	Diospyros nigra	Maclura tinctoria	Sideroxylon capiri	Cynodon dactylon
Calyptranthes chiapensis	Diphysa americana	Mangifera indica	Sideroxylon foetidissimum	Pennisetum purpureum
Castilla elastica	Diphysa carthagenensis	Manilkara zapota	Spondias mombin	

SM 3. Table 1. Characterization of the ecological subsystem of the Silvopastoral Network's SES

Subsystem	Elements	Descriptors	Variables	Values
Ecological subsystem	Soil	Chemical and Physical properties	Main soil types **Source:** Soto-Pinto et al. 2010	Regosols, Leptosols and Cambisols
			Soil bulk density (g/cm3) **Source:** Villanueva-López et al. 2015	Silvopastoral systems (1.30) Pastures without trees (1.50)
			Soil texture **Source:** Villanueva-López et al. 2015	Silvopastoral systems (Silt clay) Pastures without trees (Clay)
			Soil pH **Source:** Villanueva-López et al. 2015	Silvopastoral systems (7.23) Pastures without trees (7.53)
		Nutrient contents	Soil organic carbon (Mg C ha-1) **Source:** Soto-Pinto et al. 2010	Silvopastoral systems (68.5) Pastures without trees (75.1)
			Total carbon (Mg C ha-1) **Source:** Soto-Pinto et al. 2010	Silvopastoral systems (142.5) Pastures without trees (78.8)
			Soil nitrogen (%) **Source:** Villanueva-López et al. 2015	Silvopastoral systems (29%) Pastures without trees (25%)
	Vegetation	Tree and shrub component	Total trees (Number of trees)	66,318
			Tree and shrub diversity (Number of species)	106
			Average density of trees (trees/hectare)	17
			Average percentage of live fences per hectare	32%
		Pasture component	Diversity of grass species (Number of species)	9
			Livestock pasture area (hectares)	4,674
	Cattle	Cattle species	Main cattle species	Cebu, Suizo, Charolais, Hereford, Gyr, Ongole
			Average number of bovine species per system	2
			Total cattle (Number of cattle)	11,098
			Average animal load	2.52
		Animal welfare	Average forage per bovine (m2)	51
			Average trees per animal	8.6
			Days of grazing in the same pasture	21
			Water availability (% of year)	98

SM 3. Table 2. Characterization of the Silvopastoral Network's social subsystem.

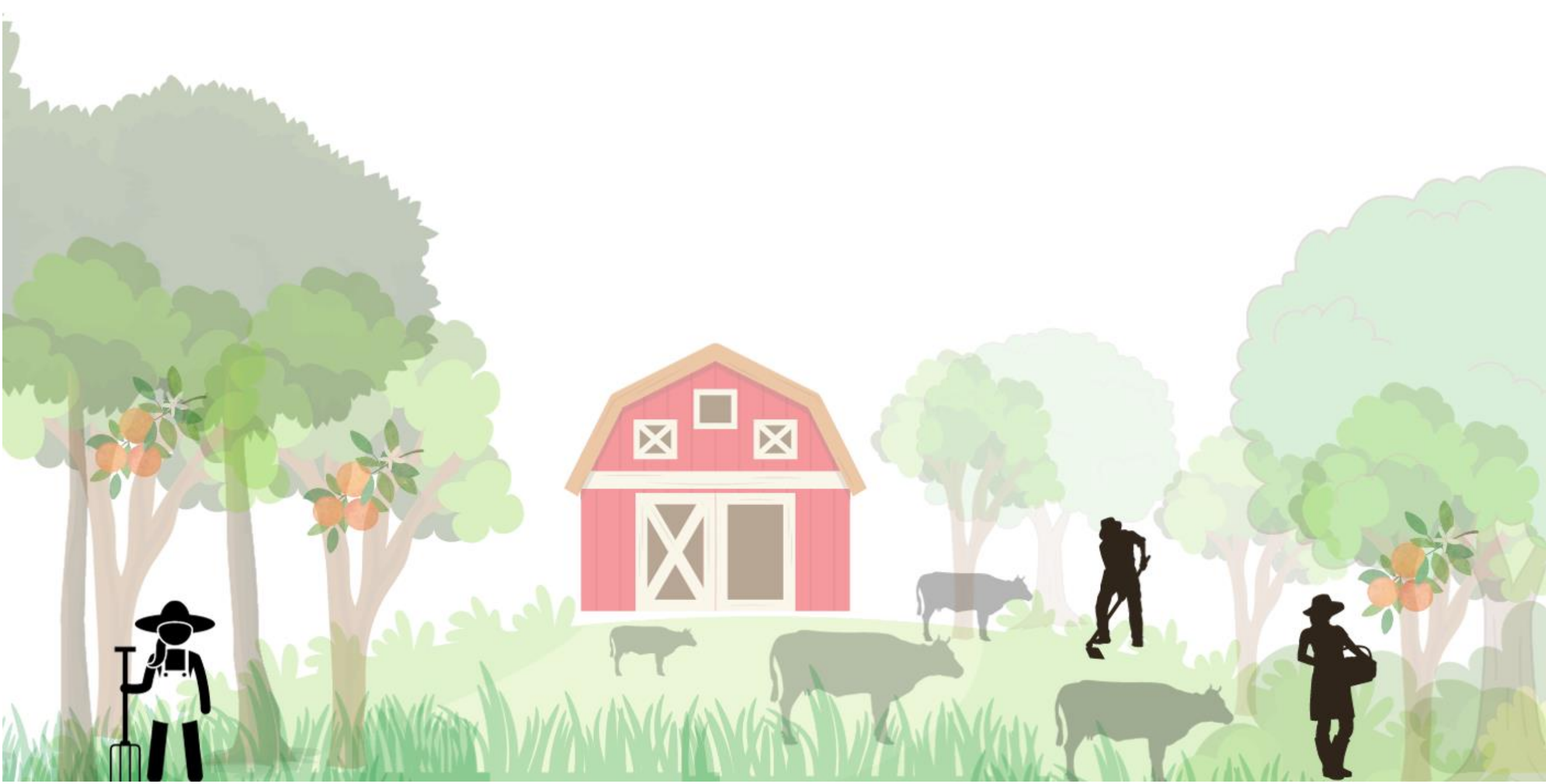
Subsystem	Elements	Descriptors	Variables	Values
Social subsystem	Producers	Internal non-governmental actors (producers)	Total number of managers and workers	1,129
		Sex, age and schooling	Men in production units (%)	89
			Women in production units (%)	11
			Average age of producers	54 years old
			Average schooling	Elementary school
	Livestock associations	Partnership description	Number of member associations	9
			Total member producers	350
			Physical capital as a network	Cameras, GPS
		Spatial influence	Municipalities of influence in the state of Chiapas	Ocosingo, Maravilla Tenejapa, Marques de comillas, Tectapan, Mezcalapa, Pijijipan
		Membership conditions and structure	Years of aggregation	9 years
		Linkage strategies	Number of government projects	2
			Number of research projects	1
	Rules	General rules	Types of rules	Operational Rules, Collective Action Rules
			Operating rules topics	Network operability
			Collective action rule topics	Collective decision making, Communication and coordination among partners, Partner participation, Inclusion and exclusion of partners
		Resource management rules	Resource management topics	Resource Management and Accountability, Heritage Care
	Institutions	Government actors	Government institutions	Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT), Comisión Nacional para el Conocimiento y Uso de Biodiversidad (CONABIO)
		Non-governmental actors (e.g., research institutions)	Non-governmental institutions	El Colegio de la Frontera Sur (ECOSUR), La Universidad de Ciencias y Arte de Chiapas (UNICACH), Global Environment Facility (GEF)

SM 3. Table 3. Characterization of the Silvopastoral Network's economic subsystem.

Subsystem	Elements	Descriptors	Variables	Values
Economic Subsystem	Infrastructure	Structural capacities	Total area used for livestock activities (hectares)	5,342
			Type of infrastructure available	Stables, Corrals, Feeding troughs, Drinking troughs, Water fountains
		Machinery and equipment	Type of machinery and equipment available	Grinders, Motorpumps, Sprinklers
		Reproduction and feeding	Total forage (m2)	568,145
			Types of dietary supplements	Mineral salts and ground maize
			Types of insemination	Natural and Artificial
	Jobs	Internal Jobs	Total number of internal (family) jobs	750
			Days worked per year	From 12 to 365 days
		External Jobs	Total number of external jobs	379
			Days worked per year	From 12 to 365 days
			Hours worked per day	8 to 12 hours
	Market circuits	External non-governmental actors	Main type of sale	Indirect (through intermediaries)
			Type of intermediary	Local and regional
			Network producers selling to local intermediaries (%)	78%
			Network producers selling to regional intermediaries (%)	22%
		Products traded	Type of product traded	Cattle for breeding (Calves), half-fattened (Heifers), finished cattle (Cows and Bulls), milk and cheese
	Income	Income of producers	Network revenues per year (mexican pesos)	$39,000,000.00
		Income of workers	Average pay per day of work (mexican pesos)	$70.00
		Trade prices	Price range per kilogram of meat (mexican pesos)	Bulls: (25 - 45), Cows (18 - 35), Heifers (23 - 40), Calves (30 - 40)
			Price range per liter of milk (mexican pesos)	Milk (4 - 6)

Capítulo 4

Assessing sustainable intensification for the planning and management of cattle ranching in the tropics: A case study in southern Mexico



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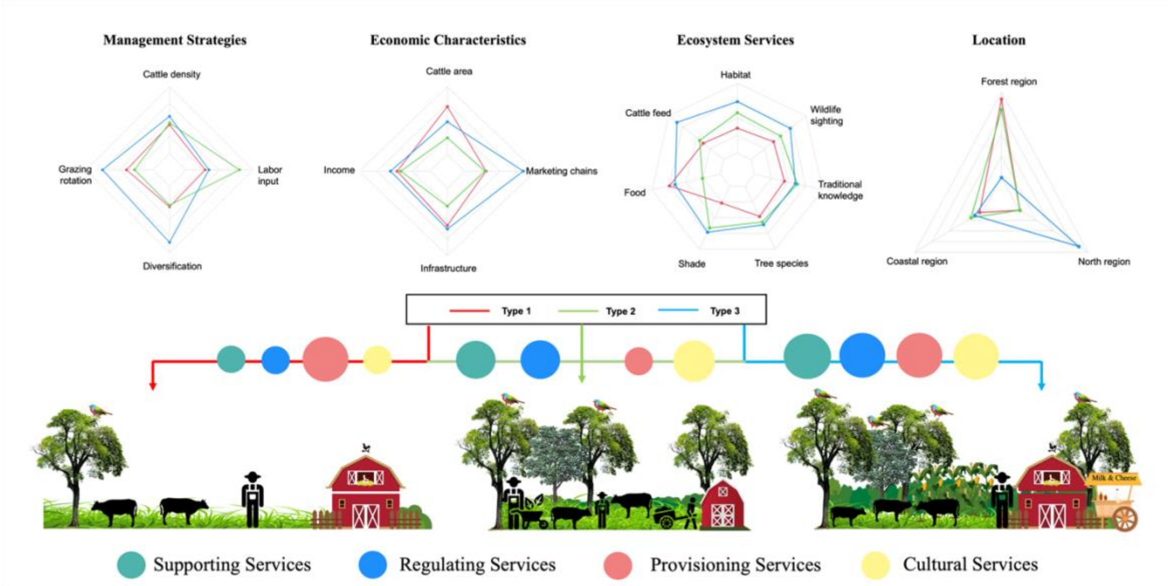
Manuscript status: submitted to ***People and Nature***

Abstract

Sustainable intensification of cattle ranching is essential for promoting rural development and minimizing grazing land expansion in the tropics. However, intensification's role in providing ecosystem services (ES) has been incipiently explored and remains under debate. Based on primary data obtained from interviews with 350 producers in southern Mexico, this paper develops a typology of cattle ranches that seeks to facilitate the analysis of sustainable intensification in the tropics. In addition, based on structural equation modeling, it explores the relationships between management strategies, economic characteristics, ES provision, geographic location, and sustainability in cattle ranches. The typology analysis identified three types of silvopastoral cattle ranches in an intensification gradient. We have shown that the intensification of small and medium ranches, even within differential economic and geographic realities, ensures improvements in the provision of ES relevant to the ecosystem and society functioning. We found that increases in the values associated with the management strategies evaluated (cattle density, grazing rotation, labor input, and diversification) positively impact the sustainability of cattle ranches. Similarly, it minimizes grazing area while increasing the provision of habitat, shade for cattle, cattle feed, and traditional knowledge drives the sustainability of the cattle ranches. Sustainable intensification in the tropics is an alternative to extensive systems if it is accompanied by the consolidation of marketing chains, diversification, and income improvement as crucial issues that support the provision of all types of ES and the expected positive effects of land-sparing on sustainability.

Keywords: Ecosystem services, Livestock, Mexico, Structural Equation Modeling, Typology.

Graphical abstract:



1. Introduction

Beef cattle are prominent within the cattle ranching sector in the tropics, despite being the least efficient converter of feed into consumable food products, the most resource-demanding model (Rask and Rask, 2011). Sustainability debates around animal ranching focus on animal welfare, different forms of environmental footprint (e.g., carbon, nitrogen, and water), and the impacts of excessive meat and dairy consumption on human health (Steinfeld et al., 2006; Aleksandrowicz et al., 2016; Beal et al., 2023). The multiple environmental impacts of grazing in the tropics include land use changes, loss of soil fertility, overuse and contamination of water, impacts on biodiversity, and greenhouse gas emissions (Rudel et al., 2015; Solorio et al., 2017; Figueroa et al., 2020). However, cattle unsustainability is highlighted by widespread land conversion to support cattle production in the tropics. Grazing occurs at the expense of forests and other deforested native vegetation, causing significant losses of ecological functions and ecosystem services (ES) (Rao et al., 2015; Figueroa et al., 2021).

It is recognized that sustainable livestock systems must be environmentally friendly, economically viable for ranchers, and socially acceptable (Lebacq et al., 2013; Broom, 2016).

However, these conditions are often complex to measure and, therefore, to address.The unsustainability of livestock ranching is widespread, and although its particularities vary geographically, the sector continues to expand rapidly (UN, 2015). An increase in meat and milk consumption has been observed globally; however, the rise in intake occurs unevenly. Increases in per capita demand have been observed in China (> 300 %), Brazil (> 40 %), West Asia, and North Africa (> 40 %) (Herrero et al., 2018). Estimates predict that if current trends continue, supply sustainment will fall on tropical countries, which are already the primary producers of cattle and fodder consumed in Asia and Europe (Idem), so the transformation of the ways of producing becomes crucial to achieve sustainability of the sector and maintain the multiple benefits that the cattle ranching bring to society.

Cattle ranching is fundamental to people's diets, traditions, and livelihoods. The tropics are home to much of the world's rangelands and some of the poorest people who depend on agriculture for food and income (Henry et al., 2018). The importance of cattle systems in the tropics varies according to the dependence of stakeholders (e.g., processors, marketers, consumers) on the various ES obtained from agricultural systems (Rao et al., 2015). The main supporting ES obtained from cattle ranching include habitat, gene pool protection, soil moisture retention, and pasture productivity (e.g., Murgueitio et al., 2011; Figueroa et al., 2020). Provisioning ES includes all products obtained from ecosystems and cattle (e.g., pasture, feed, timber, food, fiber, and water) (e.g., Tauto et al., 2018). Regulating ES includes groundwater recharge, soil fertility, carbon sequestration, nitrogen fixation, and microclimatic regulation derived from shade for cattle (e.g., Accatino et al., 2019; Figueroa et al., 2020). Cultural ES includes the aesthetic appreciation of nature and landscape, ecosystem protection, recreational activities, spirituality, educational values, and safeguarding worldviews (e.g., Tauro et al., 2018; Dumont et al., 2019).

In Latin America, tropical grazing cattle production occurs mainly in extensive systems and, to a lesser extent, in intensive systems (Figueroa et al., 2022). As the dominant production model, cattle ranching is practiced mainly in grazing areas with low-productivity pastures, scarce trees, degradation processes in the soil and pasture, inadequate infrastructure, and low capital (Herrero et al., 2016). Currently, agroforestry, particularly silvopastoral systems

(SPS), and good livestock practices are viable options to reverse extensive livestock systems. In the SPSs, the producer uses the soil's biodiversity and diverse native and planted vegetation strata (Murgueitio et al., 2011). The benefits of SPS have been documented (Chará et al., 2019; Calle, 2020); for example, SPSs have improved the systems' diversification and profitability, and this strategy has been recognized as viable and within reach of producers for the sustainable intensification of cattle ranching in the tropics (Boval et al., 2017; Lerner et al., 2017). Sustainable intensification is about producing more products with more efficient use of all inputs - in a sustainable way - while reducing environmental damage and strengthening the flow of ES (The Montpellier Panel, 2013). That is, the definition of "intensive" in tropical regions means increasing production per unit area while increasing ES provision on the same land (land-sparing) (Lerner et al., 2017) and avoiding the deforestation involved in producing extensively.

In tropical regions of Latin America, socioeconomic vulnerability, land degradation, extensive land use, and climate change create significant sustainability challenges regarding cattle production, distribution, and consumption (Figueroa et al., 2022). Mexico stands out as the world's sixth largest beef producer in the region, with 35 million head of cattle occupying 56 % of its territory (109.8 million hectares) and 881,000 people who depend on grazing for subsistence (SIAP-SADER, 2020). The Mexican tropics contain one-third of the country's total cattle herds managed within extensive pastures (SIAP, 2018a), with significant implications for sustainability (Rivera-Huerta et al., 2016; 2019; Figueroa et al., 2020). Some efforts by Mexican peasants have succeeded in establishing SPS in the tropics, mainly by strengthening governance through alliances between different social sectors (e.g., producers, development agencies, academia, and governments) and due to their need to take advantage of available vegetation, and the economy which is less market-oriented and therefore with fewer resources available for purchasing inputs (Jiménez-Ferrer et al., 2008; Apan-Salcedo et al., 2021).

The establishment of SPS has allowed small and medium producers to cope with high temperatures and changes in the frequency and magnitude of rainfall most of the year (Figueroa et al., 2020). However, in Mexico, as in the rest of tropical Latin American countries, public policies have not yet supported actions promoting sustainable livestock intensification (Figueroa et al., 2022). Therefore, it is necessary to recognize, within the different types and practices of SPS, the levels of intensification that have promoted social and ecological benefits to a lesser or greater extent to continue gathering evidence that can be used to demand political changes in the territories (Milán and González, 2022). In addition, the tradeoffs resulting from intensification still need to be addressed to protect biodiversity, ensure the provision of all types of ES and reduce resource use (Herrero et al., 2018; Accatino et al., 2019). Developing typologies might help disentangle the heterogeneity of situations that arise and their underlying factors (Milán and González, 2022), for example, associated with the levels of intensification that emerge from SPS, therefore supporting decision-making at the ranch and region levels.

Cattle ranching typologies capture the variability of ranches, facilitating the development of appropriate management strategies and policies that are well adapted to the different co-existing realities and can foster sustainability (Escribano et al., 2016; Milán and González, 2022). However, to the best of our knowledge, no typology includes ecosystem service provision to track levels of sustainable intensification within SPS, although it is recognized that the magnitude of service losses (e.g., soil organic carbon) represent an intensification gradient associated with different agricultural and cattle ranching practices given the pre-existing social, economic, and ecological context (Baldassini and Paruelo, 2020; Baethgen et al., 2021; Paruelo and Sierra, 2023). Identifying the limitations and potential of SPS could help facilitate ranching's transition toward sustainability (Valdivieso-Pérez et al., 2019). Addressing ranch sustainability in the tropics is particularly challenging due to the multiple related factors and the contextual diversity of ranching (Broom, 2021) that escape from univariate analysis. As a general aim, we proposed to conduct a regional-scale assessment that typifies cattle ranches, explores the impacts of intensification, and tests using a multivariate method, the relationships between the social, economic, ecological, and spatial components that enhance or constrain sustainability. To achieve this, we set two specific objectives:

- To develop a typology of cattle ranches based on management strategies, economic characteristics, ES provision, and geographic location to capture the differentiation of intensification of cattle ranching systems.

- To test the relationship between ES provision, economic characteristics, management strategies, and geographic location with the sustainability of cattle ranches in the tropics in the southern of Mexico.

2. Material and methods

2.1 Case study

The state of Chiapas is in southern Mexico (Fig. 1) and has 75,634 km2, representing 3.8% of the country's total surface area. It presents a complex morphology formed by large mountainous zones that support various climates and soils (INEGI, 2016). Fifty-four percent of Chiapas has a warm, humid climate, 40% has a warm sub-humid climate, and the remaining 6% has a temperate humid climate. The average annual temperature varies depending on the region between 17º C and 30º C. The plant communities integrate 17 vegetation types, including, for example, 1,516 tree species (INEGI, 2016). The state of Chiapas is the poorest in the country, with 5,464,136 inhabitants, of which 76.4 % are in some poverty category (CONEVAL, 2018). Cattle ranching is the most important agricultural activity in Chiapas (Orantes-Zebadúa et al., 2014).

Historically, cattle arrived in Latin America along with the European settlers; the first species introduced was *Bos taurus* with minimal requirements for extending pastures, so SPS was maintained predominantly for more than 400 years until the introduction of zebu cattle (*Bos indicus*) (Guevara & Noriega, 2011). The replacement of this type of cattle since the green revolution led to the massive opening of pastures to the detriment of natural vegetation and favored the deforestation of large extensions of the territory. Since then, cattle ranching has caused significant losses of native ecosystems and the establishment of grasses of African and Asian origin (Hernández, 2001). Chiapas State ranks fourth in beef carcass meat production nationally (105,521 tons) (SIAP, 2018b). The 82,411 cattle producers manage

3,517,753 cattle (SADER, 2019) within small (2-5 ha), medium (5-15 ha), and to a lesser extent, large (15-50 ha) ranches, as typical in the Latin American tropics (Samberg et al., 2016). Although cattle production systems are mainly based on extensive pastures (62.4 %) (CEIEG, 2016), there are traditional SPS that take advantage of the high biodiversity and local knowledge to integrate forage trees and shrubs in cattle raising (Jiménez-Ferrer et al., 2008).

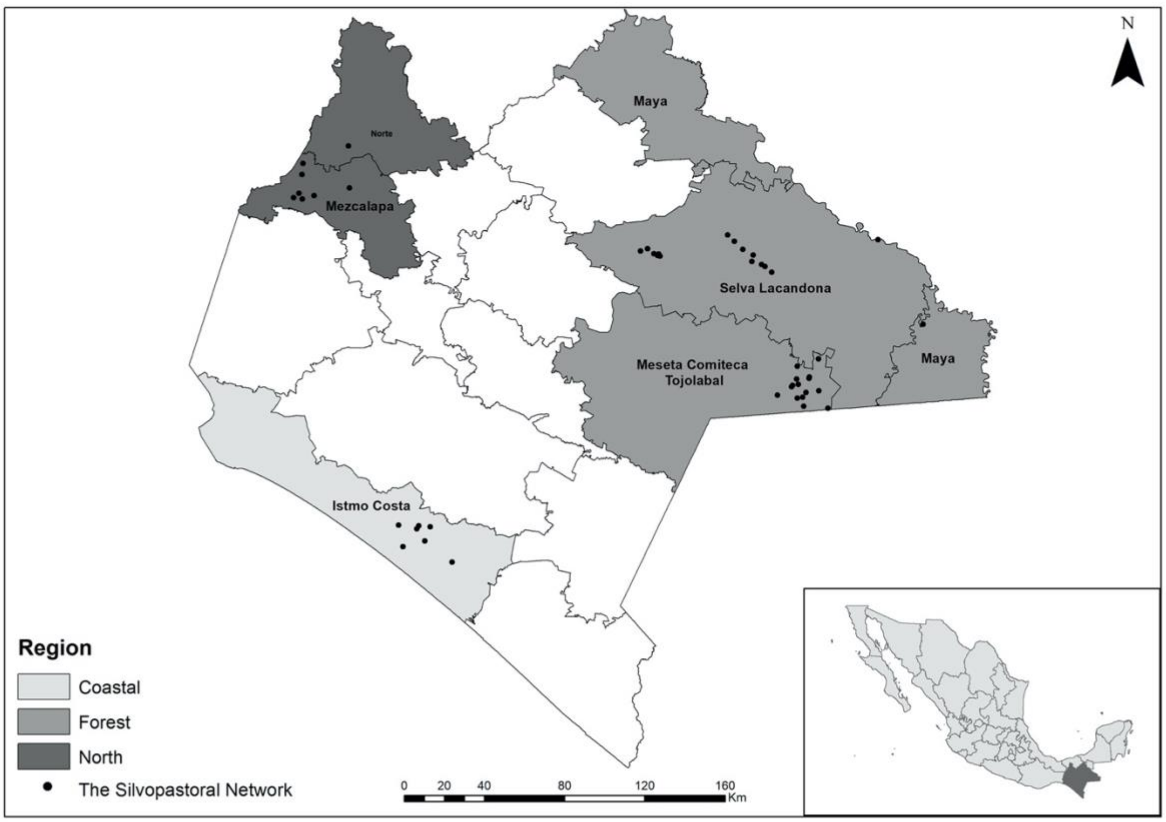


Fig. 1. Location of ranches in The Silvopastoral Network, and three regions described in Chiapas, Mexico.

We worked with The Silvopastoral Network, a cattle ranching organization created in response to the excessiveness of intermediaries and to draw attention to the goods that are produced in dual-purpose (milk and meat) of cattle-ranching systems that use regular silvopastoral practices (e.g., increased cattle density and inclusion of trees and shrubs). This network was created in 2014 as a non-profit initiative. Its members included nine cattle ranching associations - legally constituted producer groups to manage cattle production and commercialization practices - and 350 cattle producers distributed throughout municipalities across Chiapas. Three regions (north, coastal, and forest), which coincide with the distinction of some of the socioeconomic regions located in the state, were distinguished based on the producers' socioeconomic description, ranch size, and geographical characteristics (Table 1 and Fig. 1).

Table 1. Characterization of the Silvopastoral Network by production regions.

Characteristics	North Region	Coastal Region	Forest Region
Description			
Producers of the Silvopastoral Network by region	37 producers	50 producers	263 producers
% male producers	78.4 %	68 %	92.8 %
% female producers	21.6 %	32 %	7.2 %
Average age	57 years old	50 years old	57 years old
Average schooling	Secondary	Elementary	Elementary
Geographic issues			
Municipalities where the Silvopastoral Network is located	Ostuacán, Mezcalapa, Tecpatán	Mapastepec, Pijijiapan	Ocosingo, Las Margaritas, Maravilla Tenejapa, Marqués de Comillas
Köppen climate classification	Aw – Tropical wet and dry climate	Aw – Tropical wet and dry climate	Am (f) - Tropical monsoon climate
Altitude (m.a.s.l)	120 - 560	40 - 60	200 - 1500
Predominant ecosystems and agroecosystems	Sub-tropical forests, cultivated grasslands with maize	Deciduous forests, cultivated grasslands, banana, coco and maize	Tropical rainforests, cultivated grasslands, maize, coffee and sugar cane
Population and land in municipalities			
Total population	128,581	198,816	810,096
Indigenous population (%)	25 %	1.25%	72.2 %
Production units	10,972	16,150	28,431
Productive area (hectares)	183,609	83,694	407,435
*****Ejidal surface (%)	37 %	33.18 %	16.63 %
*Communal surface (%)	1.89 %	0.01 %	4.41 %

Notes:
Population data (INEGI, 2020)

Production units, productive area and social land tenure (ejidal and communal) data (INEGI, 2007)

*****Ejidos and communities are the forms of social land tenure that cover the largest area in the Mexican countryside, and 93% of them are used for agricultural and cattle ranching activities (Morett-Sánchez and Cosío-Ruiz, 2017).

2.2 Data collection

Semi-structured face-to-face interviews were performed between July and October of 2018 with 350 ranchers of The Silvopastoral Network. The questionnaire (SM1. Table 1) was designed to capture values associated with ecological (e.g., ES), social (e.g., management strategies), and economic (e.g., marketing and economic capacity) in 10 thematic blocks as part of the project "Systems of sustainable production and biodiversity" by National Commission for the Knowledge and Use of Biodiversity (CONABIO in Spanish), Ministry of Environment and Natural Resources (SEMARNAT in Spanish), and the Global Environment Facility (GEF). The interviews in the field were conducted by technicians belonging to each cattle ranching association, who received prior training for this purpose. The local technicians returned the information (questionnaires, notes, and photographic evidence) at the end of the interviews, which lasted, on average, between 1:30 and 2:00 hours each. The information was systematized in an Excel matrix for analysis, and the data was disaggregated at the producer level, each representing one cattle ranch (N = 350 ranches).

2.3 Data processing

The variables for analysis were obtained from the questionnaires that guided the interviews. Seeking to be representative of the four types of ES that have already been reported in cattle ranching systems, we selected two supporting ES (habitat and gene pool protection), one regulating ES (shade for cattle), two provisioning ES (food from ranching, and cultivated fodder), and two cultural ES (traditional knowledge, and recreation and mental health). The indicators, units, transformations, and interview questions that supported the data collection associated with the ES are shown in Table 2. In addition, we selected four indicators that described management strategies (cattle density, grazing rotation, labor input, and diversification) and four indicators associated with economic characteristics (cattle area, income, marketing chains, and infrastructure). We included the location of the producers based on the grouping by regions (north, coastal, and forest, see section 1.1). The units, transformations, and questions of the interview that support the data on cattle management, ranch economics, and spatial location are shown in Table 3. Although the transformed data improved in distribution and the magnitudes of the variables became comparable, the Kolmogorov-Smirnov normality tests for all parameters failed, so non-parametric tests were used for further analyses.

Table 2. Ecosystem services assessed.

Type of ES	ES	Indicator	Unit	Transformation	Interview question
Supporting ES	Habitat	Habitat	Meters of live fences/hectare	Ln + 1	How many total linear meters of live fences do you have?
	Gene pool protection	Tree species	Number of tree species	Ln	How many tree species do you have?
Regulating ES	Shade for cattle	Shade	Number of trees/hectare	Ln + 1	How many trees do you have in pastures?
Provisioning ES	Food from ranching	Food	Number of cattle	Ln + 1	How many cattle do you have?
	Cultivated fodder	Cattle feed	Square meters	Ln + 1	How many square meters of cane and/or maize do you have cultivated for feed?
Cultural ES	Traditional knowledge	Traditional knowledge	Number of vegetation uses	Non-transformed data	How many uses do you give to your vegetation? (according to key*****)
	Recreation and mental health	Wildlife sighting	Number of wildlife sightings	Square root	What wildlife do you usually observe in your pastures in a week?

***Key to vegetation uses:** 1) edible for human consumption, 2) protein fodder, 3) fiber fodder, 4) construction, 5) manufacture of handicrafts, 6) fuel, 7) medicinal, 8) shade, 9) rubber, 10) colorant, 11) condiment, 12) other uses.

Table 3. Management strategies, economic characteristics and location of cattle ranches.

	Indicator	Unit	Transformation	Interview question
Management strategies	Cattle density	Cattle/hectare	Ln + 1	How many cattle do you have?; How many hectares do you have for cattle?
	Grazing rotation	Days of rotation/year	Ln	How many days per year do you move cattle from pasture?
	Labor input	Jobs/cattle	Square root	How many employees do you have on your ranch?
	*Diversification	Level of diversification	Non-transformed data	What productive practices are carried out on your ranch?
Economic characteristics	Cattle area	Hectares	Ln	How many hectares do you have for cattle?
	Income	Mexican pesos/cattle	Ln + 1	What price do you get for each product?
	♦Marketing chains	Levels of chain consolidation	Non-transformed data	Who buys your products?
	♣ Infrastructure	Tools availability	Non-transformed data	What tools do you have for production?
Location	♠Location	Region Category	Non-transformed data	Region in which the ranch is located

Categorical variables:

* Diversification: 1. Cattle grazing only; 2. Grazing and feedlot; 3. Grazing, feedlot, sale of milk and cheese making.

♦ Marketing chains: 1. Low consolidation (sale to local intermediary); 2. Medium consolidation (sale to regional intermediary); 3. High consolidation (sale directly to butcher and/or supermarket).

♣ Infrastructure: 1. Basic: Cattle troughs; 2. Sufficient: Cattle troughs and cattle corrals; 3. Abundant: Cattle troughs, cattle corrals and grass cutter.

♠ Location: 1. Forest Region; 2. Coastal Region; 3. North Region.

2.4 Data analysis

2.4.1 Typology

We built a typology knowing that the producers of the Network have differentiated advances in establishing SPS. We proposed to trace the different types of existing cattle ranches based on the supply of ES offered, the economic characteristics of the producers, the management strategies used, and the spatial location. For this purpose, we performed a Multiple Factor Analysis (MFA), -a multivariate data analysis method for summarizing and visualizing a complex data table in which individuals are described by several sets of variables (quantitative and qualitative) structured into groups- (Abdi et al., 2013). Thus, from a small number of variables, one obtains syntheses of similarities between individuals, links between variables, and links between groups of variables. As input to the MFA, we used sixteen variables (4 categorical and 12 continuous) (Table 2 and Table 3). We grouped the data into four sets: economic characteristics, ES, management strategies, and location. We obtained the percentage of accumulated variance and eigenvalues from the first dimensions (SM2. Table 1).

Subsequently, we performed a Hierarchical Cluster Analysis (HCA) - a general approach to cluster analysis in which the objective is to group objects or records that are "close" to one another- (Köhn and Hubert, 2014) using Ward's method to infer the most appropriate number of clusters (initial partition). We then used the Manhattan distance to plot all possible paths and determine the closeness between variables and the K-means method for the final partition. Finally, we applied the Kruskal-Wallis test - a non-parametric analysis of variance for more than 60 data - to see if there were statistically significant differences between the clusters found for the sixteen measured variables included in the analysis. We used Tukey's test as a post hoc comparison method. We scaled the means to values from 0 to 10 to construct radar plots where differences between ranch types could be observed for the sixteen variables included. All analyses were performed in R studio software (ver. 4.1.3).

2.4.2 Structural Equation Modeling

- **Conceptualization of sustainability**

Structural Equation Modeling (SEM) represents a multivariate method that allows deciphering the relationships between variables, determining the most relevant relationships, and understanding how much they impact a complex phenomenon as a latent variable - an unmeasured variable that is constructed from the relationship between measured variables - (Kline, 2015). The SEM combines factor analysis with linear regression to test the degree of fit of the observed data to a hypothesized model expressed by a diagram or mental map (Hair et al., 2017). SEM uses available information, including prior knowledge of specialists, to shape the potential relationships to be tested. We constructed a conceptual model (mental map) with hypothetical relationships between the measured variables (boxes) with a latent variable (circle) (Fig. 2).

In general, our SEM explores the relationships between the variables that were used to make the typology, except for the location variable that, in this case, was disaggregated to explore how each region was related to management and economic particularities (Fig. 2). In addition, it evaluates how variable measures impact on the sustainability of ranches as a latent variable - a hypothetical factor that reflects a continuum that is not directly observable - that is constructed from the simultaneous interaction between measured variables (Kline, 2015). Specifically, in the case of The Silvopastoral Network, we tried to determine whether the geographic location influences management strategies and economic characteristics within ranches (indirect impacts on sustainability) (Carvalho et al., 2020). In turn, we analyze whether management strategies and economic characteristics have feedback on each other (Sayre et al., 2013; Murgueitio et al., 2011) and impact on ES provision (indirect impacts on sustainability) (Tauro et al., 2018; Sánchez-Romero et al., 2021). Finally, we explored whether management strategies, economic characteristics, and ES contribute to or hinder the sustainability of cattle ranches (direct impacts on sustainability) (Fig. 2) (Figueroa et al., 2022).

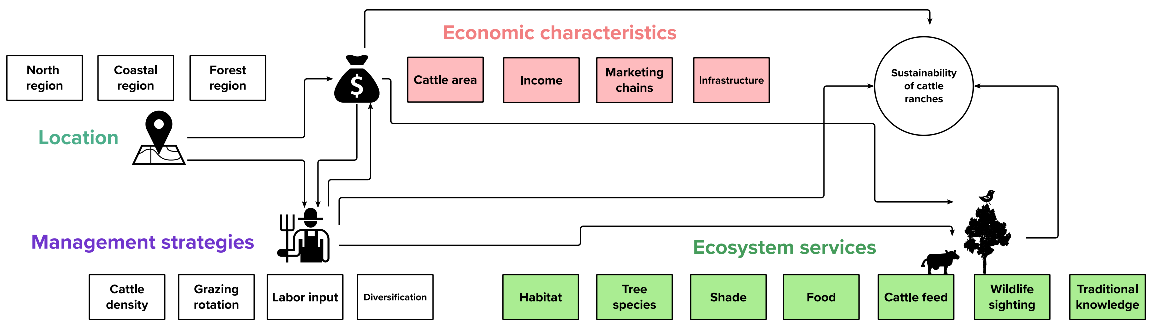


Fig. 2. The proposed conceptual model for sustainability in cattle ranches in the tropics. The multiple path diagram involves measured variables (boxes) as proxies of sustainability as a latent variable of the model (circle).

- **Application and fit of the SEM**

The relationships or associations (not necessarily causality) between variables are tested through covariance structure analysis (Kline, 2015). First, the bivariate covariance, defined as follows for two continuous variables x and y, was computed as the basic statistics of SEM:

$$COV_{xy} = r_{xy}\, SD_x\, SD_y$$

Where r_{xy} is the Pearson correlation coefficient and SD_x and SD_y are their standard deviations (Kline, 2015). Then, non-standardized and standardized path coefficients were calculated using the maximum likelihood estimator, picking out the variables that maximize the likelihood that the data (the observed variances) were extracted from a target data population. Our hypothetical conceptual model was assessed through the fit of SEM to the data. A good-fitting model is reasonably consistent with the data and does not require re-specification. This fit was tested using the root mean square error of approximation (RMSEA) and comparative fit index (CFI), which are two widely applied metrics to assess SEM (Lai and Green, 2016; Galeana-Pizaña et al., 2021). The overall model fit was verified with CFI values greater than 0.9 and RMSEA $\leq$ 0.05, which can be considered good fit values (Schermelleh-Engel et al., 2003).

If the fit was not good, re-specification was applied to the model, excluding measured variables that did not show statistical significance from the initially measured variables. The SEM was constructed using the Confirmatory Factor Analysis (CFA) within the Lavaan R-package (Rosseel, 2012). Quantitative interpretation of the SEM results focuses on the standardized path coefficients and significance levels (p-value ≤ 0.05) for each relationship plotted between measured variables. The highest and statistically significant path standardized coefficients (std. coeffs) determine the most important relationships within the analysis (greater magnitude of association). In turn, the signs of the coefficients determine whether the variables are contributing (positive standardized coefficients) or hindering (negative standardized coefficients) the sustainability of cattle ranches.

3. Results

3.1 Typology of tropical cattle ranches

MFA showed that the first two dimensions described 40.9% of the cumulative variance, and six dimensions accounted for 75% of the total variance (SM2. Table 1). The factor map shows the overall proximity between the different variable groups, reflecting the data structure. Support (habitat and tree species), regulation (shade), and cultural (traditional knowledge and wildlife sighting) ES indicators (ES bundle) were mainly associated with ranch location and most management strategies (Fig. 3). Indicators of ES provisioning (food and cattle feed) (ES bundle) were mainly associated with all economic characteristics analyzed and cattle density. At the same time, the rest of ES were close to each other and associated with location and diversification. The variables "Location" and "Marketing chains" contributed the most to the variability contained in the analysis (SM2. Fig. 1).

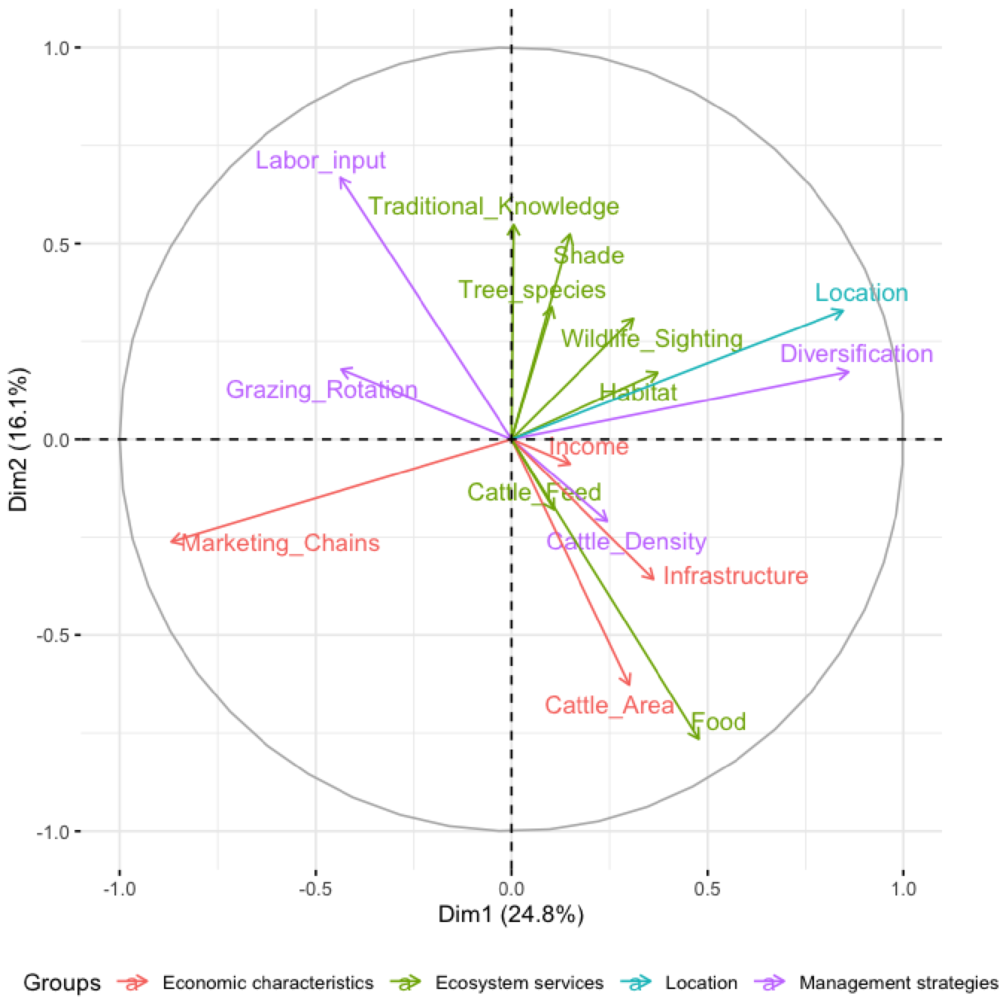


Fig. 3. Factor map with the two principal dimensions of MFA.

The HCA yielded three distinct clusters (SM2. Fig. 2), which we subsequently compared to develop the typologies of cattle ranches. The first cluster grouped 122 ranches, the second cluster 191 ranches, and the third cluster 37 ranches. The Kruskal Wallis test showed significant differences between the three types of ranches according to the variables analyzed (Fig. 4 and SM2. Table 2) and that there is an intensification gradient within The Silvopastoral Network. For each cluster, we chose a name that represents its most characteristic features, especially ranch size and the level of intensification, given the supply level of all ES analyzed.

Type 1. Large Silvopastoral Ranches with Low Intensification: Management strategies within this group involve low labor input, intermediate cattle density (~ 2.0 cattle/ha), low levels of diversification (ranches used only for cattle grazing), and intermediate frequency of grazing rotation (~ 20 days of rotation/year) (SM2. Table 2). Concerning economic characteristics, they have a large cattle area (~ 25 ha), medium incomes, low levels of consolidation of marketing chains (many intermediaries involved), and sufficient infrastructure available for production. The provision of ES is focused on guaranteeing "Food from ranching" (~ 52 cattle in production) and presents the lowest provisions in the other evaluated ES (Fig. 4 and SM2. Table 2). 91.8% of the ranches are in the forest region, 6.55% in the coastal region, and 1.65% in the north region (SM2. Table 3).

Type 2. Small Silvopastoral Ranches with Intermediate Intensification: Management strategies include more labor input than the other ranch types (Fig. 4), intermediate cattle density (~ 2.45 cattle/ha), low levels of diversification, and low frequency of grazing rotation (~ 14 days of rotation/year). In terms of economic characteristics, they have the lowest cattle area for production (~ 5.6 ha) and low income, reflecting the low levels of consolidation of marketing chains and basic infrastructure available for production (SM2. Table 2). ES provision is centered on intermediate contributions from the support, regulatory, and cultural ES and low on the indicator of the provision ES "Food from ranching" (~ 14 cattle in production) (Fig. 4 and SM2. Table 2). 79.6 % of the ranches are in the forest region, 18.83 % in the coastal region, and 1.57 % in the north region (SM2. Table 3).

Type 3. Medium Silvopastoral Ranches with High Intensification: Management strategies include low labor input, high cattle density (~ 3 cattle/ha), high levels of diversification, and high frequency of grazing rotation (~ 38.8 days of rotation/year). The economic characteristics encompass a medium cattle area (~ 15 ha), higher incomes reflecting high levels of marketing chain consolidation, and sufficient infrastructure available for production (SM2. Table 2). The provision of supporting, regulating, cultural and provisioning ES is the highest, except for the indicator "Food from ranching" (~ 44 cattle in production), for which it has intermediate values of provision (Fig. 4 and SM2. Table 2). 86.48 % of ranches are located in the north region and 13.52 % in the coastal region (SM2. Table 3).

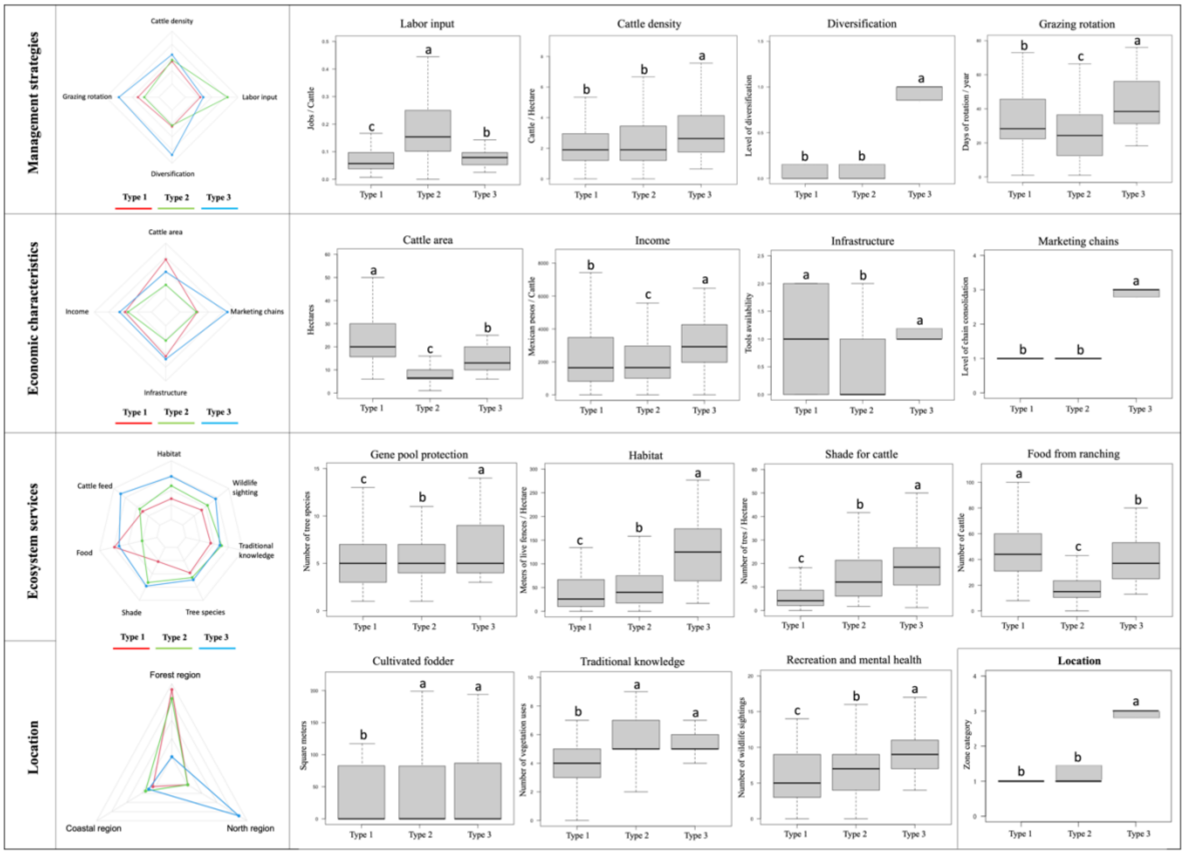


Fig. 4. Typology of cattle ranches. The radar graphs show the means obtained for the variables analyzed by ranch type—the box plots below the distribution of the data and the statistically significant differences. Different letters indicate significantly different means between the three ranches types (Tukey's test).

3.2 Assessing the sustainability of ranches

Our model included 350 observations, used the maximum likelihood estimator, and converged after 130 iterations. The SEM indicated a good fit: the CFI value was 0.995, and the RMSEA value was 0.025; both values are considered a good fit (Schermelleh-Engel et al., 2003; Kline, 2015).

3.2.1 Indirect impacts on sustainability

- **Location → Management strategies and Economic characteristics**

The SEM showed that being in the north region of the state of Chiapas contributes positively to increases in grazing rotation (std. coeffs: 0.081), higher levels of diversification (std. coeffs: 0.050), and higher levels of consolidation of marketing chains (std. coeffs: 0.778) (Fig. 5 and SM2. Table 4). In contrast, being in the forest region contributes negatively to the availability of infrastructure (std. coeffs: -0.096) necessary for production (Fig. 5).

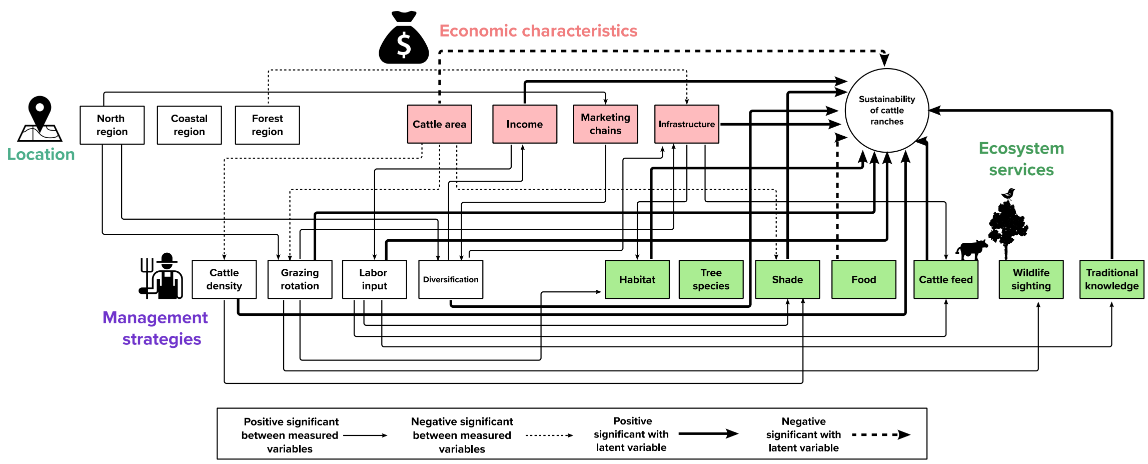


Fig. 5. Structural equation model of cattle ranches. Solid lines represent significant positive relationships, and dotted lines represent significant negative relationships. The thickness of the line determines if the relationship is between measured variables (thin lines: relationships between measured variables that reflect indirect impacts on the sustainability of the ranches; thick lines: relationships with the latent variable that reflect direct impacts on the sustainability of the ranches).

- **Economic characteristics → Management strategies and Ecosystem services**

Economic characteristics primarily impact management strategies, and only the infrastructure available for production affects ES provision. Large cattle areas contribute negatively to the increase in cattle density (std. coeffs: -1.264) and shade for cattle (std. coeffs: -0.276) available in pastures (Fig. 5 and SM2. Table 5). Higher on-ranch income contributes positively to the increase in labor input (std. coeffs: 3.061), so improving on-ranch income could imply an increase in the number of jobs generated. Higher levels of consolidation in marketing chains contribute positively to increased diversification (std.

coeffs: 1.660), and greater availability of infrastructure contributes positively to increased provision of habitat (std. coeffs: 0.046) and cattle feed (std. coeffs: 0.081) (Fig. 5 and SM2. Table 5).

- **Management strategies → Economic characteristics and Ecosystem services**

Management strategies mainly impacted ES provision, and only diversification levels affected the ranches' economic characteristics (Fig. 5 and SM2. Table 6). Increased cattle density contributes positively to improvements in shade provision for cattle (std. coeffs: 0.142). Increased frequency of cattle rotation positively impacts increases in habitat provision (std. coeffs: 0.053) and wildlife sightings (std. coeffs: 0.183). Increased labor input positively impacted the provision of shade (std. coeffs: 0.080), cattle feed (std. coeffs: 0.040), and traditional knowledge (std. coeffs: 0.074). Higher levels of diversification were found to contribute positively to increased income (std. coeffs: 0.556) and greater availability of infrastructure (std. coeffs: 0.238) (Fig. 5 and SM2. Table 6).

3.2.2 Direct impacts on sustainability

Directly, increases in the values associated with all management strategies evaluated (cattle density, grazing rotation, labor input, and diversification) have a positive effect (positive std. coeffs) on the sustainability of cattle ranches (Fig. 5 and Table 4). Regarding economic characteristics, higher income and infrastructure availability (positive std. coeffs) and lower cattle area (negative std. coeffs) contribute positively to sustainability. The increased control of marketing chains (consolidation resulting from fewer intermediaries) had no direct effect on sustainability (not significant std. coeffs) (Fig. 5 and Table 4). Finally, improvements in the provision of habitat, shade, cattle feed, traditional knowledge (positive std. coeffs), and a decrease in the indicator "Food" as provisioning ES (negative std. coeffs) have a positive effect on sustainability. As part of the ES, the indicator "tree species" had no direct or indirect contribution (not significant std. coeffs) on the latent variable (Fig. 5 and Table 4). Our SEM identified that increases in grazing rotation, diversification, and shade for cattle; and decreases in cattle area are fundamental (higher values of std. coeffs) for the sustainability of cattle ranches (Table 4).

Table 4. Standardized maximum likelihood coefficients relating the variables describing management strategies, economic characteristics, and ecosystem services with the sustainability of cattle ranches.

Sustainability of cattle ranches		**Std. Coeffs**	**Std. Error**
Management strategies	Cattle density	0.257***	0.023
	Grazing rotation	3.092***	0.739
	Labor input	0.114***	0.007
	Diversification	1.099***	0.017
Economic characteristics	Cattle area	-1.801***	0.039
	Income	0.501**	0.151
	Marketing chains	0.005	0.018
	Infrastructure	0.196***	0.037
Ecosystem services	Habitat	0.282**	0.087
	Tree species	0.048	0.028
	Shade	1.243***	0.052
	Food	-0.719***	0.029
	Cattle feed	0.461***	0.132
	Wildlife sighting	0.091	0.052
	Traditional knowledge	0.531***	0.089

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 "." 0.1 ' ' 1

4 Discussion

4.1 Tropical cattle intensification

The way to produce, transform, distribute, and consume cattle is a priority research topic (Ellis et al., 2019). Identifying the different types of cattle ranching systems in a given area is the first step to informing and encouraging the government from academia to promote sustainable management (Escribano et al., 2016). The three types of silvopastoral ranches we evaluated include intensification strategies increasing cattle density (2-3 cattle/ha) (SM2. Table 2) concerning extensive pastures in tropical regions where they graze ~ 0.5 cattle per hectare (FAOSTAT, 2018). In addition, they integrate grazing rotation (14 – 38 days of rotation/year), trees (8.25 – 22.50 trees/hectare), and shrubs cover (59.28 – 122.67 meters of live fences/hectare) (SM2. Table 2) as strategies that are often absent from extensive management where grazing is continuous within cleared areas (Eaton et al., 2011). Increasing carrying capacity – the number of animal units that can be grazed for a specific time – by maintaining or including more vegetation and avoiding overgrazing by reducing animal pressure by rotating cattle are intensification practices that promote improvements in cattle ranching management in the tropics (Diaz-Pereira et al., 2020; Figueroa et al., 2020). With this, we demonstrate that all The Silvopastoral Network producers have notions of some silvopastoral practices; however, the socioecological benefits obtained in each type of ranch are differentiated.

Understanding that the sustainability of intensification goes beyond management, we identified a gradient of intensification with particular attention to ranch size and levels of ES provision, two issues relevant to the tropics. Large ranches with low intensification focus on producing "Food" as the provisioning ES neglects improvements in providing all other types of ES (Calle et al., 2009; Herrero et al., 2016). The prioritization of meat production, and the low provision of other ES, especially shade and habitat (low availability of trees and shrubs), coupled with large grazing areas (~ 25 ha) and little labor input, demonstrate that on large silvopastoral ranches the intensification is focusing almost exclusively on increasing cattle production and grazing areas (low sustainable intensification). That is, they are production systems with a logic similar to that of extensive grazing management in Latin America (Allen et al., 2011)

Small silvopastoral ranches (~5 ha) have an intermediate supply of ES, have higher labor input, have the lowest income captured by The Silvopastoral Network producers, and have scarce infrastructure. It has already been documented in Chiapas that small ranches have low investment in technology and little capital due to exclusively manual tools and a lack of essential services (e.g., roads, electricity, water) (Valdivieso-Pérez et al., 2019). We consider that intensification in small silvopastoral ranches is intermediate because although an improvement in supporting, regulating, and cultural ES was demonstrated, as expected from the establishment of SPS (Murgueitio et al., 2011), provisioning ES continues to show little progress. In the tropics of Mexico, low-income ranches do not usually substitute supporting and regulating ES because their provision is crucial to guarantee the few provisioning ES generated within the ranches (Aguilar-Fernández et., 2020). For example, smallholders in Chiapas conserve secondary forest areas that includes herbaceous perennial vegetation to maintain soil fertility and forage quality to promote production improvements (Idem). Although there are critical socio-ecological benefits resulting from the intensification of small ranches, the scarce availability of ES "food from ranching" on these ranches increases the economic vulnerability of producers, as cattle are often the principal asset (Herrero et al., 2011) used as an immediate source of cash in the face of crop seasonality (Figueroa and Galicia, 2021).

Medium silvopastoral ranches (~15 ha) with high intensification present favorable economic characteristics (higher income, sufficient infrastructure available for production and transformation, and improved levels of consolidation of marketing chains). In addition, they implement management strategies that are compatible with agroforestry practices. The higher frequency of cattle rotation, cattle density, diversification, and availability of multiple vegetation strata indicate that several intensification practices are contemplated to guarantee the provision of all types of ES without expanding grazing lands. As in other SPS, on these ranches, the incorporation and use of available tree and shrub vegetation to feed cattle improve the provision of ES (Murgueitio et al., 2011) at higher levels than those reported in extensive systems (Buttler et al., 2009; Calle et al., 2009). These SPS are conceived as multifunctional systems resulting from a diversified landscape configuration that fosters the provision of multiple services in a bundle (Venturi et al., 2021).

Overall, measuring the provision of ES allowed us to validate the levels of intensification and explore whether intensification is focused on promoting sustainable scenarios. There are successful examples of sustainable intensification in cattle systems; most of them have been associated with the availability of inputs (high-quality feed, fertilizers, Etc.), external services (veterinary, extension), and the development of markets and value chains (McDermott et al., 2010; Herrero et al., 2018). The importance of ES within sustainable intensification has been explored in some work in the tropics (e.g., McDermott et al., 2010; Rao et al., 2015; Rudel et al., 2015; Lerner et al., 2017). However, measuring all types of services in specific realities has been nascent within the formal study of sustainable intensification. Beyond the tropical context, multiple ES from cattle ranching is often overlooked and rarely quantified (Dumont et al., 2019). The small and medium silvopastoral ranches in our case study include the intermediate and high provision of all types of ES, which poses a more sustainable scenario for land-using cattle ranching.

In contrast, large silvopastoral ranches with low intensification present more remarkable similarities with extensive ranches where provisioning SE (especially cattle breeding) is prioritized, demonstrating that intensification is less sustainable and poses multiple areas of opportunity in terms of improving the flow of regulating, supporting and cultural ES (Broom, 2021; Pérez-Lombardini et al., 2021). Sustainable intensification is still under debate due to the need for local thresholds and uncertainty regarding managing possible perverse incentives (Lerner et al., 2017). However, it is not currently debatable that it is a priority to "produce more with less" through cattle ranching that does not expand in the area, uses few inputs, and minimizes impacts on nature (Lal, 2023). Sustainable intensification can be an alternative if it guarantees the provision of all ES, contains deforestation, and is accompanied by improvements in the economic conditions of producers and other ranch workers (Coppock et al., 2017).

4.2 Sustainability of tropical cattle ranches

The sustainability of food production systems is often assessed using a narrower set of factors (Broom, 2021). As a multivariate method, our SEM showed that different direct and indirect relationships are essential to understanding and enhancing cattle ranches' sustainability. The geographical location of cattle ranches in the tropics can impact sustainability challenges and potentials (Carvalho et al., 2020). In our case, the ranches located in the north region of Chiapas tended to show higher levels of diversification and greater consolidation of marketing chains (few intermediaries). The north region has been identified as having the potential for converting extensive cattle ranching to more sustainable schemes if producers' capacities continue to be developed through advice, technical assistance, and ongoing financial and commercial support (Valdivieso-Pérez et al., 2019). Improving access to agricultural markets motivates producers to increase their productivity, with which they cover their consumption and sell surpluses at more competitive prices than those offered by intermediaries (Herrero et al., 2011).

In contrast, the ranches in the forest region tended to show low availability of the necessary infrastructure for production. The poverty situation of 90% of the population living in the municipalities of the forest region (CONEVAL, 2018), many of whom are indigenous (see Table 1), exerts intense pressure on food subsistence and the sale of surpluses, which often integrates production with rudimentary infrastructure that prevents the improvement of yields of ranching practices (Aguilar-Fernández et., 2020; Garduño and Perrings, 2020). Recently, the population of this region saw their supply and marketing chains severely affected by the effects of the SARS-CoV-2 pandemic, and they continue to face the challenges derived from the health emergency with little support.

Productive diversification leads to higher incomes and less dependence on supply ES for subsistence (Dai et al., 2023). We show that unleashing the socioecological benefits of diversification requires first consolidating marketing chains, and this implies facing local challenges, such as the excess of intermediaries (Calderón et al., 2012) who oversee 59 % of cattle sales transactions in Chiapas and retain part of the profits (between 10 % and 30 % of each sale of cattle) (Calderón et al., 2012; INEGI, 2017). In addition, the local scenario is nested within national cattle marketing realities, which are complex by the demands of other nations covered within highly globalized value chains (Figueroa et al., 2022). All this implies transfers of value, nutrients and pollutants, energy, water, and labor (Firbank et al., 2018), which as externalities, are not compensated for by the producing countries. For example, most of Mexico's agricultural products are currently marketed within conventional commercial chains that do not add value to alternative production (Nahed et al., 2012; Valdivieso-Pérez et al., 2019).

For Mexico, diversification means improvements in rural food security (Galeana-Pizaña et al., 2021) and a decrease in high deforestation rates (Figueroa et al., 2021). Increased diversification of cattle ranches in our case study, including grazing, feedlot, and sale of milk and cheese making, and enhanced by the consolidation of marketing chains, cascades into improvements in infrastructure and income. In turn, having infrastructure available for production contributes positively, on the one hand, to the provision of habitat because sufficient tools are needed for the establishment and management of live fences (Zamora-Pedraza et al., 2022). On the other hand, improving the producers' income increases the hired labor input for cattle care within the ranches. Improving the number of workers on ranches enhances: i) the provision of shade for cattle, which requires management of plantations and care of the tree canopy (Murgueitio et al., 2011), ii) the provision of cattle feed, making possible the establishment and care of forage crop zones, and iii) more traditional knowledge that promotes more uses of available vegetation. However, to ensure a sustainable scenario, it is necessary to take care of the labor conditions within the cattle ranches of the Mexican tropics because, in them, workers are often hired informally, with excess hours and low wages that exacerbate the extreme poverty of the region (Rivera-Huerta et al., 2019).

Achieving moves towards more sustainable production systems in the tropics requires that ranchers and workers obtain enough benefits. Their management choices will depend on the social, economic, environmental, and regulatory context (de Oliveira Silva et al., 2017). For example, in the southeast of Mexico and Centro America (Alyson et al., 2013; Apan-Salcedo et al., 2021; Diemont et al., 2021), the SPS, despite having received financing from Non-Governmental Organizations (NGOs), have had low adoption rates mainly due to high initial investment costs, lack of technical capacities and the lack of roots culture of SPS (Calle, 2020; Van Loon et al., 2020). The financial support needed to move from extensive systems to SPS must be accompanied by tropic cattle ranching regulation. Both strategies should be promoted through government initiatives that are possible and sustainable over time only with political will (Figueroa et al., 2022).

We found that increasing the frequency of cattle rotation is the management strategy that contributes most to ranch sustainability. The introduction of grazing rotation, where cattle are systematically moved to different fenced sub-units, allows tropical regions to control forage height, improving pasture use efficiency and avoiding overgrazing, minimizing erosion and soil compaction (Latawiec et al., 2014). This is relevant for degraded or degrading pastures in the tropics (Rudel et al., 2015; Lal, 2023) and particularly for Mexico, where grazed soils often present low fertility and high rates of erosion and compaction due to cattle pressure (Solorio et al., 2017). Generally, managed pastures with higher cattle rotation and including trees and shrubs within the systems contribute to physical soil protection (Latawiec et al., 2014) and nutrient cycling (Figueroa et al., 2020).

Increasing cattle density and grazing rotation are viable ways to increase cattle yields according to the land-sparing paradigm in the tropics (Murgueitio et al., 201; Lerner et al., 2017; Díaz-Pereira et al., 2020). In addition, the inclusion and maintenance of trees and shrubs within SPSs contain deforestation, ensure the provision of shade for cattle and habitat for other species (Murgueitio et al., 2011), and strengthen the multiple uses that vegetation can have through traditional local knowledge (Sánchez-Romero et al., 2021). Adopting alternative and context-appropriate cattle systems can be essential in providing ES (Aguilar-Fernandez et., 2020; Lal, 2023). Indeed, many regions of the Mexican tropics, including some regions in Chiapas, are suitable for reconverting extensive pastures to more environmentally friendly production schemes, given that they already use few external inputs (Nahed et al., 2018).

Finally, minimizing cattle area and food provision while increasing the provision of habitat, shade for cattle, cattle feed, and traditional knowledge are issues that contribute directly and positively to the sustainability of ranches (Table 4). This configuration of strategies is critical because it implies, on the one hand, that tropical cattle production must be carried out differently from extensive production. On the other hand, cattle ranches that tend to specialize in exclusive cattle production must diversify, improve yields and provide other ES. However, scarce financial capital, modest infrastructure, governance problems (Apan-Salcedo et al., 2021), and the isolation of producers from urban and governmental centers (Sayre et al., 2013) are challenges that make it difficult to more sustainable scenarios of production, transformation, and distribution in the tropics of southern Mexico.

5 Conclusions

Typing silvopastoral cattle ranches in a proposal that contemplated the production system and included ES, the producers' economic characteristics, and geographic location allowed us to understand how cattle are produced within The Silvopastoral Network and validate the benefits and challenges associated with intensification. Measurement of all types of ES in specific contexts has been incipient within the study of sustainable intensification, so our research helps to reduce that gap. We identified a gradient of intensification by paying particular attention to ranch size and levels of ES provision: small and medium silvopastoral ranches with intermediate and high provisions of services pose a more sustainable scenario for land-using cattle ranching. In contrast, large silvopastoral ranches with low intensification, more similar to extensive systems, where provisioning ES improvements are prioritized almost exclusively, represent a less sustainable scenario. There is an opportunity and urgency for large cattle ranches to stop expanding and, by including more agroforestry practices, activate the outstanding provision of supporting, regulating, and cultural services. This approach allows the reconversion of degraded areas and diversification with multipurpose trees.

Consolidating marketing chains by making them competitive for producers, diversifying ranches, improving incomes, increasing labor input (more dignified jobs), and the frequency of cattle rotation are indispensable strategies that support providing services and the expected positive effects of land-sparing on sustainability. Minimizing cattle area and food provision while increasing the provision of habitat, shade for cattle, cattle feed, and traditional knowledge are issues that contribute directly and positively to ranch sustainability. This configuration of strategies implies that it should be recognized that tropical cattle production must integrate agroforestry practices and contemplate a maximum limit of meat and fodder supply in order to continue to be sustained over time. Sustainable intensification is an alternative for cattle ranching in the tropics if it guarantees the provision of all ES, contains deforestation, and is accompanied by improvements in the economic conditions of the producers at levels that represent more than a short-term incentive, a transformation of the work in the field.

Acknowledgements: The authors thank the Silvopastoral Network (Red de Organizaciones Agropecuarias Silvopastoriles del Estado de Chiapas S.A. de C.V) for providing the data and Research Project in Technology and Innovation (PAPIIT) at DGAPA-UNAM: Proyecto PAPIIT 302421 for funding the publication.

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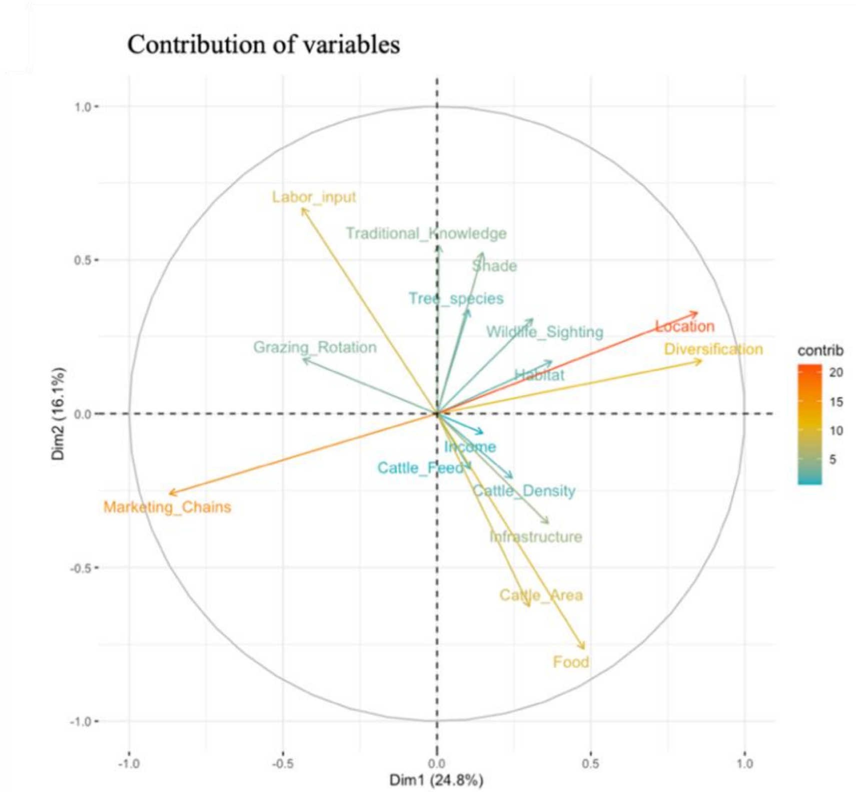
Supplementary Material (SM)

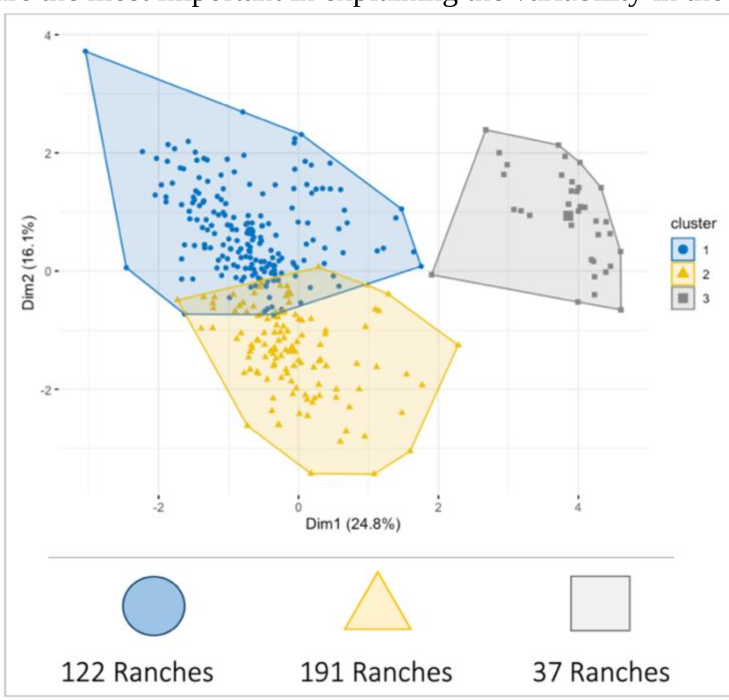
SM1. Table 1. The questionnaire that guided the semi-structured interviews of the Silvopastoral Network (see supplementary information in the previous chapter).

SM2. Table 1. Eigenvalues of multiple factor analysis

Dimensions	Eigenvalue	Variance percent	Cumulative variance percent
Dim 1	2.3470632	24.800635	24.80063
Dim 2	1.5248256	16.112324	40.91296
Dim 3	1.0386348	10.974908	51.88787
Dim 4	0.8093563	8.552198	60.44006
Dim 5	0.7600695	8.031401	68.47146
Dim 6	0.6665911	7.043646	75.51511



SM2. Fig. 1. Contribution of variables. Variables that contribute the most to Dim.1 and Dim.2 are the most important in explaining the variability in the data set.



SM2. Fig. 2. Cluster plot showing the three clusters (outcome of the hierarchical cluster analysis) in the MFA component 1and 2 plane.

SM2. Table 2. Means and Kruskal-Wallis statistic values for the groups (types of cattle ranches) obtained in the hierarchical cluster analysis.

Indicators	Kruskal-Wallis		Type 1	Type 2	Type 3
	χ^2	p-value	Mean	Mean	Mean
Management strategies					
Labor input (Jobs/Cattle)	122.06	<2.2e-16	0.07	0.19	0.09
Cattle density (Cattle/Hectare)	6.4465	0.03982	2.02	2.45	3.00
Diversification (Level of diversification)	293.39	<2.2e-16	1.08	1.00	2.94
Grazing rotation (Days of rotation/year)	26.229	2.015e-6	20.34	14.18	38.82
Economic characteristics					
Cattle area (Hectares)	177.24	<2.2e-16	24.96	5.61	15.03
Income (Mexican pesos/Cattle)	9.1037	0.01055	2,645	2,257	3,177
Infrastructure (Tools availability)	44.74	1.92e-10	1.99	1.48	2.00
Marketing chains (Level of chain consolidation)	276.1	<2.2e-16	1.03	1.02	2.86
Ecosystem services					
Gene pool protection (Number of tree species)	7.9987	0.01833	5.40	6.38	6.86
Habitat (Meters of live fences/Hectare)	40.677	1.47e-09	59.28	96.14	122.67
Shade of cattle (Number of trees/Hectare)	90.397	<2.2e-16	8.25	20.46	22.50
Food from ranching (Number of cattle)	169.66	<2.2e-16	52.3	14.41	44.13
Cultivated fodder (Square meter)	8.4966	0.01429	113.65	133.27	259.48
Traditional knowledge (Number of vegetation uses)	71.022	3.78e-16	3.95	5.67	5.40
Recreation and mental health (Number of wildlife sightings)	31.153	1.719e-7	5.38	7.05	9.37
Location					
Region Category (1.Forest region; 2.Coastal region; 3.North region)	166.55	<2.2e-16	1.09	1.22	2.86

SM2. Table 3. Distribution in percent of the zones within the types of cattle ranches.

Type	Percentage in Forest Region (%)	Percentage in Coastal Region (%)	Percentage in North Region (%)
1	91.80	6.55	1.65
2	79.6	18.83	1.57
3	0	13.52	86.48
Region category: 1. Forest region; 2. Coastal region; 3. North region.			

SM2. Table 4. Standardized maximum likelihood path coefficients linking location to management strategies and economic characteristics of cattle ranches.

LOCATION	MANAGEMENT STRATEGIES								ECONOMIC CHARACTERISTICS							
	Cattle density		Grazing rotation		Labor input		Diversification		Cattle area		Income		Marketing chains		Infrastructure	
	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error
North Region	-	-	0.081**	0.027	-	-	0.050*	0.023	-	-	-	-	0.778***	0.036	-	-
Coastal Region	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Forest Region	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-0.096**	0.028
Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 "." 0.1 ' ' 1																

SM2. Table 5. Standardized maximum likelihood path coefficients linking economic characteristics to management strategies and ecosystem services of cattle ranches.

ECONOMIC CHARACTERISTICS	MANAGEMENT STRATEGIES								ECOSYSTEM SERVICES													
	Cattle density		Grazing rotation		Labor input		Diversification		Habitat		Tree species		Shade		Food		Cattle feed		Wildlife sighting		Traditional knowledge	
	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error
Cattle area	-1.264***	0.036	-0.276**	0.042	-	-	-	-	-	-	-	-	-0.038***	0.015	-	-	-	-	-	-	-	-
Income	-	-	-	-	3.061**	0.989	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Marketing chains	-	-	-	-	-	-	1.660***	0.049	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Infrastructure	-	-	-	-	-	-	-	-	0.046*	0.023	-	-	-	-	-	-	0.081***	0.014	-	-	-	-
Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 "." 0.1 ' ' 1																						

SM2. Table 6. Standardized maximum likelihood path coefficients linking management strategies to economic characteristics and ecosystem services of cattle ranches.

MANAGEMENT STRATEGIES	ECONOMIC CHARACTERISTICS							
	Cattle area		Income		Marketing chains		Infrastructure	
	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error
Cattle density	-	-	-	-	-	-	-	-
Grazing rotation	-	-	-	-	-	-	-	-
Labor input	-	-	-	-	-	-	-	-
Diversification	-	-	0.556**	0.035	-	-	0.238**	0.076

MANAGEMENT STRATEGIES	ECOSYSTEM SERVICES													
	Habitat		Tree species		Shade		Food		Cattle feed		Wildlife sighting		Traditional knowledge	
	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error	Std. Coeffs	Std. Error
Cattle density	-	-	-	-	0.142***	0.021	-	-	-	-	-	-	-	-
Grazing rotation	0.053*	0.022	-	-	-	-	-	-	-	-	0.183***	0.044	-	-
Labor input	-	-	-	-	0.080**	0.006	-	-	0.040**	0.002	-	-	0.074**	0.008
Diversification	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 "." 0.1 ' ' 1

Capítulo 5

Ganadería bovina con menor costo ambiental: un desafío entre lo personal y lo político

Sociedad y Ambiente

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https://doi.org/10.31840/sya.vi24.2218

Resumen

La problemática de la ganadería es compleja por su naturaleza multi-escalar, multi-temporal y multisectorial. Esta diversidad de aristas desarticuladas en las que se ve embebida la ganadería, nos llevaron a plantear como objetivo: contribuir en la discusión sobre la ganadería como un tema tan personal como político, partiendo de la evidencia disponible para el mundo y aterrizando en el contexto del trópico mexicano. En ese sentido, visualizamos la encrucijada entre lo personal y político, mostramos las iniciativas existentes en torno a una producción y consumo más responsables (sistemas silvopastoriles y cambios dietarios); y recopilamos las acciones personales y políticas necesarias para promover una ganadería sostenible (leyes de regulación, campañas informativas, menor consumo de carne, incentivos económicos, mejoras tecnológicas). Finalmente, señalamos que es indispensable la participación activa de políticos y sociedad, para que deje de ser visto como alternativo el único camino sostenible que tenemos: la transformación.

Palabras clave: dieta; ganadería; silvopastoreo; sostenibilidad; transformación.

1. Introducción

La problemática en torno a la ganadería es compleja por su naturaleza multi-escalar, multi-temporal y multi-sectorial; sin embargo, su magnitud puede ser comprendida al visualizar al sector como usuario de recursos naturales, fuente de sustento y motor del crecimiento económico. En términos sociales, históricamente comer carne ayudó a los humanos primitivos a desarrollar capacidades como la inteligencia, cualidad que marcó la diferencia entre nosotros y otras especies de homínidos. La ganadería representa la base de la alimentación para 800 millones de personas en condición de inseguridad alimentaria (Herrero *et al.*, 2013), contribuye con el 17% al balance global de la alimentación y con el 33% al consumo mundial de proteínas (Herrero *et al.*, 2009). En términos económicos, las actividades pecuarias proporcionan sustento directo y beneficios financieros a 1,300 millones de productores y minoristas, son la base de los medios de subsistencia para 1,000 millones de pobres en todo el mundo, y contribuyen en un 40-50% al producto interno bruto (PIB) agrícola a escala mundial (Steinfeld *et al.*, 2006; Herrero *et al.*, 2018). De hecho, para muchas personas del campo, principalmente en los países con economías emergentes, la cría de animales constituye una fuente inmediata de dinero en efectivo frente a la estacionalidad de las cosechas. En ese sentido, parecería trivial relacionar dos fenómenos que para la mayoría de la población no están enlazados y no tienen importancia, y que para los científicos están fuertemente vinculados.

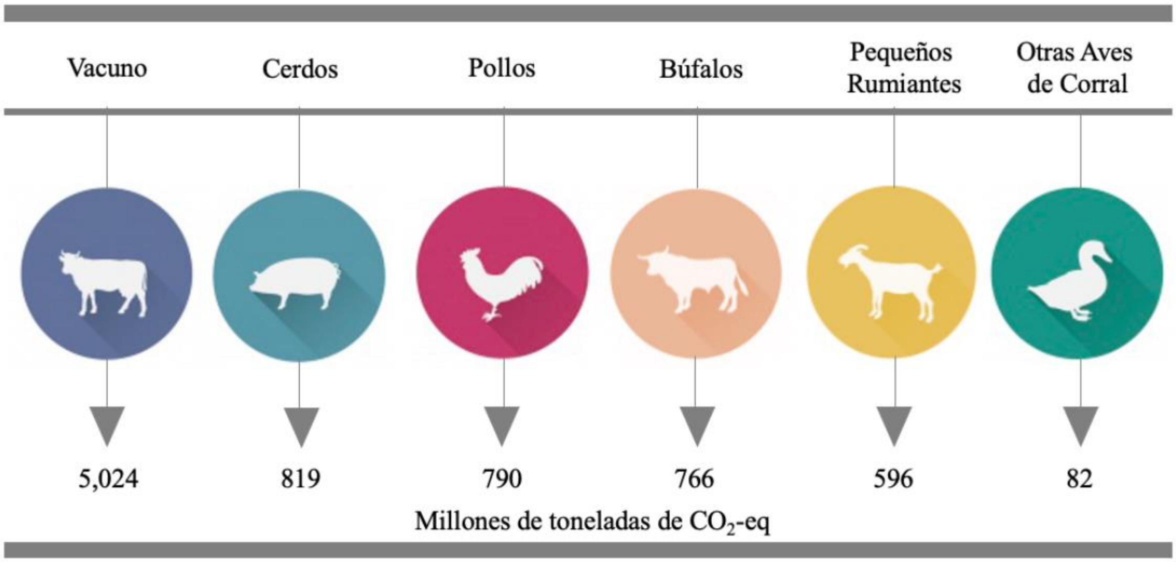
A pesar de reconocer lo arduo de comunicar y concientizar al desinformado y la complejidad de sumergirse en el conocimiento del informado, no queda duda que esos esfuerzos son apenas necesarios en tiempos en que los cambios dejaron de ser opcionales. Por ello, nos planteamos el siguiente objetivo: contribuir en la discusión sobre la ganadería como un tema tan personal como político, partiendo de la evidencia disponible para el mundo y aterrizando en el contexto del trópico mexicano. Para cumplir con dicho objetivo, se propone como ruta metodológica: 1) describir el panorama global y nacional de las prácticas ganaderas, 2) visualizar la encrucijada entre lo personal y político, 3) reflexionar sobre la urgencia de los cambios en la forma de producir y consumir productos del sector pecuario para garantizar un menor costo ambiental, y 4) explorar las oportunidades y retos para la transformación de la ganadería tropical mexicana. Se espera a través del texto, lograr transmitir a los lectores las alternativas existentes para contribuir en la transformación sostenible de la ganadería bovina.

2. El panorama socioecológico de la ganadería

La ganadería tiene impactos negativos en prácticamente todos los aspectos del medio ambiente, incluyendo el cambio del uso de suelo, el agua, la biodiversidad, la degradación del suelo y el cambio climático (Herrero *et al*., 2013; 2016). La problemática de las emisiones de gases de efecto invernadero (GEI), destaca no solo por contribuir al cambio climático, sino porque representa la principal amenaza para la producción futura de alimentos (Springmann *et al*., 2018). El ganado domina las emisiones del sector agropecuario (64-78%), de las cuales el 9% corresponde a emisiones de dióxido de carbono (CO_2) provenientes principalmente de la deforestación para su introducción, el 37% al metano (CH_4) proveniente de la digestión de los rumiantes, y el 65% al óxido nitroso (N_2O) del uso de fertilizantes sintéticos y orgánicos para la producción de alimentos y forrajes, por la gestión del estiércol y la excreción de orina (Herrero *et al*., 2016).

El ganado vacuno (bovino) es el mayor emisor de GEI con alrededor de 5,024 Gt CO_2-eq, que representan el 62% de todas las emisiones (Figura 1). El ganado vacuno de carne y el ganado vacuno de leche emiten cantidades similares de GEI. Los cerdos, las aves de corral, los búfalos y los pequeños rumiantes tienen niveles de emisión menores, que representan entre el 7% y el 11% de las emisiones totales (Gerber *et al*., 2013). En México, el Inventario Nacional de Emisiones de Gases y Compuestos de Efecto Invernadero (INEGYCEI) mostró recientemente que el 9.87% (72,469,411 Gg CO_2-eq) del total de las emisiones del país es generado por la ganadería, y el 75.23% de este valor proviene específicamente de la ganadería bovina (INECC, 2017). Además de sus inmensas contribuciones al deterioro ambiental, el sector ganadero sigue creciendo velozmente por el aumento en la demanda mundial de productos ganaderos a consecuencia del incremento de los ingresos y el crecimiento demográfico (Alexandratos y Bruinsma, 2012). Es decir, el problema no solo es de magnitud desproporcionada, sino que tiene un incremento vertiginoso. La demanda global de carne está aumentando a distintos ritmos en regiones diferentes, con el mayor crecimiento en China y la India como resultado de una clase media emergente (Ramankutty *et al*., 2018). Esto último, debe lograr transmitir por sí mismo que el tamaño de las consecuencias del incremento en la demanda de productos ganaderos será inconmensurable, teniendo en cuenta que la explosión ganadera vendrá precisamente de los dos países más poblados del planeta, y de uno de los que se espera el mayor crecimiento poblacional para 2050 (India) (ONU, 2019).

Figura 1. Estimación global de emisiones de gases de efecto invernadero por especie. Se incluyen las emisiones atribuidas a los productos comestibles y a otros bienes y servicios, como la tracción animal o la producción de lana por año.



Fuente: elaboración propia, modificado de Gerber *et al*. (2013).

Esta transición ganadera ya no está pudiendo ser contenida ni por la religión, ni por esquemas de gobiernos centralistas como ocurría en el pasado. El término "revolución ganadera" fue acuñado por primera vez por Delgado *et al.* (1999) para describir los rápidos cambios en la estructura y eficiencia de la producción del ganado. Por impresionante que parezca, el valor de mercado de los aumentos globales en el consumo de carne y leche entre 1970 y 1990 fueron dos veces mayores que el valor de mercado del aumento en el consumo de cereales a través de la conocida "Revolución Verde", específicamente de trigo, arroz y maíz (Bai *et al*., 2018). Sin embargo, la urgencia de hacer frente a la revolución ganadera no termina de permear ni en lo personal ni en lo político-institucional. Pero ¿De verdad llevamos veinte años viendo venir la ola que está por consumirnos? La respuesta es sí, y esto ha ocurrido porque sigue prevaleciendo una gran brecha entre el conocimiento y la acción individual-política.

El aumento del consumo en el continente asiático ha desencadenado presiones sobre los recursos naturales de países en AL y África, quienes destinan grandes extensiones de tierra para producir el alimento para el ganado que es exportado masivamente a China y Japón. En el territorio mexicano, la ganadería representa una actividad productiva de la que dependen miles de familias rurales campesinas (Dávila-Moreno, 2014). México es el séptimo productor mundial de carne de bovino (FIRCO, 2018) con 34,820,271 cabezas de ganado (SIAP, 2018); la superficie de pastizales es de 18,982,108 hectáreas que equivalen al 9.8% del territorio nacional (INEGI, 2016). Las actividades ganaderas se desarrollan en todo el país, sin embargo, la región tropical destaca por concentrar el 33% del total de la población de bovino existente a nivel nacional (SIAP, 2018).

En cuanto al comercio exterior, México importa una cantidad importante de carne de bovino desde Estados Unidos (81%) y Canadá (18%) para lograr satisfacer su consumo interno; al mismo tiempo, exporta cerca del 85% de los casi 2 millones de toneladas que se producen al año a cuatro destinos predominantes: Estados Unidos (61%), Japón (26%), Rusia (7%) y Corea (5%) (Cruz-Jiménez y García-Sánchez, 2014). Esta información es clave, porque el agronegocio de producción de ganado en pie de México y el de transformación del norteamericano, promueven dinámicas perversas en términos socioecológicos que actualmente se visualizan entre el norte y sur del país. En el norte predomina la engorda de bovinos con métodos tecnificados, y en el sur gran parte del ganado se lleva a media ceba; allí los productores asumen los riesgos asociados al nacimiento de los bovinos (alta tasa de mortalidad y pérdida de peso) en condiciones climáticas adversas. A ello se suma, por un lado, la ausencia de cadenas comerciales competitivas que den valor agregado y aumenten el potencial de incidencia del consumidor al poder elegir productos de menor impacto ambiental; y por otro, el exceso de intermediarios que retienen un porcentaje de la ganancia (Calderón *et al.*, 2012; INEGI, 2017) y que plantean desafíos multisectoriales.

3. La encrucijada entre lo personal y lo político

En este punto y sin afán de restarle importancia al deber y poder político (intervenciones institucionales), no es irrelevante que se siga ignorando el papel protagónico que tenemos como usuarios, que consciente o inconscientemente decidimos lo que consumimos, y con ello demandamos más productos y presionamos los recursos de países distantes que tienen particularidades sociales complejas. Lo personal de la ganadería (intervenciones sociales) también puede ser visto a través de la responsabilidad de usar la información disponible, elegir y exigir a los gobiernos que estén en sintonía con el cuidado del ambiente y reemplazarlos cuando no lo estén, además de consumir sin comprometer los recursos de las futuras generaciones. Mucho más importante en términos de las soluciones, no hay que olvidar que los humanos somos seres de costumbres, y esa característica particular hace que tengamos la capacidad de cambiar hábitos y de cambiar nuevamente cuando haga falta, recordando siempre que el cambio es la única constante digna de mantener. Entonces, para profundizar en el abordaje de la ganadería como un asunto tan personal como político, es necesario advertir que, aunque se puedan teóricamente desagregar estrategias, en la realidad no existe una barrera divisoria entre los dos enfoques pues somos seres esencialmente políticos. El consumo de productos cárnicos y lácteos, y en general de cualquier alimento, en primera instancia es un asunto muy personal. No se trata solamente de necesidad, también representa sentimientos como familiaridad y relajación; comemos en diferentes tipos de situaciones y tenemos múltiples preferencias. La satisfacción personal refleja las decisiones éticas, es decir, cada uno de nosotros decide qué comer (Stiftung, 2014), aunque esas decisiones también están respaldadas por lo que podemos comprar y por la información que tenemos del producto.

El ser humano desde distintos contextos culturales e históricos tiene una relación especial con la carne como alimento, mucho más que con otros productos de las dietas cotidianas. En casi todas las culturas del mundo, la carne más allá de tener un significado como alimento, forma parte de los imaginarios culturales sobre bienestar, es sinónimo de abundancia y ausencia de hambrunas; y constituye un ingrediente clave en las tradiciones culinarias que convocan a la mesa como un acto familiar, social y cultural. Esto se refleja incluso en la abstención del consumo de algunas o de todas las carnes, que durante siglos ha sido una práctica promovida por convicciones éticas y religiosas en la mayoría de las religiones del mundo y en muchas culturas (Stiftung, 2014). Es decir, comemos impulsados por lo que somos, por lo que creemos y por lo que dicta nuestro poder adquisitivo.

Es en este punto donde aparece la naturaleza política del fondo de la decisiones personales, y con ella muchas otras preguntas complejas de resolver (Stiftung, 2014): ¿Quiénes pueden acceder?, ¿Quiénes y en donde se puede y/o debe producir?, ¿Cómo puede el consumidor promedio comprender el impacto global causado por el consumo individual de carne?, ¿Cuánta gente entiende que la demanda de carne en Europa y China es directamente responsable de la deforestación del Amazonas?, ¿Quién está consciente de las consecuencias que la producción industrial de ganado tiene en temas como la pobreza, el hambre, el desplazamiento forzado, el bienestar animal, el cambio climático y la biodiversidad? En investigación, el tema de la política en torno a la ganadería ha sido abordado y se ha reconocido que las políticas, la regulación y las asociaciones público-privadas eficaces son necesarias para garantizar una mejor armonización de los objetivos entre los distintos actores del sector pecuario, a fin de lograr el bienestar humano sin comprometer la integridad de los ecosistemas (Herrero *et al*., 2017). A pesar de esta claridad, la política global (intervenciones institucionales) no se ha comprometido más allá de los acuerdos planteados en el papel, y con la falta de acción a escala planetaria, se ha desencadenado confusión e inacción a través de otras escalas espaciales y temporales. Sin duda, las políticas vistas transversalmente a diferentes niveles tienen un papel fundamental que desempeñar para asegurar que existan incentivos y regulaciones que promuevan el fortalecimiento del sector pecuario a un menor costo ambiental.

La mayor parte del trabajo en esta materia se ha realizado sobre las políticas de oferta, con un enfoque en los impuestos y subsidios, y su papel potencial en la reducción de los cambios en el uso de suelo y las emisiones (Herrero *et al*., 2015). Sin embargo, se necesitan intervenciones de política desde la demanda, tanto en economías prósperas como en economías emergentes, que apoyen el consumo sostenible de productos pecuarios producidos bajo una lógica de responsabilidad ambiental. Aunque los cambios en la dieta tienen un gran potencial teórico para mitigar los impactos ambientales (Stehfest *et al*., 2009; Hedenus *et al*., 2014; Green *et al*., 2015), la mayoría de los análisis en el tema se han basado en cambios hipotéticos en la forma de alimentarse, con poca consideración de las preferencias de los consumidores que tienden a ser conservadoras en todos los estudios (Herrero *et al*., 2015). Se sabe poco sobre la eficacia de políticas para promover y garantizar el establecimiento de sistemas de producción alternativos, y para orientar las dietas hacía alimentos producidos con menor impacto; la investigación en cambios dietarios ha sido direccionada principalmente desde un enfoque de salud (Thow *et al*., 2014; WHO, 2015), haciendo necesario considerar estrategias que incluyan las decisiones personales como parte del cambio. Por estas razones, aquí exploramos dos alternativas: una asociada a la producción con menor impacto ambiental (sistemas silvopastoriles) y otra con la disminución en el consumo (cambio en la dieta), con el fin de ejemplificar que el éxito de ambas iniciativas tiene un carácter tan personal como político.

3.1 Posibles estrategias para disminuir el costo ambiental de la ganadería

Existe un diálogo global que enfrenta el dilema de mantener e incluso aumentar la producción de alimentos sin destruir el medio ambiente; los sistemas de ganadería extensiva usan grandes áreas despejadas donde sólo se cultivan plantas herbáceas como forraje, junto con infraestructura para alojar a los animales o materiales relacionados con la producción (Steinfeld *et al*., 2006; Bacab *et al*., 2013). Los efectos de esta actividad incluyen remoción de árboles y arbustos (deforestación), introducción de plantas no nativas que comprenden una o un número pequeño de especies. Estos sistemas, implementan pastoreo libre en su mayor extensión y son totalmente dependientes de la disponibilidad de pastos para su alimentación y del cultivo de concentrados basados en granos. A pesar de su gran extensión, sólo el 9% de la producción mundial de carne de bovino y el 30% de la carne de ovino y caprino procede de estos sistemas (Herrero *et al*., 2010), datos que evidencian su baja eficiencia en términos de superficie y recursos utilizados.

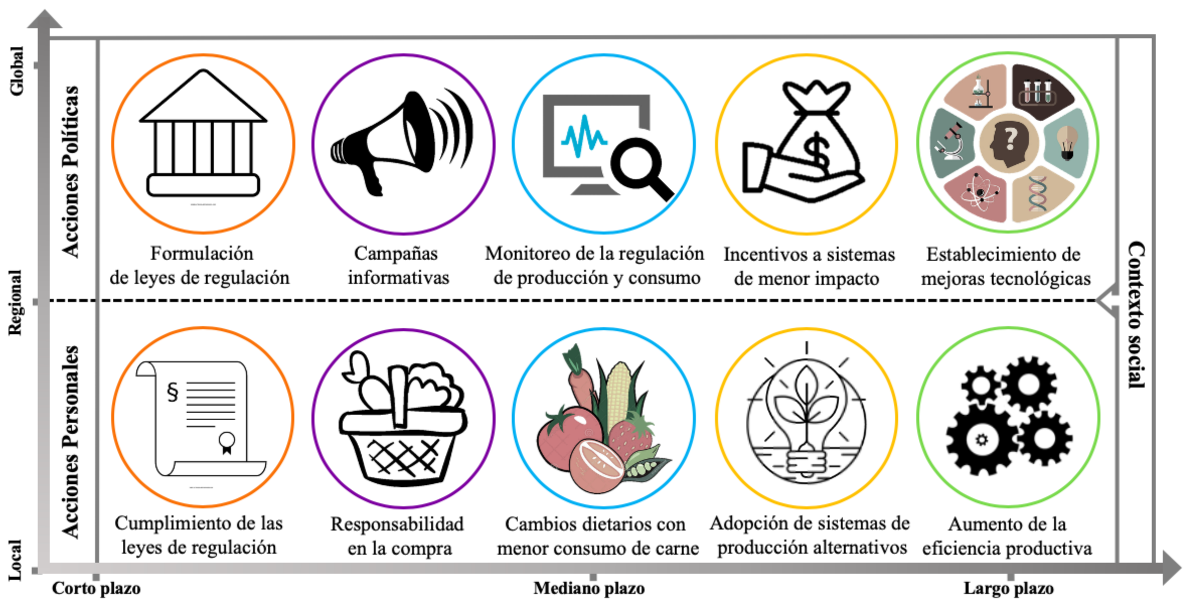
En contraste, los sistemas silvopastoriles (SSP) son sistemas de producción animal que integran paisajes ganaderos multifuncionales basados en la interacción de plantas leñosas perennes (árboles o arbustos), leguminosas herbáceas y pastos en diferentes arreglos y estratos para la alimentación y el bienestar del ganado bovino, que aumentan la producción por unidad de recursos utilizados y proporcionan forraje nutritivo y fijación de nitrógeno atmosférico (Murgueitio *et al*., 2014). Los SSP presentan gran capacidad de reducir las emisiones de GEI, especialmente de metano, fomentan la reforestación y reducen la dependencia del uso excesivo de granos y fertilizantes nitrogenados. Estos sistemas de producción ponen en tela de juicio la incompatibilidad de las pasturas y los árboles, idea que ha estado arraigada desde la revolución verde en la ganadería tropical y ha provocado deforestación de bosques y selvas para el establecimiento de pastizales extensivos (Calle *et al*., 2013). La aplicabilidad de los SSP puede hacerse a los pequeños productores usando una variedad de tecnologías, bancos forrajeros y cercos vivos que cuestan la mitad de la infraestructura de los sistemas estabulados, y mucho menos que adquirir grandes extensiones de tierra para producir de forma extensiva; sin mencionar que en ellos se puede aumentar en un 250% la carga animal, los rendimientos e ingresos de productores (Murgueitio *et al*., 2011).

Aunque el silvopastoreo es prometedor en términos de la sostenibilidad, el éxito de su implementación depende de la voluntad política-institucional para fortalecer las capacidades de los productores, ofreciendo incentivos económicos y técnicos, y fortaleciendo circuitos de comercialización que aumenten el valor del producto, mejoren los medios de vida del productor y sus familias y amplíen las opciones de compra para el consumidor. Además, se necesita de la decisión del productor para adoptar el sistema, lo que implica producir de forma diferente garantizando las ventajas ambientales esperadas; y del poder del usuario (consumidor) en exigir productos de mejor calidad, producidos con mínimo impacto ambiental y a precios justos para todas las partes involucradas. En cuanto a los cambios en la dieta, existe una fuerte relación entre la riqueza y el consumo de productos pecuarios, esto ha hecho que muchos den por sentado que el aumento de la demanda de alimentos estará impulsado por la creciente prosperidad de los países en desarrollo (Herrero *et al*., 2018). Pero ¿Qué pasaría si la riqueza y el consumo de productos pecuarios pudieran disociarse?, ¿Qué pasaría si la población mundial comiera menos carne por decisión personal? Aunque hay pruebas que cuantifican el potencial teórico de mitigación del cambio climático derivado de las modificaciones en la demanda, con un fuerte énfasis en la reducción del consumo de carne, se ha investigado mucho menos cómo lograr los cambios necesarios para disminuir en términos reales el consumo (Springmann *et al*., 2018).

La decisión de producir y consumir productos pecuarios siempre está potenciada desde lo personal, tanto de los políticos que toman decisiones éticas cuando plantean las agendas agrícolas de los países, como de los productores y consumidores. Las soluciones deben ser construidas combinando acciones personales-políticas, y deben combatir los retos de la implementación: garantizar beneficios socioeconómicos y ecológicos. Dentro de las alternativas se han mencionado restringir o minimizar el consumo de carne, incentivar modos de producción de menor impacto a través de medidas fiscales (Garnett *et al.,* 2015) e innovaciones tecnológicas (*e.g.,* cercados virtuales y superalimentación como algas o gramíneas con alto contenido en aceites), (Campbell *et al.,* 2018; CSIRO, 2018), cambiar la gobernanza de la producción y el comercio (Garnett *et al.,* 2015), promover colaboraciones y acuerdos compartidos entre naciones e industrias, cambiar normas de producción, informar y sensibilizar a la sociedad a través de campañas de consumo responsable (Herrero *et al.*, 2018); acciones que en conjunto tienen el potencial de dar forma a una ganadería sostenible (Figura 2).

Con el paso del tiempo, es cada vez más claro que no basta una única acción, por el contrario, se necesita un enfoque integrador que comprenda un marco regulatorio y fiscal sólido, y un entorno propicio para las actividades y colaboraciones voluntarias de la industria en combinación con la sensibilización y la educación de la sociedad (Herrero *et al.*, 2018). A pesar de la pertinencia de un enfoque holístico, existen retos de implementación especialmente en un sector con tantos intereses involucrados como lo es el ganadero. Otro reto reposa sobre el manejo de las acciones personales y políticas que están inmersas y mezcladas en distintas escalas espaciales y temporales, por lo que el alcance de cada acción depende potencialmente de un contexto social variante, construido por el conjunto de valores morales y retroalimentado por el interés económico de cada actor involucrado. A la luz de esta discusión, es evidente que la ganadería es un asunto tan personal como político, y que su abordaje requiere la combinación de estrategias diseñadas a través de las distintas escalas en las que operarán. Algunas acciones desde el ámbito personal (tanto del productor como del consumidor) surgen a escalas locales y pueden ser ejecutadas en un corto plazo (*e.g.*, cumplimiento de las leyes de regulación y responsabilidad en la compra). Otras que se consolidan tras una decisión personal, requieren información, monitoreo e inversiones institucionales planeadas a escalas regionales, y se concretan a mediano plazo (*e.g.*, cambios dietarios, adopción de sistemas de producción alternativos, disminución en los desperdicios asociados a la transformación y consumo de ganado). En contraste, las acciones políticas suelen originarse a escalas regionales (*e.g.*, formulación de leyes de regulación y campañas informativas), y globales (*e.g.*, incentivos a sistemas de menor impacto, desarrollo y establecimiento de cambios tecnológicos), son implementadas en el largo plazo y pueden detonar bienestar socioecológico (Figura 2). Independientemente del lugar y el tiempo en el que históricamente ocurren, dichas iniciativas tienen el potencial de impactar a mayores escalas espaciales y de ser establecidas en menor tiempo, dependiendo en casi todos los casos de la voluntad personal-política. Lograr disminuir el impacto ambiental y al mismo tiempo hacer frente a la revolución ganadera es imperativo y requerirá cambios transformativos.

Figura 2. Acciones personales y políticas a través de escalas espacio-temporales. La implementación de las acciones está determinada por contextos sociales particulares, la línea punteada refuerza la idea de la combinación de medidas para producir y consumir productos ganaderos a un menor costo ambiental, y la permeabilidad entre las esferas personales y políticas. Las acciones en círculos del mismo color están directamente relacionadas.



4. Oportunidades y retos para la transformación de la ganadería tropical mexicana

En las regiones tropicales predominan los sistemas ganaderos de doble propósito, extensivos o semi-extensivos, basados en monocultivos de pastos reconocidos por su baja productividad e impactos negativos al ambiente (Bacab *et al*., 2013). El trópico posee fuertes limitantes que impiden incrementar la productividad de la ganadería, dentro de ellas serios problemas de alimentación animal (disponibilidad y calidad del forraje), presencia de pasturas degradadas o en proceso de degradación, escasez de agua y variabilidad topográfica y climática (Bacab *et al*., 2013; Solorio *et al*., 2017). La producción bovina en el trópico mexicano, usa pastoreo en sistemas extensivos en los que se desarrolla ganado bovino lechero, cárnico, doble propósito (carne y leche) y triple propósito (leche, carne y fuerza de trabajo), constituido por más de 30 razas o cruzas de bovinos para la producción. El clima de cada región en el país determina la gestión y el propósito del hato (DISEMINA, 2011), y a pesar de los desafíos ambientales y socioeconómicos, en algunas zonas del trópico mexicano se está transitando hacia prácticas ganaderas orientadas a la intensificación, usando de manera más eficiente los insumos, con suplementación en condiciones de pastoreo o terminación por períodos cortos de tiempo en confinamiento, rotación continua, e inclusión de gramíneas y arbustos en SSP (Zorrilla-Ríos *et al*., 2013; Fuentealba y González-Esquivel, 2016; Rivera-Huerta *et al*., 2019), a los cuales se les atribuye un aumento en la productividad, eficiencia biológica y económica del ganado y mitigación de emisiones de metano (Ibrahim *et al*., 2010; Solorio *et al*., 2017).

Aunque los sistemas extensivos de bovinos en México pueden mejorar su eficiencia al mejorar la calidad de los pastos en la etapa de pastoreo, esta producción podría tener mayor impacto en el cambio climático, menor eficiencia en la producción, mayor uso de la tierra; y en el futuro podría no ser aplicable como la principal forma de producción en México (Rivera-Huerta *et al*., 2016). La ganadería en el trópico de México debe incorporar estrategias de mejoras genéticas, inserción de especies leguminosas, guiar la suplementación hacia dietas más nutritiva y fortalecer circuitos de comercialización competitivos; acciones que se consideran primordiales para la planificación sostenible de la ganadería tropical en AL (Rao *et al*., 2015; Rudel *et al*., 2015). Otro reto implícito es diseñar programas de política distintos a los existentes en el país (*e.g.*, PROGAN y Crédito a la Palabra), que están orientados al repoblamiento y la mejora en infraestructura relacionada con la producción extensiva, y no promueven explícitamente estrategias de reforestación, conservación de ecosistemas y mantenimiento de servicios ecosistémicos. Las condiciones biofísicas combinadas con los desafíos económicos, falta de programas gubernamentales que orienten la ganadería hacia sistemas eficientes de menor impacto ambiental, han llevado al subdesarrollo del sector en la mayoría de los países tropicales, especialmente los de economías emergentes como México (Rao *et al*., 2015). Por lo tanto, la comprensión de las características ecológicas y socioeconómicas de los sistemas de producción pecuaria es fundamental para la creación de instrumentos de política, planificación y monitoreo que detonen un cambio hacia la sostenibilidad (Rivera-Huerta *et al*., 2019). Las políticas pecuarias en México deberán estar en sintonía con la evidencia global y nacional, es decir, tendrán que promover una transformación de la producción extensiva a través de apoyos económicos, técnicos y comerciales que garanticen la adopción de sistemas viables ambiental, social y económicamente. En este sentido, dichas políticas tendrán que planificar y gestionar a los sistemas ganaderos desde un enfoque de sistémico, y desarrollar una agenda nacional que apoye el desarrollo de sistemas ganaderos sostenibles.

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Conclusiones

La complejidad y el dinamismo social, económico y ambiental de la ganadería bovina hace necesario abordar la planeación sostenible, y en concreto la intensificación sostenible del sector en AL desde un enfoque sistémico. Partiendo de una revisión sistemática de literatura, se identificó que la investigación pecuaria en AL en lo que va del siglo XXI se ha concentrado geográficamente en México, Colombia, Brasil y Argentina, debido principalmente al papel protagónico de estos países en la producción y comercialización de ganado a escala local, regional y global. El marco teórico de los SSE que implica una visión integrada ha sido incluido de manera incipiente (16%) en la investigación ganadera en AL entre el 2000 y el 2020. Rastreamos una desconexión entre el reconocimiento y la medición de la sostenibilidad y los SE. Aunque el 83% y 48% de los estudios mencionaron los conceptos, sólo 4% y 5% de los estudios aplicaron un método para cuantificar la sostenibilidad y los SE, respectivamente. Respecto a las escalas y niveles de análisis reportados, los estudios ganaderos realizados en niveles institucionales de análisis en AL incluyen predominantemente componentes socioeconómicos y factores externos al SES local, e integran cuestiones ambientales, lo que muestra nociones de integración socioecológica. En contraste, los estudios realizados en niveles ecológicos de análisis mantienen un enfoque estrictamente ambiental, y la mayoría de ellos ignoran las dimensiones sociales y económicas que dan forma a los ecosistemas y que son indispensables para mejorar la sostenibilidad. Conocer las escalas espaciales y temporales e incorporar a la ganadería dentro de un análisis holístico sigue siendo un reto para la gestión de bovinos y la elaboración de políticas. En ese sentido, esta investigación contribuye a reducir la brecha existente en la comprensión de las escalas en el contexto ganadero de la región. Además, propone un marco conceptual de SSE para su estudio desde una visión integrada.

El marco conceptual de SSE para la ganadería bovina tropical de AL propuesto resultó de la información que se obtuvo en la revisión sistemática de literatura. El marco incluye los pricipales componentes (ecológicos, sociales y económicos) que la integran, y una zona de interfaz que contiene conceptos de frontera (multifuncionalidad, servicios ecosistémicos y acción colectiva). Los componentes del subsistema ecológico incluyen factores bióticos y abióticos entre los que destacan el suelo, la vegetación y el ganado que se gestionan a escala local mediante estrategias que emergen del SSE del que forman parte, como resultado de decisiones sociales y arraigos culturales, contextos económicos y ecológicos. El subsistema social está compuesto por: 1) Productores, una categoría que incluye a propietarios, administradores y trabajadores de los sistemas de producción, es decir, actores internos no gubernamentales que desempeñan un papel crucial al ser responsables de las estrategias de manejo y de las decisiones de comercialización; 2) Asociaciones ganaderas, a través de las cuales se realizan los acuerdos entre los productores y las comunidades del área espacial de influencia (local y regional) de las asociaciones ganaderas; 3) Reglas, relacionadas con acciones constitucionales, operativas y colectivas, y 4) Instituciones, conformadas por actores gubernamentales que participan y promueven el desarrollo de las actividades productivas, e instituciones de investigación que contribuyen al conocimiento de la ganadería en AL.

El subsistema económico se compone de cuatro elementos: 1) Infraestructura que los productores y asociaciones de ganado utilizan para las actividades agrícolas, entre las que destacan las estructurales (por ejemplo, establos, sistemas de refrigeración, mataderos), maquinaria y equipo, 2) Empleos que se generan; 3) Cadenas de comercialización, que se definen por el tipo de comercialización (directa o indirecta) y están formadas por actores externos no gubernamentales (p. ej., intermediarios, supermercados, carnicerías, productores industriales) y los productos que se venden; y 4) Ingresos, que incluyen los beneficios totales obtenidos por los productores, los ingresos anuales de las asociaciones ganaderas e incluso los precios de los distintos productos. La zona de interfaz propuesta es un espacio socio-ecológico que resulta de la integración de tres elementos (multifuncionalidad, SE y acción colectiva). Debe entenderse dentro del análisis de la ganadería tropical dada la escala temporal de cada estudio, como una medida de desempeño socioecológico preexistente, actual o futuro. Por lo tanto, operacionalizar la interfaz en el análisis integral de la ganadería es relevante para diagnosticar y promover transiciones hacia sistemas de producción de bovinos sostenibles.

El marco conceptual que se propuso ayuda a caracterizar sistemas ganaderos que se basan en el pastoreo de bovinos, identificar impactos socioecológicos y promover estrategias más sostenibles para la ganadería tropical en AL. La operacionalización del marco contempló la caracterización de un SSE focal realizada a través de 350 entrevistas semi-estructuradas a ganaderos de la Red Silvopastoril de Chiapas; y la definición de doce descriptores de sostenibilidad ganadera (socioeconómicos y de SE) asociados a distintos umbrales de avance en intensificación sostenible que fueron construidos en un taller participativo con productores de la Red. Los siete descriptores socioeconómicos incluyeron la densidad de ganado, la frecuencia de rotación, la creación de empleo, la participación familiar, la diversificación, la infraestructura y la comercialización. Los cinco descriptores restantes representan avances en términos de provisión de SE, y estuvieron asociados a la sombra para el ganado, hábitat, forraje cultivado, diversidad de cruzas bovinas y disponibilidad de agua. De esta manera fue posible identificar factores comunes que impiden el desarrollo de las actividades ganaderas y reconocer cuáles pueden generalizarse a otros SSE latinoamericanos. Los desafíos incluyen:

1. La vulnerabilidad a la degradación de los suelos y la pérdida de fertilidad de estos, particularmente exacerbada por las sequías recurrentes en las regiones tropicales.

2. El excesivo número de intermediarios y la necesidad de cadenas de comercialización diferenciadas y competitivas para vender lo producido en los SSP que limitan la transformación del sistema hacia escenarios más sostenibles.

3. La baja diversificación que expone a los productores a ser altamente dependientes al pastoreo de bovinos.

La Red Silvopastoril de Chiapas podría mejorar la sostenibilidad al incluir la creación de procesos organizativos que amplíen el establecimiento de SSP, comercialicen otros productos (por ejemplo, leche, queso, semillas, granos), provean y valoricen otros SE (p. ej., bonos de carbono, frutales y árboles maderables) y reactiven la participación de mujeres y jóvenes en la producción.

Retomando la información que se obtuvo en las entrevistas, se tipificaron los sistemas silvopastoriles de la Red Silvopastoril en una propuesta que contempló el sistema de producción a través de las estrategias de manejo, e incluyó la provisión de SE, las características económicas de los productores y la ubicación geográfica. Identificamos un gradiente de intensificación prestando especial atención al tamaño del rancho y a los niveles de provisión de SE: los ranchos silvopastoriles pequeños y medianos con provisiones intermedias y altas de servicios plantean un escenario más sostenible para la ganadería de uso del suelo. Por el contrario, en los grandes ranchos silvopastoriles la intensificación es baja y se priorizan los SE de provisión, de manera similar a como ocurre en los sistemas extensivos. A través de un modelo de ecuaciones estructurales se evaluó la relación entre los principales componentes ecológicos, sociales y económicos, y se comprobó que comprende una cadena causal de forma que los componentes económicos (características económicas) influyen sobre los componentes sociales (estrategias de manejo) dificultando la intensificación sostenible y causando afectaciones sobre los componentes ecológicos (provisión de SE).

La consolidación de las cadenas de comercialización haciéndolas competitivas para los productores, la diversificación de los ranchos, la mejora de los ingresos, el aumento de la mano de obra con empleos más dignos y la frecuencia de la rotación del ganado son estrategias indispensables que apoyan la provisión de SE y la sostenibilidad en ranchos ganaderos. De igual manera, minimizar el área ganadera y el énfasis productivo que tienen los SE de provisión (producción de bovinos), al tiempo que se incremente la provisión de hábitat, sombra para el ganado, alimento para el ganado y conocimiento tradicional son aspectos que contribuyen directa y positivamente a la sostenibilidad de los ranchos. Esta configuración de estrategias implica reconocer que la producción ganadera tropical debe integrar prácticas agroforestales y contemplar un límite de oferta de carne y forraje para continuar sosteniéndose en el tiempo. La intensificación sostenible es una alternativa para la ganadería extensiva en el trópico siempre que garantice la provisión de todos los SE, contenga la deforestación y se acompañe de mejoras en las condiciones económicas de los productores a niveles que representen más que incentivos de corto plazo, dignificar el trabajo en el campo a través de la combinación de acciones personales e institucionales.

Los resultados obtenidos en los capítulos anteriores se retoma al final de esta tesis al visualizar a la ganadería como un tema personal y político para aportar evidencia teórica sobre las acciones que instituciones gubernamentales y la sociedad en general pueden sumar para promover escenarios más sostenibles en la ganadería de pastoreo del trópico de México. Entre las acciones políticas destaca la formulación de leyes que concreten condiciones justas de compra y venta de ganado para los pequeños y medianos productores que suelen tener poco poder negociador, estrategias que promuevan la diversificación productiva, campañas informativas que visualicen una dieta balanceada con menores consumos de carnes y disminución del desperdicio, y apoyo técnico y financiero a los SSP. Las acciones personales deben disminuir los consumos de carne y leche, producir con menor impacto ambiental, y reclamar acciones políticas encaminadas en la protección del medio ambiente y el mejoramiento de las condiciones sociales y económicas de los productores y sus familias

Los cambios dietarios podrían implica para México el reto de planear una alimentación que contemple, por un lado, menor ingesta de productos ganaderos sin poner en riesgo los requerimientos nutricionales; y por otro lado, la compensación de los ingresos que se dejen de percibir por la disminución en la producción de ganado. En ese sentido, las políticas agrícolas y pecuarias deben garantizar estrategias de diversificación productiva y alternativas de medios de vida para los productores y sus familias. Además, tendrán que sincronizarse con la urgencia de escalar el establecimiento de SSP en áreas despejadas de ganadería extensiva a través de apoyos económicos, técnicos y comerciales que sostengan su adopción y viabilidad en el tiempo. La diversificación en ranchos bovinos es clave para la población rural, ya que los cambios dietarios necesarios y los retos climáticos que enfrentarán con mayor frecuencia e intensidad los trópicos harán que sea poco probable que la producción de carne de vacuno siga siendo la principal fuente de ingresos para muchos campesinos en México.

Limitaciones del trabajo

Las limitaciones del trabajo de investigación contemplan la falta de desagregación espacial de la información a nivel de potrero. Contar con la ubicación espacial de los ranchos y la delimitación de las zonas de pastoreo hubiera permitido la modelación biofísica de una diversidad de SE y sus cambios en el tiempo (trayectorias socioecológicas) a través del análisis geoespacial y percepción remota. A su vez, esta información hubiera permitido incorporar variabilidad espacial en el modelo de ecuaciones estructurales, lo cual mejoraría la aproximación territorial de la influencia de la localización geográfica sobre la sostenibilidad en los ranchos bovinos. La reciente pandemia derivada del virus SARS-CoV-2 sumo retos asociados al aislamiento, implicó la reestructuración de la tesis ya que impidió ir al campo a realizar la georreferenciación y los experimentos que se habían contemplado inicialmente en el proyecto.

Retos a futuro

Transitar de la ganadería extensiva a una ganadería que incluya manejos agroforestales, es una prioridad para la planificación del sector en los trópicos. Los paisajes multifuncionales apoyan la regulación del clima, la provisión de SE y la resiliencia de la comunidad, beneficios críticos para el bienestar humano. En ese sentido, los SSP impulsan paisajes multifuncionales y disminuyen el detrimento ambiental. Sin embargo, se ha demostrado en este proyecto que el establecimiento de SSP será insuficiente sin la mejora de canales de comercialización diferenciados y sin diversificación productiva, dos temas poco explorados en la investigación ganadera y prioritarios para la sostenibilidad de los ranchos. Otra cuestión que se ha probado y que no ha sido formalmente reconocida ni estudiada, es que el aumento de la producción de bovinos en condiciones de pastoreo tropical debe contemplar un límite. Sigue siendo necesario establecer umbrales que incluyan variables de producción, mercado y nutrición, y contemplen dinámicas espacio-temporales en diversos contextos socioecológicos. Respecto a ello, existe una ventana de oportunidad para incorporar metodologías de dinámica de sistemas a través de las cuales se modele el comportamiento temporal de la intensificación sostenible de la ganadería bovina en contextos tropicales.