UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO
POSGRADO EN CIENCIAS DE LA SOSTENIBILIDAD
INSTITUTO DE ECOLOGÍA

CONTRIBUCIONES DE LA NATURALEZA POR AGROECOSISTEMAS DE MAÍZ DE PEQUEÑA ESCALA EN LA REGIÓN DE VALLES ALTOS, MÉXICO

TESIS
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Presente

Me permito informar a usted, que el Comité Académico del Programa de Posgrado en Ciencias de la Sostenibilidad, en su sesión 89 del 14 de marzo del presente año, aprobó el jurado para la presentación del examen para obtener el grado de **DOCTORA EN CIENCIAS DE LA SOSTENIBILIDAD**, de la alumna **Rodríguez Bustos Laura Alicia** con número de cuenta **516016737,** con la tesis titulada "Contribuciones de la naturaleza por agroecosistemas de maíz de pequeña escala en la región de Valles Altos, México", bajo la dirección del Dr. Leopoldo Galicia Sarmiento.

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Sin más por el momento me permito enviarle un cordial saludo.

ATENTAMENTE,

"POR MI RAZA HABLARA EL ESPIRITU"
Cd. Universitaria, Cd. Mx., 25 de agosto de 2023.

Dr. Alonso Aguilar Ibarra
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RESUMEN

La tecnificación de la agricultura forma parte de un proceso histórico global conocido cómo la Revolución Verde (RV). Este período inició alrededor de 1950, consiste en el desarrollo y operación de políticas y actividades dirigidas a aumentar la productividad de los cultivos, principalmente de los granos que alimentan al mundo: maíz, arroz y trigo. Algunas de las actividades desarrolladas bajo la RV son investigación para el mejoramiento de cultivos, diseño de infraestructura agrícola, y el desarrollo de mercados regionales. La operación de la RV se ha logrado a través del financiamiento público por parte de los gobiernos, e inversiones privadas de actores y agencias internacionales interesadas. A nivel global, la RV ha generado disyuntivas debido a la incongruencia entre la forma tradicional de hacer agricultura y la agricultura altamente industrializada, y sus impactos ambientales negativos como la degradación del suelo, contaminación del agua, pérdida de saberes tradicionales y disminución de la agrobiodiversidad. El planteamiento conceptual de este trabajo integra el marco conceptual de Sistemas socio-ecológicos (SSE) y el de Contribuciones de la naturaleza para las personas (CNP), con el objetivo de proponer indicadores de desempeño agrícola que consideren elementos y prácticas del manejo agrícola asociados a la conservación de funciones ecológicas, agrobiodiversidad y patrimonio cultural. Para esto, posicionamos la investigación en un modelo de estudio con agroecosistemas de maíz de pequeña escala con agricultura de temporal, localizadas bajo el mismo contexto geográfico y político.

El trabajo de tesis se presenta en dos capítulos, el primero consiste en la integración de los marcos conceptuales de SSE y CNP a través de una revisión de literatura, y la categorización y descripción en amplio del modelo de estudio como un SSE. Los resultados muestran que es posible relacionar ambos marcos conceptuales y operacionalizar la propuesta a través de un caso de estudio concreto. En este caso, se operacionalizó en los agroecosistemas de maíz de pequeña escala de Valles Altos, México, donde mostró que los agricultores que participaban en el programa MasAgro tomaron decisiones autónomas sobre el manejo, y estas formaron un mosaico muy diverso de prácticas, por lo tanto, los agricultores no pudieron clasificarse categóricamente como un grupo homogéneo. Por otra parte, permitió relacionar los elementos del manejo agrícola, como el tipo de labranza, la variedad de maíz, la semilla, o el tipo de fertilización, con algunas contribuciones de la naturaleza. Concluimos que, incluir una visión integral como la de SSE y CNP es una oportunidad para vincular el manejo agrícola con indicadores de bienestar social, como la seguridad alimentaria, el patrimonio biocultural y la conservación de los ecosistemas.

El segundo capítulo presenta el análisis de los agroecosistemas a través de una tipología de manejo y su interpretación sobre la presencia de CNP en cada tipo de manejo. Los resultados indican que en Valles Altos hay tres tipos de manejo agrícola definidos principalmente por el tipo de semilla, el destino de la cosecha y el tipo de labranza. Cada tipo de manejo tiene una contribución única de regulación, material y aportes no materiales, definidos por el uso de semilla nativa, uso de rastrojo y diversificación de manejo. Concluimos que, es fundamental establecer nuevos incentivos que incluyan la diversidad biológica y cultural de los agroecosistemas y las motivaciones individuales de los agricultores. Esto puede ayudar a conservar los valores naturales y culturales de la agricultura y diseñar incentivos apropiados para la agricultura a pequeña escala.

ABSTRACT

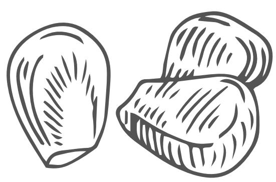
The modernization of agriculture is part of a global historical process known as the Green Revolution (GR). This period began around 1950 and consists of the development and operation of policies and activities aimed at increasing the productivity of crops, mainly the grains that feed the world: corn, rice, and wheat. Some of the activities developed under the RV are research for crop improvement, the design of agricultural infrastructure, and the development of regional markets. The operation of the RV is achieved through public financing by governments and private investments by interested international actors and agencies. GR has generated dilemmas at a global level due to the inconsistency between the traditional way of doing agriculture and highly industrialized agriculture, and its negative environmental impacts include soil degradation, water pollution, loss of traditional knowledge, and a decrease in agrobiodiversity. The conceptual approach of this work integrates the conceptual framework of Socio-ecological Systems (SSE) and that of Contributions of Nature to People (CNP), to propose indicators of agricultural performance that consider elements and practices associated with agricultural management. to the conservation of ecological functions, agrobiodiversity, and cultural heritage. We position the research in a study model with small-scale maize agroecosystems with rainfed agriculture in the same geographic and political context.

The thesis work is presented in two chapters; the first consists of integrating the conceptual frameworks of SSE and CNP through a literature review and the broad categorization and description of the study model as an SSE. The results show that it is possible to relate both conceptual frameworks and operationalize the proposal through a specific case study. In this case, it was operationalized in the small-scale maize agroecosystems of Valles Altos, Mexico, where it showed that farmers participating in the MasAgro program made autonomous management decisions, and these formed a

very diverse mosaic of practices, therefore Thus, farmers could not be categorically classified as a homogeneous group. On the other hand, it allowed us to relate the elements of agricultural management, such as the type of tillage, the variety of corn, the seed, or the type of fertilization, with some contributions from nature. We conclude that including a comprehensive vision such as that of SSE and CNP is an opportunity to link agricultural management with indicators of social well-being, such as food security, biocultural heritage, and ecosystem conservation.

The second chapter presents the analysis of agroecosystems through a management typology and its interpretation of the presence of CNP in each type of management. The results indicate that in Valles Altos, three types of agricultural management are defined mainly by the type of seed, the destination of the harvest, and the type of tillage. Each type of management has a unique contribution of regulation, material, and non-material contributions, defined by the use of native seed, stubble, and management diversification. We conclude that it is essential to establish new incentives that include the biological and cultural diversity of agroecosystems and the individual motivations of farmers. This can help conserve agriculture's natural and cultural values and design appropriate incentives for small-scale farming.

INTRODUCCIÓN GENERAL



1. INTRODUCCIÓN GENERAL

1.1 Marco teórico

Agricultura y el marco conceptual de Sistemas socio-ecológicos

La expansión agrícola ha transformado y fragmentado los bosques y selvas tropicales de manera drástica (Deakin et al. 2016). Cómo resultado de este proceso, las regiones tropicales se han configurado como un mosaico diverso con extensas coberturas arboladas, asentamientos humanos, y unidades agrícolas y ganaderas (Deakin et al. 2016; Perfecto et al. 2009). Debido a esto, la provisión de servicios ecosistémicos y la conservación de la biodiversidad están estrechamente relacionadas con el manejo de los ecosistemas (Perfecto et al. 2009). Los agroecosistemas varían entre culturas y paisajes porque los conductores biofísicos, institucionales, sociales y económicos originan diferentes contextos; de modo que el efecto del manejo agrícola sobre los componentes sociales y ecológicos del sistema es distinto entre formas de producción (Álvarez et al, 2014). La importancia de los agroecosistemas radica en que son el fundamento de los sistemas alimentarios, desde los esquemas industriales con un manejo intensivo y propósitos comerciales, hasta los de pequeña escala, con un manejo menos intensivo y propósitos de autosuficiencia; por lo tanto, es en estos sitios que ocurren los procesos necesarios para asegurar el éxito de la producción de alimento (Hurni et al, 2015).

Establecer modelos de producción agrícola sustentables es uno de los mayores retos que enfrenta la humanidad (Tilman 2011). La agricultura es el mayor conductor de deforestación y pérdida de hábitat en el mundo, principalmente por la expansión de esta actividad, pero también por su intensificación (Tilman et al., 2011; Boomarco et al., 2018; Maxwell et al., 2016). La intensificación aumentó el rendimiento de los cultivos que alimentan al mundo, maíz, trigo y arroz, cultivos que ahora están adaptados a regímenes de manejo intensificados, con agroecosistemas poco fértiles, y fuente de contaminación de cuerpos de agua y emisores de CO_2 (Norton, 2016; Robertson y Swinton, 2005; Chavaz, 2017; Cassman et al, 2003; Sweeney et al, 2013). Los agricultores realizaron algunas prácticas de manejo intensificadas para aumentar la productividad; sin embargo, fueron forzados a gastar cada vez más dinero en fertilizantes y herbicidas químicos para contrarrestar los efectos negativos que el monocultivo y la aplicación de fertilizantes tuvieron sobre sus tierras (Acevedo 201; Sebby 2010). Los efectos negativos a los cuales quedaron expuestos los agricultores, son suelos degradados, pérdida de biodiversidad y dependencia a insumos de producción (Acevedo 2011). Los agricultores son los tomadores de decisiones más importantes para lograr una agricultura sustentable, especialmente cuando tienen la capacidad de decidir sobre el tipo de cultivos, insumos, balance comercial, y canales de comercialización del alimento. De modo que, considerarlos en el diseño de la política agrícola, es una vía para propiciar escenarios de ganar-ganar entre los sectores involucrados (Ickowitz et al. 2019).

Las disyuntivas entre los beneficios económicos y las consecuencias ambientales de la agricultura industrializada se reconocieron tardíamente, pero la problemática ahora es reconocida en la política pública internacional, y los programas de gobierno buscan incorporar directrices para la sustentabilidad en los agroecosistemas. La justificación de la Revolución Verde fue alimentar al mundo. Sin embargo, las políticas de intensificación se tornaron obsoletas al considerar que actualmente hay 800 millones de personas que no consumen la comida mínima necesaria; 2 billones de personas sufren de desnutrición y 2 billones tienen obesidad (IFPRI, 2014). Ante estos problemas emerge la siguiente pregunta ¿el aumento del rendimiento agrícola atendió los problemas de seguridad alimentaria a nivel mundial? Se sabe que ahora hay menos gente con hambre, pero la calidad nutricional de las dietas no mejoró y los efectos ambientales son irreversibles (Liao and Brown 2018; Pinstrup-Andersen, 2013; Ickowitz et al, 2019). La industrialización mejoró el diseño de la producción en agroecosistemas de gran escala; sin embargo, empeoró las condiciones laborales y el acceso a insumos de producción en el caso de los pequeños productores (Hurni et al, 2015). En el ámbito social, las formas de hacer agricultura se estandarizaron y los sistemas agrícolas adoptaron métodos cada vez más similares para cultivar variedades mejoradas con fertilizantes químicos, pesticidas y maquinaria; este cambió en los paradigmas de producción transformó sustancialmente todos los componentes socio-ecológicos en los agroecosistemas del mundo (Ickowitz et al, 2019; Pretty and Bharucha, 2014).

Los sistemas socio-ecológicos (SSE) son una postura teórica ampliamente aceptada para estudiar las relaciones y la dinámica entre actores sociales (individuales y colectivos; las políticas y las instituciones) y los ecosistemas (naturales y manejados) (Zurlini et al. 2008; Turner et al. 2003; Turner et al. 2007) (Figura 1). Este marco se desarrolló a partir de la teoría de la complejidad y se concentra en identificar componentes, su estructura organizativa e interacciones; para comprender el efecto que algunos cambios, dentro o fuera del sistema, pudieran tener sobre las estructuras socio-ecológicas, interacciones y dinámica (Turner et al. 2003; Turner et al. 2007; Liu et al. 2007; Arnaiz-Schmitz et al. 2018; Zurlini et al. 2008). Específicamente en los agroecosistemas la construcción de un SSE cubre tres objetivos principales: (i) preservar el patrimonio cultural de los paisajes y el conocimiento tradicional de los usuarios. La pérdida de conocimiento tradicional de los agricultores representa un deterioro al patrimonio cultural mundial y se requiere información más detallada acerca de las actividades humanas, especialmente de las técnicas agrícolas no documentadas. (ii) Comprender las trayectorias históricas de los procesos de cambio en el paisaje. El análisis histórico de un sitio provee información acerca de las actividades humanas y de procesos de cambio, por lo que reconocer el efecto de la intensificación de las actividades humanas sobre los ecosistemas es importante para desarrollar técnicas de manejo agrícola más sustentable. (iii) Proporcionar información para el futuro manejo. Evaluar los impactos potenciales y las consecuencias del manejo es imprescindible, además de identificar áreas aptas para conservación; y proponer estrategias de rehabilitación (Bürgi and Gimmi, 2007). La principal fortaleza de estudiar los sistemas agrícolas como SSE es que permite analizar relaciones entre ambiente y sociedad a través de la estructura y dinámica de los sistemas de producción agrícola en contextos sociales específicos. Además, permite establecer relaciones entre propiedad de la tierra, actividades económicas y flujo de materiales y energía en la producción (Cunfer and Kraussan, 2009).

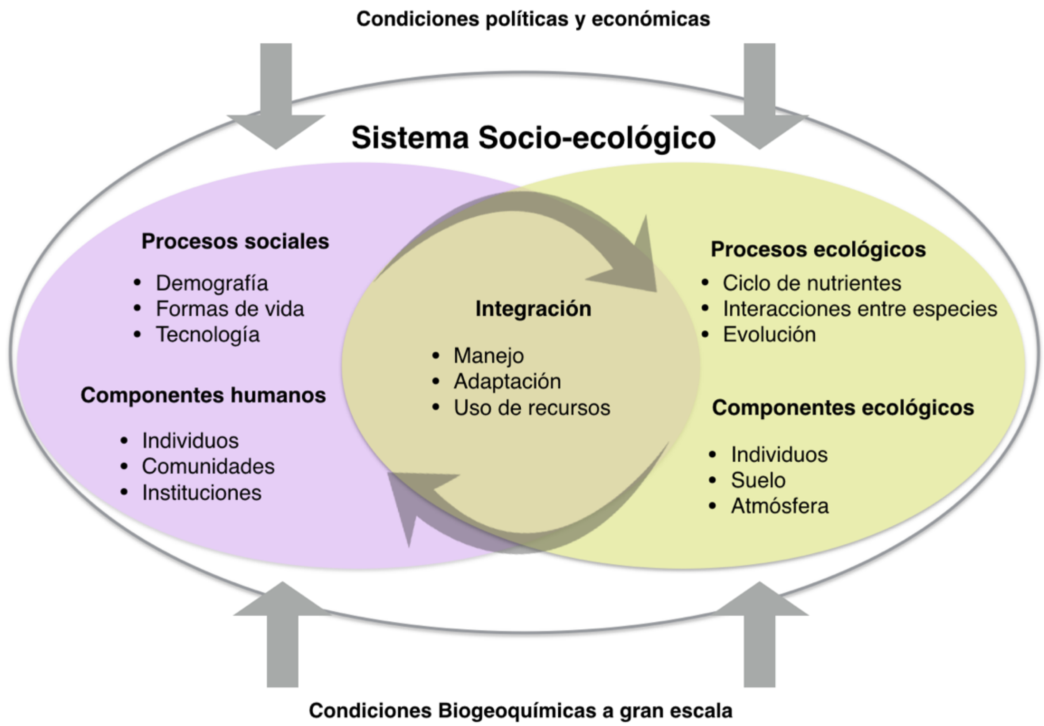


Figura 1. Esquema gráfico de un SSE con elementos del ámbito social y ecológico, la integración se logra a través de procesos relacionados con el manejo de recursos comunitario, diseño de estrategias de adaptación o el plan de manejo de recursos naturales de uso común (modificado de Virapongse et al. 2016).

El estudio de los sistemas agrícolas bajo el enfoque de SSE puede ayudar a identificar límites ecosistémicos y sociales de la producción de alimento, reconocer el contexto ambiental, los actores involucrados, las decisiones del manejo relacionadas con provisión de alimento y hacer explícita la necesidad de mantener las contribuciones y servicios (Tomich et al, 2011; Cassman, 2003; Holt et al, 2016). Acevedo (2011) señala que la oportunidad está en el diseño de modelos de investigación a escala local, monitoreo, investigación a largo plazo donde el alimento sea uno, y no el único servicio ecosistémico considerado. El principal reto para lograrlo es metodológico, porque involucra instrumentos de diferentes disciplinas, modelos explicativos, sesgos y distinto valor social e institucional delimitado por los intereses particulares de la ciencias ambientales y sociales (Rockstrom et al. 2009).

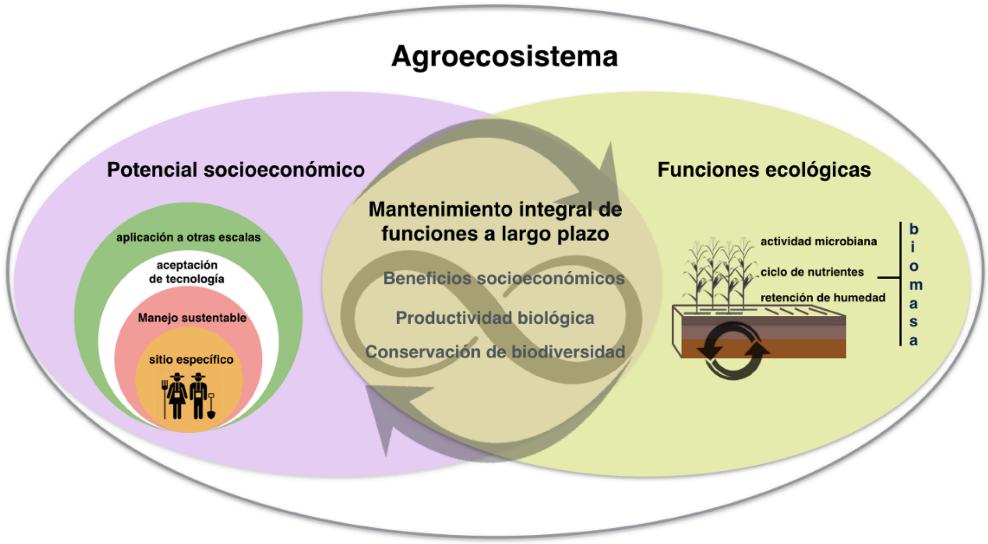


Figura 2. Agroecosistema visualizado como un sistema socio-ecológico. Elaboración propia basado en Ickowitz et al. 2019

Contribuciones de la naturaleza a las personas

Las contribuciones de la naturaleza a las personas (NCP por sus siglas en inglés) son todas las contribuciones positivas o negativas de la naturaleza hacia los seres humanos que pueden tener un impacto importante sobre su calidad de vida (IPBES 2019; Díaz et al. 2018). Algunas contribuciones positivas incluyen la purificación de agua y la provisión de alimento, mientras que las negativas, se conocen como deservicios e incluye situaciones como la transmisión de enfermedades. La connotación positiva o negativa dependerá del discurso político, cultural y de la agenda en metas de sustentabilidad (Díaz et al 2018). El marco conceptual de NCP (Díaz et al. 2015) se fundamenta y tiene similitudes con el de servicios ecosistémicos (Daily and Matson 2008; Potschin and Haines-Young 2011). La diferencia radica en que el marco conceptual de NCP se enfoca en el rol central de la cultura sobre la definición de las contribuciones en la naturaleza, en las relaciones humanas y en el conocimiento de los sistemas socio-ecológicos. Asimismo, considera la provisión real y potencial de las contribuciones bajo un planteamiento de coproducción. Mientras que la investigación basada en servicios ecosistémicos se concentraba en funciones ecológicas que proveen beneficios sin considerar el papel de las personas sobre la provisión; es decir la coproducción de beneficios.

La clasificación actual incluye 18 diferentes contribuciones de la naturaleza (IPBES 2019; Díaz 2018) y propone que una sola contribución puede aportar a la calidad de vida en diferentes aspectos (Tabla 1). Por ejemplo, la provisión de alimento contribuye sobre los recursos materiales para sobrevivir y también al patrimonio cultural y relaciones sociales de los productores (IPBES 2019). Las contribuciones son un enlace entre la naturaleza y la calidad de vida de las personas, (Hough et al. 2018; IPBES 2019) por eso es importante distinguir entre potenciales y reales. Las NCP potenciales se refieren a la capacidad de un ecosistema para proveer contribuciones y las NCP reales dependen de las capacidades ecosistémicas y humanas para su provisión y aporte al bienestar humano (IPBES 2019). Por ejemplo, un agroecosistema puede tener la base ecológica para proveer alimento; esto incluye clima favorable, suelos fértiles, dinámica de nutrientes, circulación de agua y soportar el crecimiento vegetal de los cultivos; sin embargo, los insumos humanos, como fertilizantes, cosecha o control de plagas cumplen el objetivo de proveer alimento, de otra forma esto no se realizaría.

Tabla 1. Contribuciones de la naturaleza relacionadas con agroecosistemas. Las contribuciones fueron tomadas de la clasificación de IPBES 2019, las NCP potenciales, reales y el impacto sobre el bienestar social son definiciones propuestas para le evaluación de la NCP.

Contribución de la naturaleza	***NCP potencial***	***NCP realizada***	***Impacto sobre el bienestar social***
Creación y mantenimiento de hábitat	Extensión de todos los ecosistemas naturales	Extensión del hábitat	Menor inversión en planes de restauración ambiental
Formación protección y descontaminación de suelos	suelo con carbono orgánico	agroecosistemas fértiles con crecimiento de cultivos	Mantenimiento de producción y rendimiento a largo plazo
Alimento y combustible	Agroecosistemas productivos	Cantidad y calidad de alimento producido	Disminución de hambre y malnutrición

Recursos genéticos	Diversidad genética del maíz	Variedades de maíz cultivadas	Conservación de biodiversidad
Patrimonio e identidad cultural	Estabilidad de prácticas agrícolas	Valor e identidad del estilo de vida rural	Seguridad cultural, satisfacción, salud mental

El aumento exponencial de la producción de alimento en los agroecosistemas declinó significativamente la provisión de contribuciones (Chavarría et al. 2018; Kremen y Miles 2012; Lal 2016). La agricultura industrial se ha enfocado en la productividad y adición de insumos en lugar de integrar el manejo de recursos naturales a la producción de alimento (Chavarría et al. 2018; Boomarco et al. 2018; Tilman et al. 2011). Los principales efectos son, pérdida de fertilidad del suelo, control biológico de plagas y polinización; el ciclo de nutrientes se sustituyó por la adición de fertilizantes químicos, las variedades nativas de semillas se cambiaron por híbridas y genéticamente modificadas, y el almacenamiento y manejo de agua se sustituyó por la explotación de cuerpos de agua. Debido a los niveles actuales de degradación ambiental es necesario desarrollar un modelo agrícola alternativo, que favorezca a la biodiversidad y sea socialmente justo (Kopttke et al. 2019; Chavarría et al. 2018). Un marco analítico que lo permita debería incluir el valor sociocultural de las prácticas de manejo y operar junto a la política pública. De esta forma se promovería comunicación, manejo y protección de los bienes sociales y ecológicos (Wang et al. 2018; Chavarría et al 2018).

Huogh et al. (2018) señalan que los estudios más comunes de contribuciones de la naturaleza se concentran en identificar, mapear, comunicar y conceptualizar la gama de servicios asociados a un sistema particular, pero un reto no resuelto es reconocer cuáles cambios en los componentes de un SSE afectaría la provisión de contribuciones. Se considera que los agroecosistemas pueden ayudar a identificar estos límites ecosistémicos y sociales porque reconocen el contexto ambiental, los actores involucrados y decisiones del manejo relacionadas con la provisión de alimento (Tomich et al, 2011; Cassman, 2003; Holt et al, 2016). Las contribuciones asociadas a biodiversidad y hábitat cobran relevancia al considerar que de estos mismos depende la disponibilidad local de recursos que aseguran el éxito de la producción agrícola (Boomarco et al., 2018). Las aproximaciones metodológicas para abordar este tipo de problemáticas e interpretar el papel de los agroecosistemas como proveedores de contribuciones y servicios ecosistémicos tiene defectos y no hay acuerdos preestablecidos al respecto (Constanza et al. 1997; de Groot et al. 2002; MEA 2005; TEEB, 2016). Esto ha limitado la aplicación de conocimiento para explorar manejos sustentables dentro de los límites ecológicos adecuados (Rockstrom et al. 2009). Las limitaciones de evaluar contribuciones están relacionadas con la falta de métodos estandarizados para combinar indicadores biofísicos, sociales y económicos (Nazari et al. 2015).

Cultivo de maíz en México

El maíz (*Zea mays*) es un pasto de origen tropical que se ha convertido en el grano más importante en el mundo en términos de producción total. Se calcula que la producción total anual de maíz es de 1,000 millones de toneladas. A nivel de mercado Estados Unidos es el mayor productor, seguido de China, Brasil, México y Argentina (CONABIO 2011). La mayor parte del territorio en México es apta para la producción de maíz. Actualmente se siembra desde el nivel del mar hasta los 3,400 msnm, en zonas secas, templadas de alta montaña, en ambientes cálidos y muy húmedos, valles fértiles o incluso en condiciones con suelo escaso (CONABIO 2011). En 2018 se sembraron en total 7.37 millones de hectáreas, de las cuales la agricultura de temporal representa el 80% y riego el 20% restante. A pesar de que la agricultura de temporal es la más extendida, los rendimientos más altos se producen en agroecosistemas de riego. La producción de maíz en México se divide entre maíz blanco y amarillo. El maíz blanco representa el 85% de la producción total, y cubre la demanda total de consumo. De su producción, el 18.8% se usa para consumo pecuario, el 18% para autoabasto, 6.3% se exporta, 3.8% es merma, el 0.7% se usa como semilla para sembrar, y el 52.4% se vende para consumo humano. Se calcula que un mexicano consume en promedio 196.4 Kg de maíz al año, principalmente en forma de tortillas (Secretaría de Agricultura, 2019).

El éxito del rendimiento del maíz se ha basado en el desarrollo de tecnología para la producción como las semillas mejoradas, fertilizantes sintéticos y variedades híbridas muy resistentes al estrés ambiental (Cassman et al. 2003; Sweeney et al. 2013). El maíz producido en México se usa principalmente para consumo humano; y con este fin, el maíz es canalizado principalmente a tres industrias: grano seco, grano húmedo y nixtamalización. El maíz se utiliza para muchos propósitos, como forraje para ganadería, para productos industriales como edulcorantes, aceites, pigmentos, papel, harinas, fibras transformadas a cereales, botanas, productos para hornear, jarabes de maíz, cerveza, sustituto de plástico, medicinas, cosméticos, solventes, alcohol, artesanías y fines religiosos o espirituales (CONABIO 2017).

La domesticación del maíz inició aproximadamente hace 10,000 años y continúa a través del manejo, cultivo y selección que los agricultores hacen año con año de los maíces nativos o criollos (Hernández-Xolocotzi 1988). El maíz tiene su centro de origen en México, es el cultivo más sembrado, el más consumido, y es patrimonio biocultural de los habitantes del país (CONABIO 2019; Aragón-Cuevas 2000). El sistema agrícola tradicional de México es la milpa (del náhuatl *milpan* "parcela sembrada encima de"), es un policultivo con el maíz como cultivo principal, acompañado de frijol, calabazas, chile o tomates, y más de 500 especies silvestres de herbáceas y arbustos que crecen de manera natural, conocidas como quelites. Pueden ser verdolagas, huazontles, nabos, romeritos, quelite cenizo, el de invierno, el berro, el epazote, el pápalo, la lengua de vaca, el malacote, el mozote, la hierbamora, las hojas tiernas de guaje, los quintoniles, las cebollinas, los rábanos, las guías de chayote y la chaya, entre otros (Gobierno de México 2023). La diversidad de especies cultivadas en estos sistemas tradicionales son producto del conocimiento, tecnología y prácticas agrícolas que sustenta la soberanía alimentaria de familias de campesinos y de la cocina mexicana (CONABIO, 2019).

El termino de raza se ha utilizado en el maíz para agrupar a individuos o poblaciones que comparten características de orden morfológico, ecológico, genético y de historia de cultivo para diferenciarlas como grupo (CONABIO 2011; Hernández y Alanís 1970). A su vez, las razas se agrupan en complejos raciales, las cuales se asocian a una distribución geográfica y climática más o menos definida, y a una historia evolutiva común (CONABIO 2011; Sánchez et al. 2000). Las razas de maíz se nombran por características fenotípicas, como la forma de la mazorca, tipo de grano, lugar de colecta, o por el nombre conocido dentro de grupos indígenas o mestizos que las cultivan (CONABIO 2011). En América Latina se han descrito 220 razas de maíz, de las cuales 64 se han identificado para México (Wellhausen et al. 1951), y agrupado en siete complejos raciales: grupo cónico, grupo sierra de chihuahua, grupo de ocho hileras, grupo chapalote, grupo tropicales precoces, grupo dentados tropicales y grupo de maduración tardía.

A partir de 1940 inició el mejoramiento agrícola en México a través de un programa de la entonces Secretaría de Agricultura y Ganadería y la fundación Rockefeller (Hernández-Xolocotzi 1988). El programa se implementó en regiones con suelo y clima favorables para el cultivo, que resultaron ser propiedades pequeñas (<5 ha) donde los agricultores estaban organizados y tenían acceso a créditos. Durante este proceso los agricultores y las comunidades agrarias adaptaron las nuevas tecnologías como fertilizantes, tractores y semillas, a sus diferentes capacidades y ambiciones. Con el tiempo esto derivo en una alta variabilidad espacial de nuevos regímenes de manejo, que van desde sistemas altamente industrializados de gran escala en el norte del país; hasta sistemas menos industrializados de pequeña escala que se concentran el centro y sureste (Álvarez et al. 2014).

1.2 Caso de estudio

Durante la Revolución Verde en México, el régimen de manejo tradicional basado en los policultivos cambió a uno más tecnificado basado en el uso de semillas mejoradas, agroquímicos y monocultivos. Este proceso fue resultado de iniciativas, actividades e inversión implementadas por el gobierno federal y entidades privadas, y en muchos casos se ha interpretado como una imposición de la política pública hacia el sector agrícola (Warman y Montañez 19990; Appendini 2001; CEMDA, 2017; De Rosas-Quintero 2017). Principalmente porque no está comprobado que la implementación de las prácticas garantice el aumento de la producción, sin embargo, la política se implementó a escala nacional sin importar la diversidad de prácticas y paisajes de cada región agrícola, y sin ofrecer alternativas adecuadas a los contextos locales. A nivel global, el cambio fue tan grande que, para finales de los años 90, el 75% del arroz, el 50% del trigo, y el 70% del maíz en el mundo se producían con semillas mejoradas, producto de la Revolución Verde (Lappe et al. 2000).

En México, el Servicio de Información Agroalimentaria y Pesquera (SIAP) calculó en 2015 que las semillas mejoradas se utilizan en 10.6 millones de hectáreas, esto representa el 68% de la superficie total sembrada, de las cuales el 63% es de temporal y el 37% de riego; el 32% restante corresponde a semillas nativas (CEDRSSA 2018). Los estados del país que más utilizan semillas mejoradas son Tamaulipas, Sinaloa, Zacatecas, Chihuahua, Guanajuato y Jalisco, en el caso de Tamaulipas y Sinaloa, más del 95% de la superficie sembrada es con semillas mejoradas. Los estados de Oaxaca y Yucatán son los que menos superficie sembrada con semilla mejorada registran, con menos del 20% (CEDRSSA 2018). En la Encuesta Nacional Agropecuaria del 2017 se estimó que, el 77.5% de las unidades de producción agrícola utiliza semillas nativas, esto señala que, en México, los productores que usan semillas nativas son más que los que utilizan semillas mejoradas. Sin embargo, la superficie sembrada es menor por tratarse de unidades de producción con agricultura de pequeña escala (< 5 hectáreas). El maíz es el cultivo con mayor superficie sembrada que usa semillas mejoradas con 4.2 millones de hectáreas, es decir, el 55.3% de la superficie sembrada con maíz en México se hace con semillas mejoradas. Sin embargo, hay cultivos con menos superficie sembrada, con más del 95% de su producción basada en el uso de semillas mejoradas. Es el caso del algodón, el sorgo, la soya, el tomate rojo, la cebolla, el arroz, la avena en grano, la sandía, el brócoli y la lechuga (CEDRSSA 2018).

El modelo actual de desarrollo fomentado desde la Secretaría de Agricultura y Desarrollo Rural y el Plan Nacional de Desarrollo opera a través de varios programas e incluye (i) el cumplimiento de la nueva Ley de Fomento y Protección al Maíz nativo, (ii) la ejecución del programa Producción para el Bienestar y (iii) el Programa de precios de garantía para el maíz. Este contexto político ya opera en todo el territorio nacional; sin embargo, algunas opciones son poco sustentables, como los paquetes tecnológicos y la distribución de fertilizantes. En este contexto, es necesario reconocer las implicaciones que este tipo de programas tienen sobre el manejo de los agroecosistemas, la protección del patrimonio biocultural asociado al cultivo de maíz, y la seguridad alimentaria de las personas.

MasAgro (Modernización Sustentable de la Agricultura Tradicional) fue vigente entre 2010 y 2022, se creó por un acuerdo de colaboración entre la Secretaría de Agricultura y el Centro de Mejoramiento del Maíz y el Trigo (CIMMYT). Este programa es un ejemplo de implementación de política pública al sector agrícola, cuyo objetivo fue promover la intensificación sustentable de la agricultura para tener rendimientos altos y estables (CIMMYT 2019). *MasAgro* operó a través de la oferta de un menú tecnológico; de este modo, cada agricultor tenía la posibilidad de seleccionar prácticas para cada ciclo agrícola. Los paquetes tecnológicos han sido ampliamente utilizados, y prometen balancear la disyuntiva entre el rendimiento y la expansión agrícola. Sin embargo, cualquier cambio de tecnología puede afectar la forma de vida de los agricultores (Liao and Brown 2018).

MasAgro operó en todo el territorio nacional a través de un modelo de difusión de tecnología llamado HUB. En el país existieron 12 HUB, cada uno con un contexto socio-ecológico distinto y con un menú tecnológico propio. El HUB de Valles Altos se localizó en el centro del país, son agroecosistemas de pequeña escala que cultivan maíz de temporal, con una producción basada en el uso de fertilizantes químicos, el 85% de los agricultores usaba maquinaria, más del 60% utilizó pesticidas, y las variedades de maíz utilizadas eran híbridas y nativas. Valles Altos representó un contexto particular porque las políticas de industrialización, como el uso de fertilizantes, herbicidas, maquinaria y subsidios económicos, se fusionaron con algunos rasgos tradicionales como el uso de variedades nativas de maíz utilizadas para autoabasto y venta para consumo humano.

Consideramos que algunas de las prácticas del menú de *MasAgro* y del *Programa Producción para el bienestar*, basadas en paquetes tecnológicos y prácticas intensificadas, como el uso de semillas mejoradas y la adición de agroquímicos sin adecuada planificación, promueven la estandarización de las prácticas de manejo y no aportan al bienestar social de los pequeños productores. Esto gana relevancia en un contexto político donde los paquetes tecnológicos y las políticas agrícolas se aplican a nivel nacional, sin embargo, sus efectos son distintos entre las regiones que conforman al territorio. El estudio de los agroecosistemas a partir del análisis de los componentes sociales y ecológicos ha mostrado ser un marco conceptual y metodológico clave para asegurar la sostenibilidad de la producción de alimento. Tittonell (2016) señala que la postura académica que integra sociedad y ambiente debe concentrarse en promover la seguridad alimentaria a partir del uso eficiente de insumos de producción agrícola, reducir riesgos asociados al cambio global y restaurar la capacidad de los suelos degradados para sostener la producción de alimento y otros servicios ecosistémicos; además debería visualizar propuestas con implicaciones políticas y sociales porque los resultados reflejan compensaciones socioeconómicas y ambientales tomadas por los actores implicados.

1.3 Preguntas de investigación y objetivos

El planteamiento conceptual de esta investigación está delimitado por la genuina preocupación de cambiar la concepción tradicional de que el éxito de la agricultura debe medirse exclusivamente a través del rendimiento, y que una producción agrícola exitosa depende de la sobre fertilización sintética. La presente investigación, sustentada en literatura especializada, visualiza que el uso de fertilizantes sintéticos no es una práctica sostenible porque ha promovido históricamente la intensificación del campo mexicano y la dependencia de los agricultores de pequeña escala a insumos importados con precios excesivamente altos. Ante esto, es importante diseñar nuevos esquemas de evaluación de la agricultura que respondan a la necesidad de transformarla en una más sostenible, este reto incluye reconocer cómo influyen los programas de política pública sobre la producción de alimento en los agroecosistemas de pequeña escala, proponer indicadores de éxito social y ecológico de la agricultura, e identificar algunos de los elementos socio-ecológicos que vulneran la producción a corto y largo plazo.

Objetivo General

Analizar la relación entre el nivel de industrialización del manejo agrícola y las contribuciones de la naturaleza en agroecosistemas de maíz de pequeña escala en la región de Valles Altos, México.

Objetivos Particulares

1. Construir el marco conceptual y analítico para estudiar los agroecosistemas de maíz de pequeña escala como un sistema socio-ecológico complejo.
2. Examinar los componentes y conductores del nivel de industrialización del manejo agrícola en los agroecosistemas bajo estudio.
3. Operacionalizar la provisión de contribuciones de regulación, materiales y no materiales en los niveles de industrialización de los agroecosistemas.

2. ASPECTOS METODOLÓGICOS

2.1 Área de estudio

La zona de estudio es la regionalización del HUB llamado *Valles Altos* (VA) localizado territorialmente entre los estados de México, Hidalgo, Tlaxcala y Puebla (Figura 2).

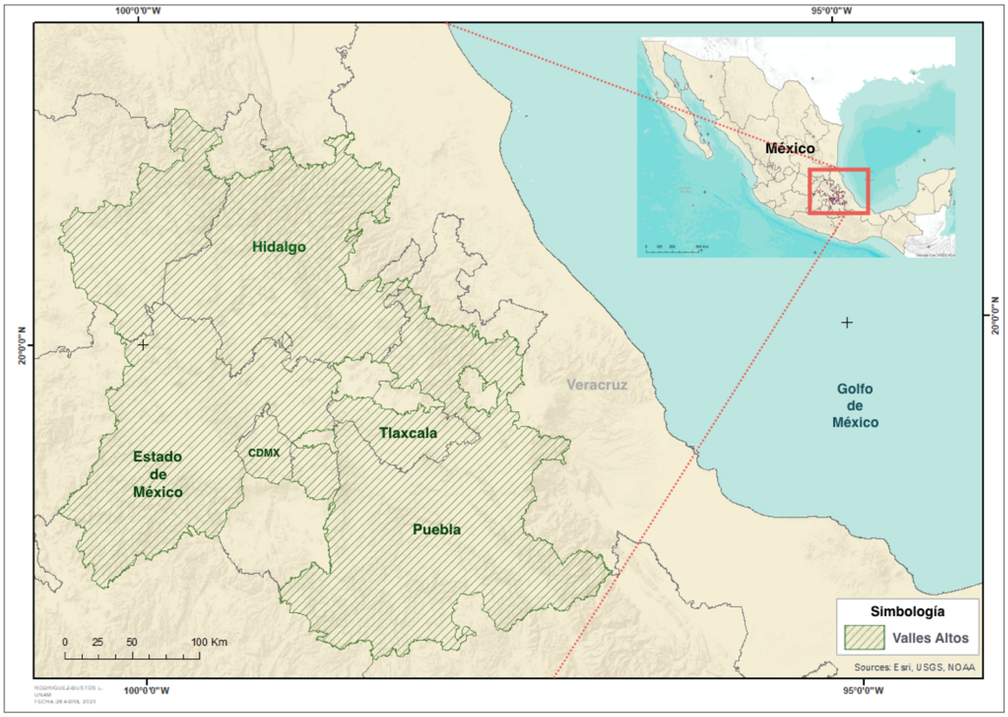


Figura 2. Mapa de localización del HUB Valles Altos.

El HUB *Valles Altos* tiene nueve plataformas experimentales, 1,462 módulos demostrativos, 7,959 áreas de extensión y más de 40,000 parcelas. Es el tercer HUB más grande del sistema *MasAgro* en el territorio nacional, el contexto ambiental de Valles Altos es el centro del país, sobre la Faja Volcánica Transmexicana (FVTM). La FVTM es una Sierra de volcanes activos e inactivos que atraviesa México en dirección oeste-este, mide 930 Km de largo, 120 Km de ancho y representa el 9% del territorio nacional; la topografía se caracteriza por conos de ceniza cuyo rango altitudinal varía entre los 1,500 y 2,500 msnm (Ferrusquía-Villafranca 1993; Bobbink y Heil 2003). Esta zona se considera de alta biodiversidad porque convergen dos zonas biogeográficas: Neártica y Neotropical; esto aunado a la intrincada disposición del relieve, origina una alta diversidad de flora, fauna y hongos. La distribución de la vegetación atiende a la altitud y se distinguen tres ecotonos: Bosque mixto, Bosque de Pino (incluye el pastizal alpino) y Bosque de Oyamel (Rzedowski 2006; Challenger 1998; CONANP 2013; Chávez y Trigo, 1996). Los suelos predominantes son de origen volcánico, donde actualmente se desarrollan diversas prácticas agrícolas e industriales en sitios que alguna vez fueron bosques templados de montaña (Bobbink y Heil, 2003; CONANP 2013; INEGI 2010). En sus alrededores se extiende un área altamente poblada, algunas actividades que se desarrollan son de tipo industrial, extractivas, agricultura, forestal y conservación (CONANP 2013; INEGI 2010).

El HUB es el modelo de transición de tecnología de *MasAgro*; consiste en un modelo de investigación compuesto por tres niveles (Figura 3):

1. **1.** Plataforma experimental: sitios controlados donde se experimenta con distinta tecnología para evaluar sistemas productivos.

2. **2.** Módulo demostrativo: es el área de adaptación de la tecnología en campo, diseñado como un medio de difusión para comparar la nueva tecnología con la convencional en la zona de estudio.

3. **3.** Área de extensión: es resultado de dos niveles anteriores, ocurre cuando el agricultor implementa la tecnología por cuenta propia dentro de su propiedad.

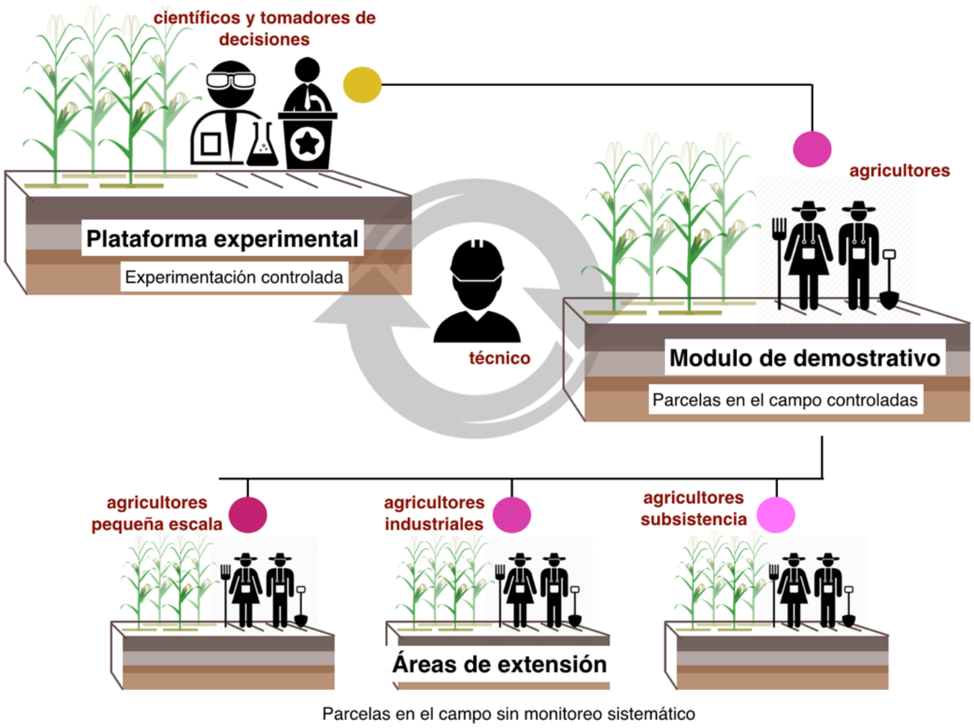


Figura 3. Organización territorial y administrativa de un HUB. La plataforma experimental son parcelas totalmente controladas y administradas por científicos y tomadores de decisiones dentro del CIMMYT. Los módulos demostrativos son parcelas, no controladas, pero están monitoreadas por los técnicos de CIMMYT y los agricultores que aprenden nuevas técnicas de manejo. Por último, las reas d extensión son parcelas no monitoreadas donde el manejo depende de las tecnologías que el agricultor continúa usando de acuerdo a sus intereses.

2.2 Ruta metodológica general

Este estudio propone la integración metodológica de tres etapas, la construcción del sistema socio-ecológico de los agroecosistemas, la definición de las prácticas agrícolas que determinan los niveles de industrialización, y la operacionalizacion de las contribuciones entre los distintos niveles de industrialización (Figura 4).

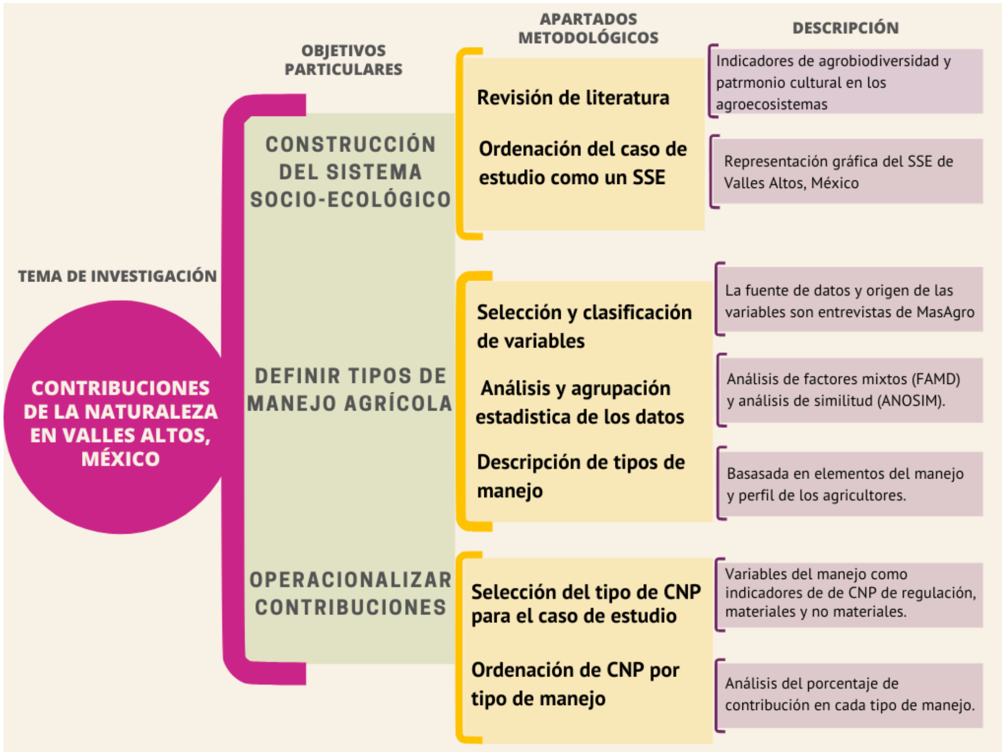


Figura 4. Ruta metodológica general. Esta figura presenta los apartados metodológicos incluidos en los dos capítulos que componen la investigación.

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CAPÍTULO I

Artículo en revisión

INTEGRATING SOCIO-ECOLOGICAL APPROACH INTO POLICYMAKING: LESSONS FROM THE MASAGRO PROGRAM IN THE HIGHLANDS OF MEXICO

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Integrating socio-ecological approach into policymaking: lessons from the *MasAgro* program in Mexico highlands

Abstract

Socioecological frameworks offer a better understanding of how agroecosystems respond to pressures such as agricultural policies designed to influence natural resources and to maintain food production while conserving biodiversity, soil and water quality, and cultural heritage. With a focus on the highlands of Mexico, this paper proposes a conceptual framework to analyze the socioecological elements that relate policy instruments to agricultural management and, therefore, to nature's contributions. Three primary sources of information were integrated: a critical literature review, direct observations, and an analysis of semi-structured interviews. The study shows that farmers from Mexico Highlands participating in the *MasAgro* program made decisions translating into a heterogeneous mosaic of crop management practices where a single element can relate to multiple contributions. Regarding sustainable development and under fluctuations in the economy and climate, native seeds, residual crop retention, and conservation tillage are crucial practices for inclusion as indicators of nature's contributions to small-scale agroecosystems. Including an integral vision such as Socio-ecological systems and Nature's contributions in agroecosystems is an opportunity to link agricultural management to social welfare indicators, such as food security, biocultural heritage, and ecosystem conservation. This framework considers the complexity of small-scale agroecosystems and represents an operational baseline that can be used for other research studies of small-scale agroecosystems in tropical landscapes.

Keywords: nature's contributions to people, socio-ecological systems, Mexico, maize, policy instruments.

1. Introduction

Agricultural intensification has significantly reconfigured agriculture practices and environmental policies; therefore, sustainable agriculture is essential for minimizing environmental and social impacts (Piñeiro et al. 2020). Maize cultivation in Mexico ranges from small-scale to highly technician practices seeking to maximize grain yield (Sweeney et al. 2013). Since the green revolution more than 50 years ago, traditional agriculture has shifted toward highly technician monoculture involving high-yielding varieties with tolerance to biotic and abiotic stress, using primarily hybrid seed and synthetic fertilizers and pesticides (Cassman et al. 2003; Sweeney et al. 2013; McAfee 2017). These agronomic practices have contributed to the loss of biodiversity, soil fertility, dietary diversity, and biocultural heritage (CEMDA, 2016). The transformation of intensive agriculture into a sustainable one requires, among many factors, new policy instruments that operate at a local scale and finance, monitor, and implement new management practices adopted by farmers (Shriar 2002; Galli et al. 2020; Piñeiro et al. 2020). Policy instruments are often introduced as social assistance programs aimed at protecting, increasing, or conserving agrarian production to the benefit of producers while improving the farm sector's competitiveness (Galli et al. 2020). Therefore, they often support technification policies to maintain or increase yield regardless of the impact on environmental and social sustainability (Hatt et al. 2016; Piñeiro et al. 2020).

The decision to adopt a sustainable management approach depends on the farmer's economic preferences, needs, and benefits, as well as on the instrument guidelines, the type of incentive, and the farmer's cultural background (Tilman 2011; Shriar 2002). Today, the international agenda addresses sustainability policies because the objective is to maintain food production while conserving biodiversity, maintaining, or improving soil and water quality, and promoting the replication of the cultural heritage of agroecosystems (Hatt et al. 2016; FAO 2020). For example, the Sustainable Development Goals (SDGs) require that, by 2030, it will be possible to secure food availability for human health, ensure healthy diets, preserve the biocultural heritage of agroecosystems, and ensure the maintenance of ecosystem service provisioning. Despite this demand on the international agenda, agricultural policy instruments rarely include indicators of ecological, nutritional, or social well-being (Hurni et al. 2015).

In the Mexican context, the 2019-2024 National Development Plan (NDP) — the main political instrument in the nation — pointed to the need to move forward to agroecological management (DOF, n.d.). Currently, agricultural policy has been dominated by instruments based on economic incentives to enable farmers to cover production costs (Warman 2001). They are designed to operate at a national level without reference to the diversity of agricultural management in the country (Warman 2001; Alvarez et al. 2014). Such political instruments bring short-term economic benefits without enhancing agriculture's value and do not incentivize farmers to adopt a sustainable management plan (Shriar 2002). Accordingly, farmers' decisions associated with cultural elements, such as self-sufficiency, management of local resources, and cultural value of native seeds, are poorly recognized on international and national agendas (Boege 2008; Tomich et al. 2011; Sujithkumar et al. 2016; Martín-López et al. 2019; Arroyo-Lambaer et al. 2021).

This study integrated the conceptual frameworks of Socioecological Systems (SES) and Nature's Contributions to People (NCP) (Diaz et al. 2018). SES is a theoretical perspective to explore the relationships and dynamics between individual and collective social actors and between natural and managed ecosystems (Turner et al. 2003; Zurlini et al. 2008; Turner et al. 2007). It allows the conceptualization of a case of study as a complex system arising from interactions between people and nature (Berkes and Folke 1998; Martín-López et al. 2009; Colding and Barthel 2019). The NCP framework studies all the goods obtained from nature and the role of culture and local knowledge in delineating man-nature relationships (Diaz et al. 2018; Martín-López et al. 2019). The NCP framework is based on and shares similarities with the ecosystem services (ES) framework (Costanza et al. 1997; Potschin-Young and Haines-Young 2011). The SE framework analyzes ecological functions and the beneficiaries' central role in achieving the provisioning's success (MEA 2003; Daily and Matson 2008). NCP assigns a core role to the producer of benefits, whereas the cultural context defines the contributions, relates to the actors, and promotes the shared production of benefits (Díaz et al. 2018).

An agroecosystem can be regarded as an SES that integrates the environmental context while recognizing the central role of farmers and their decisions related to food production and supply (Cassman et al., 2003; Tomich et al., 2011; Holt et al., 2016; Norton 2016). In Mexico, maize is the most critical component of urban and rural diets, and its diversity and uses constitute a biocultural heritage associated with ecosystem conservation. Heritage includes crop fields, germplasm, and traditional knowledge of farmers, processors, and consumers (Boege 2008; MacAffe 2017; Bellon et al. 2018). Yet, no available framework exists in Mexico that conceptualizes the critical relationships among agroecosystems, agricultural policy, and social organization. This investigation takes the maize cropping in the Mexico highlands region as a case study to propose a conceptual framework for analyzing the socioecological elements that relate policy instruments to agricultural management and, therefore, to the provision of nature's contributions to people. This framework integrates the ecological and social components of sustainability to identify the elements, actors, and relationships that play critical roles in agricultural production and proposes NCPs as indicators of agrarian success based on the sustainability of management practices.

2. Materials and Methods

2.1 Case Study

MasAgro (Sustainable Modernization of Traditional Agriculture) was a public policy program to promote sustainable intensification in Mexico through technical advice on selecting farming technologies (CIMMYT 2020). It was launched in 2010, terminated in 2021, and was primarily supported by public funds from the Ministry of Agriculture of Mexico (CIMMYT 2020). The program operated throughout Mexico, focusing on the central and southern regions. It used a hub structure, with each area having technological options and technical assistance (Gardeazabal et al. 2021). A MasAgro hub integrated three types of areas: (i) the experimental platforms of controlled sites where scientists run trials such as cover crops options or the performance of a new maize hybrid; (ii) demonstration modules, which were field plots that allowed farmers to observe the performance of MasAgro innovations; and (iii) extension areas, i.e., field plots where the farmer himself implemented the innovations that they choose appropriate for their fields and needs (CIMMYT 2016). MasAgro offered farmers a technological menu that included specific management practices such as fertilization diagnosis, integral fertilization, conservation agriculture, market diversification, and seed variety (CIMMYT n.d.). Participants decided the type of technology they wished to adopt during agricultural cycles and were advised and assisted with a sustainable implementation.

Mexico highlands was the third largest MasAgro hub, involving parts of the states of México, Hidalgo, Tlaxcala, and Puebla in the center of the country (Figure 1). The region surrounding Mexico highlands is densely populated, in the vicinity of the capital city of Mexico. In addition to forestry and agriculture, industrial activities predominate, including processing and food packaging (Bobbink et al. 2003). Its operational model comprised nine experimental platforms, 1,462 demonstration modules, and 7,959 extension areas (CIMMYT 2016). This investigation was designed under the demonstration modules scheme because the technology transfer from MasAgro and the decision-making by the farmers took place at these sites. The implementation of the program in the region represents an opportunity to test the operationalization of a conceptual framework through its elements and actors because all agricultural plots of Mexico highlands lie within the same geographic region and are managed under the same policy instrument.

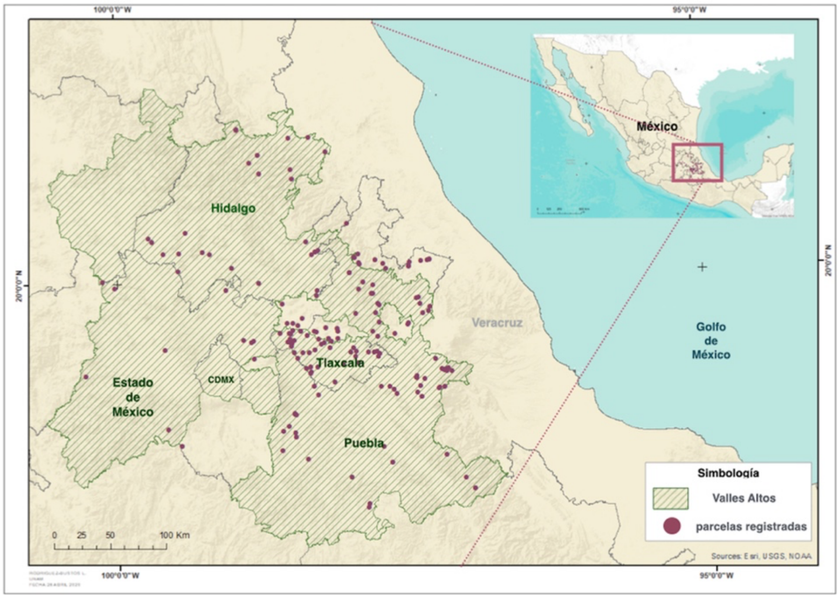

Figure 1. Location map of *Mexico highlands*. The states comprising the *Mexico highlands* region are green; the plots sampled in this study are purple.

2.2 Socioecological Approach

The present study interpreted the Mexico highlands region as a Socioecological system. Social elements include the social ownership of land and the autonomy of farmers to decide on the use of technologies, considering ecological aspects such as soil, climate, and germplasm for agricultural production. Construction and theoretical interpretation of Mexico highlands as an SES used the modified Socioecological Systems dynamics approach of Tenza et al. (2017). The classification of NCP's used was from the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (2019) because it reflects the type of operational variables needed to evaluate the current and future provision of NCPs. We modified the original methodological route to integrate information from three primary sources: literature review, fieldwork, and semi-structured interviews. This approach conceptualizes a case study whose final hypothesis is presented through a diagram that includes the variables of interest and the links and interactions among these variables.

2.3 Critical literature review

This study used the Search, Appraisal, Synthesis, and Analysis (SALSA) protocol proposed by Grant and Booth (2009) to identify pertinent literature on the subject (Table 1). The objective was to identify, compare and contrast literature written in English that linked agricultural policy instruments with agricultural management and production sustainability globally and in Mexico. The search engine selected was Scopus because it gathers the most significant number of titles of specialized publications (Gavel and Iselid 2008). The search filters were the keywords in the topic, title, or abstract: socioecological systems, food security, public policy, and agricultural management. The specific code for the search was (TITLE-ABS-KEY ({socioecological systems} AND {food security}) OR TITLE-ABS-KEY ({socioecological systems} AND {public policy}) OR TITLE-ABS-KEY ({socioecological systems} AND {agricultural management})). We applied a date-related filter to select publications from 2015-2020. To compare the information, we selected 22 publications that included original studies and reviews with analyses of socioecological relationships and political instruments. Appendices Table 1 summarizes the frameworks, areas of development, strengths, and sustainability indicators of each article revised for the SES in Mexico Highlands. The 22 publications were analyzed as a narrative that supported the conceptual framework of Mexico highlands SES.

Table 1. Summary of the SALSA protocol used for the literature review.

	STEP	OUTCOME	APPLIED METHOD
SALSA PROTOCOL	Search	Definition of the search strategy	Specific code with keywords and date in one database
	Appraisal	Selection of studies	Only original studies that analyze socioecological relationships and policy instruments
	Summary	Data categorization	One database with reference, framework, sustainability scope, sustainability indicators, and inclusion of policy instruments
	Analysis	Data analysis	Narrative analysis through a socioecological framework for *Mexico highlands*.

Modified from Mengist et al. (2020).

2.4 Fieldwork and Interviews

To learn how farmers collaborate with *MasAgro*, we analyzed the information available from MasAgro's unique logbook (CIMMYT n.d.), a semi-structured interview that MasAgro field technicians applied during the spring-summer and autumn-winter agricultural cycles between 2016 and 2019. The information included 202 farmers whose rainfed maize plots work under the MasAgro system (Table 2). All farmers in Mexico highlands are dedicated to agriculture as economic activity. The seed type, type of tillage, and harvest destination define different types of farmers' profiles and motivation management. So, the heterogeneity of management in the region of study is partly driven by the motivation of reaching food self-sufficiency or earning an income from harvest sales (Rodríguez-Bustos et al. 2022) Each interview presented 50 open and optional questions arranged according to four topics: farmer's characteristics, property characteristics, farmer's choices on the technological menu, and detailed information on agronomic management. Four field visits between August 2018 and February 2020 yielded partial qualitative information about Mexico highlands through informal discussions with farmers regarding their agricultural practices, interests, and perspectives on management practices (Hernández et al. 2020).

Table 2. Participants in the interviews from MasAgro's unique logbook

Category	**Category in MasAgro Hub**	**Farm size** (average)	**Yield** (avg. kg /ha))	**Seed types**	**Production porpoise**	**Land property**	**Number of participants**
Farmers	Demonstration module	1.0 ha.	3	Native and hybrid	Self-sufficiency and sold for tortilla industry	Private and ejido	202

2.5 Data Analysis and Definition of the Conceptual Approach

Information from the 202 interviews was summarized and integrated with the data from the literature to construct the SES framework. From it, 173 interviews containing the complete dataset were analyzed with descriptive statistics to summarize and integrate information, identify commonly used practices, and determine which technologies proposed by MasAgro were selected by farmers in Mexico highlands.

The information from the literature and interviews is depicted in three figures: 1) the conceptual definition of the SES, including a graphical hypothesis of the critical components and their relationships within a small-scale agricultural SES; 2) a scheme displaying the diversity in the adoption of the technological menu offered by MasAgro in Mexico highlands, and 3) the diversity of agricultural management approaches in plots displayed as a tree diagram based on the proposal of López-Ridaura et al. (2021).

3. Results

The conceptual framework in Mexico highlands shows the complexity of elements and actors in Mexico highlands; each structural component is represented with different features and actors, and it allows to visualize how each policy and agricultural management component relates to the conservation and provision of nature's contributions (Figure 2). The structural components in our framework are a) policy instruments, in this case, represented by the MasAgro program; b) agricultural management, defined by management practices recorded during field interactions and datalog information; and c) nature's contributions to people, which can be assessed as operational indicators through some agricultural management practices.

The left-hand column of Figure 2 describes the social actors (not elements) related to each socio-ecological interaction. The policy is represented by scientists, politicians, and decision-makers involved in the design of technology, policies, and programs. Agricultural management is defined by individual farmers, i.e., landowners and laborers, and agrarian technicians who assist in implementing technologies and policies. Social actors are represented again by farmers, but now collectively because, as a group, they should be the primary beneficiaries of agricultural production and conservation of nature's contributions and because most of the land in the study site is under social tenure. All the components in our framework can serve as a platform to integrate new operational variables that adapt the analytical scale to different contexts in other cases and help to assess sustainability.

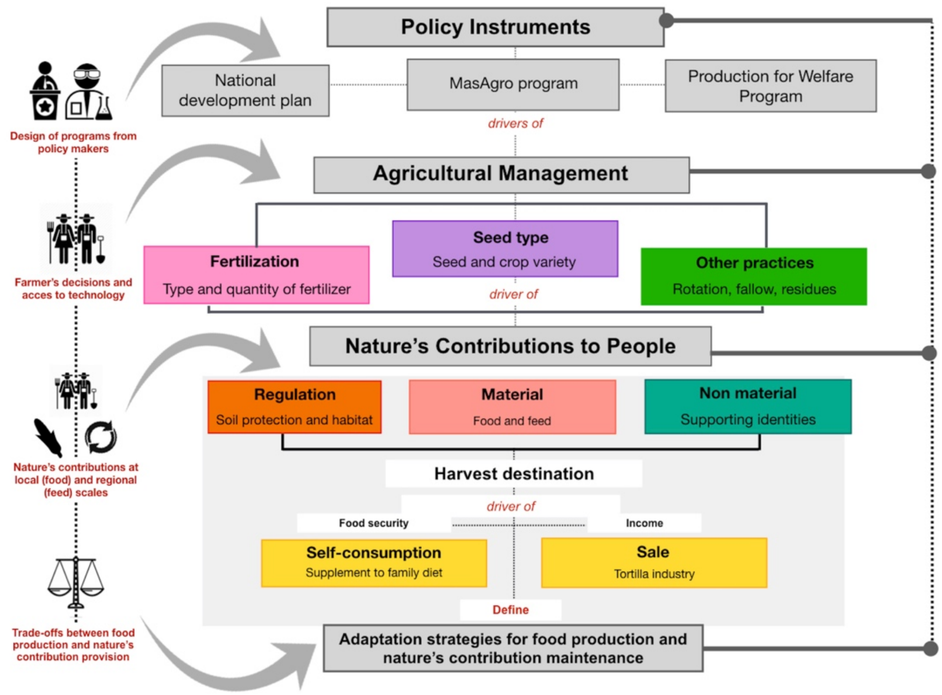

Figure 2. Socioecological System in *Mexico highlands*. Policy instruments define the agricultural management regime. Individual farmers' decisions represent agrarian management. Nature's contributions to people are represented by soil protection and habitat, food and feed, and supporting identities. The harvest use determines two indicators of human well-being: self-consumption associated with food security and sale associated with farmer's income.

The agricultural management compartment is positioned in the middle because it represents the interaction between the social and ecological elements of the SES. Nature's contributions are represented as regional because the socioecological benefits provided surpass the plot boundaries. This conceptual proposal requires every contribution to have positive and negative feedback in the dynamic system. For this reason, we have included a potentially damaging effect related to losing a set of contributions.

Policy instruments operating in Mexico highlands are the National development plan (NDP) and Producción para el bienestar (Production for welfare), in addition to MasAgro, financed by public and private resources. Each has ways of operating in the field: for example, Producción para el bienestar works through incentives given as direct payment to farmers before fulfilling specific criteria (extension area, cultivated crops, etc.), and MasAgro through an innovation menu, capacity building, and constant technical assistance. The innovation menu included management alternatives designed by scientists and technicians, the technical staff of MasAgro offers these alternatives to farmers in demonstration modules to validate their effectiveness under non-controlled conditions.

The innovation menu comprises categories (Figure 3) from which the farmer can choose one or several options for on-field application. In Mexico highlands, 101 had chosen technology related to seed type, 18 for fertilization diagnosis, 99 for integral fertilization, 89 for conservation agriculture, 16 for market diversification, and 33 for post-harvest management. The willingness in Mexico highlands to adopt and combine technology with traditional practices may be partial because it is a regional maize marketing area for the tortilla industry, with 54% of farmers securing the sale of their crop and 85% having the financial access to invest in machinery and plot leasing to increase their production.

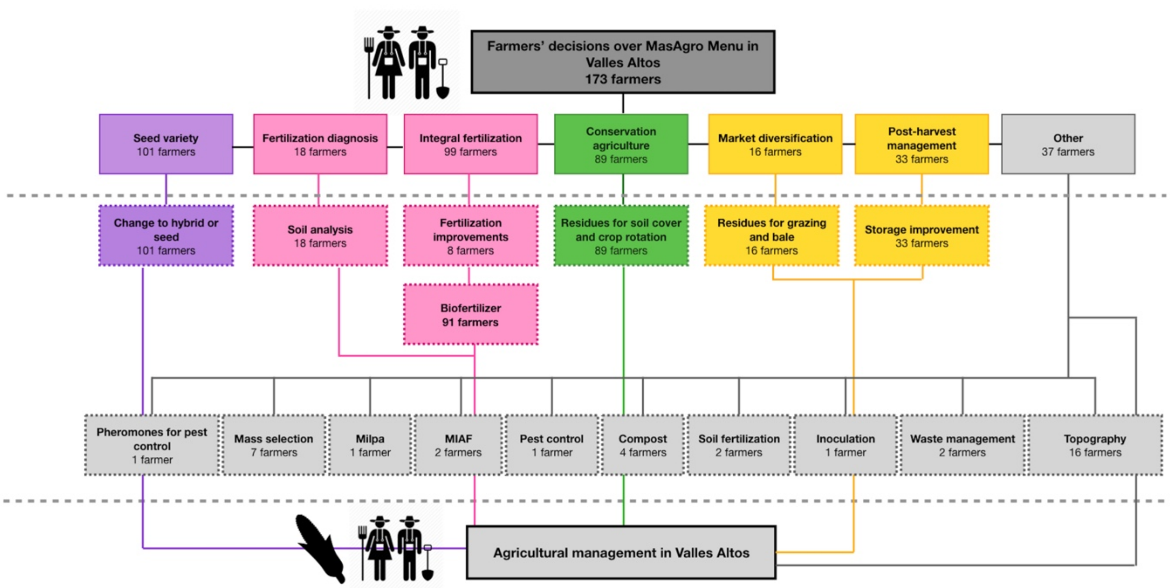

Figure 3. Representation of the *MasAgro* menu and selection of technologies by farmers in *Mexico highlands*. The upper gray box represents the total number of farmers in *Mexico highlands* working under *MasAgro*. Boxes with solid outlines are the *MasAgro* type of technology and the number of farmers who select it. One farmer can select many technologies. Boxes with dotted lines are the specific description of the type of technology.

Agricultural management options for maize in Mexico highlands within the MasAgro program included at least three types of tillage, four types of fertilization, the use of landraces or improved germplasm, four alternatives for crop residue management, and three uses of the maize harvested (Figure 4). Of the 173 plots considered in this study, 148 (86%) used conventional tillage, with the use of machinery for planting and harvesting; 10% used zero tillage, i.e., not tilling the soil with machinery, animals or manually; and 5% used conservation tillage, defined as minimal soil movement. With the MasAgro program in Mexico highlands, technological innovations were merging with traditional small-scale agriculture. All plots are small-scale because their area is less than 5 ha (avg. 1.8 ha), all parcels operate under rainfed conditions, and the dominant crop is native maize, grown by 62% of farmers. Management also involves synthetic fertilizers and herbicides; 96% of farmers use synthetic fertilizers (avg. 257.7 kg/ha) and herbicides (avg. 3.5 kg/ha), 85% report mechanical tillage, and 32% sow hybrid maize purchased from seed distributors. In plots managed under conventional tillage, 75% used synthetic fertilizers applied at 257 kg/ha on average, 21% of the farmers did not report the preferred type of fertilization, and the remaining 4% used either biofertilizers or a combination of biofertilizers with synthetic fertilizers (Figure 4). 20% of farmers do not incorporate residues into agricultural management, and 80% use residues for soil cover, use it as stover to graze their livestock, sell it for other livestock or burn it (Figure 4).

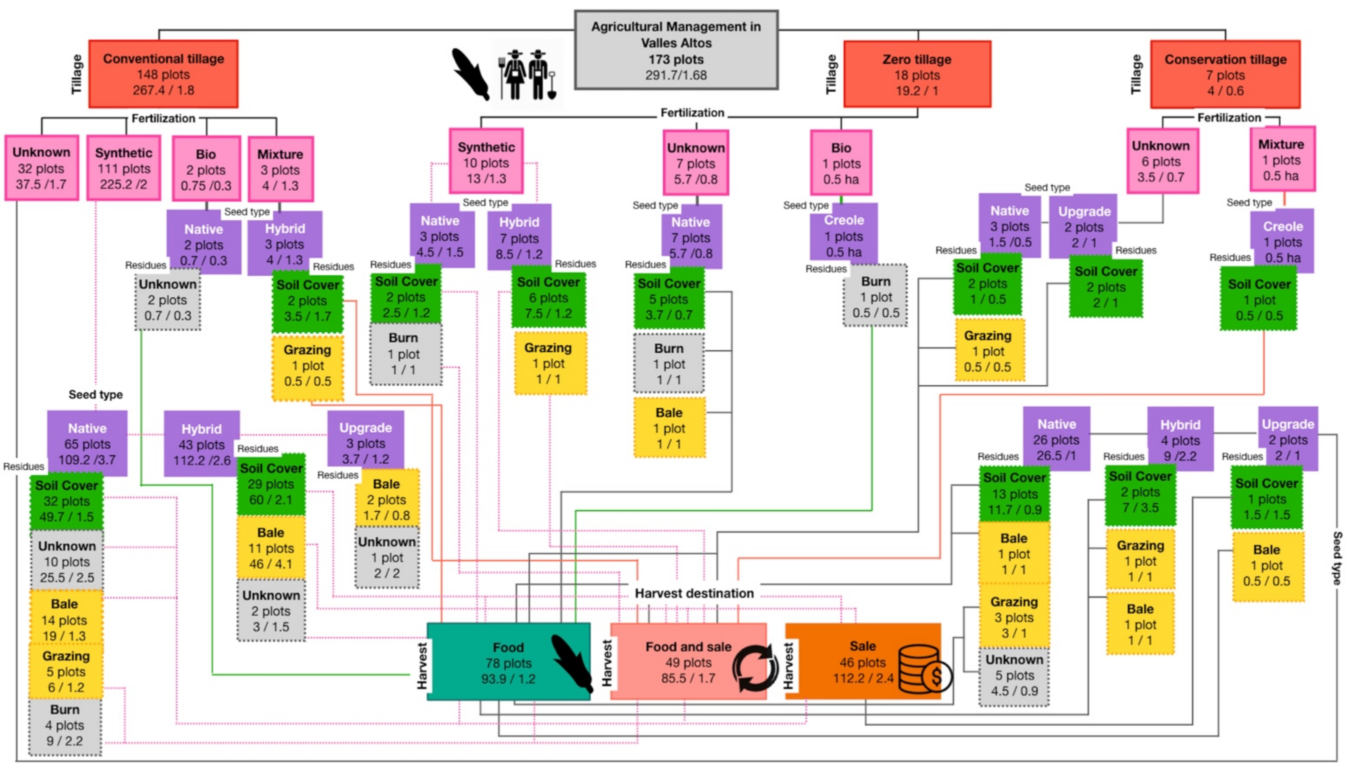

Figure 4. Agricultural management in *Mexico highlands*. Incorporates information from field surveys. Within each box: total area (ha)/ average area (ha) under that management practice. This figure summarizes the policy level in the first node because it includes only plots managed under *MasAgro*. The second node is fertilization type with colors depicting different options within the *MasAgro* system (pink; synthetic fertilizer; green, biofertilization; orange, mixed fertilization; gray, unknown). The third node is seed type (native or hybrid) and shows the color of the fertilization type. The fourth node refers to plant residue management (soil cover, bale, grazing, burned, and unknown). The sixth node, displayed at the bottom of the figure, represents the final

destination of harvested maize (food, sale, or both). The dotted lines: represents sale and self-consumption. Solid lines are for self-consumption. Across all nodes, “Unknown” refers to information recorded in field logbooks but neither mentioned nor specified by the interviewees.

Nature’s contributions to people indicators

New sustainability indicators should assimilate farmers’ vision of the success of agricultural production in terms of economic, social, and ecological benefits. Our SES model proposes three indicators to evaluate nature’s contributions: soil fertility and crop diversity as a regulation contribution, food quantity and quality as a material contribution, and native seed and cultural practices as a non-material contribution (Figure 5). One desirable characteristic for assessing sustainability in an SES is the inclusion of operational indicators because this can confer a conceptual perspective on diverse geographic contexts. For this reason, our conceptual framework integrates operational socioecological elements from agricultural management, which should be considered drivers of the actual or potential provision in a contribution assessment scheme (Figure 5).

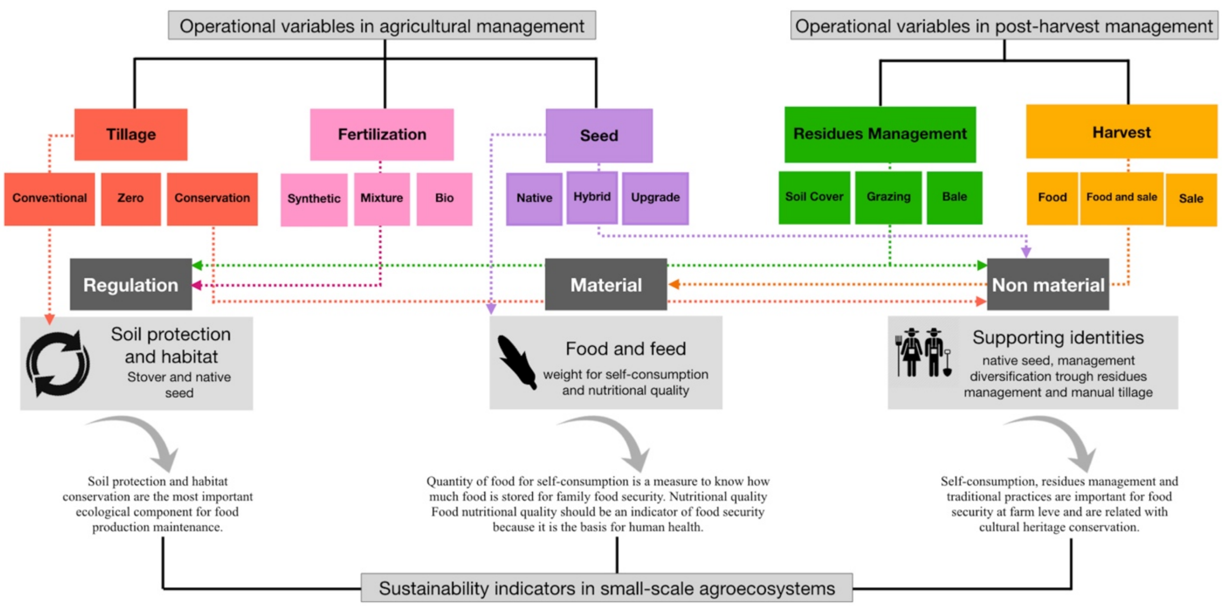

Figure 5. Elements of agricultural management can be interpreted as indicators of nature’s contributions to the *Mexico highlands* SES.

4. Discussion

The implications of agricultural management for policymaking

We have re-examined how an existing conceptual tool — the SES — can be used in novel ways as operationalizing and mainstreaming the idea of Nature's contributions to people (Gaba and Bretagnolle 2020; Partelow 2019). Our study proves that the usefulness of the SES for scientists may be paralleled by its convenience for agricultural farmers. The SES for Mexico highlands was designed to avoid the artificial separation of the system's ecological and social elements; with the placement of the structural components (a), (b), and (c) at its core. This framework differs from others because it visualizes NCPs as emerging properties resulting from the interaction between the social and ecological elements of the SES, involving a close collaboration of practitioners and scientists to use relevant knowledge that promotes effective management on the ground. For example, this allows us to show that management practices depend on multiple factors, including personal needs, cultural preferences, market trends, and the biophysical characteristics of plots (Piñeiro et al., 2020); the political context affects their decisions and may present them with technological options and incentives that are not always sustainable.

The operationalization of agricultural management within SES in Mexico highlands revealed that the relationship between a political instrument and its effect on the technification of agricultural management is not homogeneous because individual farmers' decision-making also defines agrarian management. The four key findings can be summarized as follows: (i) most agriculture in Mexico's highlands is technician because all plots use either machinery, fertilizers, or hybrid seeds; (ii) the diversification of crop residue management is associated with the use of native seeds; (iii) in Mexico highlands, harvested maize goes to the market, self- sufficiency, or a combination of the two; and (iv) plots that grow maize only for the market (no self- sufficiency) use hybrid seeds only. The SES shows that most plots in Mexico highlands grow native varieties under a community management system through exchange between farmers. However, the use of the MasAgro menu indicates that at least 50% of farmers in Mexico highlands intended to include hybrids (Figure 4). Hybrid and native maize are consumed as food. Native maize is used for household self- sufficiency as elote [fresh maize], dough, and tortilla; the hybrid seed is sold to the nixtamalized masa tortilla industry and the maize-flour sector (Figure 4). Any management approach depends on individual and collective decisions by farmers in selecting the type of practices they carry out on their plots and the availability of resources such as water and nutrients. The agricultural management compartment includes fertilization schemes, cultivated varieties, and other techniques such as tillage and crops residual management because, according to the literature review, all related to the degree of agricultural intensification and industrialization (Caulfield et al. 2020; Ruíz-Almeida and Rivera-Ferre 2019; Williams and Kramer 2019; McKenzie et al. 2018).

In Mexico highlands, conventional tillage with machinery and synthetic fertilization is the most common practice among farmers; therefore, soil fertility will be regulated by the intensity of these practices (Figure 5). MasAgro proposes zero-tillage and the use of stover as alternative management practices; however, the operationalization of our SES shows that there is no conservation agriculture in Mexico highlands because all plots have incorporated a technological element into their management. The use of stover can offset the adverse effects of mechanized tillage and synthetic fertilization, provided the intensity and frequency of these practices decrease. Retention of stover is a sustainable cultural practice recognized as effective for soil conservation (Lal 2016). Removing residues has adverse consequences on nutrient balance, crop nutrition, soil biological activity, soil moisture retention, and organic matter content, as demonstrated in the soil macrofauna (Melman et al., 2019). When stover remains in situ, it contributes to soil fertility and, when used in combination with techniques such as polyculture and conservation tillage, it also stabilizes agricultural yield even during episodes of climate stress; therefore, stover retention increases the resilience of the system (Peterson et al., 2018). In Mexico highlands, new incentives are needed to promote stiver retention in combination with less intensive mechanized tillage.

Strategies for sustainable agriculture need to optimize machinery used to reduce soil degradation and synthetic fertilizers (Lal, 2016). Reduction in the use of machinery can lower fossil fuel consumption per hectare by almost 12% and greenhouse gas emissions by 2 Gt within six years (Bennet et al., 2013). The sustainable transition will depend on adequate incentives to ensure the prosperity of the farmers, involving decisions by the farmers themselves. A collaborative participation approach promotes the adoption of family practices while reducing the dropout of farmers from agricultural programs (Nilsson et al., 2019). New policy instruments that operate through technological menus, such as MasAgro, can learn from previous experiences and ensure continuous improvement of the policies by involving farmers in designing practices and incentives to match their socio-ecological context. Promoting diversified agriculture is essential to change local management practices and maintaining the biocultural heritage (Martín-López et al. 2019). The clearest example of policies' effect on agricultural management has been the Green Revolution implemented in the seventies and supported for at least four decades. The introduction of technology packages based on synthetic fertilizers and herbicides, machinery operating on fossil fuel, and improved seeds, especially hybrids in the case of maize, resulted in unsustainable maintenance costs, crop dependence on fertilizers, and degradation of ecosystems on a global scale (Boege 2008; Lal 2016).

The potential effectiveness of Nature's contributions as sustainability indicators

Crop yield and nutritional quality are appropriate operational variables for assessing food production (Figure 5). Yield is the most critical variable to define harvest success because it can be interpreted as an indicator of food availability. Nutritional quality is a significant factor of sustainable development to eradicate world hunger, mid-and long-term goals should aim to produce sustainable, accessible, nutritious, and culturally meaningful food (FAO 2020). In Mexico's highlands, all farmers are dedicated to producing maize that will be consumed as food; hence, the nutritional quality of the crop is essential, as well as its quantity. The main concern is family food security; most farmers store at least 1 ton of grain for their family's annual consumption (3-5 members). In the generation of long-term management strategies, a policy instrument appropriate to the socio-ecological context of Mexico highlands should include small producers and self- sufficiency indicators of agricultural sustainability.

Soil fertility is suitable for evaluating regulation contributions because soil sustains biodiversity, biological activity, and productivity; regulates water and sediment flow; filters break down and immobilize organic and inorganic pollutants; and regulates nutrient dynamics (Bautista-Cruz et al. 2012). In addition, the soil is the basis for global food production as most of the food we consume is grown directly in soil (Etchevers et al. 2015). Conservation of ecological functions at the local level requires that soil fertility be considered a contribution and an indicator of sustainable agriculture. Incentives focused on local conservation processes, such as strategies to conserve soil fertility, are more valuable in terms of long-term productivity than incentives such as the supply of synthetic fertilizers that adopt globalization and market processes as top priorities. Considering soil fertility in the design of incentive programs would be an opportunity to scale sustainability based on the joint development of policies between the government and farmers (Shilomboleni and De Plaen et al. 2018; Ratna-Reddy et al. 2020).

Nature is critical in the provision of materials that are essential to physical well-being and the preservation of people's culture (IPBES 2019). Food is a vital material resource for human existence, and the implications are global; the main problems are food insecurity and malnutrition, which are regulated by food availability, access, and use (Chavaz 2017; Krausmann and Langthaler 2019). In Mexico highlands, maize grain for sale and self-sufficiency is directly or indirectly allocated to human food. Food self-sufficiency is an indicator of the ability of a peasant's family to reduce poverty and secure access to food and its daily caloric intake. Our theoretical proposal included the total nutrient concentration of C, N, and micronutrients as a reliable indicator of the nutritional quality of the grains produced (Figure 5). From our perspective, evaluation of the nutritional quality of maize harvested in Mexico highlands can be used to assess its nutritional contribution to peasant families and hence to their food security because nutritional quality can give added value to the grain sold to the tortilla production industry. In Latin America, maize accounts for nearly 30% of the calories consumed (FAO 2003). Still, there needs to be more information about the volume of crops used as food for self-sufficiency (Falconnier et al. 2018). In the past, maize breeders focused on increasing yield, but now there is a growing demand for hybrid varieties with an adequate nutritional profile (Palacios-Rojas et al. 2020).

Non-material contributions are part of people's cultural heritage; traditions transmitted from generation to generation are central to their perception of nature (IPBES 2019). The integration of cultural and social elements has underpinned Mexican agriculture throughout history (Boege 2008). The management elements that can be interpreted as a biocultural heritage are the genetic resources associated with cultural biodiversity, the culinary use of crops, the symbolic management of natural resources, and the social value of agriculture (Zimmerer et al. 2019). For instance, the informal inheritance of maize seeds from one generation to the next has a cultural significance that determines the organization and political stance of peasants on food sovereignty (Rodríguez et al. 2020).

From our perspective, one of the main challenges lies in associating biocultural heritage with operational variables that can be assessed directly in the field. Our proposal integrates native seeds, waste management, and self- sufficiency as potential indicators of the conservation of the biocultural heritage because each of these practices represents the cultural past of the farmers (Toledo et al. 2008). In this context, native seeds are an indicator of the conservation of biocultural heritage and a socioecological element related to the resilience of agroecosystems that rely entirely on rainfall, soil, and native seeds (Mercer et al. 2012). The native seed has material value, but its cultural value is the incentive that supports its conservation because its importance to farming communities relates to their cultural roots and beliefs (Rodríguez et al. 2020). In addition, by planting native maize, communities have made their crops' evolution possible in response to variations in management and the climate (Bellon et al. 2020). The value of the SES lies in conveying scientific knowledge to other actors and improving communication and sharing knowledge between actors, e.g., peers, through social learning. We recommend that traditional agricultural practices assess their role in conservation, and at the same time as an opportunity to evidence the diversity of practices whose survival in tropical regions is threatened.

Conclusions

Regarding sustainable development and under fluctuations in the economy and climate, native seeds, residual crop retention, and conservation tillage are crucial practices for inclusion as indicators of sustainability in small-scale agroecosystems. Future agricultural policies and adaptation strategies should further acknowledge and promote cultural practices and their implications for maintaining nature's contributions in the long term and ensuring farmers' wellness. Including an integral vision such as the conceptual frameworks of SES and NCP in agroecosystems is an opportunity to link agricultural management to social welfare elements such as food security, biocultural heritage, and ecosystem conservation. Agricultural management expressed as a heterogeneous mosaic of practices limited the ability to generate an adequate synthesis of the context of the region and, therefore, to generalize about the effect of MasAgro on food production in Mexico's highlands. The framework represents an operational baseline that can be used for other research studies to address the complexity of small-scale agroecosystems in tropical landscapes.

Authorship statement

LRB and LG formulated the research questions, LRB, LG, NP, and MB designed the study, LRB carried out the study, LRB analyzed the data, LRB, LG, NP, and MB interpreted the findings, and LRB wrote the article.

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Competing interests

NP was employed by CIMMYT. The remaining authors report that there are no competing interests to declare.

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Appendices

Table 1. Literature review for the narrative discussion of the SES conceptual framework.

Reference	Conceptual Framework	Scope of sustainability	Area of development	Type of research	Sustainability indicators
Leal-Filho et al. (2019)	SES and Risk assessment	Social and ecological	Conflict resolutions	Study case: East Africa	Income, Human Development Index, degree of success in achieving SDGs
Caulfield et al. (2019)	Non-explicit	Ecological	Improvement of agrarian management	Study case: Ecuadorian Andes	Soil properties, biodiversity, and carbon stocks.
Ferchichi et al. (2020)	SES	Ecological	Integrate social and ecological dimensions	Study case: Northern Tunisia	Forest complexity, forest degradation, groundwater overexploitation, water quality, marketing of agricultural products, and tourism infrastructure.
Ruíz-Almeida and Rivera-Ferre (2019)	SES and Food sovereignty	Social and ecological	Integrate multiple visions into SES	Literature review	Total 97; grouped into categories: access to resources, production models, marketing, food consumption,

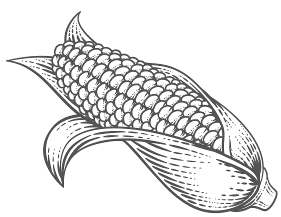
					agricultural policies, and gender.
Shilomboleni and de Plainen (2018)	Scaling-up	Social	Applied research through narratives and perspectives.	Literature review	Dissemination, technology transfer and diffusion
Williams and Kramer (2019)	SES	Social and ecological	Integrate methods for SES studies	Study case: Caribbean coast of Nicaragua	Agrobiodiversity
Ollivier et al. (2018)	Resilience, SES, Institutional analysis, and sustainability transitions	Technological transitions	Collaboration between socioeconomic and technology for SES	Literature review	Scale and time of technological transitions
McKenzie et al. (2018)	SES	Ecological	Adaptability in agroecosystems	Study case: Montana, USA	Agricultural management practices
Le Clec'h et al. (2018)	Ecosystem Services	Ecological and economic	Innovative approaches in ecosystem services	Study case: Brazilian Amazon rainforest	Climate regulation, soil fertility, water cycle, biodiversity, pollination
Gaba and Bretagnolle 2020	SES	Ecological	Integrate multiple visions into SES	Study case: Zone Atelier, France	Biodiversity of plants, arthropods, birds, and mammals
Sietz et al. 2017	Vulnerability	Social and ecological	Applied research through farm typologies	Study case: Sub-Saharan Africa	Water availability, agroecological potential, erosion, population urbanization, governance, income, and undernourishment
Eakin et al. 2017	SES and Systems Thinking	Social and Ecological	Importance of actors and their interests for SES integration	Literature review	Food security (individual and collective), economic welfare, land change, agroecological integrity, global food democracy.

CAPÍTULO II

Artículo publicado

IMPLEMENTING THE NATURE'S CONTRIBUTIONS FRAMEWORK: A CASE STUDY BASED ON FARM TYPOLOGIES IN SMALL-SCALE AGROECOSYSTEMS FROM THE MEXICO HIGHLANDS

LAURA RODRÍGUEZ BUSTOS, LEOPOLDO GALICIA, MARIANA BENÍTEZ, NATALIA PALACIOS ROJAS, IRENE RAMOS.



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Implementing the nature's contributions framework: A case study based on farm typologies in small-scale agroecosystems from the Mexico highlands

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Introduction: Integrating the heterogeneity of small-scale agriculture with the regulation, material, and non-material contributions is key to complementing the rural-support policy instruments. The objectives of the present study were to analyze the diversity of agricultural types of management in small-scale maize agroecosystems and discuss their implications for nature's contributions in the region of Valles Altos, México.

Methods: The methodology was conducted by constructing an agricultural management typology with multivariate statistical analysis for 112 small plots interviews. The operationalization of regulation, material, and non-material nature's contributions was based on the definition and counting of cultural elements from agronomic management for each class of contribution.

Results: The results indicate three different types of agricultural management defined mainly by the type of seed, the destination of harvest, and the type of tillage. This management diversity is guided by farmers' motivation to achieve food self-sufficiency or generate income from grain sales. Each management type has a unique provision of regulation, material, and no material contributions defined by the use of the native seed, use of stover, and management diversification.

Discussion: The integration of farm typology methods and nature's contributions framework reveals that it is critical to establish new incentives that include the biological and cultural diversity of agroecosystems and the individual motivations of farmers. This may help conserve the natural and cultural values of agriculture and design appropriate incentives for small-scale agriculture.

KEYWORDS
small-scale agriculture, policy, maize, *MasAgro*, Mexico

1. Introduction

Agroecosystems are socio-ecological systems widely known as sites that provide ecosystem services (Swinton et al., 2007; Potschin-Young and Haines-Young, 2011) and are closely related to ecological conservation and social welfare (Tomich et al., 2011; Eakin et al., 2015; Tenza et al., 2017). The knowledge of small-scale farmers reflects important sustainability principles such as resilience, autonomy, and self-sufficiency

(Palestina-González et al., 2021). Integrating the socio-ecological approach to managing agroecosystems and proposing new sustainability evaluation frameworks is possible if performance indicators recognize areas of sustainability such as social welfare, food security, and biocultural heritage (Tomich et al., 2011; Eakin et al., 2015; Tenza et al., 2017). The Nature's Contributions to People (NCPs) conceptual framework (Díaz et al., 2018) is based on and has similarities to Ecosystem Services (ES) (Daily and Matson, 2008; Potschin-Young and Haines-Young, 2011). The main difference is that the NCPs conceptual framework focuses on the central role of culture in defining contributions, human relationships, and knowledge of socio-ecological systems. Likewise, it considers contributions' actual and potential provisions under a co-production approach. At the same time, research based on ES focused on ecological functions that provide benefits without considering the role of people in providing (Díaz et al., 2018). This proposal eliminates the utilitarian vision of nature because it gives the same level of importance to material and non-material aspects of socio-ecological systems (Díaz et al., 2018; IPBES, 2019). This is an opportunity to reconcile visions between agricultural production and conservation; the NCPs recognize the central role of the co-production of benefits without neglecting the importance of agriculture's productive and monetary benefits.

The traditional Mexican agricultural system is the *milpa* (from the Nahuatl *milpan* "plot planted on top of"), a polyculture with maize as the main crop accompanied by beans, pumpkins, chili peppers, or tomatoes; in addition to herbaceous plants that grow naturally and are known as *quelites* (Hernandez-Xolocotzi, 1988; Aragón-Cuevas et al., 2005). The native varieties of the species cultivated in these traditional systems are the product of knowledge, technology, and agricultural practices that sustain the food sovereignty of peasant families and Mexican cuisine [Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), 2020]. Maize agroecosystems in polyculture or monoculture are considered to constitute the habitat of the genetic diversity of maize, and it is where the 64 native maize races known in Mexico are cultivated [Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), 2020]. Beginning in 1940, agricultural improvement began on small properties (<5 ha) where farmers were organized and had access to credits (Hernandez-Xolocotzi, 1988). Farmers and agrarian communities adapted new technologies such as fertilizers, tractors, and seeds during this time. Over time, this generated a high variability of new agroecosystems, ranging from large-scale, highly industrialized systems in the north of the country; to less industrialized small-scale systems concentrated in the center and southeast (Alvarez et al., 2014). Boege (2008) point out that agroecosystems are productive systems where ecosystems and cultural traditions are conserved. The government's responsibility must be channeled toward conserving agricultural fields, germplasm, and farmers' knowledge.

Understanding the heterogeneity of management practices and farmers' preferences can help define proper incentives and adjust policies to the socio-ecological context of agriculture (Antoni et al., 2019; Jaleta et al., 2019; Ratna-Reddy et al., 2020). Farm typologies are a way to capture, summarize, and understand the variability of farms (Alvarez et al., 2014). Typologies are constructed from individual numerical and categorical variables highly accurate because they are recorded at plot scale (Bhattarai et al., 2017), and the results are interpreted within a broader context because it categorizes groups of plots and types of producers (Guarín et al., 2020; Hammond et al., 2020; López-Ridaura et al., 2021; Santos et al., 2021). For this reason, farm typologies help develop interventions and guide appropriate policy approaches. In small-scale agriculture, crop management partly results from decisions made by individual farmers regarding the type of incentives, technology, and inputs applied to production (Alvarez et al., 2018; Santos et al., 2021). All farmers have different needs, interests, and objectives (Davidova et al., 2012); in addition, the biophysical, institutional, social, and economic contexts can be largely heterogeneous between localities or regions, so each farmer responds differently to these drivers of change (Alvarez et al., 2014; Pinto-Correia et al., 2021).

The National Development Plan (PND) is the highest-ranking political instrument in Mexico; it defines small-scale as agricultural production of up to 0.2 hectares with an irrigation system and up to 5 hectares of rainfed land (Gobierno de México, 2020). Small-scale agriculture is a priority for the national economy because it represents 54% of food production and 80% of contracted and paid employment (Gobierno de México, 2020). Production is mainly for self-sufficiency, and the main crops are maize, sugar cane, coffee, beans, and squash, concentrated in the country's central region (Gobierno de México, 2020). Maize cropping has a wide distribution throughout the territory. Its biological diversity is linked to management practices, with more than 59 native maize varieties grown in small-scale systems (<5 ha) (Bellon et al., 2018, 2021). This biological and cultural diversity of maize agriculture is represented in rural policy programs protecting maize diversity and the milpa system, with the "Ley Federal para el Fomento y protección del maíz nativo" (Federal Law for protection and promotion of native maize) (Diario Oficial de la Federación, 2020). In other initiatives, the government promotes economic and material incentives through payments and fertilizer distribution with programs like *"Fertilizantes para el bienestar"* (fertilizers for welfare) (Gobierno de México, 2022). The lack of information regarding the high diversity of agricultural management types in Mexico and their relationship with contributions to people hinders the inclusion of biological and cultural diversity in national and international sustainability policies (Piñeiro et al., 2020).

Despite the versatility of farm typologies (Ragkos et al., 2017; Alvarez et al., 2018) and the wide biological and cultural diversity in maize agriculture in Mexico (Acevedo et al., 2011; Bellon et al., 2021), the application of typologies to assess agroecosystems' contributions to people or inform agricultural policies have been scarce and limited to the center and Southeast of the country, however, some studies address water resource conflicts (LaFevor et al., 2021), economic productivity (Zepeda-Villarreal et al., 2020), and to document farmers' perspectives (Novotny et al., 2021). The objectives of the present study were to analyze the diversity of agricultural management in small-scale maize agroecosystems and discuss its implications for the provisioning of NCPs in the highlands of Mexico. The methodological approach is based on integrating the social-ecological system (SES) and NCPs frameworks. It can be replicated in other social-ecological contexts to recognize the influence of management on the contributions, agricultural production, and wellbeing of farmers' families. This study proposes that agroecosystems' management practices, inputs, and elements can be operationalized and interpreted as regulation, material, and non-material indicators under the NCPs framework.

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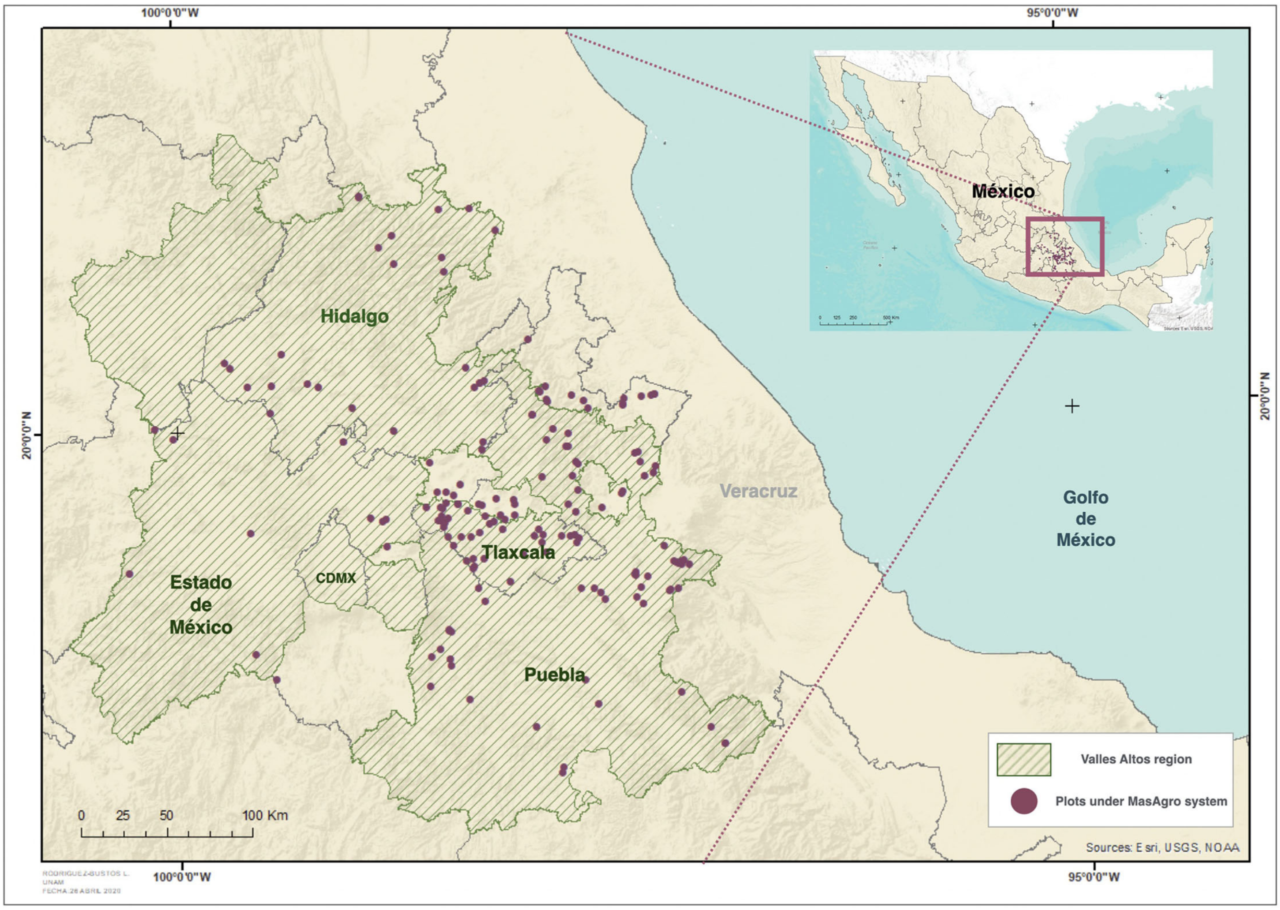


FIGURE 1
Location map of Mexico highlands. The Mexico highlands region states are shown in green; the plots considered in this study are marked purple.

2. Materials and methods

2.1. Case of study

Mexico highlands is a geomorphological region characterized as a central highland with an altitude between 2,200 and 2,600 (m.a.s.l), surrounded by a mountainous volcanic area with natural temperate forest ecosystems. The climate is temperate-humid, with precipitation concentrated between May and September (Bobbink et al., 2003). In this area, the stratovolcanoes Iztaccíhuatl (5,220 m a.s.l.), Popocatépetl (5,450 m a.s.l.), and Matlalcueye (4,461 m.a.s.l.) dominate the landscape (Bobbink et al., 2003). The prevailing soil type is Andosol developed over pyroclastic fall materials such as tephra, ash, and pumice [World reference base for soil resources (WRB), 2015]. The region comprises parts of the states of Estado de Mexico, Hidalgo, Tlaxcala, and Puebla in the center of the country (Figure 1). The area is densely populated and located in the vicinity of the capital city of Mexico. The surrounding area is highly populated, and industry, forestry, and agriculture are practiced in areas once covered by temperate mountain forests dominated by pines and oaks (Rodríguez-Bustos et al., 2022a). In addition to agriculture, food processing and packaging activities predominate (INEGI, 2010). Mexico highlands was the third largest region included in *MasAgro* (*Modernización Sustentable de la Agricultura Tradicional,* Sustainable Modernization of Traditional Agriculture), which was a public policy program to promote sustainable intensification in Mexico through technical guidance on the selection of farming technologies Secretaría de Agricultura y Desarrollo Rural (SADER), (n.d.); Turrent-Fernández et al., 2014; Centro Mexicano de Derecho Ambiental (CEMDA), 2016; Centro Internacional para el mejoramiento del Maí-z y el Trigo (CIMMYT), 2020.

MasAgro offered farmers a technological menu that included specific management practices such as fertilization diagnosis related to soil nutrients analysis before the agronomic cycle started, integral fertilization associated with a complete scheme of recommendations for fertilization, conservation agriculture, market diversification, and seed availability [Centro Internacional para el mejoramiento del Maí-z y el Trigo (CIMMYT), (2012)]. It was launched in 2010 and ended in 2020, primarily supported by public funds from the Board of Agriculture and Rural Development of Mexico and private donors [Secretaría de Agricultura y Desarrollo Rural (SADER), (n.d.); Centro Internacional para el mejoramiento del Maí-z y el Trigo (CIMMYT), 2020]. The implementation of *MasAgro* in the region represented an opportunity to test the operationalization of a conceptual framework through its elements and actors because all agricultural plots analyzed in this investigation are located within the same geographic area and are managed according to a standard policy instrument through which they have been characterized. The

112 plots use maize as a major food crop, have an average farm size of 1.68 ha, and the land property is ejido or private (Table 1). The ejido in Mexico is one of the modalities of land tenure, it refers to a type of agrarian social property. Its configuration is historical because its objective was to restore agricultural land to peasants during the revolutionary period. In this type of property, tenure is collective and is regulated by an ejidal assembly, which is the command center in which the decision-making process is concentrated [Centro de Estudios Sociales y de Opinion Publica (CESOP), 2019].

2.1.1. General methodology

The interpretation of contributions is based on the conceptualization of *Mexico highlands* as a social-ecological system (SES). The key elements are three social-ecological interactions: policy programs, *in-situ* agricultural management, and NCPs (Rodríguez-Bustos et al., 2022a). The general methodology for this investigation is presented in Figure 2, describing data sources and products. The first data source was the semi-structured interviews performed by *MasAgro* technicians in the field and registered at the plot level between 2016 and 2019. The interviews contain detailed information about agricultural management, which was used to perform a farm typology, and a farmer profile for each farm typology. The second data source was the workshops conducted by the research team with farmers and partners of the International Center for Maize and Wheat Improvement (CIMMYT) in in-person and remote meetings between 2019 and 2021, respectively. The main objective of the workshops with CIMMYT partners was to operationalize the NCPs framework by defining a set of management practices that can be interpreted as regulation, material, or non-material contributions. The operationalization was used to identify each management type's contributions. Workshops with the farmers were attended to validate the selection of contributions. The group of ten farmers for the workshops was made up of men between the ages of 45–65, with high school as the highest level of studies and Spanish as their only language. The sections below describe in detail each step of this general methodology.

TABLE 1 Biophysical and agronomic characteristics of agricultural plots in Mexico's highlands.

Characteristic	Mexico highlands
Biophysical	
Altitude (m a.s.l.)	1,500–2,500
Annual precipitation (mm)	700–800
Dominant soil type (FAO)	Andosol (volcanic)
Agronomic	
Average farm size (ha)	1.68
Major food crop	Maize
Land property	Private and Ejido

2.1.2. Data source

Access to the data for this investigation was established through a collaboration agreement between CIMMYT partners and the research team. The data source for the construction of farm typologies was a set of semi-structured interviews put together in what was called by the program officers "*bitácora*

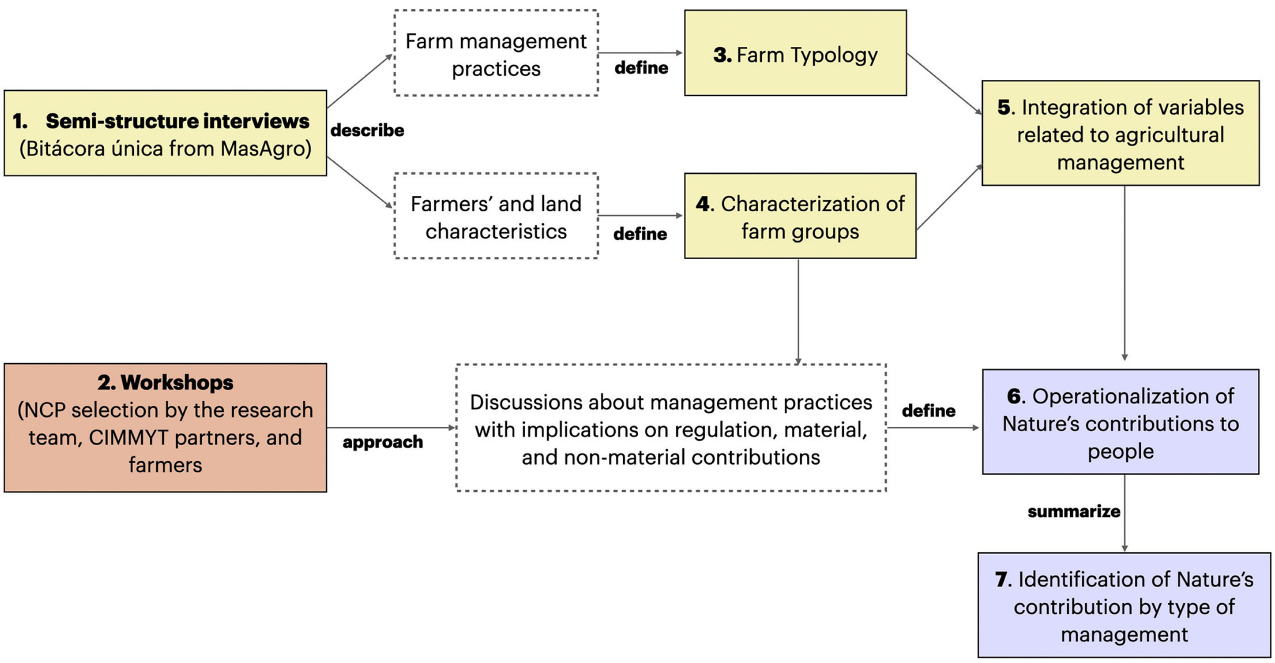


FIGURE 2
General methodology in this study. The data sources are marked with numbers 1 and 2, the boxes with solid lines and numbers indicate methodological steps, and the numbers indicate the order of the methodology. The boxes with dotted lines indicate elements of interest in each step.

única," a log book used by field technicians from the program to keep a record of all data related to a single plot. MasAgro technicians applied these interviews between 2016 and 2019. They included 50 open and optional questions organized into four topics: farmer's information, property description, technological menu, and agronomic management (Supplementary Table 1). Questions were aimed at obtaining information about plot localization, harvest destination, agronomic management, soil management, tillage, fertilization, irrigation, pest control, insecticides, crop rotation, and crop varieties as indicators of management practices. In total, 112 plots of rainfed maize for the spring-summer cycle with complete information were analyzed [Centro Internacional para el mejoramiento del Maí-z y el Trigo (CIMMYT), (2012)].

The farm typology was built based on the methodology proposed by Alvarez et al. (2014), summarized in three steps: (i) selecting the variables that define the typology based on a heterogeneous set of variables associated with agricultural management practices, (ii) recognizing the importance of each variable on the separation of management types, and (iii) describing the classified management types. The main objective of this typology was to organize agricultural management information to evaluate the provision of contributions by type of management. In this case study, most agricultural practices' heterogeneity was given at the plot scale. Therefore, plot-based numerical and categorical variables were selected to build the typology (Table 2). This set included variables reported for all 112 plots in the "*bitácora única*" and could be interpreted under the conceptual framework of NCPs.

2.1.3. Statistical analysis

The methodology of Alvarez et al. (2014) was performed using factor analysis of mixed data (FAMD) to reduce the dimensions of interest. The main strength of the methodology proposed by Alvarez et al. (2014) is that it allows summarizing heterogeneous information from different management systems, FAMD allows giving the same importance to the numerical and categorical variables of agricultural management because it does not separate the data for treatment (Alvarez et al., 2018; Sinha et al., 2022). Based on the coordinates of each plot in the FAMD, a cluster analysis of agricultural management types was carried out using the NbCluster algorithm. Significant differences between the management types were determined using a similarity analysis (ANOSIM). Statistical analysis and figure drafting were conducted in R and Python. The anonymized database and scripts used are available in the GitHub repository.

2.2. Operationalization of Nature's Contributions to People framework

The operationalization of NCPs was divided into two steps; the first one implies the selection of operational variables from the agricultural management related to contributions. In this step, the selected variables for each category were defined with the responses of *MasAgro* partners, three groups of farmers participating in *MasAgro*, and the input of four university academic scientists in the area of Sustainability Science (Table 3). According to the IPBES (2019) conceptual framework, NCPs were classified into regulation, material, and non-material.

TABLE 2 Variables for farm typology.

Variable	Description	Units or categories
Fertilizers	Fertilization intensity	kg/ha
Seed	Type of seed	Native, open-pollinated variety, or hybrid
Tillage	Type of tillage	Manual or mechanical
Residues	Use of CROP residues	Sale, stover
Yield	Productivity per farm	tons/ha
Harvest use	Type of use	Sale, food self-sufficiency, or both
Food self-sufficiency	Amount of the harvest used for self-sufficiency	kg
Land property	Land tenure	Ejido or private

The second step was establishing the relationship between the type of management and NCPs. This step is expressed through a presence/absence table that classifies the operational variable for each management type. Finally, the contribution level per management type was classified as low, regular, or high according to the percentage of farms with the presence of the operational variable for every contribution.

3. Results

3.1. Farming systems in Mexico highlands

The FAMD constructed from agricultural management variables accounted for 40% of the data variability in the first two dimensions (Figure 3). Harvest use, type of tillage, and seed type separate the data in the first dimension (DM1) of the FAMD and explain 23.5% of the variance (Figure 3). Harvest use explains 24.5% of the variance in DM1. It refers to the destination of the crop, which is either sold to the tortilla industry or used for food self-sufficiency for farmers and their families, and, in some cases, for both purposes. The type of tillage accounts for 26% of the variance in DM1; tillage is manual when only simple tools and human force are used; animal tillage refers to a conventional plow pulled by cattle, and mechanical tillage refers to tractors or threshers used for cleaning and harvesting. Seed type accounts for 18.5% of the variance in DM1 and refers to native, hybrid, or open-pollinated variety seed planting. Native seed is a farmer-owned maize variety stored during the previous agricultural cycle; the hybrid seed is a trademark sold as agricultural input by seed companies, intended for yield stabilization purposes; improved seed still lacks a trading name because it is in the experimental phase. The second dimension (DM2) of the FAMD explains 15.9% of the total data variability. In DM2, plant residues as stubble and plant residues for sale in packages are the main variables that separate the data. The variable use of residues as stubble accounts for 40.2% of the variance. It refers to maize residues as organic fertilizer and a protective layer to prevent soil erosion and moisture retention. Using crop residues for sale accounts for 40.6% of the variance and refers to the sale of forage for livestock (Figure 3).

In Figure 4, plots are shown colored according to three variables to illustrate the reduced dimensions of the FAMD. Concerning seed type, native seeds (green) represent 60% of plots in Mexico highlands;

TABLE 3 Participants for the selection and validation of nature's contributions.

Focus of participation	Category	Description	Number of participants
Validation	Farmers	Three focal groups at the municipalities of Piedra Canteada, Sanctorum y Nanacamilpa	10
Selection	International agencies	Technician, HUB manager, and scientist from CIMMYT	4
	Research team	Academic team in this research	4

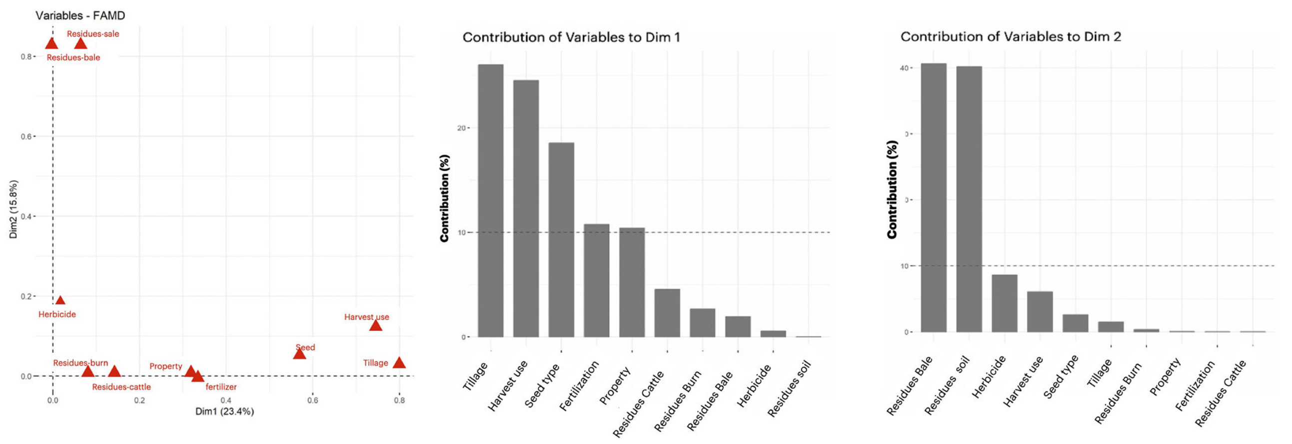


FIGURE 3
The graph on the **(Left)** shows the coordinates from the variables that construct the FAMD. The main variables in DM1 (23.5%) are tillage, harvest use, and seed type. In DM2 (15.9%), the main variables are the use of crop residues for sale or use as bale. The weight (%) of variables in each FAMD component is shown in the **(Central)** graph for DM1 and on the **(Right)** for DM2.

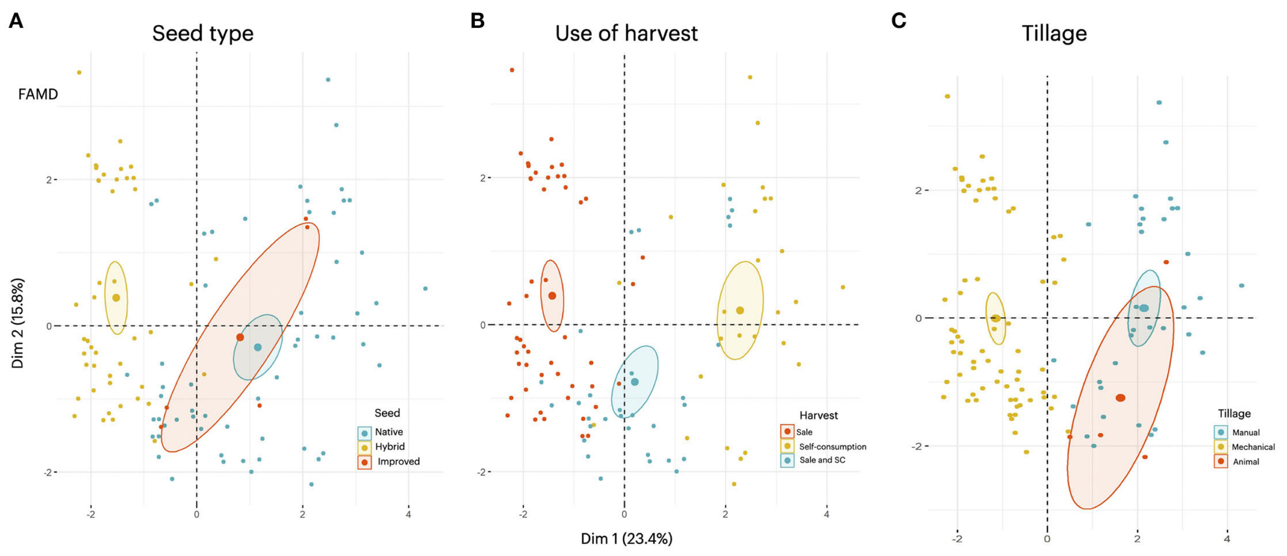


FIGURE 4
FAMD for farm typologies. Graphical representation of Mexico highlands plots and their distribution, showing each plot according to the type of property **(A)** seed type, **(B)** use of the harvest, and **(C)** type of tillage. Each dot corresponds to one plot in the field; the color of the dots highlights the categorical variable in the legend; ellipses correspond to confidence ellipses around the mean.

improved variety (red) is used by 5% of farmers; hybrid seed (yellow) is used by 35% of farmers (Figure 4A). Then, concerning harvest use, food self-sufficiency (yellow) is practiced by 45% of farmers; harvest for sale (red) is practiced by 26.5% of farmers; and mixed-use (green), characterized by selling the crop and storing it for food self-sufficiency, is practiced by 28.5% of farmers in the region (Figure 4B). The last variable, tillage, shows that mechanical tillage (yellow) is used by 85% of farmers, manual (green) is used by 10% of farmers, and animal tillage is used in 5% of plots (red) (Figure 4C).

The cluster analysis from NbClust results in three clusters that describe the number of management types in Mexico highlands (Figure 5A). The similarity analysis (ANOSIM) shows that the variance between the clusters is greater than the internal variance in each one (Figure 5B). Results show three groups of plots that are statistically different, each corresponding to a type of management ($R = 0.85$; $P = 0.001$).

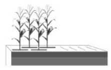
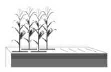
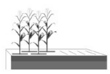
The results from farm typology classification show that type one comprises 46% of the plots where more than one-half of farmers sow the hybrid seed and sell the grain to the tortilla industry; 50% of farmers in this cluster save an average of 408 kg of grain for the family food self-sufficiency and use residues for stubble. Type two comprises 29% of the plots and is characterized by conservation-oriented traditional agriculture; 100% of farmers in this cluster sow native seed, apply manual tillage, and practice food self-sufficiency and diversification of practices. Farmers store an average of 1 ton of grain for food, which meets their annual consumption of maize. Diversification of agricultural practices is observed in residue management because it is allocated for use as stubble, feed for cattle, and sold as bales. Type three accounts for 24% of the plots and is characterized by industrial agriculture for maize grain marketing. All farmers in this cluster plant a hybrid seed, apply mechanical tillage, use the residue for stubble, and sold as bales. Fertilizers and herbicides are widespread in *Mexico highlands*, with 95% of plots using them, no matter the type of management, but types one and three use twice the amount of fertilizer as type two. Regarding herbicides, type three uses twice as much as types one and two. In terms of yield, types one and three double the yield of type two (Table 4; Supplementary Table 1).

3.2. Nature's contributions

Table 4 shows the operationalization of NCPs in *Mexico highlands*, the first and the second row present the general classification of contributions in regulation, material and non-material, and the names of contributions according to IPBES (2019). The operational indicator refers to a management element selected to evaluate the presence or absence of each contribution. The table also briefly describes the importance and interpretation of each operational indicator for NCPs. The regulation class was represented by the protection of soils and habitat creation contributions, and the operational indicators were the use of the native seed. The management of vegetal residues as stover to cover the soils until the next agronomic cycle. The material contributions were represented by two elements, food and feed. Food is related to the material resources produced in the agroecosystems sold to the tortilla market; in this case, the operational indicator is the presence of yield. Feed is related to the material resources produced in the agroecosystems used for the self-sufficiency of the farmer's family. The non-material contributions were represented by Supporting identities, defined as a contribution related to the cultural heritage of farmers. The operational indicators selected were a native seed, manual labor of the land, and management diversification.

The results of NCPs operationalization show that each management type has different levels of contributions (Figure 6). Type 1, compared to types 2 and 3, is a regular contributor to all regulation, material, and non-material contributions. Type 2 is the highest contributor to habitat creation, feed, and supporting identities; but is the lower contributor to the protection of soils and food. Type 3 is the highest contributor to the protection of soils and food but is lower for habitat creation, feed, and supporting identities. From a socio-ecological perspective, the results of NCPs reveal the elements of agricultural management related to a particular class of contributions.

TABLE 4 Integration of management, farmers' profile, and plot characteristics.

Farm type	Characterization of management, farmers' profile, and plot characteristics	
Type I		The management is intensive, characterized by the use of synthetic fertilizers, mechanized tillage, use of stover, and mainly hybrid seeds.
		All farmers are dedicated to agriculture as economic activity, they sell maize for the tortilla industry. Half of the farmers sow native seeds and store the maize for food self-sufficiency.
		The land is in a communitarian property called ejido, and the size of plots is bigger in comparison with types two and three.
Type II		The management is of conservation agriculture, characterized by the use of native seeds, synthetic fertilizers, less intensive than the other types, and manual and animal tillage.
		All farmers are dedicated to agriculture for food self-sufficiency and a quarter part of them also use maize for sale.
		The land is private property, and the size of plots is smaller in comparison with the other types.
Type III		The management is intensive, characterized by mechanized tillage, the use of synthetic fertilizers, and hybrid seeds.
		All farmers are dedicated to agriculture as economic activity and sell their maize for the tortilla industry. Less than 10% of farmers also use native seeds, use maize residues to feed cattle and sell maize residues in a bale.
		The land is in a communitarian property called ejido, and the size of the plots is medium in comparison with types one and two.

4. Discussion

4.1. Farm diversity

The farm typology indicates that in *Mexico highlands*, management practices separate farmers with different use of harvest and probably different socioeconomic histories. The seed type, type of tillage, and harvest destination defined the three types of management. This suggests that the heterogeneity is partly driven by the motivation of reaching food self-sufficiency or earning an income from harvest sales. Some studies highlight the remarkable heterogeneity in farmers' decisions related to incentive programs (Hasler et al., 2019), mainly promoted for incentives that do not count the heterogeneity of practices (Kaiser and Burger, 2022). The FAMD reveals that the differentiation of management is likely due to the shared evolution of farmers with different goals or possibilities; this appears to be expressed by the type of seed because this variable

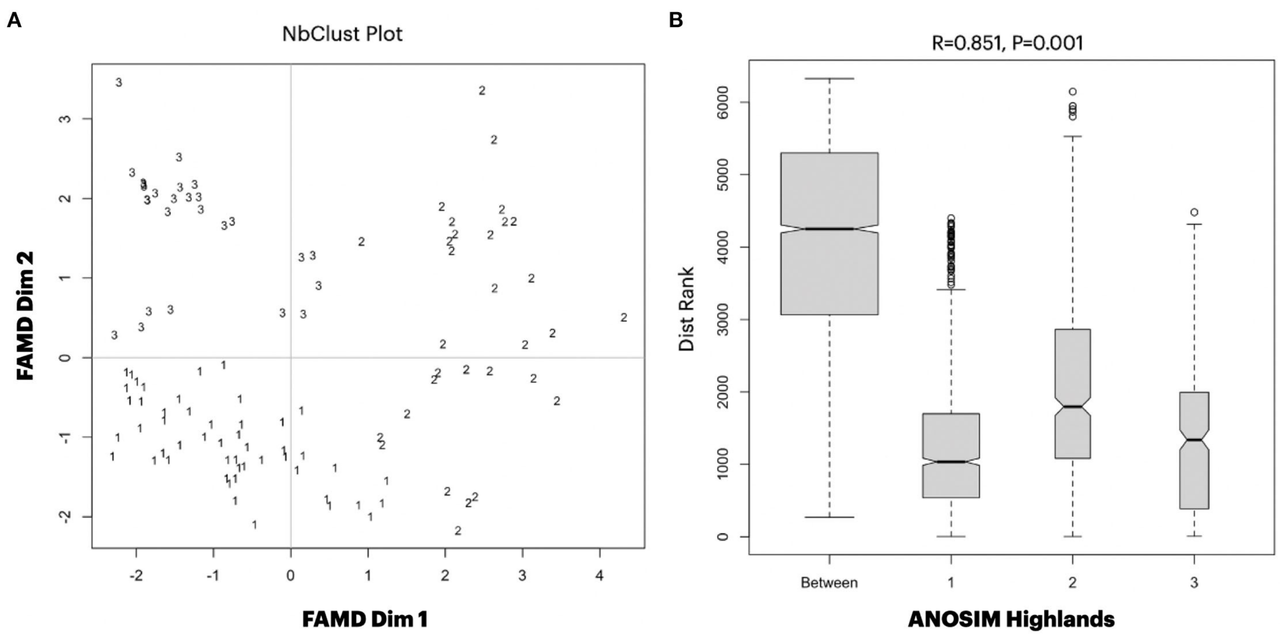


FIGURE 5
Similarity analysis for farm typology. **(A)** Shows the cluster analysis from NbCluster. Each plot is displayed according to its coordinates in the FAMD, with an assigned management type ranging from 1 to 3. **(B)** Shows the results of the significance test with ANOSIM. The ANOSIM X-axis shows the significant differences calculated between groups (between) and within each group (1, 2, and 3).

separate management affinities and defines harvest destination and type of tillage.

Individual practices such as fertilization or seed type in each management type are interrelated and can even be interpreted as a "bundle" of practices (Santos et al., 2021). In *Mexico highlands,* seed type was more important than yield as an indicator of production success. A high yield is essential for commercially driven agricultural management such as type three. In contrast, for management based on food self-sufficiency, such as type two, a lower yield is not critical as long as food demand is met and seeds are obtained for the next agronomic cycle. Pradhan et al. (2014) point out that yield and self-sufficiency should be viewed as supplementary indicators of food security benefits at the local, regional, and global scales because yield indicates physical accessibility to food, but self-sufficiency describes feeding affordability. Besides identifying different types of management, the farm typology emphasizes the importance of socio-cultural elements of agricultural management that go beyond yields, such as the importance of seed type, tillage, and the diversification of agricultural practices. The social aspects of management involve the prevailing attitudes toward farming, ideas about nutritional value, seed conservation mechanisms, and organized interests (Smith et al., 2010; Ingram et al., 2015). This is probably because farmers prioritize their decisions over any institutional scheme and define their management based on cultural preferences, even though political programs offer them other options (as is the case of *MasAgro*).

Agricultural management also represents an opportunity for farmers to establish cultural differentiation related to purchasing capacity (Warde, 2005; Kaiser and Burger, 2022). For example, selecting a seed type, either native or hybrid, reflects social relationships on a local scale or across scales (Santos et al., 2021). The exchange of native seed varieties between farmers indicates a local governance process, while the use of hybrid seed indicates multi-national trade transactions (across scales) (Gaventa, 2006; Martin-Lopez et al., 2019). Recognizing the type of social relationships also means recognizing power relationships (Gaventa, 2006). We suggest that management based on native seeds in *Mexico highlands* attain higher control of their sovereignty, and empowerment is based on community-based management of production inputs. While management based on hybrid seeds could be influenced by external factors like the market, seed price, access to seed, and their influence over seed price commercialization. Hernández et al. (2022) note that in *Chiapas Highlands*, agricultural practices based on the use of native seeds are conceived as a resistance and autonomy tool toward forms of power from outside the community; therefore, today and in the future, the use of native seed is a way to maintain political and economic autonomy. This suggests that the social relationships within a particular management system evidence the role of native seeds in the formulation of development projects in rural communities. For *Mexico highlands*, is necessary to identify how these power interrelations are regulated by formal institutions (laws and ejido), or informal institutions (habits and customs) (Martin-Lopez et al., 2019). This information may even influence the region's political and territorial scope programs.

Synthetic fertilization and herbicide were not crucial for farm typologies in *Mexico highlands* because both are widespread practices and are used in 95% of plots. This does not mean that fertilization is not an essential element; quite the contrary, because, in Mexico highlands, maize monocrops predominate, which is critical to minimize the use of synthetic fertilizers to ensure the sustainable transition of agriculture. One of the common issues of conventional agriculture is the tendency to over-fertilize based on the assumption that more is better than less (Hasler et al., 2019). In *Mexico highlands,* we found a synergy between fertilization intensity and seed type. For example, the fertilization intensity in type three (where farmers

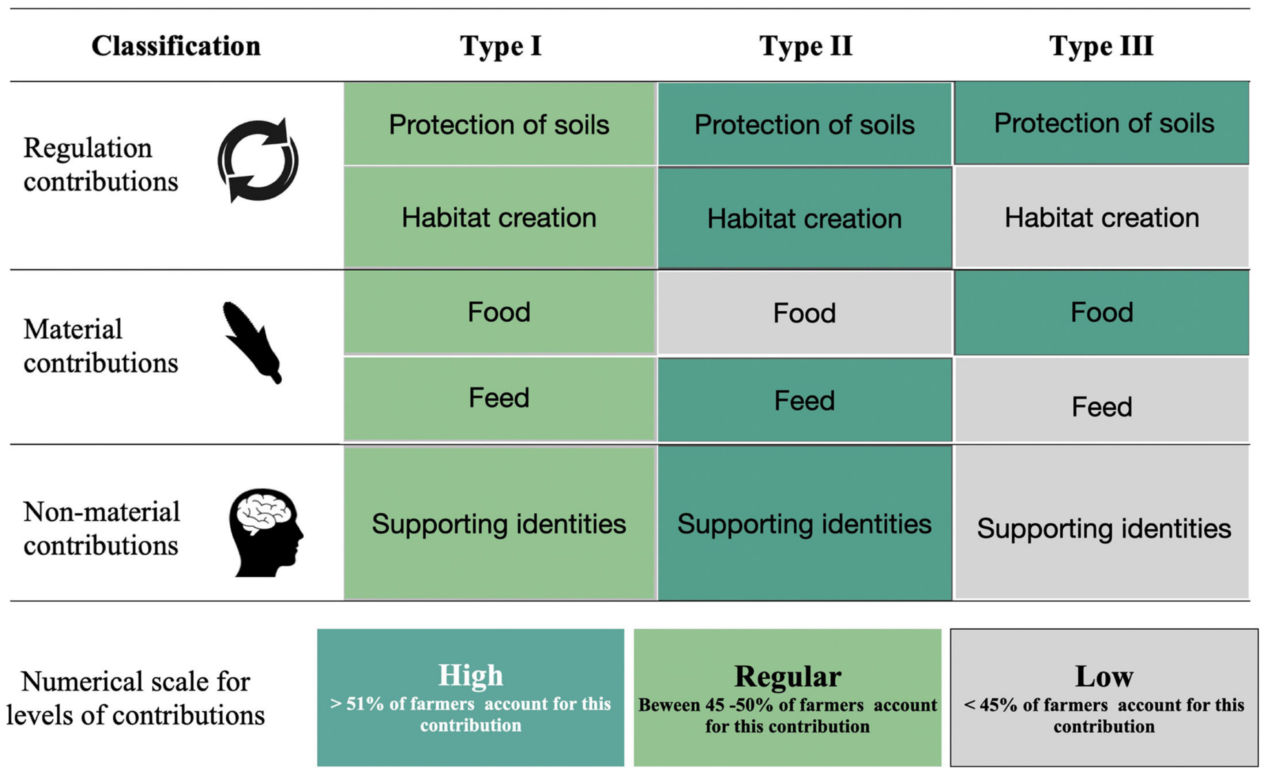


FIGURE 6
Nature's contributions in maize agroecosystem from Mexico highlands. The shades of gray show the level of contribution in the management types, the dark gray means a high level of contribution, light gray means a regular level of contribution, and white means a low level of contribution.

use exclusively hybrid seed) doubles the intensity of type two (with exclusive use of native seed). This is consistent with two case studies in Southeastern Mexico, where farmers planting native seeds are more labor-intensive and less agrochemical-intensive (Perales et al., 2005; Soleri et al., 2006). Unlike native seeds, fertilization is linked to the farmer's purchasing power (Hamid et al., 2021). Hammond et al. (2020) observed in small-scale maize systems in the African tropics that the management types use higher fertilizer when it is more accessible or affordable. In *Mexico highlands* there are high rates of fertilization. The interviews indicate that the widespread use of fertilizers is open to incorporating organic amendments, mainly because farmers recognize undesirable characteristics of synthetic fertilizers, such as increased production costs and the requirement to apply them at exact dates. The most crucial evidence of disagreement is that farmers use it less in crops intended for food, which in all cases involves native seed. This reality should be a wake-up call to Mexican authorities to modify incentive programs such as "*Fertilizantes para el bienestar*," based on providing synthetic fertilizers as incentives for crop production rather than promoting practices based on the conservation of ecological soil functions.

4.2. Nature's Contributions to People: A framework for wellbeing

The farm typology approach allowed exploring the relationships between policy, management, and contributions from two perspectives: the response of contributions to management practices and the coherence of agricultural management (Santos et al., 2021). The response of contributions to management practices refers to the impact—usually adverse—of management on biodiversity and loss of cultural heritage (Santos et al., 2021). In this study, the NCPs framework highlights the positive effect of management practices on soil protection, habitat, and supporting identities. Material contributions are the most important in agroecosystems because they represent food production. In agricultural landscapes, these contributions are indicators of food security because they distinguish the use of crops as either family food or for other users (Gaba and Bretagnolle, 2019), and the primary source of livelihood and income for farmers. In *Mexico highlands* all management types contribute to food security. Still, if harvest continues to be valued only through yield, the role of these small-scale systems in food security at local and regional levels could not be recognized. The operationalization of NCPs makes it possible to distinguish between the contribution to food self-sufficiency and food for markets. Within the regulation contributions, using stubble in all management types is critical for soil conservation in *Mexico highlands*. Especially considering that it is the only regulation contribution represented in management type one, where stubble is an effective way to compensate for the potential adverse effects of fertilizers and mechanical tillage (Lal, 2016). Rodríguez-Bustos et al. (2022b) point out that using manure to keep the soil covered reduces erosion and increases soil fertility.

Agricultural values refer to the specific relations of human nature constructed among broader values held by diverse stakeholders to produce better social-ecological outcomes in land systems (Ellis et al., 2019; Bruley et al., 2021). Each type of management in *Mexico highlands* reflects the unique value of agriculture for farmers (Díaz et al., 2018). The native seed, use of stubble, and residues to feed livestock are practices associated with conserving maize genetic resources, soil protection, supply of organic matter to the soil, and the design of resilient agriculture. Bellon et al. (2021) note that using native maize seed is the only strategy contributing to the local and regional food supply. In this research, we consider that native and hybrid seeds contribute to food security; native seeds contribute locally, and hybrid seeds at the regional scale. However, only the native seed gives continuity to what Bellon et al. (2021) called *additional incentives* related to maize, summarized as maintenance of genetic evolution, self-sufficiency, and alternative trade networks.

The coherence of agricultural management refers to agroecosystems with a particular farming system displaying individual (each farmer) but shared (farmers with similar management) goals. For example, in *Mexico highlands* each farmer selects the management practices applied in their plots. Even so, the purpose of attaining food self-sufficiency or selling to earn an income is shared with other farmers. For this reason, the NCPs identified from a management type could be integrated into the design of incentives according to the objective of management, the motivation of farmers, and the conservation of specific contributions. The contributions associated with cultural practices should not be deemed "additional" to the other benefits of agriculture, mainly because of the challenge of assigning a monetary or substitute value to the relationship of people with their environment (Swinton et al., 2007; Hanaček and Rodríguez-Labajos, 2018). In *Mexico highlands* agroecosystems that include traditional knowledge, like types one and two, are essential to understanding people's cultural identity and environmental sustainability (Hanaček and Rodríguez-Labajos, 2018). In these types of management, unlike type 3, we could identify that agriculture is their principal occupation, they have autonomous decisions about agricultural management, and their activities are subsistence-oriented. These are characteristics that, according to Wolf (1955), are common expressions of cultural values among peasants. Additionally, we agree with the vision of Rendón-Sandoval et al., 2021 by highlighting that traditional knowledge is expressed through the co-production of knowledge between the people who control and manage their resources because they represent a closer relationship with nature, compared to those who assume their autonomy from the market (Ploeg, 2010). Based on the present study results, integrating the typology with the NPC framework is an appropriate way to evaluate agricultural sustainability. It would reduce the focus on incentives in implementing a general management approach or disregarding the conservation of contributions and services. However, it is necessary to broaden the study of these aspects through an ethnographic vision, which lays the theoretical foundations and deepens aspects of traditional knowledge.

4.3. Land management sustainability in agroecosystems with cultural and natural value

Studies that quantify and integrate NPCs into agricultural ecosystems are vital for identifying benefits and trade-offs and making decisions involving these dualities. The response of governments to the 2030 Agenda to transition to sustainable agriculture has focused only on adjusting their policies to improve agricultural performance, such as promoting payment-based incentives to reduce agricultural expansion, funding for intensification, and incentives to implement environmentally friendly practices (Santos et al., 2021; Yazdanpanah et al., 2021). *MasAgro* was a technology transfer-based program, and the evidence indicates that it included intensification and environmentally friendly practices. However, there is evidence of the program's potential effect on farmers' decisions because the *bitácora única* characterizes the technologies the farmer intends to implement in the short term (Rodríguez-Bustos et al. in review). The sustainable transition of maize agroecosystems in Mexico requires understanding the adoption of specific management practices by farmers and the values assigned to different NPCs in all maize agricultural systems, from the milpa to monocrops. Before implementing actions affecting the natural and cultural value of small-scale maize agroecosystems, authorities should consider this. Some examples cannot be replicated, such as the political program named "*Kilo por Kilo*" in Mexico (1995–2000), which consisted of exchanging native for hybrid seeds to increase yield (Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), 2020). One of the adverse effects of the program was the cross-breeding between native and hybrid seeds that led to the permanent modification of maize varieties in the southeast region [Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), 2020].

Bellon et al. (2005) point out that policy programs based on technology transfer play a central role in farmers' decision-making, mainly because they address limited access to improved seeds and synthetic fertilizers. In *Mexico highlands* the "*Fertilizantes para el Bienestar*" (Fertilizer for Welfare) program delivers up to 600 kg of synthetic fertilizers to small-scale maize farmers [Secretaría de Agricultura y Desarrollo Rural (SADER), (n.d.)] because the Mexican government prioritizes programs to improve access to fertilizers and hybrid seeds (Dionne and Horowitz, 2016). Continuing this type of incentive does not visualize the cultural appropriation of maize for farmers seeking management alternatives based on environmental protection practices (Dyer and Taylor, 2008; Hernández et al., 2022). We recognize that there is a counterpart from the government through the "Ley Federal para el fomento y protección del maíz nativo" and "Eliminación de Glifosato." However, at the time of this investigation, no farmers declare to be part of these initiatives. In the future, it will be necessary to evaluate the effect of these policies on agricultural management. These effects should be recognized in all agroecosystems because the effects will not be the same in polyculture and conservation systems, such as the milpa. Compared to small and large-scale monocultures, where the use of fertilizers is a common practice.

5. Conclusions

Based on FAMD and NbClust, the operationalization verifies that in *Mexico highlands,* the NCPs is regulated by the type of agricultural management. The factor analysis of mixed data showed that categorical variables such as seed type and tillage contribute to a greater extent to the definition of a management type than numerical variables such as yield or amount of fertilizer to separate groups and identify practices or objectives shared among farmers or farmer groups.

Identifying contributions associated with management practices is key to communicating the importance of the cultural value of agricultural landscapes. *Mexico highlands* is a region characterized by small-scale agriculture where the main contribution of nature, in addition to food production, is the cultural value of the conservation of native maize, the permanence of agricultural practices such as manual tillage and seed exchange, and the contribution of native maize to food self-sufficiency in the region. These cultural elements need to be recognized in the current political programs. The identified contributions can be included in agricultural sustainability assessments and used to consolidate a new strategy for communicating the cultural value of agriculture to decision-makers.

The evidence from the *MasAgro* program points out that achieving sustainable development goals requires avoiding policy programs based on yield evaluation success and proposing incentives for groups of farmers with common objectives or motivations. This information and political action can consolidate new planning tools and establish more effective strategies for communicating agriculture's natural and cultural values to decision-makers. The agricultural history of Mexico has been dominated by social movements and global economic impositions that have led it to operate based on economic incentives, which has yet to be entirely successful. Transitioning toward sustainable agriculture means including agroecosystems' natural and cultural value in financial incentives to conserve them.

Data availability statement

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

Author contributions

LR-B, LG, and MB participated in the project's design and coordinated the study. LR-B, LG, and NP-R participated in the design of the fieldwork. MB, IR, and LR-B participated in the design of methodology and data analyses. LR-B wrote the manuscript. LG, NP-R, MB, and IR reviewed the manuscript. NP-R included relevant information because of expertise in the region of study. All authors contributed to the article and approved the submitted version.

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Conflict of interest

NP-R was employed by CIMMYT.

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

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1009447/full#supplementary-material

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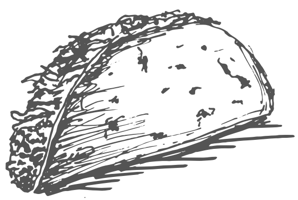
DISCUSIÓN Y CONLUSIONES



4. Discusión y conclusiones

La discusión y conclusiones se presentan en orden y concordancia al objetivo general y los objetivos particulares del trabajo de tesis.

El objetivo general de esta investigación fue analizar la relación entre el nivel de industrialización del manejo agrícola y las contribuciones de la naturaleza en agroecosistemas de maíz de pequeña escala en la región de Valles Altos, México. A partir de los resultados concluimos que, la importancia de estos modelos a pequeña escala radica en que constituyen el espacio físico donde se determina el éxito de la producción de alimento para las personas que compran el grano; y la seguridad alimentaria de las familias campesinas que cultivan para autoabasto (Bellón et al. 2021). Actualmente, los agroecosistemas de pequeña escala producen el 80% del alimento a nivel global (FAO 2019). Sin embargo, no hay sustentabilidad en todas las prácticas de manejo, y alcanzarla, debería estar enfocada en atender la demanda de alimento, y al mismo tiempo conservar biodiversidad y proveer beneficios directos e indirectos para las personas. Asegurar bienestar para el ser humano es una demanda internacional; la agenda política a través de la segunda meta de desarrollo sostenible, llamada *hambre cero*, incluyó explícitamente al sector agrícola para ofrecer soluciones a los problemas socio-ecológicos relacionados con la producción, abasto y desperdicio de alimento (ONU 2015; Liao and Brown 2018). Esta investigación reconoce que no todo puede optimizarse; las disyuntivas entre producción de alimento y conservación de la biodiversidad son un problema complejo que no puede atenderse a partir de soluciones simples o unidireccionales. Lo mismo ocurre con la conservación del patrimonio biocultural. Sin embargo, consideramos que los indicadores alternativos al rendimiento agrícola deberían incluirse como un nuevo esquema de evaluación de la agricultura, sobre todo en sitios con producción basada la pequeña escala y/o producción bajo principios de producción agroecológica.

En México, el modelo de desarrollo agrícola fomentado desde la Secretaría de Agricultura y Desarrollo Rural es concentrar esfuerzos al año 2024 para desarrollar una agricultura más sostenible. Los requerimientos operativos para esta meta están desarrollándose a través de iniciativas como la Estrategia

Nacional de Suelo para la Agricultura Sostenible (ENASAS) y un modelo de precios de garantía para el maíz; esto incluye generar acciones específicas para promover el cuidado y la salud del suelo, pagar la cosecha a más de dos millones de agricultores, y alcanzar la autosuficiencia de maíz en México. La ENASAS reconoce la importancia del ámbito ecológico para la sustentabilidad de los sistemas agrícolas en el largo plazo, delimita sus acciones en la urgencia de actuar para atender los problemas de degradación del suelo en México, y promueve la conservación del suelo como un plan de acción efectivo para la producción de alimento a largo plazo, y alcanzar la autosuficiencia alimentaria (Ortiz-García et al. 2023). El precio de garantía es una iniciativa favorable para la producción del maíz en México porque al aumentar el precio, la producción aumenta; y en sinergia con otras iniciativas, como el aumento del precio de importación, ayuda a disminuir la brecha para alcanzar la autosuficiencia alimentaria del país (Santiago et al., 2022).

A pesar de que hay iniciativas y programas para el campo favorables para acortar las disyuntivas entre producción y conservación; existen otros programas, como Producción para el bienestar y Fertilizantes para el bienestar, que han sido criticados porque no están conceptualizados bajo un esquema de sustentabilidad. El primero, conserva un objetivo basado en incentivos económicos (Gobierno de México 2022). El segundo, es un incentivo material que opera bajo el esquema de paquete tecnológico porque entrega hasta 600 kilogramos de fertilizantes a los pequeños para aumentar la productividad de cultivos básicos (Gobierno de México 2022). En 2009, Rockstrom y colaboradores mostraron que la intensificación agrícola basada en el uso de fertilizantes sintéticos es una forma de producción insostenible porque el suelo de los agroecosistemas ha perdido sus funciones ecológicas básicas, como el mantenimiento de los ciclos de C. N y P. La intensificación aumentó el rendimiento de los cultivos, sin embargo, ahora los agroecosistemas son poco fértiles, y fuente de contaminación de cuerpos de agua y emisores de CO_2 (Cassman et al, 2003; Robertson y Swinton, 2005; Sweeney et al, 2013; Norton, 2016; Chavaz, 2017). Ya no existe un balance energético entre los insumos y la producción agrícola, de modo que la intensificación rebasó la capacidad del suelo para mantener el ciclo de nutrientes, y ahora el crecimiento de cultivos está condicionado al uso de fertilizantes (Folke et al. 2002; Rockstrom et al., 2017).

Producción para el bienestar y Fertilizantes para el Bienestar evalúan el éxito de los programas a través del aumento del rendimiento agrícola, y lo consideran una variable adecuada para evaluar el avance hacia la autosuficiencia alimentaria en el país. La productividad agrícola comúnmente se evalúa a través del rendimiento, la ventaja de este parámetro es que es fácil de entender, es comparable entre tipos de cultivo y puede proyectarse a corto y largo plazo (FAO, 2020). Sin embargo, el rendimiento es una variable reduccionista de la complejidad de procesos que operan para lograr el mantenimiento de la producción de alimento. Otras variables específicas en el ámbito biofísico como la fertilidad del suelo, la calidad del agua, el manejo de residuos y la intensidad de fertilización no están reflejadas en el rendimiento. El caso de los procesos sociales tampoco tiene un indicador de evaluación agrícola, y procesos como la gobernanza entre campesinos, la seguridad alimentaria o el auto abasto tampoco pueden resumirse a una sola variable de productividad como el rendimiento (Tomich et al, 2011; Acevedo, 2011).

El primer objetivo de esta investigación fue construir el marco conceptual y analítico para estudiar los agroecosistemas de maíz de pequeña escala como un sistema socio-ecológico complejo. A partir de los resultados y de la investigación documental, podemos concluir que la inclusión de marcos analíticos de las Ciencias de la sostenibilidad son una guía conceptual adecuada para generar una agricultura con una visión más flexible e integral, que considere tanto a la conservación de los sistemas naturales, y al bienestar de las personas. Los resultados muestran que los marcos conceptuales de Sistemas socio-ecológicos (SSE) y el de Contribuciones de la Naturaleza para las personas (CNP) pueden operacionalizarse en un contexto regional de agricultura de pequeña escala, y permiten vincular a la gestión agrícola con elementos de bienestar social como la seguridad alimentaria, el patrimonio biocultural y la conservación de los ecosistemas. Toda parcela agrícola es un universo, y está moldeada por las decisiones individuales de los agricultores, reconocemos que esto limita las posibilidades de crear marcos analíticos o políticas generalizadas. Ante esto, el marco conceptual del capítulo 1 y la propuesta analítica del capítulo 2 son una base operativa que se puede utilizar para otros estudios de investigación que aborden la complejidad de los agroecosistemas a pequeña escala en paisajes tropicales.

Integrar sociedad y ambiente para el manejo de los agroecosistemas de pequeña escala debe promover la autosuficiencia alimentaria a partir del uso eficiente de insumos de producción, reducir riesgos asociados al cambio global y restaurar la capacidad de los suelos para producir alimento y otras contribuciones (Tittonell 2016; IPBES 2019). Además, debería visualizar propuestas con implicaciones políticas y sociales porque los resultados reflejan compensaciones socioeconómicas y ambientales tomadas por los actores implicados. Las aproximaciones metodológicas para abordar este tipo de problemáticas e interpretar el papel de los agroecosistemas como proveedores de contribuciones y servicios ecosistémicos tiene defectos y no hay acuerdos preestablecidos al respecto (Constanza et al. 1997; de Groot et al. 2002; MEA 2005; TEEB, 2016). Consideramos que integrar el enfoque socio-ecológico al manejo de los agroecosistemas y proponer nuevos marcos de evaluación de sustentabilidad es posible, siempre y cuando se integren nuevos indicadores de éxito productivo. Los nuevos indicadores pueden ser las contribuciones de la naturaleza porque reconocen el rol central de la coproducción de beneficios sin dejar de lado la importancia de los beneficios productivos y monetarios de la agricultura.

El segundo objetivo particular fue examinar los componentes y conductores del nivel de industrialización del manejo agrícola en los agroecosistemas bajo estudio. Los resultados muestran qué, el uso de semillas mejoradas y maquinaria son dos componentes del manejo agrícola que definen al nivel de industrialización del manejo agrícola en Valles Altos. La hipótesis inicial en esta investigación consideró que la fertilización sintética sería el componente del manejo que marcaría de manera más significativa la industrialización. Sin embargo, en el contexto de Valles Altos, la fertilización sintética es una generalidad, por lo tanto, la industrialización no se refiere a una práctica de manejo en particular, sino a un conjunto de prácticas asociadas que definen la industrialización de la agricultura. En la región de estudio la fertilización sintética, las semillas híbridas y el uso de maquinaria son el conjunto de variables que regulan el nivel de industrialización. Los componentes del manejo que estuvieron más distanciados de la industrialización fueron las semillas nativas, el uso de rastrojo, menos fertilización sintética y la labranza de conservación. A partir de este resultado podemos señalar que este tipo de prácticas pueden considerarse indicadores de sostenibilidad en los agroecosistemas de pequeña escala, y proponemos que las futuras políticas agrícolas y las estrategias de adaptación al cambio climático deberían reconocerlas y promoverlas para mantener las contribuciones a largo plazo.

El tercer objetivo particular fue operacionalizar la provisión de contribuciones de regulación, materiales y no materiales en los niveles de industrialización de los agroecosistemas. Las aproximaciones teóricas para estudiar e interpretar el papel de los agroecosistemas como proveedores de servicios ecosistémicos tiene defectos y no hay acuerdos preestablecidos al respecto (Costanza et al., 1997; de Groot et al., 2002; MEA, 2005). Es poco reconocido cómo las decisiones del manejo, la intensificación y la implementación de desarrollo tecnológico impactan la diversidad de servicios ecosistémicos asociados a estos sistemas manejados (de Groot et al., 2002; Perfecto et al, 2009). Los servicios ecosistémicos son comúnmente usados como indicadores del funcionamiento de un sistema a presiones locales y globales de cambio porque sirven como un enlace entre los componentes sociales y ecológicos (MEA, 2005; Hough et al., 2018). Los servicios ecosistémicos asociados a biodiversidad y hábitat cobran relevancia al considerar que de estos mismos depende la disponibilidad local de recursos que aseguran el éxito de la producción agrícola (Boomarco et al., 2018). Por ejemplo, el rendimiento agrícola está determinado por la fertilidad del suelo, pero reconocer el rendimiento sin exhibir la fertilidad diferencial del suelo en sistemas de manejo resulta poco práctico para describir la dinámica de un sistema, y sobre todo para identificar problemas asociados a la producción de alimento.

Uno de los principales retos es promover la aceptación y el escalamiento de los nuevos enfoques conceptuales y dirigirlos hacia los tomadores de decisiones. Las contribuciones de la naturaleza propuestas en esta investigación, pueden incluirse en las evaluaciones de sostenibilidad agrícola y utilizarse para consolidar una nueva estrategia para comunicar el valor cultural de la agricultura a los tomadores de decisiones. La evidencia del programa MasAgro señala que alcanzar metas de desarrollo sostenible requiere eliminar a los programas de política basados en el éxito de la evaluación agrícola a través de un solo indicador, en este caso el rendimiento. La propuesta más viable para eliminar esta visión reduccionista de la agricultura, es promover incentivos adecuado para los grupos de agricultores que buscan resaltar el valor cultural de sus parcelas, de su organización, de sus prácticas de manejo, y que además compartan objetivos o motivaciones comunes.

La historia agrícola de México se ha basado en incentivos económicos que tienden a intensificar la agricultura, lo que no ha sido del todo exitoso. Hacer la transición hacia una agricultura sostenible significa incluir el valor natural y cultural de los agroecosistemas en los incentivos financieros para conservarlos. El altiplano de México es una región de contrastes donde convergen la agricultura altamente industrializada y la sobrepoblación, con la agricultura a pequeña escala cuyo principal aporte, además de la producción de alimentos, es el valor cultural de la conservación de los maíces nativos, la permanencia de prácticas agrícolas como la labranza manual y el intercambio de semillas, y la importancia de los maíces nativos a la autosuficiencia alimentaria en la región. Estos elementos culturales están reconocidos de manera limitada en los programas políticos actuales, si se continúa dando mayor peso al rendimiento agrícola, la agricultura de maíces nativos en pequeña escala podría desaparecer. El pasado nos ha enseñado que aumentar la producción de alimento tuvo impactos ambientales irreversibles, y la expansión de algunos cultivos será inevitable para cubrir la demanda de comida; pero las disyuntivas entre los beneficios económicos y las consecuencias ambientales deben reconocerse. Los agroecosistemas son un modelo adecuado para comprender el efecto de cambios sociales y ecológicos sobre el mantenimiento de funciones ecológicas de las cuales dependen las contribuciones de la naturaleza. Una solución puede ser incluir en las evaluaciones de productividad agrícola a la calidad nutricional del alimento, al maíz nativo, y a las prácticas de manejo basadas en la conservación, porque en términos de desarrollo sostenible son parte de los elementos de la agricultura más relevantes. Las metas a mediano y largo plazo no deben enfocarse en alimentar a todo el planeta, sino en eliminar el hambre mundial con comida nutritiva, generar ingresos, apoyar al desarrollo del campo y proteger al ambiente.

Referencias complementarias

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