UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO
POSGRADO EN CIENCIAS DE LA SOSTENIBILIDAD
GOBERNANZA, PLANEACIÓN COLABORATIVA Y APRENDIZAJE SOCIAL

TRAYECTORIA HISTÓRICA DE UN SISTEMA SOCIOECOLÓGICO AGROALIMENTARIO Y EL PAPEL DE LAS INTERACCIONES SOCIALES EN SU ADAPTACIÓN

TESIS
QUE PARA OPTAR POR EL GRADO DE:
DOCTORA EN CIENCIAS DE LA SOSTENIBILIDAD

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CIUDAD UNIVERSITARIA, CD. MX., FEBRERO DE 2024

UNAM POSGRADO
Ciencias de la Sostenibilidad

Coordinación de Estudios de Posgrado
Ciencias de la Sostenibilidad
Oficio: CGEP /PCS/023/2024
Asunto: Asignación de Jurado

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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 92 del 13 de junio de 2023, aprobó el jurado para la presentación del examen para obtener el grado de **DOCTORA EN CIENCIAS DE LA SOSTENIBILIDAD**, de la alumna **Ramírez León Alejandra** con número de cuenta **93026615**, con la tesis titulada "Trayectoria histórica de un sistema socioecológico agroalimentario y el papel de las interacciones sociales en su adaptación", bajo la dirección de la Dra. Véronique Sophie Avila Foucat.

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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., 2 de febrero de 2024.

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AGRADECIMIENTOS

A la Universidad Nacional Autónoma de México.

Al Posgrado en Ciencias de la Sostenibilidad de la Universidad Nacional Autónoma de México.

Al Consejo Nacional de Ciencia y Tecnología (antes CONACYT, ahora Consejo Nacional de Humanidades, Ciencias y Tecnologías, CONAHCYT) por la beca otorgada para llevar a cabo los estudios de doctorado.

Al CONACYT y la Agencia Nacional de Investigación de Francia (ANR-France) por financiar el proyecto 290832 ANR-CONACYT "Trajectories of Social-Ecological Systems in Latin American Watersheds: Facing Complexity and Vulnerability in the context of Climate Change ("TRASSE")" en cuyos trabajos se desarrolló esta investigación.

A los proyectos PAPIIT-UNAM-IN302720 "Resiliencia y medios de vida de los hogares rurales de la costa de Oaxaca" y PAPIIT–UNAM–IV300123 "Resiliencia de socioecosistemas costeros asociados al turismo ante covid 19 y cambio climático" por las becas otorgadas para la conclusión de esta tesis.

A la profesora Sophie Avila por su respaldo, paciencia, tiempo, dedicación, y la amistad forjada a lo largo de estos años. Gracias por todas las puertas que me ayudó a abrir y por todas las veces que me motivó a seguir adelante.

A mi comité tutor, el profesor Federico Morales y la profesora Carmen Maganda, por sus conocimientos compartidos, por su paciencia, por el tiempo invertido en mi formación. Fue difícil pero agradezco todas sus atenciones, me dejaron grandes enseñanzas.

A Driss Ezzine de Blass por su apoyo y consejos para concluir la redacción de mi artículo de titulación. Al profesor Bruno Locatelli, por sus grandes enseñanzas y apoyo incondicional durante mi estancia académica en el Centro de Cooperación Internacional en Investigación Agrícola para el Desarrollo (CIRAD). A Sandra Smith Aguilar, ya que sin su paciencia, dedicación y compromiso no habría sido posible concluir el análisis de redes multiplex, gracias por tus enseñanzas.

A los cafeticultores de la cuenca Copalita y a todas las personas relacionadas con la producción de café en la cuenca que me brindaron información para realizar esta tesis. Mención especial para el Ing. Isaac Rodríguez y al Sr. Antonio Gómez, cafeticultores entusiastas que participaron en el proyecto TRASSE y en mi tesis, que ya no pudieron conocer los resultados. Q.e.p.d.

AGRADECIMIENTOS PERSONALES

A Dios por la vida que me ha otorgado.

A mi familia: Susana, Verónica, Alitzel, Yael, Ofelia, Coti, Quetzalli. Por su apoyo incondicional y todo su cariño.

A la memoria de mi madre, Otilia León. Hasta que nos volvamos a encontrar.

A Angel Merlo, por la amistad forjada en cada trayecto a lo largo de la cuenca Copalita y fuera de ella. Por su solidaridad, respeto y complicidad.

A Hilda Zamora, por su amistad y apoyo incondicional, así como por sus consejos académicos.

A Jimena Deschamps por su amistad y compañía recorriendo las entrañas de la cuenca Copalita.

A Lucy Neyra e Isael Fierros que con su amistad y motivación me animaron a seguir en este proceso.

A la gente que conocí haciendo esta investigación y que me abrieron las puertas de su hogar: Graciela Rojas, Florinda Pacheco, Homero Blas…

A tod@s los amig@s que, durante este proceso, me dieron su apoyo incondicional.

Gracias.

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RESUMEN

Los sistemas agroalimentarios son sistemas socioecológicos que surgen de las relaciones complejas entre sociedad y naturaleza para producir alimentos. Esas relaciones evolucionan con el tiempo debido a factores de cambio que moldean esas interacciones y por la evolución en la tecnología, las políticas públicas y las preferencias de los consumidores, entre otros. La producción de café constituye uno de estos sistemas; además, es una de las bebidas más consumidas a nivel mundial que es producida principalmente en países en desarrollo ubicados en zonas tropicales para ser consumido en países desarrollados. La cadena de valor que se forma para ponerlo a disposición del consumidor aumenta la complejidad de esas interacciones ya que se caracteriza por un desequilibrio en la distribución de ganancias, donde el poder de negociación y las mejores capacidades de respuesta a las perturbaciones están en manos de los actores que se encuentran en las etapas de transformación y comercialización. Esta investigación analiza la trayectoria histórica de un sistema socioecológico agroalimentario (SSEAG) de café en Oaxaca, México, a fin de identificar los principales factores de cambio que lo han moldeado y su capacidad para adaptarse y ser resiliente a pesar de los embates enfrentados a lo largo de 40 años. Asimismo, se hace un acercamiento al papel que han tenido en los últimos 20 años, las interacciones sociales en la cadena de valor del SSEAG, a fin de encontrar patrones de diversidad y conectividad en las redes que se forman entre actores para impulsar su capacidad de adaptación. Para realizar esta investigación se obtuvo información primaria colectada a través de entrevistas semiestructuradas y encuestas de datos relacionales que fueron aplicados entre 2019 y 2020. Estos datos fueron analizados mediante un análisis cualitativo de contenido utilizando el programa MAXQDA versión 20.4.0, y un análisis de redes multiplex realizado con el paquete MuxViz versión 3.1 en el programa R, respectivamente. Los resultados muestran que: i) diversos factores de cambio sociales y naturales (como el cambio de las políticas públicas y el huracán Paulina, respectivamente) impulsaron modificaciones en un SSEAG y se originaron en diferentes escalas; además, tuvieron efectos diferenciados a nivel producción, transformación o comercialización; ii) las estrategias de adaptación y persistencia pueden tener un límite, ya que a largo plazo pueden generar nuevas condiciones de estrés; iii) es más relevante la conectividad que la diversidad entre actores sociales para fortalecer la capacidad de adaptación; iv) los actores se reorganizan a sí mismos para adaptarse y en particular los actores colectivos son clave para fortalecer la capacidad de adaptación y resiliencia del sistema.

ABSTRACT

Agri-food systems are socio-ecological systems that arise from the complex relationships between society and nature to produce food. These relationships evolve over time because of drivers of change that shape those interactions and due to evolution in technology, public policies and consumer preferences, among others. Coffee production constitutes one of these systems; besides, it is one of the most consumed drinks worldwide that is produced mainly in developing countries located in tropical areas to be consumed in developed countries. The value chain that is formed to make it available to the consumer increases the complexity of these interactions since it is characterized by an imbalance in the distribution of profits, where the bargaining power and the best response capabilities to disturbances are in the hands of the actors who are in the transformation and commercialization stages. This research analyzes the historical trajectory of a coffee socio-ecological agri-food system (SSEAG) in Oaxaca, Mexico, in order to identify the main factors of change that have shaped it and its ability to adapt and be resilient despite the attacks faced over 40 years. It also analyzed the role that social interactions have had in the last 20 years in the SSEAG value chain, in order to find patterns of diversity and connectivity in the networks that are formed between actors to boost their ability to adaptation. To carry out this research, primary information was obtained through semi-structured interviews and relational data surveys that were applied between 2019 and 2020. These data were analyzed through qualitative content analysis using the MAXQDA version 20.4.0 program, and through a multiplex networks analysis carried out with the MuxViz version 3.1 package in the R program, respectively. The results show that: i) various social and natural drivers (such as the discontinuity in public policies and Hurricane Paulina, respectively) drove modifications in a SSEAG and originated at different scales; furthermore, they had differentiated effects at the production, transformation or marketing level; ii) adaptation and persistence strategies may have a limit, since in the long term they can generate new stress conditions; iii) connectivity is more relevant than diversity among social actors to strengthen the capacity for adaptation; iv) actors reorganize themselves to adapt and in particular collective actors are key to strengthening the system's capacity for adaptation and resilience.

Foto: López, Enrique. 2019. Proceso de secado de café de calidad bajo sombra en Finca Chelín, Candelaria Loxicha, Oax.

INTRODUCCIÓN

Los sistemas agroalimentarios (SAG) abarcan la cadena de valor alimentaria que incluye producción, transformación y comercialización de alimentos hasta llegar a un consumidor final (FAO, 2021). A escala mundial, estos sistemas producen alrededor de 11,000 millones de toneladas de alimentos al año y son la columna vertebral de muchas economías nacionales (FAO, 2021). Al mismo tiempo, la agricultura representa uno de los principales factores de impacto ambiental a escala mundial (Chapman et al., 2017) ya que contribuye a las emisiones globales de gases de efecto invernadero, la degradación de la tierra, la eutrofización y el agotamiento de la calidad del agua (Oteros-Rozas et al., 2019). Esta degradación se aceleró por la evolución en la producción agrícola, la cual se triplicó entre 1960 y 2015 gracias al uso de tecnologías que aumentaron la productividad. También hubo un rápido proceso de industrialización y globalización de la alimentación y la agricultura, provocando que las cadenas de suministro de alimentos se alargaran a medida que aumentaba la distancia física entre los campos de cultivo y la mesa de los consumidores (Campanhola & Pandey, 2019; Oteros-Rozas et al., 2019).

La integración de la economía global ha agudizado los efectos de las crisis económicas mundiales afectando el comercio, los movimientos cambiarios y los precios internacionales, los cuales impactan el comportamiento comercial de las materias primas (commodities) en el sector agrícola (Schipanski et al., 2016). Aunado a ello, los SAG enfrentan otra serie de retos asociados a las condiciones climáticas y ecológicas indispensables para la producción de alimentos. Por ejemplo, alteraciones en los ciclos biogeoquímicos, alteraciones en el ciclo del agua, aumento de la temperatura, degradación de suelos, aumento de frecuencia e intensidad de eventos climáticos extremos, aparición de enfermedades y plagas, principalmente (FAO, 2018).

Por otro lado, los SAG representan un medio de vida para agricultores de pequeña escala. Según cifras de la Organización de las Naciones Unidas para la Alimentación y la Agricultura (FAO por sus siglas en inglés) (2021) existen más de 608 millones de granjas familiares en todo el mundo que ocupan entre el 70% y el 80% de las tierras agrícolas globales y producen aproximadamente el 80% de los alimentos mundiales. Alrededor del 70% de esas granjas familiares tienen terrenos agrícolas con menos de una hectárea de extensión, el 14% tiene terrenos que van entre una y dos hectáreas, y sólo un 10% tienen terrenos con una extensión de entre dos y cinco hectáreas. Mientras que sólo el 1% de las granjas agrícolas mundiales tienen más de 50 hectáreas, y un 40% de estas son explotaciones con más de 1,000 hectáreas.

Las situaciones descritas generan inequidad, pobreza y marginación; por ejemplo, los pequeños productores agrícolas que participan en las cadenas de valor de productos agrícolas tienen diferencias significativas en términos de riesgos, ingresos, acceso a los recursos y vulnerabilidad a la volatilidad de los precios y el cambio climático (FAO, 2015; ICO, 2019). Los segmentos de transformación, comercialización y distribución de alimentos son los que obtienen mayores ganancias y poder de negociación por encima de productores, quienes tiene capacidades limitadas para participar en ellos (Aboah et al., 2019; FAO, 2015; ICO, 2019). Asimismo, el alargamiento de las cadenas de suministro ha fomentado la desvinculación social y política entre la producción agrícola, la producción alimenticia y el impacto al medio ambiente (Lamine, 2015).

Las situaciones descritas funcionan como factores de cambio que generan condiciones de incertidumbre y presión para mantener el suministro constante de alimentos. Además, cada uno de estos factores de cambio se repite a diferentes escalas espaciales generando efectos que pueden ser más intensos a nivel local. Asimismo, estos no se manifiestan de manera aislada, sino que se conectan a través de interacciones entre aspectos sociales, políticos, económicos y ecológicos de manera tal que se retroalimentan positiva o negativamente para intensificar los impactos generados a distintas escalas. Si esto fuera poco, los SAG evolucionan con el tiempo ya que los factores de cambio van modificando condiciones locales y contextos específicos que van transformando las interacciones y las condiciones de estos sistemas, acumulando efectos a lo largo del tiempo. En otras palabras, los SAG son dinámicos, inciertos, cambian con el tiempo y son capaces de auto organizarse para mantener sus interacciones básicas por lo tanto, pueden ser interpretados como sistemas socioecológicos agroalimentarios (SSEAG) (Cabel & Oelofse, 2012; Darnhofer et al., 2010; Duru et al., 2015),

I. El sistema agroalimentario de café

El café es uno de los productos agrícolas que más se consumen globalmente con 3 mil millones de tazas de café diarias (ICO, 2019). El grano de café se cultiva en más de 70 países de América Latina, Asia y África ubicados en las zonas tropicales el mundo, mientras que los principales consumidores son Estados Unidos, países de la Unión Europea y Japón (Bacon, 2005; ICO, 2019). La producción de café se ha incrementado en 65% con respecto a la producción de 1990, debido al aumento del consumo en economías emergentes y países productores (ICO, 2019). No obstante, los países productores todavía exportan la mayor parte de su producción (cerca del 70%), generando alrededor de 20 mil millones de dólares en exportaciones al año; en contraste, se estima que los ingresos anuales de la industria del café superan los 200 mil millones de dólares que se dispersan entre los sectores de transformación y comercialización en los países consumidores (FAO, 2015; ICO, 2019). Al mismo tiempo, este cultivo es el principal medio de vida de entre 12.5 y 25 millones de plantaciones agrícolas familiares en el mundo; aunque la proporción de cafeticultores que viven por debajo del umbral de pobreza de 1.90 dólares al día, aumentó entre un 7% y un 50% entre 2018 y 2019 (ICO, 2019).

Por otro lado, es menester señalar que el cultivo y procesamiento de café también genera impactos en los ecosistemas tropicales donde crece. Por ejemplo, se han documentado impactos severos a ecosistemas nativos donde se han deforestado bosques tropicales para introducir plantaciones de café y se han contaminado cuerpos de agua con los desechos generados de su lavado. Esta transición ha sido detonada por el aumento del consumo global y se ha observado en América Latina y países del sudeste asiático donde se han extendido las zonas para su plantación (Hite, 2011; Hite et al., 2017; O'Brien & Kinnaird, 2004). Sin embargo, hay experiencias de cultivo de café de sombra que, a pesar de haber impulsado la transformación de bosques nativos, a través de su manejo permite conservar servicios ecosistémicos como refugio a la biodiversidad, infiltración de agua, regulación de la temperatura, regeneración de suelo, entre otros (Bhattarai et al., 2017; Meylan et al., 2017; Perfecto et al., 2003). En este sentido, destaca el papel que han jugado los certificados de café con denominaciones como "orgánico", "justo", "sostenible", "amigable con la biodiversidad", "amigable con las aves", entre otros, que han favorecido que el cultivo de café de sombra de la variedad arábica continúe brindando servicios ecosistémicos. Aunque el aporte de estos certificados de café en el bienestar socioeconómico de los productores puede ser polémico, es un hecho que pueden detener procesos de cambio de uso de suelo y deforestación en situaciones particulares (Bray & Neilson, 2017; Buchanan et al., 2017; Perfecto et al., 2019). De tal modo, pequeños productores de café de sombra manejan ecosistemas en algunas de las regiones más diversas (en términos culturales y biológicos) del mundo, convirtiendo esas plantaciones en una reserva de capital natural y servicios ecosistémicos (Bacon, 2005; Moguel & Toledo, 1999; Soto-Pinto et al., 2000).

Este cultivo es especialmente susceptible a perturbaciones ecológicas, climáticas y socioeconómicas que se incrementan por la dependencia de las exportaciones que expone a los agricultores a importantes riesgos agrícolas y de mercado (Aboah et al., 2019; Ponte, 2002). El mercado de café estuvo controlado por los gobiernos de países productores hasta finales de los 80's, eventualmente fue desregulado y dominado por la iniciativa privada liderada por empresas trasnacionales de países consumidores (Ponte, 2002). Desde los 90s el comercio internacional de café ha sido dominado por los compradores (Díaz Cárdenas, 2015), donde los productores han perdido poder de negociación e ingresos y las ganancias se concentran en segmentos de transformación, distribución y comercialización, o en productores líderes. La cadena de valor del café es muy compleja, con varias etapas y un elevado número de actores que intervienen a lo largo de ella, lo que genera interacciones sociales y ecológicas que influyen casi al mismo tiempo en todos los procesos (Aboah et al., 2019; García Cáceres & Olaya Escobar, 2006; Utrilla-Catalan et al., 2022), modificando así la capacidad de respuesta y adaptación de cada etapa y la articulación entre las mismas.

Aunque el mercado del café ha ido creciendo a nivel mundial, existe incertidumbre sobre el futuro de la industria cafetalera debido al cambio climático, las plagas y enfermedades, la volatilidad de precios, incluso la innovación tecnológica y los acuerdos político-económicos que influyen en el sector (Murphy et al., 2023; Utrilla-Catalan et al., 2022). Así, esta investigación se propuso conocer la trayectoria histórica de un SSEAG cafetalero para entender cómo se ha adaptado y qué le ha permitido ser resiliente y mantener su funcionalidad e identidad. Para ello, este estudio se enfoca en el caso de la producción de café en un SSEAG ubicado en las cuencas Copalita-Huatulco en el estado de Oaxaca, México. El café fue introducido en la región desde finales del siglo XIX y actualmente aún predomina el cultivo de café de sombra de variedad arábiga.

Este cultivo ha tenido un gran arraigo en la región y actualmente ha contribuido a mantener servicios ecosistémicos relevantes para los ecosistemas de la cuenca y los asentamientos humanos ubicados en ella (González-Mora et al., 2006; Lozano-Trejo et al., 2020; Ramos Olivera, 2015). Desde la década de los 90, la producción de café en las cuencas Copalita-Huatulco ha experimentado grandes cambios en respuesta a las tendencias del mercado internacional, a los cambios en políticas nacionales agrícolas, a fenómenos climáticos y otros conflictos sociales locales. Estos factores de cambio han influido en la modificación de prácticas de cultivo, la disminución de la producción de café, a la vez han impulsado la organización colectiva entre productores y modificado la política cafetalera del Estado. En este contexto, resultó importante conocer la trayectoria histórica del SSEAG de las cuencas Copalita-Huatulco y los factores que le permitieron adaptarse y ser resiliente para continuar produciendo café de sombra en la región a lo largo de 40 años. El periodo de estudio inició en 1980, década que marcó una época de grandes transformaciones en el comercio mundial del café y que tuvo impactos importantes a nivel nacional y cuyos efectos se han acumulado a lo largo de los años. El estudio concluyó en 2020[1], debido a que se

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[1] Este año coincidió con la pandemia mundial por el virus de covid 19, pero al momento de recolectar la información ningún participante mencionó afectaciones por la pandemia, motivo por el cual no figura en esta investigación.

identificó la conclusión de un ciclo de recuperación por las afectaciones de la roya del café (*Hemileia Vastatrix*) que impactó en la zona de estudio en 2015.

Muchas investigaciones han abordado varios de los factores de cambio descritos hasta ahora. Por ejemplo, los estudios que abordan la gobernanza de la cadena de valor de café a escala global para analizar los desequilibrios de poder y las contradicciones de los denominados *voluntary sustainability standards* que promueven mecanismos de mercado utilizados con un doble propósito (conservación y superación de la pobreza) (Bennett, 2017; Dietz et al., 2018; Grabs, 2018). Otras investigaciones se enfocan en analizar los rendimientos de la producción con relación al tipo de manejo en parcela (Barham & Weber, 2012; Haggar et al., 2017; Jezeer et al., 2018); otros se enfocan en el papel de los sellos de certificación en el aumento de los ingresos de los cafeticultores y sus implicaciones en la superación de la pobreza a nivel local (Glasbergen, 2018; Bray & Neilson, 2017; Buchanan et al., 2017). Otros se concentran en el manejo en las plantaciones de café y su aporte a los servicios ecosistémicos y la conservación (Blackman & Naranjo, 2012; Caudill & Rice, 2016; Jha et al., 2011). Varios abordan el papel de las organizaciones de productores de café en el empoderamiento de los cafeticultores (Vicol et al., 2018; Ebata & Hernandez, 2017; Mujawamariya et al., 2013). Y aquellos que analizan el comportamiento del comercio internacional de café y su cadena de valor (Utrilla-Catalan et al., 2022; Clay et al., 2018; Mithöfer et al., 2017).

Estas investigaciones han contribuido a comprender y caracterizar los problemas que enfrentan los sistemas agroalimentarios cafetaleros; sin embargo, al tratar de identificar interacciones y relaciones de causalidad para mantener la resiliencia de estos, sólo se abordan algunas interacciones o aspectos del sistema. Diversos estudios sobre SAG (Loconto et al., 2018; Mishra & Dey, 2018; Mithöfer, van Noordwijk, et al., 2017) han señalado la necesidad de cambiar la perspectiva teórica de análisis para pasar de un enfoque centrado en sólo aspectos técnicos, agrarios, económicos o sociales de la producción de alimentos a adoptar un enfoque que permita entender las relaciones complejas entre sociedad y naturaleza para la producción de alimentos. Dado que el enfoque de sistemas socioecológicos (SSE) no se enfoca en el entendimiento detallado de las partes sino en cómo los componentes clave contribuyen a la dinámica de un sistema completo (Resilience Alliance, 2010), permite analizar las diferentes escalas en que se dan las interacciones sociedad-naturaleza, así como los factores de cambio internos y externos que influyen en su evolución. En particular, entender las relaciones entre actores que determinan la dinámica del sistema a través del análisis de redes multiplex resulta relevante en este contexto.

Por tanto, fue importante entender cómo el SSEAG han atravesado por una trayectoria de cambio a lo largo de 40 años y qué factores han contribuido a su resiliencia a fin de identificar los retos para su trayectoria futura. Comprender estos elementos contribuirá a identificar *trade-offs* y sinergias para impulsar una trayectoria sostenible de largo plazo que sea resiliente e inclusiva donde se produzcan alimentos suficientes conservando los ecosistemas locales a través de mejores prácticas agrícolas, teniendo condiciones de comercio más justas, y proporcionando bienestar a las comunidades locales que dependen directamente de ellos (FAO, 2022). De tal suerte, esta investigación propuso las siguientes preguntas y objetivos de investigación.

PREGUNTA DE INVESTIGACIÓN

¿De qué manera las interacciones sociales pasadas influyen en la capacidad de adaptación de un sistema agroalimentario de café para ser resiliente en el largo plazo?

OBJETIVOS DE INVESTIGACIÓN

Objetivo general

Conocer la trayectoria histórica de un sistema socioecológico agroalimentario de café localizado en las cuencas Copalita-Huatulco y el papel de las interacciones sociales en su adaptación y resiliencia a lo largo de 40 años.

Objetivos específicos

1. Entender a profundidad los factores de cambio y la trayectoria histórica del sistema socioecológico agroalimentario de café localizado en las cuencas Copalita-Huatulco y cómo han determinado las condiciones actuales del sistema.
2. Analizar las interacciones sociales en el sistema socioecológico agroalimentario de café localizado en las cuencas Copalita-Huatulco para identificar los arreglos entre conectividad y diversidad que determinan su capacidad de adaptación y resiliencia.

Para cumplir los objetivos y contestar así la pregunta de investigación, este trabajo empleó un enfoque de resiliencia general en SSEs (Biggs et al., 2012; Folke et al., 2010) para abordar la exposición del SSEAG de café a múltiples estresores. Utilizó una metodología semicuantativa que combinó el análisis de contenido cualitativo y el análisis de redes sociales multiplex para hacer un mejor acercamiento al estudio de la capacidad de adaptación y resiliencia del SSEAG de café de sombra. El capítulo 1 expone los conceptos teóricos que dan sustento a los capítulos 3 y 4 que fueron desarrollados en formato de artículos. El capítulo

2 describe el SSEAG analizado incluyendo sus condiciones biofísicas, sus componentes e interacciones; también muestra el método empleado.

El capítulo 3 es el artículo requisito para titulación publicado en una revista indizada y su principal objetivo fue dar cumplimiento al objetivo específico 2 de esta investigación, el cuál consistía en entender a profundidad los factores de cambio y la trayectoria histórica del SSEAG. Esto se realizó mediante un análisis de contenido cualitativo con datos colectados mediante entrevistas semiestructuradas aplicadas en muestreo dirigido a 30 actores clave. Muestra la trayectoria histórica del sistema en las cuencas Copalita-Huatulco, Oaxaca, en un periodo de 40 años. Los resultados mostraron que las interacciones del sistema fueron afectadas por estresores y shocks económicos (comercio internacional de café), sociales (cambio en las políticas públicas) y ambientales (huracán y cambio climático) que afectaron diferentes escalas temporales y espaciales. Los efectos acumulados de estos factores de cambio junto con las estrategias de adaptación han influido en que el sistema no cumpla con el proceso de sucesión del Ciclo Adaptativo. Además, los resultados mostraron que algunas estrategias adaptativas pueden convertirse en nuevos factores de cambio con el tiempo.

El capítulo 4 es el segundo artículo (primera versión enviada) que se desprende de esta investigación con el cual se dio cumplimiento al objetivo específico 2 de este trabajo, el cual consistía en analizar las interacciones sociales en el sistema en las cuencas Copalita-Huatulco para identificar los arreglos entre conectividad y diversidad que determinan su capacidad de adaptación y resiliencia en un periodo de 20 años. Este capítulo empleó un análisis de redes multiplex con datos colectados mediante una encuesta de datos relacionales aplicada en muestreo dirigido a 46 actores clave. Los resultados mostraron que la capacidad adaptativa de todo el SSEAG en la década de 2000 a 2020 fue robusta pero los arreglos entre conectividad y diversidad en cada componente (producción, transformación, comercialización) del sistema fueron diferentes. Además, se encontró que la conectividad fue el atributo más relevante para fortalecer la capacidad adaptativa del SSEAG de café; asimismo, los actores colectivos jugaron un papel clave para la adaptación del sistema.

Por último, el capítulo 5 muestra la discusión y conclusiones de todo el trabajo de investigación, abordando tanto implicaciones teóricas sobre el estudio de la resiliencia socioecológica como implicaciones empíricas para el SSEAG de café. Por un lado, este estudio hace un aporte teórico - metodológico relevante para estudiar desde una aproximación semicuantitativa la trayectoria histórica de un SSEAG y el papel de las interacciones sociales para favorecer la capacidad adaptativa y su resiliencia. En este sentido, se aportaron evidencias relevantes sobre los límites que tiene la adaptación en el impulso a la resiliencia, así como las contradicciones que se pueden generar entre resiliencia y sustentabilidad. Ya que, en el caso estudiado, aunque el sistema ha sido resiliente y se ha adaptado a múltiples estresores manteniendo las funciones e interacciones que le dan identidad, las condiciones de vida de los cafeticultores (en especial los más pequeños) no han mejorado sustancialmente. De este modo, aunque el SSEAG de café es hoy en día un importante proveedor de servicios ecosistémicos para el complejo hidrológico de las cuencas Copalita-Huatulco, su permanencia y mejoramiento a largo plazo es incierta.

A lo largo del texto se presentan fotos de las cuencas Copalita-Huatulco a fin ilustrar el sitio de estudio e identificar la transición entre capítulos.

Foto: Ramírez León, A. Diciembre 2019. Sistema agroforestal de café afectado por la roya del café (Hemileia vastatrix) en San Pedro Cafetitlán, San Pedro Pochutla, Oax.

CAPITULO 1. MARCO TEÓRICO

La cadena de valor fue definida por primera vez como una colección de actividades que son realizadas por una empresa para diseñar, producir, comercializar y distribuir sus productos (Porter, 2001); siendo entendida como secuencias lineales de actividades que crean valor a nivel empresa pero pasando por alto la importancia de los actores y las interacciones que se dan entre ellos y entre las actividades dentro de esa cadena (Canevari-Luzardo, 2019). Actualmente, una cadena de valor en un sistema agroalimentario se considera como un "sistema que abarca todas las actividades, organizaciones, actores, tecnología, información, recursos y servicios involucrados en la generación de productos agroalimentarios para los mercados de consumo" (OCDE & FAO, 2017). Abarca el suministro de insumos agrícolas (como semillas, fertilizantes, equipo), la producción, la manipulación post-cosecha, el procesamiento, el transporte, la mercadotecnia, la distribución y la venta al por menor. También incluye servicios de soporte como los de extensión, investigación y desarrollo e información de mercado. Involucra una gran variedad de actores que van desde los pequeños agricultores, organizaciones de productores (secundarias o de segundo nivel), cooperativas, empresas locales, empresas multinacionales, agencias del gobierno, financiadores privados, y organizaciones de la sociedad civil (OCDE & FAO, 2017).

En una cadena de valor agroalimentaria los actores están unidos por flujos de recursos y actividades compartidas o vinculadas que se retroalimentan entre sí y que influyen en la ventaja competitiva de los actores dentro de esa cadena (Canevari-Luzardo, 2019). Los alimentos que crecen en regiones tropicales como el café, son especialmente susceptibles a perturbaciones ecológicas y climáticas y sus cadenas de valor son dominadas por los compradores lo que los hace más susceptibles a perturbaciones socioeconómicas (Aboah et al., 2019; Gereffi et al., 2005). Dadas las características de una cadena de valor agroalimentaria como la del café es posible definirla como un sistema socioecológico.

El marco de sistemas socioecológicos (SSE) reconoce que los sistemas humanos y los ecosistemas son inseparables y se enfoca en comprender las relaciones y retroalimentaciones que definen su dinámica y características (Berkes et al., 2003; Preiser et al., 2018). Los SSE están conformados por múltiples elementos sociales y ecológicos que interactúan estrechamente entre sí en múltiples escalas para crear una entidad más compleja (Resilience Alliance, 2010). Según Duru et al. (2015), los sistemas socioecológicos agroalimentarios (SSEAG) son sistemas adaptativos complejos caracterizados por un comportamiento emergente y no lineal con una alta capacidad de autoorganización y adaptación basada en experiencias pasadas. Por tanto, en esta investigación un SSEAG es definido como un sistema adaptativo complejo que abarca la producción, transformación y comercialización de alimentos hasta llegar a un consumidor final bajo condiciones de comportamiento emergente y no lineal con una alta capacidad de autoorganización y adaptación basada en eventos pasados.

Un SSEAG de café es resultado de las interacciones de varios elementos sociales y ambientales donde hay factores de cambio externos que afectan de diferente manera a los componentes del sistema (producción, transformación y comercialización), los cuales pueden cambiar lenta o rápidamente. Por ejemplo, un huracán puede afectar las plantaciones y el ecosistema en general de manera súbita pero los efectos de esas alteraciones ecológicas se acumularán a largo plazo dificultando que haya una respuesta efectiva en materia de manejo o políticas públicas para resarcir los daños del huracán a largo plazo. Además, los efectos de ese huracán serán diferentes en los componentes del sistema a pesar de afectarlos al mismo tiempo. Este ejemplo muestra que las personas dentro del SSE responden a los factores de cambio a través de mecanismos institucionales, formando un circuito de retroalimentación que influye en los servicios ecosistémicos y el bienestar humano (Folke et al., 2010; Resilience Alliance, 2010).

Así, un SSE responde a los cambios específicos en ciertos componentes detonando retroalimentaciones que pueden amplificar el cambio en todo el sistema o pueden estabilizar sus efectos. A través de estas interacciones los SSEAG pueden autoorganizarse, adaptarse o emerger configuraciones nuevas después de un disturbio (Resilience Alliance, 2010). Los factores de cambio que afectan a un SSE impulsan la transición a un estado diferente del sistema. Un estado es un conjunto de variables sociales y ecológicas que pueden fluctuar y crear retroalimentaciones que estabilizan al sistema y lo mantienen en una condición particular; estas interacciones se pueden amplificar y empujar el sistema hacia una nueva configuración equivalente a un nuevo estado (Resilience Alliance, 2010).

Cuando los SSE ajustan sus respuestas y evolucionan, desarrollan un camino o trayectoria (Preiser et al., 2018) que puede estar dentro de un dominio de estabilidad o pasar a otro estado. Esa trayectoria es definida por la dirección que toma un sistema y su patrón de cambio a lo largo del tiempo (Bagchi et al., 1998; Resilience Alliance, 2010) y es el resultado de las interacciones históricas entre los componentes del sistema y los efectos acumulados de los factores de cambio (Duru et al., 2015). Un SSE está en transición cuando cruza entre dos estados y está en transformación cuando ha cruzado un umbral; la transición entre estados puede ser lenta y gradual o abrupta y rápida (Folke et al., 2010; Resilience Alliance, 2010). Los umbrales entre los estados del sistema advierten sobre cambios inminentes, así como oportunidades para prevenir cambios indeseables en el sistema (los cuales son subjetivos y dependen del contexto); una vez que los umbrales se han cruzado ya no hay forma de volver a un estado anterior, lo que implica que el sistema ha perdido su resiliencia (Folke et al., 2010), aunque eso no significa que el estado anterior sea mejor (Ávila Foucat et al., 2020; Resilience Alliance, 2010).

Si un sistema mantiene el mismo estado es porque preserva su estructura, función e identidad principales, que residen en la presencia continua, tanto en el espacio como en el tiempo, de componentes y relaciones clave sin cruzar un umbral (Cumming & Collier, 2005). Así, estudiar la resiliencia de un SSEAG implica comprender cómo evoluciona sin perder los rasgos esenciales que lo caracterizan. La resiliencia como propiedad emergente de un SSE "es el resultado de tres capacidades de un sistema que conducen a diferentes respuestas a corto plazo: capacidad de absorción que conduce a la persistencia, capacidad de adaptación que conduce a ajustes o cambios incrementales y adaptación, y capacidad de transformación que conduce a respuestas transformadoras" (Béné et al., 2016). La capacidad de absorción es la capacidad de persistir a través de cambios mientras se sigue realizando la misma función. La capacidad adaptativa implica la capacidad de adquirir conocimientos, integrar experiencias pasadas, adaptar las respuestas a la evolución de factores externos y dinámicas internas, y mantener operaciones en curso (Béné et al., 2016; Berkes et al., 2003). La capacidad transformadora establece un sistema completamente nuevo cuando las estructuras ecológicas, económicas o sociales hacen que el sistema existente sea inviable (Béné et al., 2016; Walker et al., 2004).

Entonces, el estudio de la resiliencia en SSEAG permite identificar la trayectoria histórica de un sistema, la capacidad de adaptación que influye en su resiliencia y el papel de las interacciones sociales como mecanismos institucionales que contribuyen en esa adaptación (Hendrickson, 2015). El ciclo adaptativo (AC) se ha utilizado como modelo heurístico útil para estudiar las trayectorias y la resiliencia de los SSE (Folke, 2016); este describe la dinámica endógena de un SSE generada por procesos internos de autoorganización y evolución en el tiempo a través de la sucesión de cuatro fases: crecimiento, conservación, colapso y renovación (Holling, 2001). Este proceso evolutivo depende de las intensidades de los factores de cambio y de las condiciones y capacidades del sistema para responder, absorber perturbaciones y reorganizarse para mantener el mismo estado (Folke et al., 2010; Walker et al., 2004).

En este contexto, Bracken et al. (2023) definieron la resiliencia como "la capacidad de las personas para mantener y mejorar sus oportunidades de subsistencia y su bienestar a pesar de las perturbaciones"; por lo tanto, esta investigación entiende la resiliencia en un SSEAG de café como la capacidad de la cadena de valor para gestionar y mitigar las perturbaciones a fin de mejorar la capacidad de las personas para sostener y mejorar sus medios de vida. Por otro lado, Cabel & Oelofse (2012), Darnhofer et al. (2010) y Meuwissen et al. (2019) han propuesto los atributos de un sistema resiliente para evaluar la resiliencia en

SSEAG. Estos atributos se consideran factores que pueden fortalecer las capacidades de un sistema para ser resiliente, entre los más relevantes se encuentran: (i) diversidad, que se refiere a tener diferentes elementos para responder a las perturbaciones, (ii) modularidad, que consiste en subgrupos conectados con mayor fuerza dentro de ellos y hacia otros subgrupos en el sistema que presentan funciones diferentes (similar a la redundancia); (iii) conectividad, que consiste en las relaciones internas y externas de los sistemas; (iv) rigidez de las retroalimentaciones, es decir, las relaciones dentro del sistema donde la respuesta de un elemento cambia a otros y (v) reservas del sistema (es decir, activos de capital natural, económico y social) que el sistema puede utilizar para responder al estrés y las crisis (Meuwissen et al., 2019).

Varios estudios han abordado la resiliencia de un SSEAG de café, como los que se han enfocado en analizar los impactos del cambio climático en sistemas agroforestales de café y las estrategias que pueden implementarse entre productores y otros actores para su adaptación y resiliencia, tales como Bracken et al. (2023), Zaro et al. (2022), Campbell (2021), Tucker et al. (2010), Frank et al. (2011) y Quiroz-Guerrero et al. (2022). Otros han estudiado la resiliencia de la cadena de valor del café, como son Utrilla-Catalan et al. (2022), quienes estudiaron la dinámica y evolución del mercado internacional del café verde mediante un análisis de redes multicapa e indicadores asociados como centralidad por grado e intermediación y modularidad. Clavijo-Buritica et al. (2023) propusieron métricas para evaluar la resiliencia de la cadena de suministro de café en países de economías emergentes asociadas a disponibilidad y conectividad mediante programación matemática. Borda-Rodriguez & Vicari (2015) analizaron el papel que juega la innovación para fomentar la resiliencia de cooperativas cafetaleras para hacer frente a limitaciones organizativas y de mercado a partir de un análisis de percepción. Otras investigaciones han analizado el papel de la diversidad y la conectividad para la resiliencia en SSEAG mediante el análisis de redes sociales (Albizua et al., 2020; Bruce et al., 2021; Canevari-Luzardo, 2019).

Sin embargo, hasta ahora no se han encontrado investigaciones que hayan analizado la trayectoria histórica de una SSEAG definida a partir de las fases de una cadena de valor en una cuenca productora de café, ni cómo emergen atributos como la diversidad y la conectividad a partir de las interacciones entre actores utilizando una aproximación de análisis de redes y su cambio con el tiempo. Para llenar este vacío, esta investigación presenta una propuesta analítica-metodológica para analizar la resiliencia de un SSEAG de café a nivel cuenca a lo largo de 40 años y su capacidad para adaptarse y autoorganizarse a partir de las interacciones sociales entre actores utilizando un enfoque de análisis de redes multiplex. Este enfoque permite la comprensión de interacciones complejas en SSE (Preiser et al., 2018).

Foto: Ramírez León, A. Diciembre 2019. Tostador de café en San Pedro Cafetitlán, San Pedro Pochutla, Oax.

CAPITULO 2. METODOLOGÍA

2.1 Descripción del sistema socioecológico agroalimentario de café (área de estudio)

2.1.1 Condiciones biofísicas y servicios ecosistémicos. El caso de estudio está localizado en un SSEAG a una escala de cuenca localizada en el complejo hidrológico formado por las subcuencas de los ríos Copalita y Huatulco en las regiones costa y sierra sur del estado de Oaxaca, en el pacífico mexicano. En este complejo se localizan 19 municipios con aproximadamente 181,715 habitantes (Figura 1) (INEGI, 2020). En 2015, 87% de sus habitantes sufrían de algún grado de pobreza y tenía ingresos por debajo de la línea de bienestar (CONEVAL, 2020). Esta región alberga climas cálido, semicálido, templado y semifrío subhúmedos con una precipitación media anual de 1,693mm y con una temperatura promedio de 19°C (García Alvarado et al., 2017). Los tipos de vegetación dominantes son los bosques templados (pino-encino), la selva baja caducifolia, las selvas medianas (sub- caducifolia y -perennifolia) y los manglares. Es una de las zonas de mayor diversidad ecológica del estado, donde se han transformado ecosistemas naturales a sistemas agrícolas que van desde monocultivos, como el maíz, hasta sistemas agroforestales diversificados como es el caso del café de sombra (Mokondoko et al., 2023). Predomina la producción de café bajo sombra donde las principales variedades son arábica, mondo novo y caturra que son cultivadas en altitudes que varían de los 230 a los 1,970 metros sobre el nivel del mar, en aproximadamente 13,909 hectáreas equivalentes a 7.16% de la superficie total de ambas cuencas (194,268 hectáreas) (García Alvarado et al., 2017; Mokondoko et al., 2023).

Entre 1989 y 2018, la actividad agropecuaria impulsada por el cultivo del café, la ganadería extensiva y otros cultivos agrícolas redujeron de manera significativa la distribución de los diferentes tipos de vegetación nativa. Aunque las zonas urbanas aún no representan un porcentaje importante de la superficie (0.82%; 2,324 ha), los asentamientos humanos aumentaron en 164% en el mismo periodo debido principalmente a la influencia del Centro Integralmente Planeado Huatulco. Por lo que, el potencial de provisión de servicios ecosistémicos en la región se ha visto afectado, debido a la pérdida de la vegetación, los procesos de erosión y la disminución del agua disponible, que tienen como principal causa los cambios de uso del suelo, la intensificación del manejo en los cafetales y el cambio climático (Mokondoko et al., 2023).

En particular, la producción de café de sombra es dominada por pequeños productores que tienen el 90% de las plantaciones de café, pero en extensiones menores a 5 hectáreas (Secretaría de Agricultura y Desarrollo Rural, 2020). Estas plantaciones coinciden geográficamente con los *hotspots* de biodiversidad designadas por la CONABIO (CONABIO, 2004), creando así un paisaje que brinda servicios ecosistémicos fundamentales como el almacenamiento de carbono, polinización, la retención de sedimentos, infiltración de agua, entre otros (Mokondoko et al., 2023). Sin embargo, para aumentar la productividad y adaptarse ante los factores de cambio, los cafeticultores han tenido que intensificar el manejo, cambiar las variedades de café arábica por otras variedades híbridas o de café robusta, sustituir el cultivo de café, y diversificar los cultivos para integrar otros más rentables (Mokondoko et al., 2023; Ramírez-León et al., 2023). Estas situaciones alteran drásticamente la biodiversidad y los servicios ecosistémicos de la cuenca (Mokondoko et al., 2023; Rivera Silva et al., 2013).

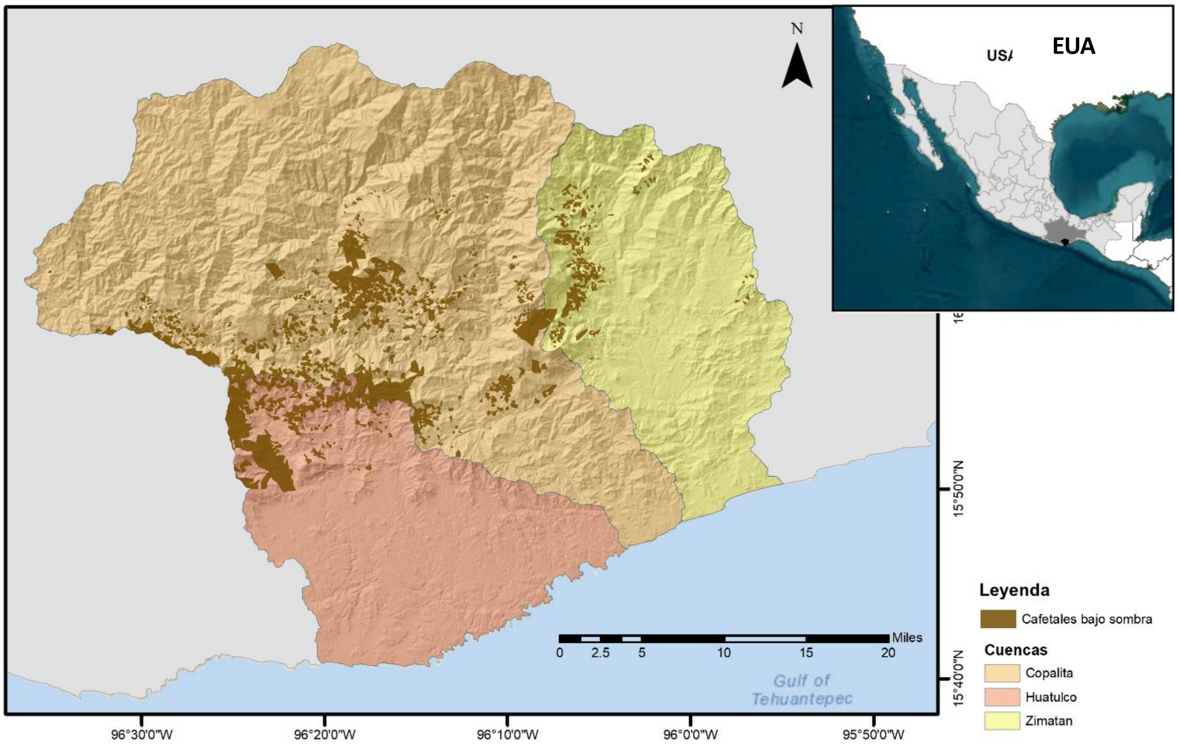


Figura 1. Mapa de las subcuencas Copalita, Huatulco y Zimatán y la distribución de las plantaciones de café bajo sombra. Fuente: Mokondoko et al. (2023). La subcuenca Zimatán no se incluyó en esta investigación.

2.1.2 Componentes del SSEAG e interacciones sociales. El SSEAG es un sistema gestionado con la intención de producir, transformar y comercializar café y está estructurado por tres componentes asociados al concepto de cadena de valor: producción, transformación y comercialización (Figura 2). En el componente productivo se cultiva café y el grano se lava y transporta a puntos de acopio. El cultivo de café se desarrolla en terrenos con pendientes fuertes (15-35°), con riesgo de erosión hídrica y degradación de suelos; entre los 600 a los 1,700 msnm y con niveles de sombra que van de medio a alto (García Alvarado et al., 2017). Se pueden clasificar diversos tipos de productores de acuerdo con el manejo que realizan en su parcela: los productores que llamaremos "convencionales" o "tradicionales" caracterizados por prácticas de poca conservación de suelo y con poco uso de insumos naturales y químicos; productores "agroecológicos" que usan gran cantidad de insumos naturales y pocos insumos químicos; y los productores "intensivos" que usan gran cantidad de insumos tanto naturales como químicos. En general, las plantaciones de café se encuentran en regiones montañosas y muy accidentadas, donde el clima, relieve, altitud y árboles de sombra son factores que influyen en la cantidad y la variabilidad espacial de los patrones de provisión de diferentes servicios ecosistémicos (Mokondoko et al., 2023).

En el componente de transformación, el grano lavado (denominado café pergamino) es seleccionado y procesado para obtener café verde. Para llevar a cabo este proceso se requiere información, insumos y servicios especializados. En el componente de comercialización se realiza la compra y venta de café en varias presentaciones (café pergamino, verde, tostado y envasado); esta actividad requiere promoción comercial y servicios especializados. Hay varios actores en el SSEAG como proveedores de insumos y servicios; cafeticultores de diferentes características y condiciones; organizaciones de productores integradas por cooperativas (organizaciones secundarias o de segundo nivel); cooperativas; intermediarios; y compradores. Como actores de soporte están las agencias gubernamentales; organizaciones no gubernamentales; iniciativa privada e incluso académicos. Todos estos actores están ubicados en diferentes escalas geográficas e institucionales. Las interacciones que ocurren entre ellos generan relaciones de interdependencia y retroalimentación resultantes de acciones semiautónomas e intereses particulares de cada actor y modifican las prácticas de cultivo, la vegetación y las estrategias de adaptación (Darnhofer et al., 2010). Estas interacciones cambian y se adaptan con el tiempo, incluso los actores se han transformado para participar en toda la cadena de valor del café.

Las interacciones también pueden involucrar espacios fuera de los límites físicos del SSEAG. Asimismo, existen factores de cambio externos que generan perturbaciones sobre el sistema, como las condiciones climáticas o ciertas políticas públicas (agrícolas o ambientales) que pueden alterar las decisiones y la trayectoria de cualquiera de los componentes y que se originan en diferentes escalas. En cuanto a los factores de cambio internos, estos abarcan las estrategias de afrontamiento y adaptación (*coping and adaptive strategies*) que surgen como respuesta a los factores de cambio externos y que pueden ir evolucionando a lo largo del tiempo generando nuevas condiciones de cambio internas.

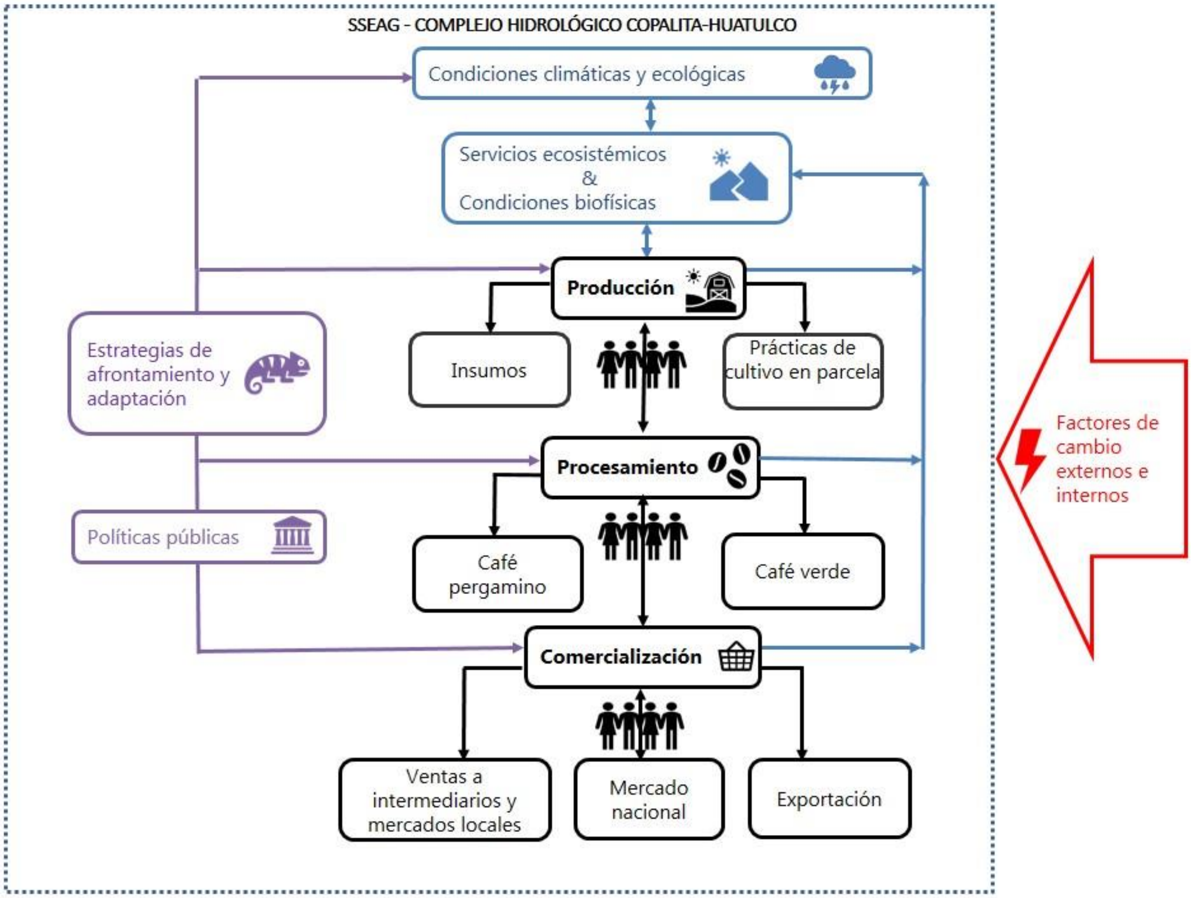
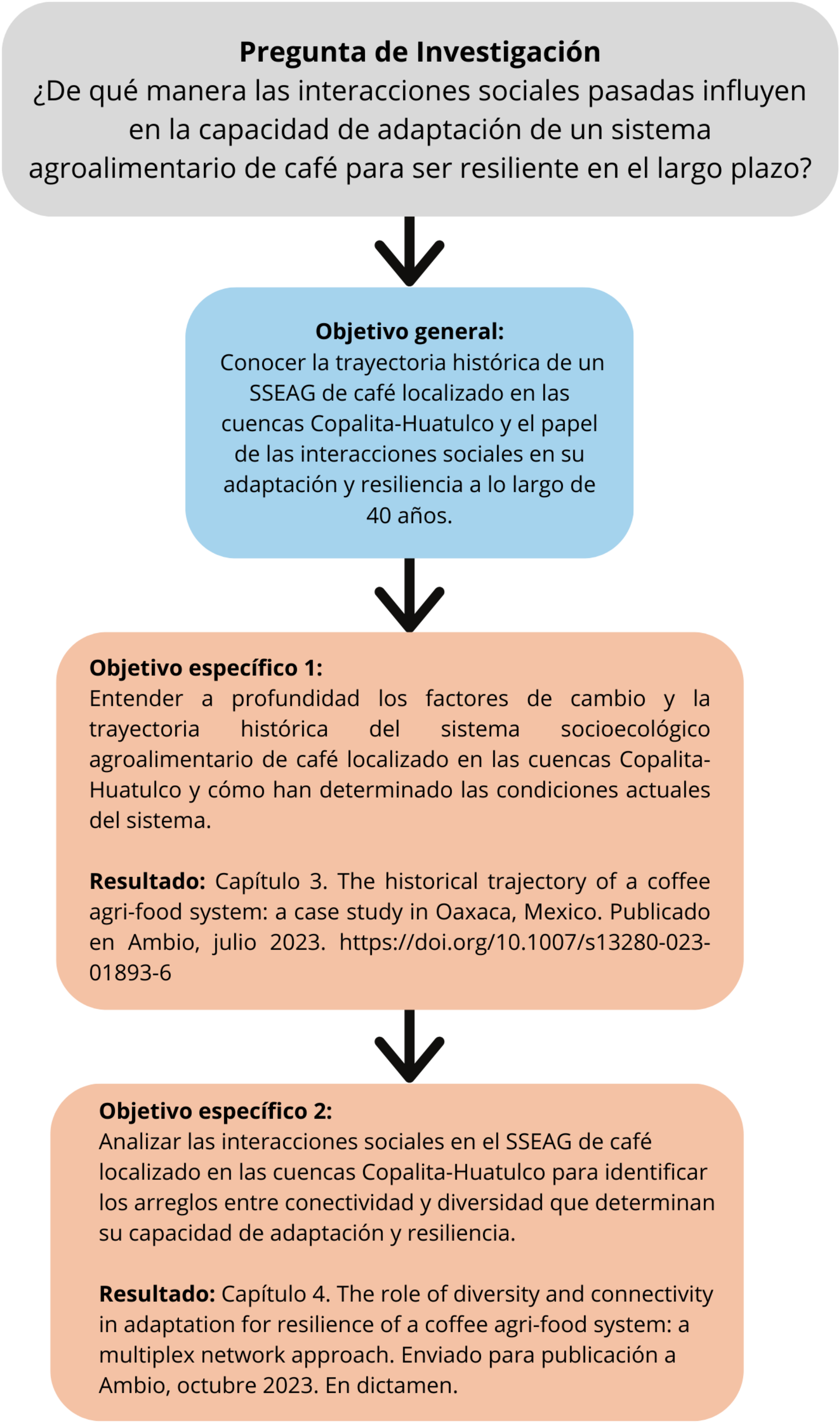


Figura 2. Esquema descriptivo del sistema socioecológico agroalimentario de café del complejo hidrológico Copalita-Huatulco. Fuente: elaboración propia.

2.2 Método.

Para dar respuesta a la pregunta de investigación y cumplir el objetivo general de investigación se siguió la secuencia mostrada en la Figura 3. En particular, se describen con detalle las acciones realizadas para cumplir los objetivos específicos de investigación en las Figuras 4 y 5.



Pregunta de Investigación
¿De qué manera las interacciones sociales pasadas influyen en la capacidad de adaptación de un sistema agroalimentario de café para ser resiliente en el largo plazo?

Objetivo general:
Conocer la trayectoria histórica de un SSEAG de café localizado en las cuencas Copalita-Huatulco y el papel de las interacciones sociales en su adaptación y resiliencia a lo largo de 40 años.

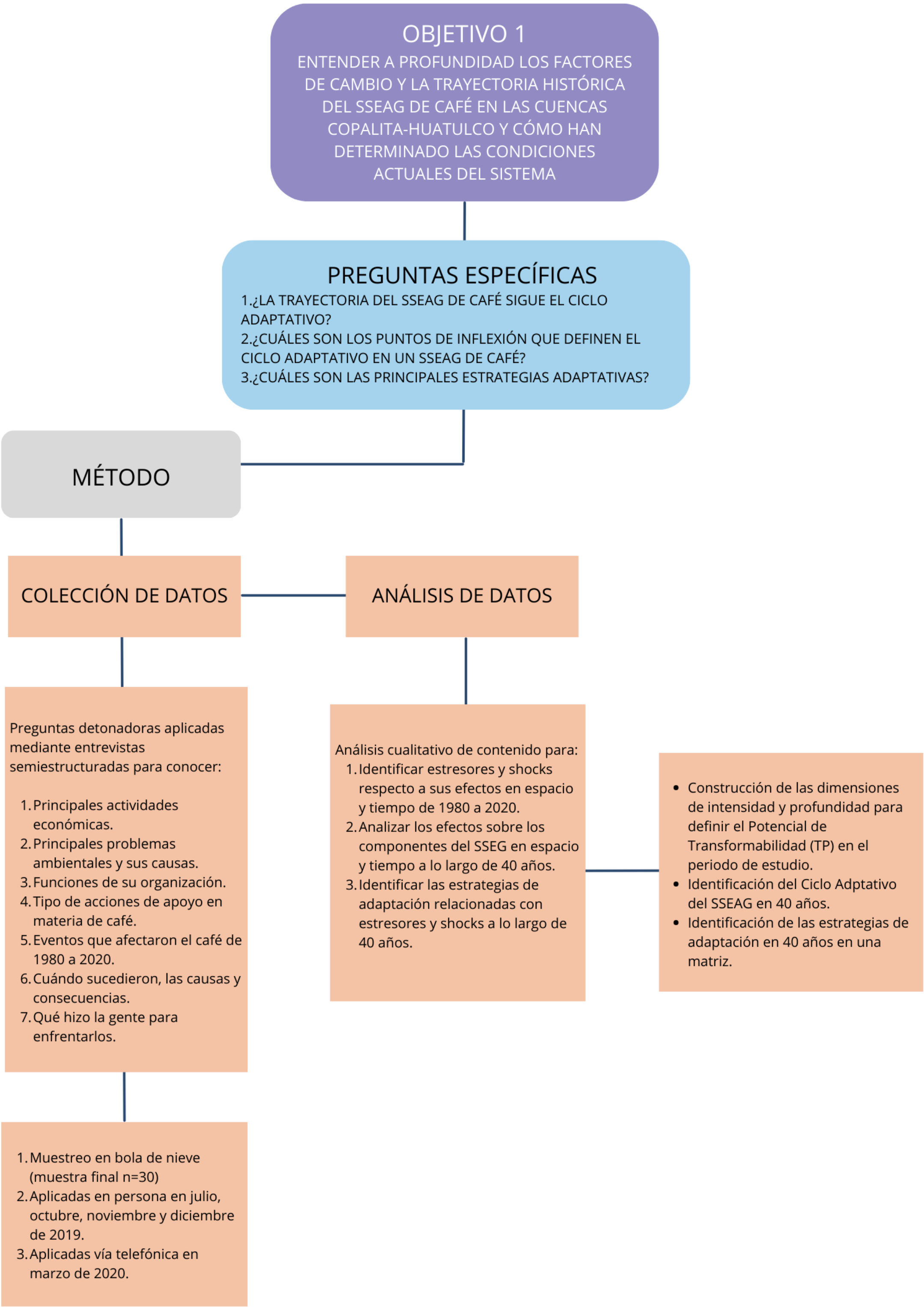
Objetivo específico 1:
Entender a profundidad los factores de cambio y la trayectoria histórica del sistema socioecológico agroalimentario de café localizado en las cuencas Copalita-Huatulco y cómo han determinado las condiciones actuales del sistema.

Resultado: Capítulo 3. The historical trajectory of a coffee agri-food system: a case study in Oaxaca, Mexico. Publicado en Ambio, julio 2023. https://doi.org/10.1007/s13280-023-01893-6

Objetivo específico 2:
Analizar las interacciones sociales en el SSEAG de café localizado en las cuencas Copalita-Huatulco para identificar los arreglos entre conectividad y diversidad que determinan su capacidad de adaptación y resiliencia.

Resultado: Capítulo 4. The role of diversity and connectivity in adaptation for resilience of a coffee agri-food system: a multiplex network approach. Enviado para publicación a Ambio, octubre 2023. En dictamen.

Figura 3. Secuencia para contestar la pregunta de investigación. Fuente: elaboración propia.



OBJETIVO 1

ENTENDER A PROFUNDIDAD LOS FACTORES DE CAMBIO Y LA TRAYECTORIA HISTÓRICA DEL SSEAG DE CAFÉ EN LAS CUENCAS COPALITA-HUATULCO Y CÓMO HAN DETERMINADO LAS CONDICIONES ACTUALES DEL SISTEMA

PREGUNTAS ESPECÍFICAS

1.¿LA TRAYECTORIA DEL SSEAG DE CAFÉ SIGUE EL CICLO ADAPTATIVO?
2.¿CUÁLES SON LOS PUNTOS DE INFLEXIÓN QUE DEFINEN EL CICLO ADAPTATIVO EN UN SSEAG DE CAFÉ?
3.¿CUÁLES SON LAS PRINCIPALES ESTRATEGIAS ADAPTATIVAS?

MÉTODO

COLECCIÓN DE DATOS

ANÁLISIS DE DATOS

Preguntas detonadoras aplicadas mediante entrevistas semiestructuradas para conocer:

1. Principales actividades económicas.
2. Principales problemas ambientales y sus causas.
3. Funciones de su organización.
4. Tipo de acciones de apoyo en materia de café.
5. Eventos que afectaron el café de 1980 a 2020.
6. Cuándo sucedieron, las causas y consecuencias.
7. Qué hizo la gente para enfrentarlos.

1. Muestreo en bola de nieve (muestra final n=30)
2. Aplicadas en persona en julio, octubre, noviembre y diciembre de 2019.
3. Aplicadas vía telefónica en marzo de 2020.

Análisis cualitativo de contenido para:

1. Identificar estresores y shocks respecto a sus efectos en espacio y tiempo de 1980 a 2020.
2. Analizar los efectos sobre los componentes del SSEG en espacio y tiempo a lo largo de 40 años.
3. Identificar las estrategias de adaptación relacionadas con estresores y shocks a lo largo de 40 años.

- Construcción de las dimensiones de intensidad y profundidad para definir el Potencial de Transformabilidad (TP) en el periodo de estudio.
- Identificación del Ciclo Adptativo del SSEAG en 40 años.
- Identificación de las estrategias de adaptación en 40 años en una matriz.

Figura 4. Síntesis de la metodología utilizada para identificar la trayectoria histórica del SSEAG. Fuente: Elaboración propia

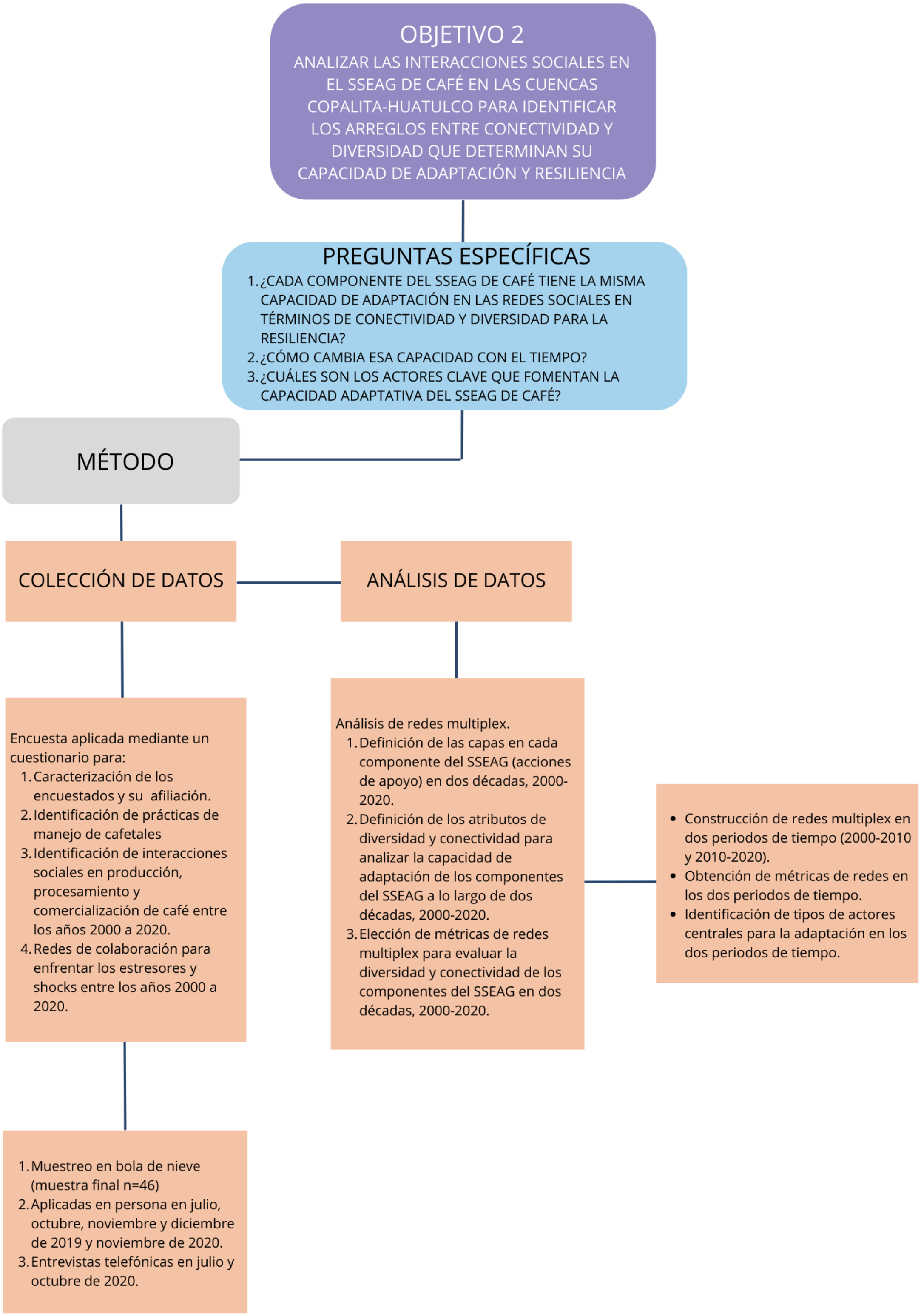


Figura 5. Síntesis de la metodología utilizada para identificar el papel de las interacciones sociales en la adaptación del SSEAG. Fuente: Elaboración propia

Con respecto al proceso de colección de datos, todas las entrevistas y encuestas fueron aplicadas explicando el objetivo de la investigación y el uso de la información a los participantes. Busqué que todos los informantes fueran líderes, encargados, o en su caso, que tuvieran el cargo de responsabilidad más alta dentro de la organización que representaban. En los casos de cooperativas, organizaciones de productores o agencias de gobierno, la primera persona contactada me indicaba si debía dirigirme a otra autoridad como presidente, director o jefe de área para solicitar autorización para realizar esta investigación y solicitar cita. En todos los casos mostré una carta de presentación de mi tutora como coordinadora del proyecto de investigación que desarrollaba, además de acreditar mi identidad mostrando mi credencial de estudiante de la UNAM y del Instituto Federal Electoral. En muy pocos casos los participantes se negaron a brindar información o requirieron autorizaciones de otras personas. Cabe decir que no se requirieron autorizaciones especiales para ingresar a comunidades o localidades, ya que las citas y contactos se hicieron entre particulares.

De tal suerte, obtuve su consentimiento libre e informado para participar en esta investigación con mi compromiso de mantener toda la información brindada como confidencial incluyendo sus datos de contacto. También solicité su autorización para grabar las conversaciones y/o para tomar fotos de ellos/ellas, sus parcelas u oficinas. Al despedirnos, informe que volvería a mostrarles los resultados de esta investigación; al día de hoy, aunque no he podido contactar a todos los participantes que me recibieron ya he compartido información con muchos de ellos. Esto en el marco del trabajo de difusión que hemos realizado junto con mi tutora y otros investigadores que formaron parte del proyecto *Trajectories of Social-Ecological Systems in Latin American Watersheds: Facing Complexity and Vulnerability in the context of Climate Change* (TRASSE), en el que se desarrolló este trabajo.

Foto: Ramírez León, A. Diciembre 2019. Instalaciones de la Unión de Trabajadores Agrícolas de Oaxaca (UNTAO) donde se realiza el beneficio seco para obtener café verde.

CAPITULO 3. THE HISTORICAL TRAJECTORY OF A COFFEE AGRI-FOOD SYSTEM: A CASE STUDY IN OAXACA, MEXICO

Ramírez-León, A., Avila-Foucat, V. S., & Ezzine-de-Blas, D. (2023). The historical trajectory of a coffee agri-food system: A case study in Oaxaca, Mexico. Ambio. https://doi.org/10.1007/s13280-023-01893-6

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https://doi.org/10.1007/s13280-023-01893-6

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TRAJECTORIES OF SOCIAL-ECOLOGICAL SYSTEMS IN THE GLOBAL SOUTH

The historical trajectory of a coffee agri-food system: A case study in Oaxaca, Mexico

Alejandra Ramírez-León, Veronique Sophie Avila-Foucat, Driss Ezzine-de-Blas

Received: 21 May 2022 / Revised: 4 January 2023 / Accepted: 8 June 2023

Abstract Agri-food social-ecological systems (AFSES) embrace complex interactions and processes of food production, processing, and commercialization that are subject to constant changes. This study develops a heuristic approach using the adaptive cycle (AC) and a transformation potential measure to identify the historical trajectory of a coffee AFSES at a watershed scale in Copalita, Mexico, over 40 years from 1980 to 2020. Primary information was collected through semistructured interviews. The results show that the system interactions depend on economic, social, and environmental stressors and shocks affecting different temporal and spatial scales. The cumulative effects of driving forces and adaptive strategies have influenced the system to not complete the AC phases. Additionally, the results show that some adaptive strategies can become new stressors with time. Driving forces, adaptive strategies, tipping points, trade-offs and interactions within the AFSES could be identified as the main aspects defining system resilience.

Keywords Adaptive cycle · Adaptive strategies · Agri-food systems · Coffee · Historical trajectory · Social–ecological systems

INTRODUCTION

Agri-food systems are the result of complex interactions between society and nature, shaping a social-ecological system (SES) that provides many ecosystem services to satisfy human needs and household livelihoods (Valbuena et al. 2013). Agri-food social-ecological systems (AFSES) include food production, transformation, distribution, and consumption processes in which interactions take place defining the SES trajectory in time and space. Biophysical conditions for production and markets have been identified as some of the main forces of change, but AFSES also respond to changing contexts, such as human and technological resources, input costs, public policies, and consumer preferences (Campanhola and Pandey, 2019), as well as external driving forces such as climate change and social conflicts (Huber-Sannwald et al. 2012). In addition, the effects of the system interactions and driving forces might be different in time and space, and especially when linking production to water resources and climate, the watershed scale becomes relevant to understanding how spatial heterogeneity generated by local biophysical factors influences decisions that transform the trajectory of the SES (Enfors 2013; Mokondoko et al. 2022).

The AFSES are typically influenced by multiple stressors and shocks (agro-ecological, economic and political-social driving forces) causing changes at various levels (farm, watershed, region, country) (Darnhofer 2014). Consequently, the AFSES adjusts its responses to external and internal driving forces to evolve and learn to develop toward a pathway or trajectory (Preiser et al. 2018) that can be within a stability domain or moving from one state to another. These pathways are also the result of the historical interactions between components of the system (environmental-ecological, economical-technical, and political-social components) and the accumulated effects of shocks and stressors (Duru and Therond 2015). The system is in a transition when crossing between two states and is in a transformation when it has crossed a threshold, implying that the system has lost its resilience (Folke et al. 2010). For example, when diseases and pests appear, the farmer

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Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13280-023-01893-6.

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Keywords: adaptive cycle; adaptive strategies; agri-food systems; coffee; historical trajectory; social-ecological systems

Introduction

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The adaptive cycle (AC) has been used as a heuristic theory of change to study the trajectories and resilience of SES (Folke, 2016). The AC (figure 1) describes the endogenous dynamics of SES generated by internal processes of self-organization and evolution over time through the succession of four phases: growth, conservation, collapse, and renewal (Holling, 2001). During the growth or exploitation phase (r), the system enters a slow and cumulative progressive cycle. In the conservation phase (K), resources become increasingly blocked, and the system becomes progressively less flexible and receptive to external disturbances. The loop formed by r-K consists of a self-regulating system that makes a system responsive and capable of adapting to both internal and external changes; it is marked by continuous accumulation of different forms of capital facilitated by self-reinforcing feedback loops between the system's components, which leads to accumulating resources, know-how and welfare (Kuhmonen and Kuhmonen, 2013:3). These conditions maintain the system with a certain range of variability or within a certain domain of attraction, that is, it maintains the same characteristics that identify it (Cabel and Oelofse, 2012). This phase is followed by a chaotic collapse and a release phase (Ω), which quickly gives way to a reorganization or renewal phase (α), in which innovation and new opportunities are possible and consequently allow the system to stay in the same state and be resilient. The reorganization phase is the degree to which farmers, consumers, and other stakeholders can organize themselves; any configuration that they create is more likely to contribute to the overall system resilience in the long term because it was created by their initiative in response to a real need (Cabel and Oelofse, 2012; Holling, 2001).

This evolutionary process depends on the intensities of shock and stressors and on the conditions and capacities of the system to respond, absorb disturbances and reorganize to maintain the same structure and identity (Walker et al., 2004; Folke et al., 2010). Three types of capacities have been recognized: persistence or absorptive capacity (ability to resist effectively, absorbing the shock impacts without changing their function, status, or state); adaptability or adaptive capacity (incremental changes and adaptations that people undergo to continue functioning in response to a shock or growing stress), and transformability or transformative capacity (human actions taken to create or enable a fundamentally new system) (Béné et al., 2016; Sinclair et al., 2017).

These three capacities depend on the initial conditions of the systems, such as assets or ecosystem services but also on the agency of actors (executed by people who make decisions) influencing the system through different types of responses linked to different intensities of shock or change (Béné et al., 2016). For example, persistence emerges from coping strategies by which its members moderate or buffer the impacts of shocks on their livelihoods and basic needs. Adaptive capacity refers to incremental changes without major changes to the way SES operates (adaptive strategies). The transformative capacity emerges when the changes required in response to shocks or stresses are so large that the system is altered, changing its functioning or structure (Béné et al., 2016).

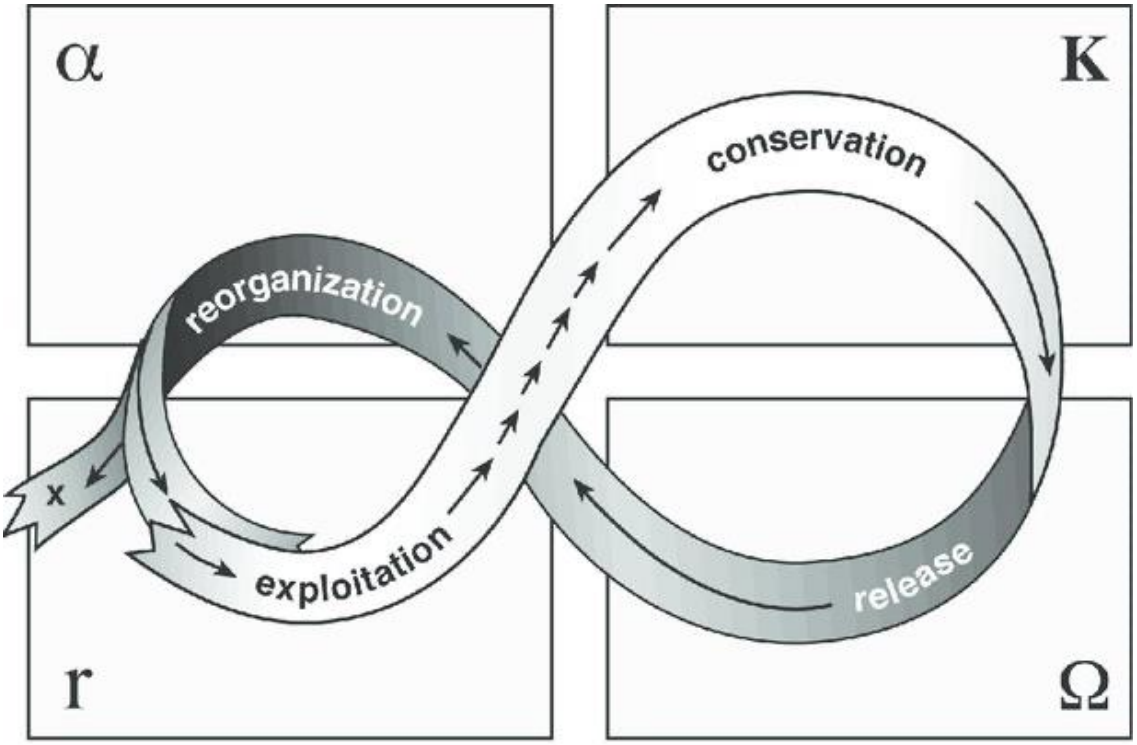


Figure 1 Adaptive cycle. Source: Gunderson and Holling 2022.

The AC has been useful to identify drivers of change, key variables, and the effects of stressors on SES in studies about forest management (Beier et al., 2009), agropastoral subsystems (Rasmussen and Reenberg, 2012), and ecosystem services (Pérez-Orellana et al., 2020). Other studies related to farming SES, such as Abel et al. (2006), Beier et al. (2009), and Antoni et al. (2019), have used this approach to analyze the evolution of SES and changes of state, as well as their components and relationships. In addition, other studies have used AC to address the resilience of AFSES (Cabel and Oelofse, 2012; Santos Prado et al., 2015; Sinclair et al., 2017; Darnhofer et al., 2010; Meuwissen et al.2019). Darnhofer (2010), Cabel and Oelofse (2012) and Meuwissen et al. (2019) proposed frameworks to assess resilience as well as indicators related to the attributes of a resilient AFSES, such as diversity, modularity, reflective and shared learning, social self-organization, and ecological self-regulation, among others.

All the cited studies that used AC to address the resilience of AFSES agree on the importance of analyzing the different types of changes and their effects, as well as the different intensities in time and space. They highlight that those interactions at different spatiotemporal scales can generate unpredictable effects that will inevitably modify the future trajectory of a system;

however, few studies specify spatial effects within a watershed. They also point out the relevance of identifying the thresholds and/or tipping points and the role played by the agency and governance to achieve desirable system transitions. Santos Prado et al. (2015) concluded that the analysis of trade-offs among components needs to be considered, balancing both the positive and negative aspects and considering the cross-scale connections, and highlighted the need for a more quantitative method to determine transitions and thresholds. Within the revised literature using the AC approach, historical data and qualitative interpretation have been used to identify transition phases before a complete transformation.

The AC has demonstrated its usefulness in explaining how SES experience periods of gradual change interrupted by shorter episodic disturbances that may reconfigure the system (Darnhofer et al., 2010; Gunderson et al., 2022). In addition, it allows us to identify relationships and feedback between natural and social variables. This makes it possible to identify how internal and external driving forces affect the system and its trajectory over time, which influences and shapes current and future trends (Preiser et al., 2018). The analysis of the historical trajectory of SES can provide important information to understand the actual conditions and the challenges imposed for resilience and sustainability in planning and decision-making (Nguyen et al., 2019). However, few studies using AC have deepened the relationship between shock and stressor effects on the system, causing adaptive capacities to address system resilience. Thus, we used AC as a theoretical point of reference to identify transition and transformation and the role played by adaptive capacity related to them. The analytical-theoretical framework proposed combines the AC and the concepts of dimensions of change (Fazey et al., 2018) to characterize quantitatively the effects of driving forces to determine when transitions happen.

The case of the coffee AFSES is used as empirical evidence due to its economic importance and its wide geographical distribution. Coffee is commercially grown in tropical developing countries, mainly in conditions of marginalization and poverty (Bacon, 2005; Olsson et al., 2014) where climate and biophysical factors are key aspects; its international trade is dominated by a few transnational companies with profits concentrated in processing and commercialization, which are estimated to surpass USD 200 billion (ICO, 2019). This in turn is proof of the complexity of this AFSES, and learning about its trajectory can generate many insights into resilience theory.

Specifically, the case study is located in the Copalita-Huatulco watersheds (CHW) in Mexico, where coffee production represents 24% of Oaxaca state production, being the fourth largest coffee region in Mexico (SIAP, 2021). Here, shade coffee production predominates as an agroforestry system that contributes to regulation ecosystem services such as regulation of local climate, conservation of soil fertility, and biological regulation of water flows, among others (FAO, 2020). The global conditions related to the coffee market are characterized by instability of markets, affectations by climate change, and limited bargaining power of farmers in the coffee value chain, have influenced the local conditions distinguished by price speculation, an increase of temperature, and poverty among coffee smallholders. These conditions suggest that CHW has suffered from tipping points that have taken the system from a condition of relative stability to a context of crisis and uncertainty that we want to determine. Figure 2 represents the coffee AFSES located in the CHW; it shows the four components of the system and the interactions among them, as well as its geographic location in the watershed.

This study aims to analyze the historical trajectory of the coffee AFSES of the CHW from 1980 to 2020 to understand the system dynamics and possibilities for enhancing its resilience. We ask the following questions: Does the coffee AFSES trajectory follow the AC? What are the tipping points defining the AC of a coffee AFSES, and does the method proposed help to identify them? What are the main adaptive capacities identified? The coffee AFSES could have recovered by maintaining the same structure and returning to the coffee bonanza, or it could have transformed into a system with a completely new structure and characteristics where coffee would have been abandoned and new economic activities carried out to have a more stable state. This paper aims to contribute to the literature assessing trajectories and resilience in AFSES at a watershed scale by identifying the transition phases and tipping points using the AC and a transform ability potential. This knowledge will improve our understanding of the management of complex AFSESs and can also be used in other similar systems around the world and provide information for local adaptation planning. In the 1980s, major international coffee crisis occurred, which influenced a process of socioeconomic restructuring in the CHW that was exacerbated by environmental events such as hurricanes (Jaffee, 2019). We choose the start of this disruptive event that triggered a series of abrupt changes (Speelman et al., 2014; Nayak and Armitage, 2018; Nguyen et al., 2019) to establish the study period from 1980 to 2020.

Method

Description of the area of study. The Copalita-Huatulco watershed (CHW) is located on the Pacific coast of Mexico in Oaxaca state, it covers approximately 187,576 hectares and is formed by the Copalita and Huatulco subwatersheds (Figure 3). Based on the type of vegetation, we established three areas of the watershed: the upper part ranged between 1,501 and 2,900 meters, the middle part ranged between 501 and 1,500 meters, and the lower part ranged between 0 and 500 meters. In the upper part, pine-oak forests prevail; in the middle part, there are sub evergreen and mesophyll forests; and in the lower part, there is deciduous forest (SAGARPA and SEDAPA, 2015). Since the ecosystems vary according to the altitudinal range, there are economic activities that can be better developed in specific parts and not in the entire watershed. The CHW is the home of nineteen municipalities with 181,715 inhabitants (INEGI, 2020). In 2015, 87% of the population of the CHW suffered from poverty and had income below the welfare line (CONEVAL, 2020).

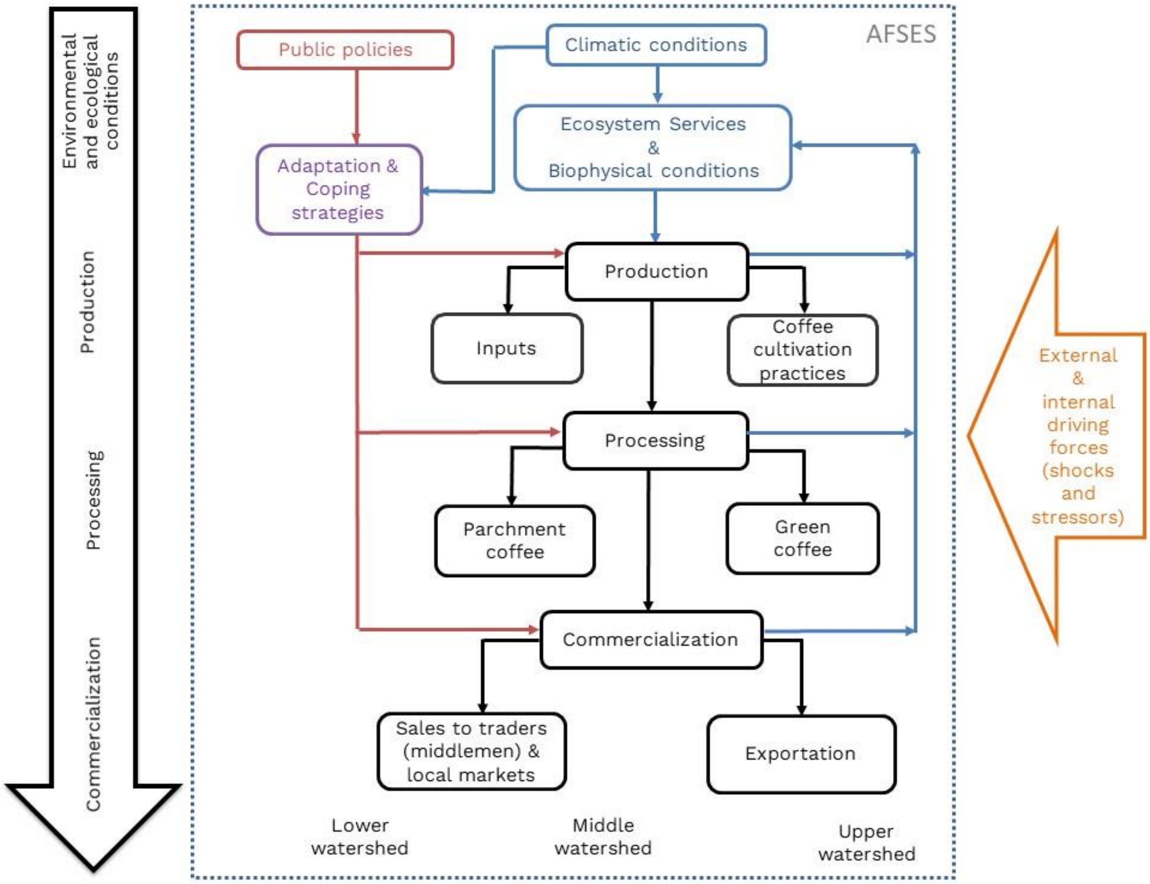


Figure 2. Coffee agri-food social-ecological system (AFSES) of Copalita Huatulco Watersheds (CHW). Source: Own elaboration.

The watershed provides favorable conditions for coffee cultivation (INEGI, 1997), which was an economic mainstay in the region from the 19th century until the second half of the 20th century. In the watershed, there are different growing conditions for coffee. The upper basin is home to 30% of the cultivated coffee area, and forestry is also an important economic activity there. The middle basin presents 50% of the cultivation area for coffee dominated by landowners with more than ten hectares (50% of coffee farmers). In the lower basin is 20% of the cultivated coffee area. Small producers are located throughout the basin and they are owners of 37% of the cultivated area, comprised of 8,240 households that own up to five hectares of land. Only 12% of producers are medium farmers with plots between 5 and 10 hectares (SAGARPA and SEDAPA, 2015). Fishing and livestock activities are in the middle and lower parts, and self-subsistence crops are cultivated throughout the watershed. Tourism and off-farm jobs are more important within the coastal limits of the basin due to the Huatulco resort.

Data collection. We conducted semistructured interviews with stakeholders using the snowballing method (Corbin and Strauss, 2012). The first contact was with a representative of a nongovernmental organization that provides advice on agroforestry systems; he recommended speaking with a retired researcher who specialized in the cultural and political changes in the coffee sector in the state of Oaxaca. She helped us to identify the first key actors who could provide historical information about the CHW. The face-to-face visits to conduct interviews began in July 2019 and were repeated in October, November, and December 2019. The last interviews were carried out by phone in March 2020 due to the beginning of the COVID-19 pandemic.

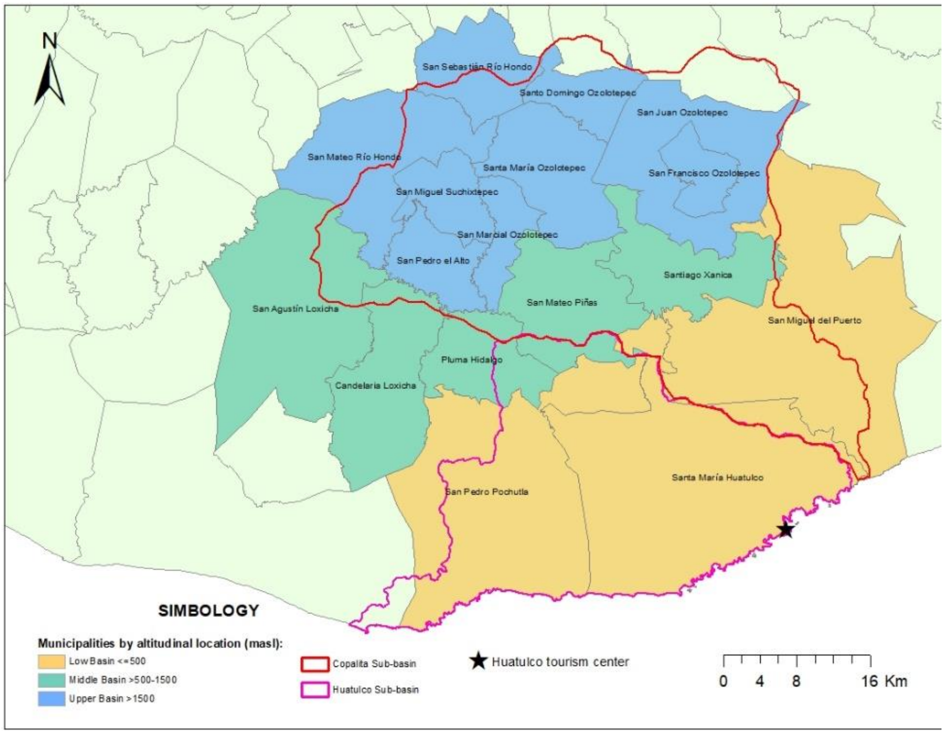


Figure 3 Copalita-Huatulco Watersheds (CHW). Source: Own elaboration

An interview applied face to face had an average duration of 90 minutes because several people were excited to narrate their experience in the coffee sector and the problems they faced. Phone interviews had an average duration of 50 minutes. The objective of the research was explained to each participant and at the time of the interview, authorization was requested to record the conversation under conditions of anonymity and confidentiality. We conducted thirty interviews that we transcribed for analysis. The respondents were leaders of producer organizations (n=4); entrepreneurs who promote economic diversification (n=3); representatives of nongovernmental organizations (NGOs) (n=10); delegates of government (n=8); researchers (n=2); and coffee farmers (n=3). The people interviewed have a position of leadership in political, social, environmental or economic issues related to coffee activity in the CHW; therefore, their views represent the systemic changes of the coffee AFSES.

When the interviewee was a farmer, the first section of questions focused on characterizing his or her community: the main economic activities, the main environmental problems, and their causes. In the case of institutional representatives, the first section asked about the functions of their organization and the type of support actions provided regarding coffee. In the second section, the main stressors and shocks were identified by asking what events affected coffee, when they happened, the causes and consequences and what people did to confront them. Secondary information was consulted to complement the information given by the interviewees. The complete questions are in Appendix 1, and examples of relevant testimonies are in Appendix 2.

Data analysis. Qualitative content analysis was used to classify the collected information into more interpretable units of analysis (Corbin and Strauss, 2012; Abela, 2012). This classification was carried out using three steps to 1) identify stressors and shocks based on their effects on spatial distribution and time frame; 2) analyze the effects over the components of the AFSES (described in figure 1) in terms of spatial distribution and time frame; and 3) identify the adaptive strategies related to them. The coding system used to classify the information is in Appendix 3. This analysis was carried out using MAXQDA version 20.4.0.

The identification of stressors and shocks was based on their impacts in terms of the spatial and temporal effects within the AFSES: effects may entirely or partially (upper, middle or lower part) cover the watershed and may be felt over the short term (several months to a few years), long term (several years or decades), or ongoing (initiated in the past manifested in the present and with no identified conclusion). These data were classified using the categories: driving forces; components of the AFSES; and processes, situations and actors. A shock was defined by a short-term acute event with a rapid onset and a typically short duration, while stressors were usually chronic with a slow onset and a typically protracted duration (Sagara, 2018). The effects were assessed using the concepts of breadth and intensity. Breadth is related to the spatial presence of the impacts on the watershed, and intensity is the temporality of the effects quantifying their time frame.

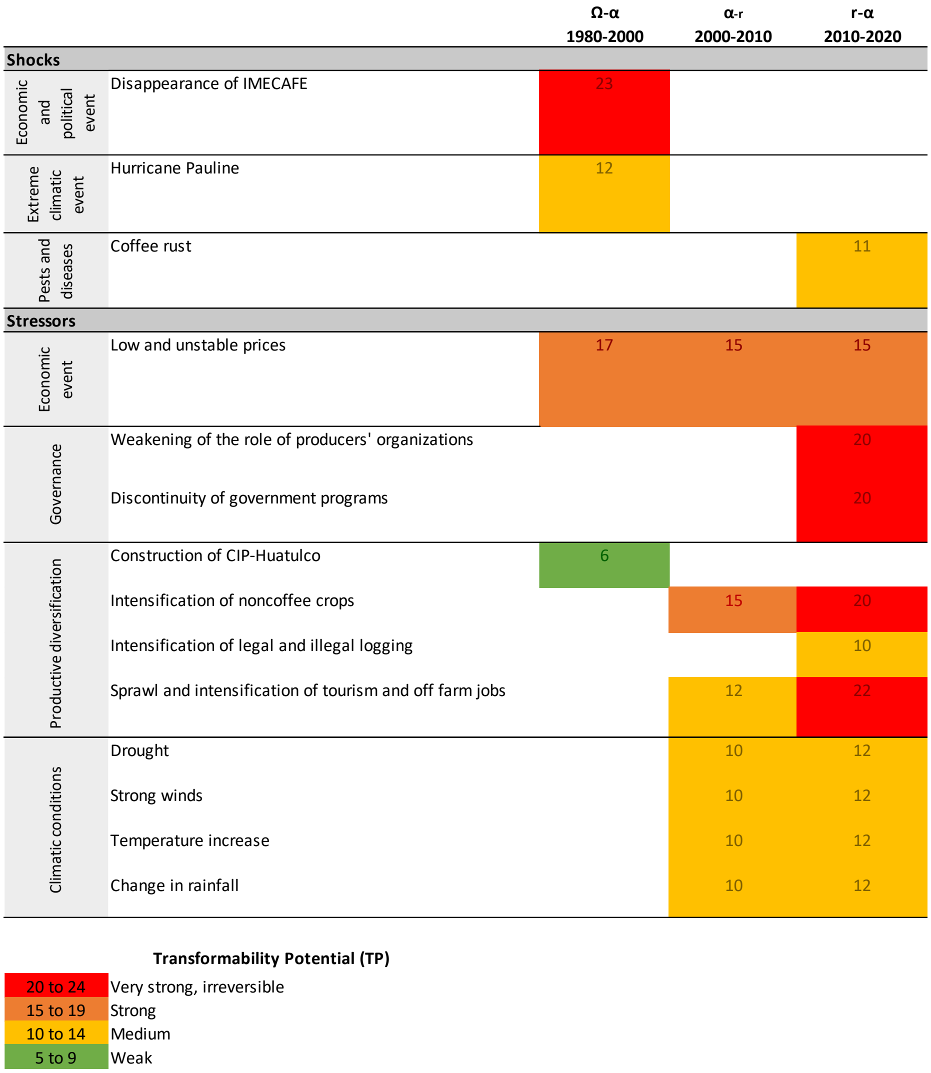
Through the temporal and spatial scale categories, we identified the data that allowed us to establish breadth and intensity for each stressor and shock; the results obtained were used to attain a matrix that quantified those concepts. In this matrix, the values of breadth were established through a binary measure of presence-absence (1-0); if a shock or stressor affected any component of the AFSES in any of the three parts of the watershed, we assigned a value of 1. If all parts of the watershed were affected, the maximum value obtained was 3. Intensity was weighted on a scale between 1 and 3, where the highest value (3) indicates a definitive and irreversible effect (when the effects are short-term and there is no way to reverse them), followed by incremental effect (2) (when the effects started at a point in the past, were maintained in the long term or are still manifesting), or temporal effect (1) (when the effects started and ended in a specific period). The sum of breadth and intensity represents the total effect of each stressor and shock on the AFSES, called the transformability potential (TP), which was adapted from the concept of transformability.

The TP supports the identification of the transition in the AC through a scale defined as very strong or irreversible with a TP between 20 and 24 points; strong with a TP between 15 and 19; middle with a TP between 10 and 14; and weak with a TP between 5 and 9. The highest range (very strong or irreversible) corresponded to an irreversible transformation in which the driving force triggered the beginning of a new AC in the AFSES (Ω); the next ranges (strong, middle, and weak) represented the push of the driving force to advance in the succession of the AC to the next phases (α, r, K) until reaching together a new phase of transformation (Ω). For example, Hurricane Paulina was identified as a shock and its breadth and intensity were calculated, whose values were 6 for both cases, giving a TP equal to 12. According to the defined scale, Hurricane Pauline had a medium TP (between 10 and 14), since it did not affect the entire basin or all the components of the system to the same extent. The TP of each driving force was used to attain a matrix to identify the AC of the system. According to the defined scale, Hurricane Paulina had a medium TP (between 10 and 14) since it did not affect the entire basin or all the components of the system to the same extent. The third step was to describe adaptive strategies through the choices and activities that individuals and groups made in response to stressors and shocks. The subcategory adaptive and coping strategies was used to identify those elements and obtain a matrix that summarizes the driving forces, their effects, and the adaptive strategies related to them.

Results

The AFSES has transitioned through three phases of the AC: from crisis to rearrangement (Ω-α phase) between 1980 and 2000; reconfiguration and innovation (α-r phase) between 2000 and 2010; and reorganization to new arrangements (r-α phase) between 2010 and 2020. Table 1 summarizes the TP of shocks and stressors of different natures and how they influence the transition in the AC.

Table 1. Transformability potential (TP) of stressors and shocks based on the Adaptive Cycle (AC)



		Ω-α 1980-2000	α-r 2000-2010	r-α 2010-2020
Shocks				
Economic and political event	Disappearance of IMECAFE	23		
Extreme climatic event	Hurricane Pauline	12		
Pests and diseases	Coffee rust			11
Stressors				
Economic event	Low and unstable prices	17	15	15
Governance	Weakening of the role of producers' organizations			20
	Discontinuity of government programs			20
Productive diversification	Construction of CIP-Huatulco	6		
	Intensification of noncoffee crops		15	20
	Intensification of legal and illegal logging			10
	Sprawl and intensification of tourism and off farm jobs		12	22
Climatic conditions	Drought		10	12
	Strong winds		10	12
	Temperature increase		10	12
	Change in rainfall		10	12

Transformability Potential (TP)

20 to 24	Very strong, irreversible
15 to 19	Strong
10 to 14	Medium
5 to 9	Weak

Source: Own elaboration.

From crisis to rearrangement (Ω-α phase) between 1980 and 2000. The first phase (Ω-α) was a period of creative destruction triggered by the disappearance of the Mexican Institute of Coffee (IMECAFE) (TP equal to 23), which was a shock that paralyzed all components of the AFSES (production, processing, commercialization and environmental and ecological conditions, figure 2) throughout the entire watershed and generated the irreversible transformation of the system. In addition, the duration of its effects on economic, political, and organizational issues was incremental and has accumulated to this day. Another shock, Hurricane Pauline (TP equal to 12), struck the entire basin, and its effects were irreversible for coffee production and are still being felt specifically for production and environmental conditions. The main stressors were low and unstable prices (TP equal to 17) and the construction of the touristic center of Huatulco (CIP-Huatulco) (TP equal to 6). Low prices directly affected production, commercialization and environmental conditions throughout the watershed, and their effects were incremental. The construction of CIP-Huatulco in the coastal limits of the CHW initiated a series of gradual changes in production, environmental and ecological conditions; consequently, its effects were incremental.

These driving forces generated a stage of chaos that led to strategies that allowed the AFSES to continue evolving, which mainly were the offer of new jobs in the tourism sector (coping strategy) (which made it possible to supplement the income of the families of coffee growers), the collective organization of coffee farmers (coping strategy), the sales of other crops that grew in the CHW (coping strategy), incursion in new certified coffee markets (adaptive strategy) and the implementation of reconstruction programs to face the damages of the hurricane (coping strategy), among others. On the other hand, according to the testimonies collected (Appendix 2), the residues from washing coffee beans, which generated contamination in streams and rivers during the most productive years, reduced due to the decrease in production, which in the long term improved the supply of drinking water for human settlements. Table 2 summarizes the relationships between the driving forces, their causes and effects, and the strategies adopted to address them in this period.

Table 2. Relationships between the driving forces, causes, effects, and strategies adopted in the phase Ω-α, crisis and rearrangement (1980-2000)

Ω-α crisis and rearrangement (1980-2000)					
Driving force (type)	**Year**	**Cause(s)**	**Effect(s)**	**Adaptive Strategy/ies (type)**	**Evidence (testimony)**
Construction of CIP-Huatulco (stressor)	1984	This Construction was planned by the federal government to promote mass sun and beach tourism in the region.	It encouraged the construction of urban centers and introduced off-farm jobs which impacted production and environmental conditions at the lower part.	Alternative employment in jobs related to tourism (Coping strategy)	Testimony no. 2, Appendix 2 Testimony no. 3, Appendix 2 Jaffee, 2019
Disappearance of IMECAFE (shock)	1989	Interruption of international coffee agreements. Consequently, national public spending in the agricultural sector was reduced.	Political and commercial restructuring to deregulate the production, processing and commercialization of coffee carried out by IMECAFE from 1968 to 1989.	Integration of collective organizations of coffee farmers to absorb the functions of IMECAFE in large organizations (e.g. the State Coordinator of Coffee Producers of Oaxaca, CEPCO) (Coping strategy) These organizations came to manage governmental programs. (Adaptive strategy)	Testimony no. 1, Appendix 2 Paré, 2001
Low and unstable prices (stressor)	1980s	The international price of coffee suffered several ups and downs	Increase of production costs. Speculation with local coffee prices by local intermediaries. Impoverishment and social exclusion among coffee farmers. First wave of abandonment of coffee cultivation.	Sales of noncoffee crops that were already grown in coffee plantations, such as bananas. (Coping strategy) Incursion in international certification seals to obtain price premium (e.g. Fair Trade). (Adaptive strategy) Incursion in the processing of coffee and developed of new brands. (Adaptive strategy)	Testimony no. 4, Appendix 2 Jaffee, 2019
Hurricane Pauline (shock)	1997	This hurricane hit the CHW in October 8th under category 4 according to Saffir-Simpson scale.	It generated erosion, and loss of native vegetation, springs disappeared, and the soils became more acidic. The productivity and resistance to pests and diseases decreased. Impoverishment of coffee farmers and triggered a second wave of abandonment of coffee cultivation.	The government implemented reconstruction programs for the coffee sector that included the distribution of high-yield technological packages. (Coping strategy) Migration was reinforced along the CHW (Coping strategy).	Testimony no. 6, Appendix 2 Testimony no. 7, Appendix 2 CONABIO, 2020 Vera Cortés, 2005

Reconfiguration and innovation (α-r between 2000 and 2010). In the second phase, reconfiguration and innovation (α-r), diverse stressors with incremental and cumulative effects were identified and were characterized by the strengthening of alternative economic activities. These activities were strategies adopted in the previous period and were intensified, generating new conditions that caused secondary effects. The constant presence of low and unstable prices (TP equal to 15) was maintained, resulting from the environment generated by the international coffee markets that impacted local production, commercialization and modified environmental conditions in the entire watershed. The noncoffee crops were a mainstay for the continuity of the AFSES, but they led to clearing the land to cultivate and use agrochemicals across the entire watershed. Thus, the intensification of noncoffee crops (TP equal to 15) impacted the production, commercialization and environmental conditions.

As a result of the construction of the CIP-Huatulco, tourism spread mainly in the lower and middle parts of the watershed due to the increase in visitors, but without planning or regulation, which implied greater demand for water, greater generation of waste and a high disturbance of local ecosystems. This intensification of tourism and off-farm jobs has been perceived as a stressor (TP equal to 12) and has impacted production, commercialization, and environmental conditions. However, the proximity of the tourist center favored the opening of points of sale for locally-produced products. The stressors associated with the change in climatic conditions (TP equal to 10) and their effects mainly affected the production and environmental conditions of the entire watershed.

Local studies, carried out by local government and universities, found that the shade coffee in the CHW contributed to preserve infiltration of water, refuge to biodiversity, and ecological connectivity (Ramos Olivera, 2015). Specifically, the highest rates of deforestation were observed outside the altitudinal range of coffee (400 to 1600 meters) (SAGARPA and SEDAPA, 2015), where traditional agriculture expanded by approximately 41,000 hectares over the last ten years (Olivera Ramos et al., 2015).

Among the main adaptation strategies in this phase, the noncoffee crops (coping strategy), the incursion into new markets (adaptive strategy), and the coffee processing (adaptive strategy) were maintained from the previous stage. The incursion of coffee growers into ecotourism projects also arose at this stage (adaptive strategy). In addition, government programs and NGO initiatives promoted actions to support shade coffee (such as the payment for the hydrological environmental services program and the initiative water management in watersheds, implemented by WWF Mexico) to encourage the contributions of shade coffee to the conservation of the CHW (adaptive strategy). Table 3 summarizes the relationships between the driving forces, their causes and effects, and the strategies adopted to address them in this stage.

Table 3. Relationships between the driving forces, causes, effects, and strategies adopted in phase α–r, reconfiguration and innovation (2000-2010)

α–r reconfiguration and innovation (2000-2010)					
Driving force (type)	**Year**	**Cause(s)**	**Effect(s)**	**Adaptive Strategy/ies (type)**	**Reference (evidence)**
Low and unstable prices (stressor)	2000s	The international price of coffee continued to suffer several ups and downs.	The social backwardness among coffee farmers continued and was aggravated.	Sales of noncoffee crops that were already grown in coffee plantations including oranges, soursop, or cocoa. (Coping strategy) Incursion in international certification markets. (Adaptive strategy) Development of new brands and incursion in the processing of coffee. (Adaptive strategy) Sale of coffee to intermediaries/middlemen. (Coping strategy) Incursion of coffee farmers in ecotourism offers. (Adaptive strategy)	Testimony no.9, Appendix 2. Testimony no. 10, Appendix 2. Testimony no. 11, Appendix 2
Intensification of noncoffee crops (stressor)	2000s	Intensification of nontraditional crops in the shade-grown coffee agroforestry system (e.g., avocado, peach) of commercial importance	Unplanned expansion through the clearing of land and use of agrochemicals.	Increasing of use of agrochemicals. (Coping strategy)	Ramos Olivera, 2015 SAGARPA and SEDAPA 2015
Sprawl and intensification of tourism and off-farm jobs (stressor)	2005	Expansion of tourism and off-farm jobs from the watershed's lower part to the middle part.	Urban sprawl in the lower part near the CIP-Huatulco where housing developments have been built for local inhabitants and migrants. The urban sprawl increased the demand for freshwater and food, including waste and sewage emissions management. Emigration out of the CHW of young people and the transformation of the heads of household toward single mothers or elderly people.	Implementation of governmental programs and nongovernmental strategies that favor the cultivation of shade-grown coffee to maintain water infiltration, refuge for biodiversity, and ecological connectivity. (Adaptive strategy)	Testimony no. 8, Appendix2 Testimony no. 12, Appendix 2 Ramos Olivera, 2015 (Lozano-Trejo et al., 2020) SAGARPA and SEDAPA, 2015

Climatic conditions (drought, strong winds, temperature increase, change in rainfall)	2000s	Change in local climatic conditions	Decreasing the productivity of coffee plants and increasing disease outbreaks.	Unidentified	Ramos Olivera, 2015 SAGARPA and SEDAPA 2015

Reorganization to new arrangements (r-α phase between 2010 and 2020). In the third phase, reorganization to new arrangements (r-α) was distinguished by a brief period of recovery; however, various stressors whose effects were incremental and accumulated from the previous stages exerted greater pressure than in previous decades. In addition, the coffee rust plague (Hemileia vastratix) hit the AFSES, resulting in a new crisis. First, the presence of low prices was constant (TP equal to 15), affecting the entire watershed and production, commercialization, and environmental conditions, and their effects prevailed incrementally. The role of producers' organizations lost legitimacy due to allegations of lack of transparency causing members to stop participating in them. This decreased the bargaining power of these organizations in the market and with the government. The weakening of producers' organizations became a stressor (TP equal to 20) and impacted all the components of the AFSES, with incremental effects.

The discontinuity of government programs became a stressor (TP equal to 20) because the budget allocated for conservation and sustainability in the coffee sector (already weakened) was reduced by the change in government. These programs promoted specific actions such as the reforestation, renovation of coffee varieties, and cultivation of crops associated with agroforestry systems to encourage the infiltration of water provided by coffee plantations and the conservation of native vegetation. Consequently, the absence of these programs affected all the components of the AFSES, and their effects were incremental. The intensification of noncoffee crops (TP equals 20) and the sprawl and intensification of tourism and off-farm jobs (TP equals 22) increased their pressure due to cumulative effects, and both stressors affected the entire basin and all its components.

In this phase, legal and illegal logging emerged as stressors (TP equal to 10) in the upper part of the watershed, and its effects were incremental and affected the components of production, commercialization, and environmental conditions. The stressors related to climatic conditions (TP equal to 12) also increased, and the pressure over the entire watershed increased over the production and environmental conditions. The variability of climate was associated with the appearance of pests and diseases in crops; specifically, the rising temperature triggered the sprawl of coffee rust that shocked the AFSES in 2015 (Avelino et al., 2015); it spread massively and provoked diminished productivity. Coffee rust affected the production and environmental conditions of the AFSES in the entire basin, which suffered irreversible and immediate damage resulting in partially paralyzed activities on the plots. The most affected plots were in the lower zone, and collaboration networks between farmers allowed them to share information to contain the pest; in addition, they shared stocks and capacities to continue marketing and processing coffee. Coffee production has gradually recovered since 2017 because of the knowledge acquired to improve the management of coffee plantations. Coffee rust was considered a shock, and its TP was 11.

Among the main adaptation strategies, coffee farmers increased the diversification of their economic activities through incursion into specialized coffee markets (adaptive strategy), direct sales to national consumers (coping strategy), and offering ecotourism in coffee farms (adaptive strategy). New forms of collective associations among coffee farmers emerged, including horizontal collaboration networks among producers and nonstate actors (NGOs, companies) (coping strategies). Regarding coffee rust, fumigation (coping strategy) and renovation with rust-resistant coffee plants were the main strategies (adaptive strategy). However, coffee plantations required more intensive management, resulting in an increase in the costs of production; NGOs and coffee farmers have been concerned about the possible effects of this change. In addition, although the study period reached 2020, this study did not cover the effects of the pandemic that began in that year, since in the last interview occurred before the effects of COVID-19 were perceived. Table 4 summarizes the relationships between the driving forces, their causes and effects, and the strategies adopted to address them in this decade.

The combination of the accumulation of effects generated over the years and the strategies to absorb the disturbances generated by the driving forces has shaped an interrupted AC (Figure 5). The adaptive and coping strategies have helped to maintain the fundamental relationships at the core of the AFSES, which is why it has remained in the same state. However, some strategies are currently generating uncertain feedback and trade-offs.

Table 4. Relationships between the driving forces, causes, effects, and strategies adopted in phase r-α, from reorganization to new arrangements (2010-2020)

r-α from reorganization to new arrangements, 2010-2020					
Driving force (type)	**Year**	**Cause(s)**	**Effect(s)**	**Adaptive Strategy/ies (type)**	**Reference (evidence)**
Low and unstable prices (stressor)	2010s	The international price of coffee continued to suffer several ups and downs.	The coffee cultivation was reduced to 30% lower than in 2010. Imbalance between price and production costs.	Intensification of noncoffee crops. (Adaptive strategy) Incursion in new specialized coffee markets. (Adaptive strategy) Development of new brands and processing of coffee. (Adaptive strategy) Sale of coffee to intermediaries and direct sales to national consumers. (Coping strategy) Offer of ecotourism in coffee farms. (Adaptive strategy)	(Servicio de Información Agroalimentaria y Pesquera, 2021) Jaffee, 2019
Weakening of the role of producers' organizations (stressor)	2010's	Lost of legitimacy due to allegations of corruption and lack of transparency. Complexity of internal administrative processes.	Disappearance of several cooperatives. Decrease in the participation of coffee growers.	Formation of new collective groups (civil associations, social and private companies, cooperatives) (Coping strategy)	Testimony no. 16, Appendix 2
Discontinuity of government programs (stressor)	2018	Reduction of budget allocated for conservation and enhancing sustainability in the agricultural sector. agroforestry systems.	Encouragement of change of crops and land use.	Formation of networks of collaboration between farmers, NGOs, enterprises to share knowledge, experience and capacities. (Coping strategy)	Testimony no. 18, Appendix 2 Testimony no. 19, Appendix 2
Intensification of noncoffee crops (stressor)	2010s	As a result of the intensification initiated in the previous decades.	Contamination and erosion because of the use of agrochemicals and the land clearing to cultivate.	Increasing of use of agrochemicals. (Coping strategy)	Ramos Olivera, 2015 SAGARPA and SEDAPA 2015
Intensification of legal and illegal logging	2010	Bark beetle plague and organized crime.	Increase of forestry permits to cut down infested pine trees.	Undefined	Testimony no. 17, Appendix 2
Sprawl and intensification of tourism and off farm jobs (stressor)	2010s	As a result of the intensification initiated in the previous decades.	Increase of the water consumption, waste generation, and waste sewage emissions. Clearing of land for the construction of spaces required by urban planning.	Implementation of nongovernmental initiatives to favor the cultivation of shade-grown coffee to maintain water infiltration, a refuge for biodiversity, and ecological connectivity. (Adaptive strategy)	Testimony no. 17, Appendix 2

Climatic conditions (drought, strong winds, temperature increase, change in rainfall) (stressors)	2015	Change in local climatic conditions	The rising temperature triggered the sprawl of coffee rust.	Undefined	Ramos Olivera, 2015 SAGARPA and SEDAPA 2015
Coffee rust plague (shock)	2015	The increase of temperature and low management in the plots (little pruning of shade trees, aged coffee plantations, little soil nutrition).	Devastation of plantations and temporary stoppage of coffee production	Fumigation to control it. (Coping strategy) Renovation with rust-resistant coffee plants. (Adaptive strategy) Collaboration networks between farmers to share information and useful actions to contain the pest. (Coping/adaptive strategies) Intensification of management (pruning and clearing of shade trees, fertilization of soil) (adaptive strategies)	Testimony no. 13, Appendix 2 Testimony no. 14, Appendix 2 Testimony no. 15, Appendix 2

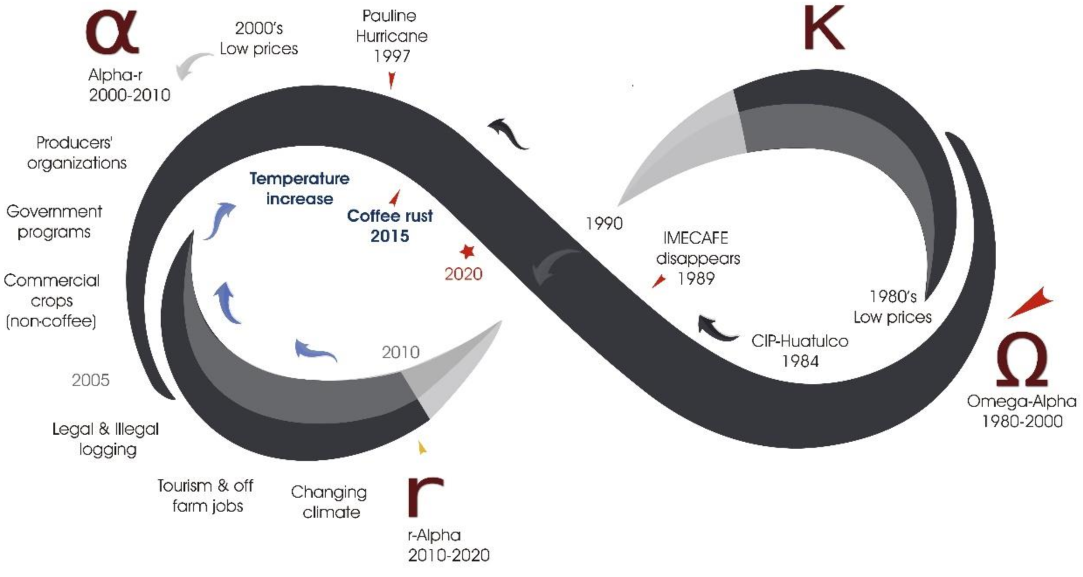


Figure 4 Trajectory of the Copalita-Huatulco SES based on the AC: 1980-2020. Source: Own elaboration. The large red arrow marks the beginning of the cycle in the 1980s, and the red star marks its end in 2020. The red arrows indicate the shocks that have affected the AFSES. The low prices of coffee have stayed constant over the 40-year period. In the 2000s, stressors accumulated because of the effects generated previously. In 2010, the cycle continued toward a phase of recovery that was interrupted and caused it to reverse; this setback is indicated by the yellow arrow.

Discussion

Proposed framework and resilience. The AC was a useful conceptual tool for understanding the long-term dynamics of change because it described endogenous dynamics resulting in the internal processes of self-organization over time (Sundstrom and Allen, 2019); however, the system did not follow the cycle steps. Although the AC supposes that the evolution of an SES can be described as a pattern, it is not the exclusive way in which a system can evolve. In AFSES, the decisions and actions taken by social actors can have multiple effects and trade-offs and are linked to various social and economic processes (Meuwissen et al., 2019). Human agency contributes to the complexity and unpredictability of change processes and the subsequent outcomes (Sinclair et al., 2017); consequently, AFSES can reorganize in multiple pathways. In our study, the CHW showed an incomplete cycle due to the differentiated TP of each stressor and shock as well as the adaptive strategies. We argue that the proposed method is useful for identifying this rupture within the AC, but it is insufficient to explain the implications of having an incomplete cycle.

The permanence of AFSES during the Ω-α phase (1980-2000) and α–r phase (2000-2010) can be explained because the components of the system interact to create conservative structures in time and space, such as the direct incursion of the producers in the processing and commercialization as well as the use of the tourist space of the CIP-Huatulco and other commercial points near the CHW. Another example is the role that government programs and other nongovernmental initiatives played in conserving shade-grown coffee. These structures resulted in persistent interactions that preserve the core of the system as a coffee AFSES (Burkhard et al., 2011). However, in the last stage, r-α (2010-2020), the AFSES confronted more diverse stressors that made it difficult to reach a system responsive and capable of adapting to both internal and external changes (loop formed by r-K). As a result, we have an AFSES that remains unstable and uncertain in the same state without entering another state.

Consequently, it can be considered that the permanence and consequent resilience of the AFSES is based on the cultivation, processing and commercialization of shade coffee and the interactions of the system that have contributed significantly to its maintenance. In this study, adaptive strategies have helped to prevent the system from being transformed. However, the transition pattern between phases (chaos-reorganization-chaos) shows us that the interactions of the system are generating trade-offs and feedbacks with both negative and positive effects that have been exacerbated by the emergence of new driving forces and the associated effects. The accumulation of these effects may lead us to a threshold of transformation of the AFSES, or a new reorganization phase could arise in the coming years.

In resilient agricultural systems, changes have the potential to create opportunities for innovation and new pathways of development (Salvia and Quaranta, 2015). For example, regarding the variability of the local climate, studies regarding the capacity of tropical agroforestry systems to address climate change (Simelton et al., 2015; Altieri and Nicholls, 2017) have found that on-farm biodiversity enhances a shorter recovery time in the face of climatic disasters. Agroforestry systems can also contribute to the more efficient use of water and improve soil productivity and nutrient cycling (Lasco et al., 2014).

The role of adaptive and coping strategies. Our proposal was able to observe the importance of adaptive and absorptive capacities for resilience in an AFSES and the strategies that support it. Specifically, these strategies have served to buffer the effects of drivers of change, thus allowing the system to transition through several phases of the same AC without reaching a new system. The literature that has studied the adaptation of coffee AFSES has identified similar strategies, for example, the diversification of crops and economic activities in coffee-producing regions and entry into certified or specialized coffee markets (Eakin et al., 2011; Castellanos et al., 2013). Additionally, community organizations should be strengthened to develop marketing schemes (Fedele et al., 2020) and emigration has been an alternative to confront climatic hazards (Schroth et al., 2009). All these strategies are similar to those taken in the CHW, where a large extent of them have been carried out internally by producers and do not come from external support.

However, our findings showed that those strategies are generating trade-offs that in some cases encouraged new stressful conditions within the AFSES. For example, the intensification of noncoffee crops and tourism and off-farm jobs are favouring land use change, contamination and ecosystem overload. Similar results were reported within existing literature that has studied the historic evolution of AFSES; for example, in monoculture crops, the use of fertilizer and pesticides has increased, and the breakout of pests resulted in an alteration of the ecological conditions (Eakin et al., 2006; Antoni et al., 2019; Babin, 2019). In addition, the ongoing processes observed during the last phase are altering the ecosystem and social conditions, enhancing the cross-feedback among its components and scales, such as the response to confront coffee rust and the uncertainty caused by the long-term effects related to the change in management.

Therefore, although it is possible to affirm that the AFSES has been resilient, important doubts arise regarding whether the current conditions are desirable and what are the risks to the future trajectory. For example, the coffee sector has created conditions of poverty and marginalization for local agricultural laborers without land (Higuera Ciapara and Rivera Ramírez, 2018). Thus, it is important to understand the effects of adaptive and coping strategies and the limits of the adaptive and absorptive capacities to identify possible trajectories of the system and thus anticipate changes toward a more desirable state. This is especially relevant for digging deeper into trade-offs and the winners and losers that result from these interactions.

Implications for the coffee agri-food system. The AFSES confronts a broad range of environmental, economic, social, and institutional stressors and shocks (Cabel and Oelofse, 2012; Salvia and Quaranta, 2015). As we observed in the CHW, the causes and effects of these driving forces are extremely complex due to the spatial and temporal scales involved; additionally, these driving forces have been exacerbated by the characteristics of the regional or local context. Important examples are the intensification of noncoffee crops and sprawl and the intensification of tourism and off-farm jobs. Regarding coffee rust, this plague could be the result of the effects of climate change, such as temperature variability (Avelino et al., 2015; Torres Castillo et al., 2020).

Increased pressure on productive systems is predicted to increase the frequency at which systems cross thresholds and abruptly shift to new states (Yletyinen et al., 2019). In this research, there are combinations of different types of elements, such as characteristics (i.e., biophysical conditions of watershed), driving forces (i.e., hurricanes), and strategies for maintaining livelihood (i.e., tourism and off-farm jobs), that generate trade-offs and selective pressures every day (Santos Prado et al., 2015). These uncertain conditions can push the AFSES toward tipping points. Although crossing thresholds and facing tipping points is inevitable, diversity has played an important role in absorbing disturbances (Meuwissen et al., 2019).

We could observe different examples of diversity in terms of livelihoods, biophysical conditions, and market access that have encouraged the permanence of the AFSES. The coffee AFSES could play an important role in the conservation and identity of its inhabitants. Consequently, to decrease the risk of undesired tipping points or, where necessary, to facilitate transitions across tipping points to a new preferred state, it is necessary to identify the windows of opportunity that triggered planning at different scales. For example, in CHW, there are opportunities to promote sustainable economic diversification that encourages other agroforestry systems or strengthen ecotourism in a planned and orderly manner to provide stable livelihoods for coffee growers and their families. It is also necessary to strengthen collaboration and dialog schemes between farmers and other nonstate actors, including governments, since these strategies have been useful during the crisis.

Conclusions

Through the theoretical-methodological proposal developed in this study to analyze the historical trajectory of a coffee AFSES, we found that this type of SES do not always comply with a succession process such as the one shown by the AC. The identity of the studied AFSES is constituted by its components and interactions among themselves, which are the production, processing, and commercialization of coffee, and the ecological and environmental conditions on which its production depends. However, over 40 years these components have changed reconfiguring their interactions and although these remain, their conditions are different, and the role of coffee has become secondary to other human activities in the study area. Among the factors that influence this situation are the diversity of stressors that affect AFSES, such as climatic conditions, market uncertainty, changes in public policies, and trade-offs of the strategies adopted to face the driving forces, which have differentiated impacts in space and time. Consequently, the coffee AFSES is in phases of constant reorganization and innovation.

On the other hand, although we identified thresholds and transitions using the AC, resilience thinking needs to provide more guidance on identifying when and where key social variables may reach thresholds that provide a “window of opportunity” or a trigger to drive system change. Additionally, we recognized that the effects generated by adaptation and coping strategies can be negative, and it is important to think about setting limits to adaptation actions. In this sense, the AC is insufficient to analyze the chances of facing several or different alternative trajectories. In addition, it is important to deepen the analysis of the trade-offs and the persistence and transformative capacities of the system to enhance resilience, which was not studied deeply in this research, and it is not clear if the AC is robust and sufficient to carry out this analysis and how the persistence capacity evolve to the adaptive capacity and its challenges.

Acknowledgments

We acknowledge the National Council for Science and Technology (CONACYT) and the French National Agency for Research (ANR-France) for funding project 290832 ANR-CONACYT

“Trajectories of Social-Ecological Systems in Latin American Watersheds: Facing Complexity and Vulnerability in the context of Climate Change (“TRASSE”)”. In addition, The National Autonomous University of Mexico awarded grants through the PAPIIT-IN302720 project and PASPA-DGAPA. Finally, a special recognition to Jimena Deschamps Lomeli for her support in preparing the map of the area of study and Antonio Ortega Santos for his thoughtful comments during the preparation of this manuscript.

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Supplementary information

Title: The historical trajectory of a coffee agri-food system: a case study in Oaxaca, Mexico

Appendix S1. Semi-structured interview, guiding questions

QUESTIONS FOR PARTICULAR COFFEE FARMERS

Section 1. First, I would like you to tell me a little about your community.

1. Do you hold a position in your community (or have you held)? What functions did or did it perform?

2. What do you do here in your community (what do you do for a living)?

3. How are they organized to make decisions? and on what issues?

4. Are there environmental problems in your community? Which are? What caused them?

5. What do you currently do? Have you always done the same activity?

QUESTIONS FOR REPRESENTATIVES OF ORGANIZATIONS

Section 1. First, I would like you to tell me about your organization and your work in it.

1. Could you tell me about the creation, objectives and actions of your organization?

2. In which municipalities/localities of the Copalita-Huatulco watersheds do your organization work? How did you choose that site (or sites)? How do they approach the town to start their work? Since when have you been working in those locations?

3. With which organizations are your institution associated (or has been associated) to work in Copalita-Huatulco watersheds?

4. What is your role in the organization? Since when have you belonged to that organization?

5. What activities does your organization carry out (or has carried out) in the Basin specifically regarding coffee growing? In which municipalities/localities? Since when?

QUESTIONS FOR ALL TYPE OF PARTICIPANTS

Section 2. The following questions refer to the coffee activity in the Copalita-Huatulco region.

5. What events have affected coffee in the Copalita-Huatulco watersheds?

6. When did that event happen? In what year? Did it happen again?

9. What were the causes of that events? what were the consequences of that events?

10. What did people do to confront them?

11. Who was involved (or has been involved) in its resolution? Did your institution participate?

12. What do you think are the main challenges for coffee growing in the watersheds?

13. Could you recommend other people like you who can talk to me about coffee growing and the problems it faces in the Copalita-Huatulco watersheds?

Appendix S2. Testimonies of interviewees

Phase Ω - α, 1980 – 2000

1. *"[…] existed IMECAFE, which was the institution that regulated the policy regarding coffee from the financial support for the establishment of crops, drying patios, pulpers, a thousand things that were done with coffee and then assuming the responsibility for marketing […] it disappeared… and most of its functions were passed on to coffee producer organizations […]" (Person 1)*
2. *"When it arrived when we were in the midst of an existential crisis of survival, the Huatulco tourist complex was created and then they began to see that it was better to sell little and little and little of things that were produced there, from a little flower to an herb, whatever, and they were creating very interesting internal markets" (Person 2)*
3. *"[...] tourism created many sources of employment[...]" (Person 2)*
4. *"The first thing they began to sell was... let's say the axis, the pillar that kept coffee in its crisis was the cultivation of bananas..." (Person 2)*
5. *"[…] the coffee business in its most productive years in the 1980s, produced so much, the risk was of contamination of rivers by coffee washing, well, if you log shade to plant coffee plantations but you kept native species. You had your shadow of "ingas" so it was quite controlled, we never had problems of this type and the contamination of the rivers was controllable so you made your waste receiving pits and you could show that the rivers were maintained" (Person 3)*

6. *"[...] we always contaminate the water with "los destapados" (dumping of water used in washing coffee into the river) but since production has fallen, since now there is not as much coffee, it is no longer contaminated as much as 40 years ago" (Person 2)*
7. *"[…] before Paulina there were coffee plants, there were coffee plantations […] of those coffee plantations we should have about 10%. Very little and then the large production units generated large markets, we did not need another activity other than coffee, which created markets and was a large movement […] Years of coffee cultivation were lost, the coffee trees […] left with the Paulina. […] all those 80-year-old plantations are gone, yes? […] that is where the beginning of the coffee end begins." (Person 2)*
8. *"[…] Hurricane Paulina was a tremendous "watershed" […] It even caused many towns that were migrating from the mountains to the coast to pick coffee, they no longer saw that flow of wool and they left elsewhere and never came back. The hurricane upset everywhere: the part of the forests, the salinity of the soil, they say that as a result, the palms died. But it was also an issue that had a very strong social impact […] I had to go out and work in something unrelated to coffee […]. (Person 3)*

Phase α – r, 2000-2010

9. *"For me, the Huatulco project is a formidable project that came to strengthen us, but it does require a lot of water" (Person 2)*
10. *[…] organic coffee certifications, […] the markets, the qualities, all of that has had to be adapted and whether to advance in the value chain […] possibly at the beginning, as there was more volume of coffee, we were more focused to an export issue and in export we were rewarded with certification seals [...] we entered into a dynamic in 2004 to 2007 of certifying all our producers [...]. (Person 3)*
11. *[...] yes, I have the wet mill, I have the dry mill, I have the toaster [.] and I have the machines to prepare the coffee, [...] we had to get into that added value (Person 4)*
12. *"[…] you don't see the big coffee trucks anymore. But if you see one in those squares […] which are Mondays in Pochutla […] you see 10, 20 people who are going to sell their ground coffee packaged in their plastic bags […] there are those who can carry 2 kilos, but there are those who can carry 100 kilos (Person 2)*
13. *"[…] In 2009, perhaps from 2009 to 2012, [...] there we tried to make the organization independent, we began to manage projects as a system, not so much as an organization, but rather the product system and its renewal project… the product system and its technical assistance project. And they became interesting amounts, because the people from the Ministry of Agriculture gave us that possibility, so we became a little more independent, we were already hitting each other here with the people from the state [...]" (Person 3)*

Phase r - α, 2010-2020

14. *“[…] many said, "it was a great teacher (rust), [it taught us] that [we have to] renew ourselves and really be producers [...] not just be collectors" (Person 5)*

15. *“[…] this time the rust comes to us for the second time and in a brutal way we have aged and poorly worked coffee plantations. Then it coincided that the super fungus arrived because it entered Chiapas from all sides and got into all the regions of the state, the high and cold humid area was spared a little, logically and it hit much harder where you had coffee plantations where the sun or the heat, and everything made the fungus develop faster. So right now, there is not a single region that is free, all the regions have rust on a greater or lesser scale in some areas it is completely gone, in others it was a 50, 60% blow and left coffee plantations in bad condition. This was from […] 2014 to 2015 […] and from then on every year there are mirages all of a sudden, you say “look there it didn't hit this section it didn't hit it, oh, we got rid of it!, let's see what variety is, we are going to take care of it” and boom! next year, it turns out that he ended up throwing it out [...]” (Person 3)*

16. *“[…] rust killed us coffee plantations killed us overnight as if you had poured burnt oil on them. There was no more coffee to cut so our process of renewing coffee plantations to reactivate economically takes 4 - 5 years... 4 - 5 years, boy! Well, there is no wallet that can hold […]. Suddenly once again a blur [...] and a new account again from scratch we are going to redo everything and that is how we have been in recent years as if reinventing something new each time and while the deterioration continues aggressively.” (Person 3)*

17. *“[…] companies that […] buy the coffee are interested in knowing not only what variety you are producing but also your production methods, all of this implies something very important for them, in fact right now you may not have an organic certificate, but they are still interested totally what your methods are not only in the primary part but in the processes that can also be contaminated. [...] then with these types of issues, in these types of issues the purchasing companies dictate a little bit the issue of how to carry out your activities in the field in an organized manner [...]” (Person 3)*

18. *"[...] it is detected as a strength of the basin, let's say [...] the good part, is precisely that belt in the part of the middle forest, which is where the coffee plantations of that area are located, and they are in the order of about 25,000 hectares [….] coffee plantations play a very important role in the middle basin, and the change in land use is taking place in the upper basin, so that is what is serious because it is causing a process of desiccation and soil impoverishment, which could alter the support service a good [part]” (Person 6)*

19. *“[…] right now, if they cut back on something, it is the environmental issue, but tremendous, that is, all the projects that were for this matter to generate projects, including productive ones in the basin areas were removed. There are no more, and I insist that if the economic part is not there then the risk is very high. (Person 3)*

20. *“How does the president of the republic expect ecosystems to be conserved or forest fires to be fought when the budget for the environmental sector has been reduced by a large percentage?” (Person 7)*

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Appendix S3. Codifying system.

The Table S1, shows the codifying system used to analyze the data. From left to right, the main categories were the roof of the analysis which began to classify the information to 1) identify shocks and stressors, and 2) identify their influence over each component of the SES's subsystems. Then, the subcategories were divided into 3) processes, situations, and actors, 4) adaptive and coping strategies, 5) spatial scale, and 6) temporal scale. First, subcategories 3 and 4 identified the effects of the drivers on the main relations of the SES, its processes, and the adaptive and coping strategies. Second, these subcategories were classified with respect to categories 5 (spatial scale) and 6 (temporal scale). Thereby, the subcategories 3 and 4 were replicated for each stressor and shock (category 1) as well as with respect to each component (category 2) according to each part of the basin (5) and temporal scale (6).

Codifying system

Main categories		**Subcategories**			
Driving forces(1)	**Components of SES (2)**	**Processess, situations & actors (3)**	**Adaptive & coping strategies (4)**	**Spatial scale (5)**	**Temporal scale (6)**
Shocks/Stressors	Environmental & ecological conditions	Pest & diseases	Economic activities ex ante Economic activities ex post Public policies Migration Diversification Intensification Producers organizations Private initiatives (individual)	Low part Middle part Upper part	Short term Long term Ongoing
		Ecosystem services			
		Environmental conditions			
		Cultivation practices			
	Production	Importance			
		Decrease			
		Coffee varieties			
		Price & production costs			
		Financing			
		Coffee farmers organizations			
	Processing	Processing			
	Marketing	Marketing			
		Public policies			
		Coffee farmers organizations			

Table S1. *Codifying system.*

KNOWLEDGE LEADER

Pioneer of processing

Coffee producer Enrique López is pushing Mexico's specialty coffee scene in a more sustainable direction, but as he tells BeanScene, it takes more than one leader to elicit change.

Fotos: Ramírez León, A. 2019 y 2020. Actores clave en las actividades de producción, transformación y comercialización de café en diferentes municipios de las cuencas Copalita-Huatulco, Oax.

CAPÍTULO 4. THE ROLE OF DIVERSITY AND CONNECTIVITY IN ADAPTATION FOR RESILIENCE OF A COFFEE AGRI-FOOD SYSTEM: A MULTIPLEX NETWORK APPROACH

Ramírez-León A., Avila Foucat V.S., Smith Aguilar S.E. 2023. The role of diversity and connectivity in adaptation for resilience of a coffee agri-food systems: a multiplex network approach. Currently under review in Ambio.

Ambio

THE ROLE OF DIVERSITY AND CONNECTIVITY IN ADAPTATION FOR RESILIENCE OF A COFFEE AGRI-FOOD SYSTEM: A MULTIPLEX NETWORK APPROACH

--Manuscript Draft--

Manuscript Number:	AMBI-D-23-00584	
Full Title:	THE ROLE OF DIVERSITY AND CONNECTIVITY IN ADAPTATION FOR RESILIENCE OF A COFFEE AGRI-FOOD SYSTEM: A MULTIPLEX NETWORK APPROACH	
Article Type:	Research Article	
Keywords:	adaptive capacity; socioecological resilience; diversity; connectivity; coffee agrifood systems; multiplex networks	
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Funding Information:	Dirección General de Asuntos del Personal Académico, Universidad Nacional Autónoma de México (IV300123)	Msc Alejandra Ramírez-León
	Agence Nationale de la Recherche	Msc Alejandra Ramírez-León
	Consejo Nacional de Ciencia y Tecnología (290832)	Msc Alejandra Ramírez-León
	Dirección General de Asuntos del Personal Académico, Universidad Nacional Autónoma de México (PAPIIT-IN302720)	Msc Alejandra Ramírez-León
Abstract:	Agri-food socio-ecological systems (AFSES) establish strongly linked relationships between society and nature to produce and transform food; consequently, they face challenges in maintaining the food supply. This study focuses on understanding how diversity and connectivity in social interactions foster adaptive capacity and the evolution of this capacity in a coffee AFSES located in Mexico. To do this, we use a multiplex network analysis to study the change of three subsystems of the AFSES between two periods (2000-2010 and 2011-2020). The data used was obtained through a survey applied to actors involved in the coffee activity. The results show that in the second decade, the adaptive capacity was stronger but with different characteristics in each subsystem. Furthermore, we found that connectivity was the most relevant attribute for strengthening the adaptive capacity of the AFSES. We also	

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Abstract

Agri-food socio-ecological systems (AFSES) establish strongly linked relationships between society and nature to produce and transform food; consequently, they face challenges in maintaining the food supply. This study focuses on understanding how diversity and connectivity in social interactions foster adaptive capacity and the evolution of this capacity in a coffee AFSES located in Mexico. To do this, we use a multiplex network analysis to study the change of three subsystems of the AFSES between two periods (2000-2010 and 2011-2020). The data used was obtained through a survey applied to actors involved in the coffee activity. The results show that in the second decade, the adaptive capacity was stronger but with different characteristics in each subsystem. Furthermore, we found that connectivity was the most relevant attribute for strengthening the adaptive capacity of the AFSES. We also identified that collective actors were key to the adaptation of the system.

KEYWORDS: adaptive capacity; socioecological resilience; diversity; connectivity; coffee agrifood systems; multiplex networks

1. Introduction

Agri-food systems encompass the primary production of food products including transformation and commercialization all the way to the final consumers (FAO, 2022). These systems are viewed as human-managed social-ecological systems (AFSES) where there is a disproportionate influence and control of the social over the ecological elements of the system (Hodbod et al., 2016). The world's AFSES are under constant pressure because they face the mandate to sustain the supply of enough food for the world's population despite the various drivers acting against them, and the impact generated over the environment (Murwani et al., 2023). To offer food to the consumer, socioecological interactions are formed within and between the production, transformation, and marketing phases in the AFSES. Those interactions provide the possibility for self-organization, adaptation capacity and resilience in the face of changes in environmental and market conditions or policy interventions, among others (Chapman et al., 2017; Preiser et al., 2018).

Consequently, the study of resilience in AFSES is relevant to identifying the capacity of the system to deal with uncertainty and the processes of self-organization to maintain continuous food availability. Resilience is an emerging property of the system that can be strengthened or weakened depending on the interactions between the farmers and other formal and informal social actors that interact in a specific agroecological context (Hendrickson, 2015; Meuwissen et al., 2019). These actors are located at different spatial, temporal, and organizational scales; furthermore, they make decisions to adapt to the drivers of change that manifest over time; therefore, the interactions between actors are dynamic and remain in constant evolution, even the actors transform themselves (Béné et al., 2016). Thus, the resilience of an AFSES is multidimensional and dynamic as it entails interactions that evolve over time among individuals, technical systems, and the environment, encompassing economic and socioecological dimensions(Aboah et al., 2019; Folke et al., 2010). To categorize those interactions (Béné et al., 2016) has proposed that resilience can be represented through the system's capacity to evolve, arguing that resilience "is the result of three capacities of a system that lead to different short-term responses: (1) absorptive capacity leading to persistence, (2) adaptive capacity leading to incremental adjustments/changes and adaptation, and (3) transformative capacity leading to transformational responses". Absorptive capacity refers to the ability to persist through changes while still performing the same function. Adaptive capacity entails the capability to acquire knowledge, integrate past experiences, adapt responses to evolving external factors and internal dynamics, and maintain ongoing operations (Béné et al., 2016; Berkes et al., 2003). Transformative capacity establishes an entirely new system when ecological, economic, or social structures render the existing system unviable (Béné et al., 2016; Walker et al., 2004).

The so-called attributes of a resilient system are considered factors that can strengthen the capabilities of a system to be resilient (Kerner & Thomas, 2014; Meuwissen et al., 2019; Van Der Lee et al., 2022) and have been used as indicators to assess resilience (Biggs et al., 2012; Meuwissen et al., 2019; Resilience Alliance, 2010). In the context of AFSES, among attributes have been pointed out as relevant for resilience and those on which there is agreement are: (i) diversity, that refers to having different elements to respond to disturbance, (ii) modularity, i.e. subgroups more strongly connected within them than to others in the system, which display different functions (similar to redundancy); (iii) connectivity, meaning the internal and external relationships of the systems; (iv) tightness of feedbacks, i.e. the relationships within the system where one element response changes others and (v) system reserves(i.e. natural, economic and social capital assets) that the system can use to respond to stress and shocks (Meuwissen et al., 2019).

General patterns of how these attributes contribute to the resilience of AFSES have not been found due to dependency on local conditions which vary widely across systems (Hendrickson, 2015; Knickel et al., 2018; Meuwissen et al., 2019). However, it has been proposed that the combination of certain attributes strengthen specific capabilities for resilience. In particular, diversity and connectivity strengthen the adaptive capacity of AFSES (Kerner & Thomas, 2014), because they shape the structure and functions of the systems by influencing the flow of knowledge, experience, interests and objectives of the individuals involved (Scoones et al., 2007; Soriano et al., 2023).

Accordingly, it is viable to assess the adaptive capacity for resilience of a system through its diversity of actor types and connectivity, based on the patterns formed by those relationships and their role. Each phase of a value chain (production, transformation and commercialization) can be considered a subsystem of the corresponding AFSES with its own actors and their interactions (in addition to being connected to the other subsystems). Therefore, the analysis of diversity and connectivity demands a method that allows analyzing this complexity (Preiser et al., 2018). The multiplex network approach allows analyzing the nature and structure of interactions between subsystems in a complex adaptive system, the flow of information between them, and the different kinds of interactions that take place among the actors involved (De Domenico et al., 2015; Preiser et al., 2018).

To study the role of diversity and connectivity for the adaptation and resilience of an AFSES modelled as a multiplex network, we chose the case of a coffee AFSES. Coffee is one of the most traded tropical commodities, having as many as twenty-five million farming households producing 80% of the world's supplies mainly in developing nations where coffee exports amount to a significant portion of national incomes and are an important source of income for households (FAO, 2023). The European Union and the United States of America are the most relevant consumers globally (FAO, 2015; ICO, 2019). The coffee market is characterized by recurrent supply-demand imbalances and asymmetric income distribution among actors in the value chain which is very complex, with many stages and actors involved, from farmers to final consumers (Aboah et al., 2019; ICO, 2019). The coffee market has been growing globally since 2000; however, there is uncertainty about the future of the coffee industry because of climate change, pests and diseases, price volatility, even technological innovation and political-economic agreements that influence the sector (Murphy et al., 2023; Utrilla-Catalan et al., 2022). Empirical evidence of AFSES resilience is observed in the Copalita-Huatulco watershed located in the state of Oaxaca, along the Pacific coast of Mexico where shade-grown coffee has been produced since the 19th century. Coffee production in this watershed has been shaped by multiple environmental, social, and economic drivers; these drivers have triggered learning and adaptation owed to the role played by the actors involved in the system (Ramírez-León et al., 2023). This activity currently contributes to the conservation of the native ecosystem and provides ecosystem services such as water infiltration and refuge for biodiversity (González-Mora et al., 2006; Lozano Trejo et al., 2015). This study considered a period of two decades from

2000 to 2020, to analyze the response of social interactions to maintain the coffee productive capacity in the watershed.

Thus, the objective of this study is to understand how the relationships between the social actors involved in a coffee AFSES have encouraged the adaptive capacity of each phase of the value chain analyzed as subsystems (production, transformation and commercialization), and how they have fostered the resilience of the entire system. To do this, we posed the following questions: Do each of the AFSES subsystems have the same adaptive capacity in terms of social network connectivity and diversity for resilience? How does that capacity change over time? What are the key actors that foster the adaptive capacity of the AFSES? We hypothesize that each subsystem should have a combination of high diversity and high connectivity as together they reflect a variety of response options and the ability to learn, collaborate, adapt, and create new strategies to ensure continued functionality (Kerner & Thomas, 2014). Furthermore, we expect that these attributes change over time in response to the internal and external drivers of change; also, we expect that the type of actors change over time. With this study we can provide key information that contributes to improving collaboration, cooperation, and management strategies to build or strengthen the resilience of the entire system.

2. Theoretical framework

2.1 Coffee AFSES description. The AFSES under study is an ecosystem managed with the intention of producing, transforming and commercializing coffee and is structured by three subsystems associated with the concept of value chain. In the production subsystem where coffee is grown, the inputs, cultivation and management practices shape the biological-ecological components of the system, modifying land use and affecting ecosystem services at local and global scales. In turn, production is influenced by external drivers such as climate change, the market, and public policies. In addition, the AFSES is subject to internal drivers such as coffee diseases and pests and to the accumulated effects of adaptation strategies taken over time. Among support actions for production there is the provision of information to improve cultivation practices, financial liquidity, and inputs for production among others.

In the transformation subsystem, the parchment coffee harvested is selected and processed to obtain green coffee that is ready to be marketed among roasting companies or is directly roasted and packaged ready for direct sale. To carry out the transformation, support actions include knowledge on appropriate processing and right technology to do it. In the commercialization subsystem, the actions of buying and selling grain in all its forms (parchment green, and roasted coffee) are carried out. Coffee can be purchased directly by any local consumer, by a national or foreign roasting house, the subsidiary of a transnational company, a producer company, coffee farmers, or intermediaries. Specialized services are also provided for marketing (i.e., customs agencies for export).

Among the active actors in the AFSES there are suppliers (companies or individuals) who provide inputs and services to coffee farmers; coffee farmers with different characteristics and conditions; diverse organizations of producers (cooperatives and secondary producers organizations integrated by cooperatives); intermediaries; and buyers (including consumers) at various scales. As supporting actors are government agencies that provide in-kind or monetary subsidies; non-governmental organizations that provide production training; private initiative and even academics. Social interactions can encourage or hinder the ability of actors to collaborate in problem solving, to anticipate and respond to crises, and to learn from past experiences (Abdul-Razak & Kruse, 2017; Gupta et al., 2016; Mandryk et al., 2015). Additionally, those interactions change and adapt over time even actor change and transform. Finally, the AFSES described considers a watershed scale, but interaction might come from outside the physical boundaries.

2.2 Background. Diverse studies have exposed the importance to analyze the AFSES as complex adaptive systems and proposed frameworks to evaluate the social-ecological resilience (defined as emergent property) of AFSES at different temporal and spatial scales (Darnhofer, 2021; Kerner & Thomas, 2014; Meuwissen et al., 2019). In this context, Bracken et al. (2023) defined resilience as “the capacity of people to sustain and improve their livelihood opportunities and well-being despite disturbances”; therefore, we argue that resilience in AFSES is the capability of the supply network to manage and mitigate disruptions to enhance the capacity of people to sustain and improve their livelihood and well-being. Into assess those capacities, Cabel & Oelofse (2012) distinguished indicators of resilience within agroecosystems to identify points of intervention to build resilience and endowed with the capacity for adaptation and transformation where there is vulnerability. The indicators proposed are broad and include social aspects such as socially self-organized; functional and response diversity appropriately connected, reflective and shared learning and autonomy. Meuwissen et al. (2019) proposed a framework to assess the resilience of farming systems to specific challenges (specified resilience) as well as a farming system's capacity to deal with the unknown and uncertainty (general resilience). The framework encompassed analyze system properties, drivers of change, indicators to measure the performance of system functions, resilience capacities and resilience-enhancing attributes which include diversity and connectivity.

Darnhofer (2021) also argued that resilience studies of AFSES have put more emphasis on identifying what enables a farm to cope with the impact of a shock, while remaining essentially unchanged, but much less emphasis has been put on what enables a farm to shape change, especially transformative change. Therefore, the author proposed the analysis of attributes for resilience: diversity, modularity, connectivity, tightness of feedbacks, system reserves, redundancy, and autonomy. Besides, Hendrickson (2015) also considers that the food system might be resilience through resistance to disruption; latitude to accommodate change; redundancy of role and function; diversity of organizational forms; and precariousness. Similarly, Hodbod & Eakin (2015) discussed the importance of diversity in terms of have different functional groups and diverse types of responses to disturbances as two key attributes that favor resilience in AFSES. AFSES resilience literature shows the relevance of measuring diversity and connectivity of actors to cope with changes, and none of the approaches described has used multiplex social network.

2.3 Key concepts description. For this study, diversity refers to the variety of characteristics, perspectives, knowledge, and resources possessed by the social actors involved in each subsystem that allows an entire AFSES system to operate and be maintained over time. Accordingly, diversity is understood as heterogeneous characteristics of actors in an AFSES (Carmen et al., 2022); this attribute contributes to the adaptive capacity because allows to have multiple options for reorganization to maintain the same functions, which fosters resilience (Hodbod & Eakin, 2015). On the other hand, connectivity is the result of dynamic interactions between the actors involved in the subsystems (Cabel & Oelofse, 2012). The effect of connectivity over the adaptive capacity depends on the interactions established among groups of actors; besides how those interactions are distributed within a system (structure), and the intensity with groups of actors are connected (Biggs et al., 2018). Furthermore, connectivity also encompasses the actors that maintain communication and collaboration between subsystems so that the system can supply the raw material available for the following phases of the value chain (Aboah et al., 2019) and maintain the supply of coffee. Therefore, if in the coffee AFSES there are many interactions with diverse actors, it will be more adaptive to confront uncertainty and change.

Although previous studies have analyzed the role of diversity and connectivity for resilience using social network analysis (Albizua et al., 2020; Bruce et al., 2021; Canevari-Luzardo, 2019), to our knowledge none has analyzed how diversity and connectivity emerge from the interactions between actors in a coffee AFSES using multiplex networks and how they change over time. To fill this gap, we present a multiplex network analysis where the attributes are determined by structures of the links between a set of actors and the links between them (Wasserman & Faust, 2023).

Diversity is related to the type of actors (nodes) and then number of these that belong to different organizations and have different occupations within each subsystem over time. Connectivity is the way in which nodes connect to transmit information and resources, where central actors and the degree of network fragmentation play a crucial role. Central actors refer to those actors able to exert influences over others in the network and are better situated to access valuable information which can put them at an advantage (Bodin et al., 2017). Nodes with a higher degree have a higher potential to disseminate resources and capacities for adaptation. On the other hand, if in a network exist different sub-groups this condition limit interaction, it precludes collective learning, resulting in less effective adaptation capacity (Bodin et al., 2017).

3. Method

3.1 Study area. The coffee AFSES is located on the Pacific coast of Mexico in Oaxaca state, it covers approximately 187,576 hectares and is formed by the Copalita and Huatulco sub-watersheds (CHW) (Figure 1) (González-Mora, 2009). It covers altitude ranges from 3,750 meters above sea level to sea level, which favors a diversity of ecosystems (from low deciduous forests, medium forests, mesophilic mountain forests, and pine and oak forests), with a high concentration of endemic vertebrates (CONABIO, 2004).

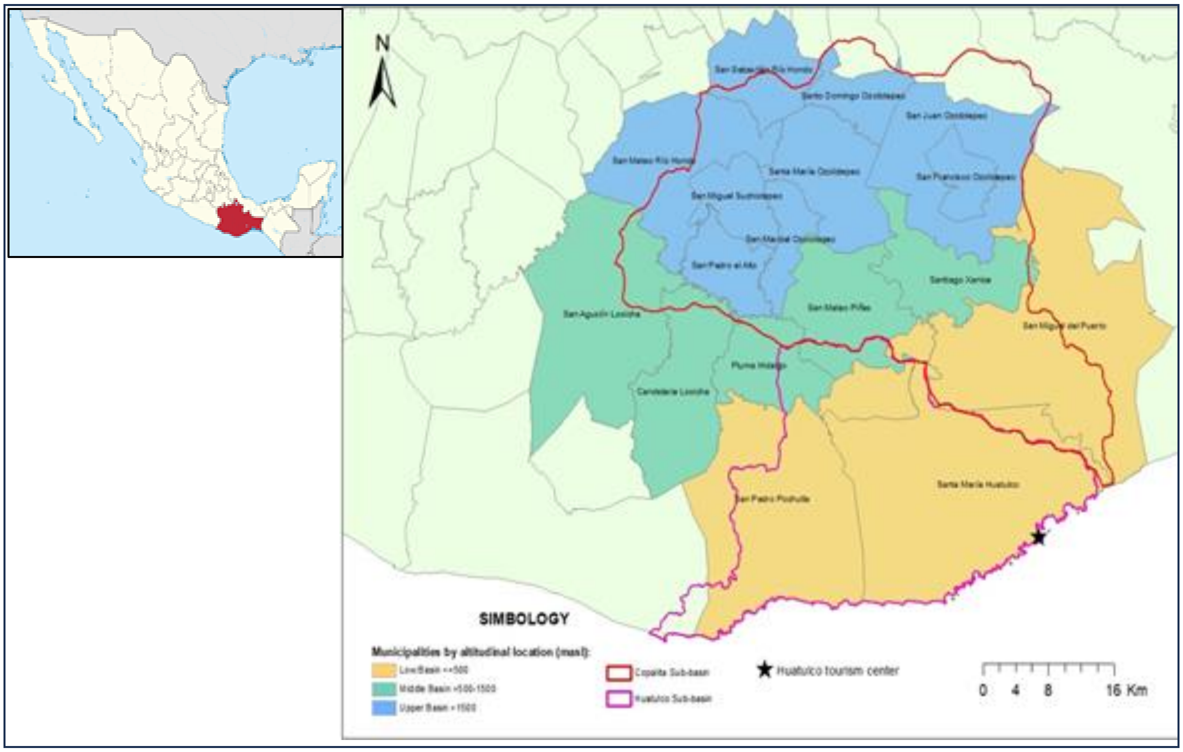


Fig. 1 Map of the Copalita and Huatulco subwatersheds. Source: adapted from Ramírez-León et al., 2023.

The CHW is the home of nineteen municipalities with 181,715 inhabitants (INEGI, 2020). In 2015, 87% of the population of the CHW had income below the welfare line (CONEVAL), 2020). The prevailing economic activities are based on primary sector activities, mainly, rainfed agriculture under the slash-and-burn system, extensive and uncontrolled cattle ranching, coffee farming primarily managed under shade and both privately and community managed forestry. Also, tourism and off-farm jobs are important within the coastal limits of the basin due to the Huatulco touristic center (SAGARPA&SEDAPA, 2015). There are different growing conditions for coffee: the upper basin concentrates 30% of the cultivated coffee area in the CHW; the middle basin has 50% of the total coffee cultivation area, mostly managed by landowners with more than ten hectares (50% of coffee farmers). The remaining 20% is found in the lower basin (SAGARPA&SEDAPA, 2015). In 2019 coffee production was 30% lower than in 2010 (SADER, 2020); however, the offer of organic and specialty coffee increased annually from 2007 to 2015 at a rate of 30% (Higuera & Ramírez, 2018). Over two decades (2000-2020) collaboration networks that formed have stood out as organizational adaptation strategies that have allowed the actors involved in AFSES to confront everything from price instability to the rust plague.

3.2 Data Collection. The data used for the multiplex analysis was collected through snowball sampling (Corbin & Strauss, 2012) to identify the actors (nodes) in the subsystems and the specific actions through which they interact in each subsystem (see Table 1). These data were collected through a survey to obtain relational information and attributes of the nodes. The questionnaire was structured in five sections: i) characterization of the actors surveyed and their affiliation organization; ii) identification of management practices for coffee plantations; iii) identification of social interactions in coffee production, processing, or marketing activities; and iv) collaboration networks to address the drivers of change. Sections (iii) and (iv) inquired about information on interactions and drivers over twenty years, from 2000 to 2020.

Table 1. Conceptualization of multiplex networks

Multiplex network	Layer	Definition (actions considered to establish links among actors)
Production	Financing	Availability of cash including government subsidies and credits or loans for production.
	Information	Transfer of knowledge about cultivation practices to combat diseases and pests, or better cultivation practices to improve quality of coffee.
	Supplies	Donation, distribution, or purchase to have inputs for production including inputs to make compost, natural pesticides, or ingredients to make them, and chemical fertilizers or pesticides. As well as tools and equipment such as pulper, shade mesh, sprinklers, washing tanks, sacks, seeds, bags for seedlings, and coffee seedlings.
Transformation	Information	Transfer of knowledge to process green coffee, including training and technical assistance for proper post-harvest handling.
	Processing	Availability of services to transform parchment coffee into green or roasted coffee; including transportation, processing services, and courier services.
	Supplies	Donation, distribution, or purchase to have machinery and tools for the transformation of parchment coffee into green and/or roasted coffee, such as toasters and packaging bags
Commercialization	Trading	Purchase sale of coffee in all its presentations (parchment, green or roasted coffee) both for export and for national and local consumption
	Promotion.	Promotion of coffee cultivated in the CHW watershed.

Before applying the questionnaire, the objective of the research was explained and consent to participate was requested from each person. All personal information was confidential, and the information provided was kept anonymous. The face-to-face visits to apply the survey began in July 2019 and were repeated in October, November, and December of that year. The restrictions due to the COVID 19 pandemic made it difficult to continue with this process; thus, we continued contacting people by phone. Phone interviews were conducted between July and October 2020. In November of 2020 we continued with the last face-to-face visits (following COVID-19 health precautions) in the most remote municipalities of the study area where phone communications were deficient. The application of the survey had an average duration of 70 minutes both in person and by phone. We obtained information from 46 key actors, including coffee producers (n=25); representatives of producer organizations (secondtier organizations and cooperatives) (n=9); NGO representatives (n=4); government representatives (n=4); and business representatives (n=4).

3.3 Data analysis

3.3.1 Defining multiplex networks. We built a multiplex network for each subsystem of the AFSES, where the layers represent activities related to the corresponding subsystem. This resulted in three layers for the production and the transformation multiplexes and 2 layers for commercialization (Table 2). The actors who participated in a certain activity (layer) were represented as nodes connected by links (edges) representing interactions related to that activity. In all cases, edges were unweighted and undirected. Layers were connected by the nodes they shared, and interlayer links were all the same. For each subsystem, we built two multiplex networks, each representing a different period: 2000-2010 and 2010-2020. This was done to assess temporal changes in diversity and connectivity by comparing multiplex properties in both periods. Therefore, in total, we built 6 multiplex networks (three subsystems at two different moments) using the MuxViz package (version 3.1) in R (version 4.3.0).

Table 2. Network metrics used to measure connectivity and diversity as attributes of resilience.

Resilience attribute	Associated network property	Description	Interpretation
Diversity	● Number of different node types in the network	Types of actors grouped by their functions and interests.	Type of actors present or absent per networks to do specific activities.
	● Number of collective actors	Subgroups of people, grouped by their functions and interests.	Number of collective actors who do specific activities per network.
	● Average degree versatility per node type (individual/collective)	Average number of edges per node type count the number of edges (inter-layer, intra-layer) one node possesses (based on De Domenico et al., 2015)	Node types with a higher degree have a higher potential to disseminate resources and capacities for adaptation.
Connectivity	● Number of nodes	Number of nodes present in a network.	The number of nodes is useful for observing the presence or absence of actors in a network and how change over time.
	● Number of edges	Number of edges present in a network	The number of edges is useful for observing the presence or absence of social ties in a network

		and how change over time.
● Density	Number of edges in a network divided by the total number of possible edges (Wasserman & Faust, 2023)	High densities (values close to 1) entail high connectivity, thus influence the way that information spreads through a network (Albizua et al., 2020).
● Number of connected components	A component is a subgroup of nodes that contains a proportion of all the nodes in the network. Therefore, the number of connected components in multiplex networks is related to subgroups connected by a sequence of nodes across layer (De Domenico, 2022)	A network can have multiple connected components, thus if there is only one connected component then the network is defined to be connected (De Domenico, 2022). If there are too many components, then there is network fragmentated and it may hamper the transmission of information and other resources on the network.
● Number of nodes in the largest connected component	A component has a significant fraction of the nodes of all the network, then it will be a giant component. Therefore, in multiplex networks, the number of nodes in largest connected components reflects the fraction of the nodes that are connected across layers (based on De Domenico, 2022).	If the number of nodes in the largest connected component is high means that a high proportion of nodes are connected and therefore can collaborate or communicate.
● Average eigenvector versatility according to node type	Eigenvector centrality identified the nodes with the least distance from other nodes (Hanneman et al., 2005). Then, average eigenvector versatility assumes that the centrality of node type with respect to one layer is influenced by its	Node types with high eigenvector centrality could have few connections but with nodes very well-connected, which means that connecting to some nodes has more benefit than connecting to many

		centrality in other layers (Iacovacci et al., 2016)	nodes (Iacovacci et al., 2016; Zeng et al., 2021)

3.3.2 Node types. We classified the actors (nodes) in the networks as either individual (coffee farmers) or collective (producer organizations NGOs, government and businesses). We then identified three types of coffee producers depending on their management practices: conventional or traditional coffee farmers (poor soil conservation and low use of natural or chemical inputs), agroecological coffee farmers (high use of natural inputs and low use of chemical inputs) and intensive coffee farmers (high use of natural and chemical inputs). Regarding collective actors they were identified as subgroups of people, such as civil society organizations, cooperatives, and companies including larger entities made up of many organizations and subgroups, such as communities, secondary producer organizations (formed by cooperatives), and government agencies.

3.3.3 Network metrics and resilience indicators. We built a multiplex network for each subsystem of the AFSES, where the layers represent activities related to the corresponding subsystem. This resulted in three layers for the production and the transformation multiplexes and 2 layers for commercialization (Table 1). The actors who participated in a certain activity (layer) were represented as nodes connected by links (edges) representing interactions related to that activity. In all cases, edges were unweighted and undirected. Layers were connected by the nodes they shared, and interlayer links were all the same. For each subsystem, we built two multiplex networks, each representing a different period: 2000-2010 and 2010-2020. This was done to observe temporal changes in diversity and connectivity by comparing multiplex properties in both periods. Therefore, in total, we built 6 multiplex networks (three subsystems at two different moments) using the MuxViz package (version 3.1) in R (version 4.3.0).

4. Results

4.1 First period, 2000-2010. During this decade, the diversity was relevant due to the number of node types identified in all layers. Also, there were high degree centrality values concentrated in a few types of nodes such as secondary producers organizations, agroecological producers in Production; government agencies, civil associations and agroecological producers in Transformation; and civil associations, secondary producers organizations and cooperatives in Commercialization (see Appendix 1). In all networks there were peripheral actors disconnected to each other forming star-shaped network (Fig. 2) which implies a highly centralized structure where the central node acts as a focal point but makes peripheral nodes highly dependent on the central node for collaborate between them (Hanneman et al., 2005). This observation was complemented by the eigenvector centrality which was higher among secondary producers organizations, conventional and intensive producers in Production; government, cooperatives, companies and secondary producers organizations in Transformation; and secondary producers organizations, conventional and intensive producers in Commercialization. These actors were very important to transfer information and resources. This panorama showed that although a high diversity value was observed in all the networks the values obtained for the connectivity indicators were low; therefore, the subsystems had difficulty dispersing information and resources to other nodes due to the fragmentation and poor connectivity in all subsystems, especially in Transformation subsystem. Therefore, the AFSES was a weak adaptive capacity for resilience.

Fig. 2 Multiplex networks of the coffee AFSES, 2000-2010

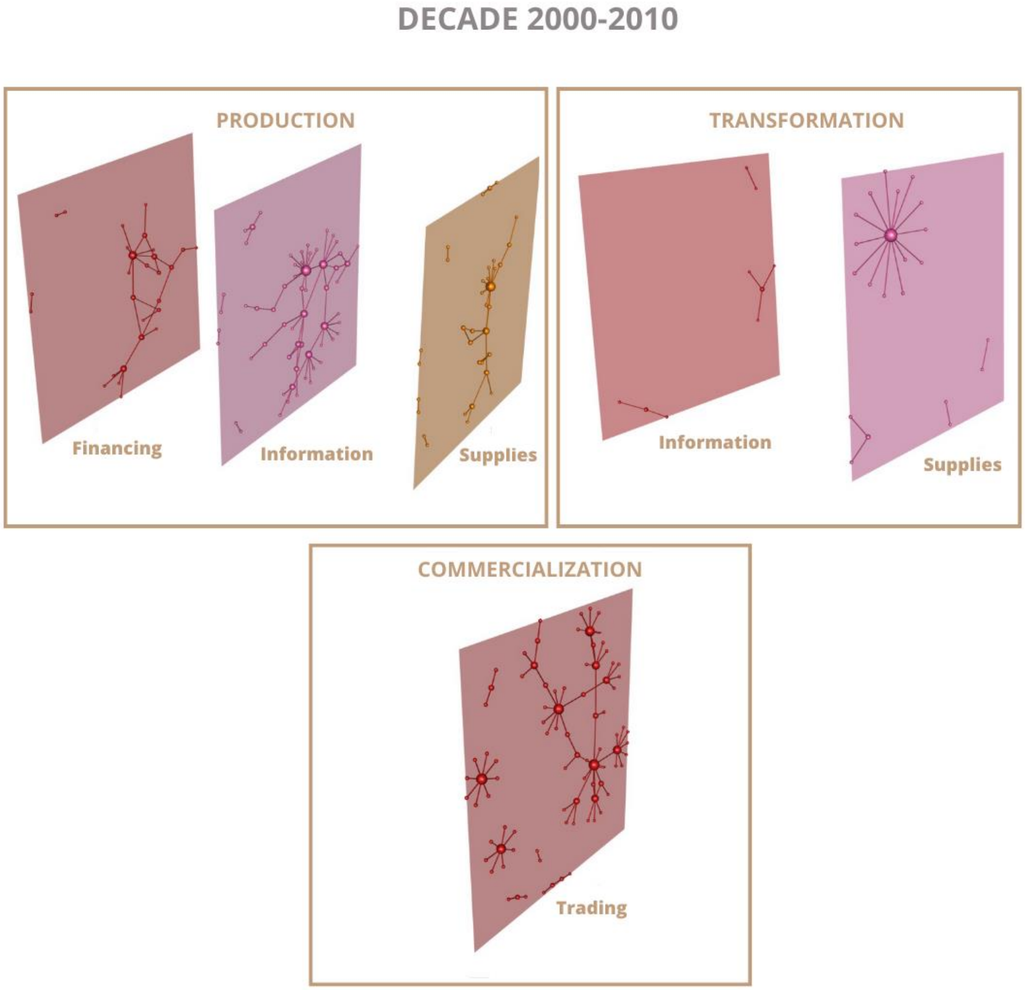


Figure 2. Graphic representation of the three multiplex networks of the coffee AFSES for the 2000-2010 period (note that the commercialization multiplex, in this case only has one layer). Nodes represent actors which participated in the activities (layers) related to each subsystem of the AFSES (production, transformation and commercialization). Nodes which interacted in a layer are connected by links (see Table 1 for activity definitions) and their size is proportional to their degree versatility to connect other nodes. Nodes which did not interact in a layer are omitted. Layers in each multiplex are shown in different colors and node position is kept the same across layers. Interlayer links are omitted for clarity.

Regarding the number of nodes (Table 3), those with the most quantity of nodes per type in Production were government agencies (n=17), and secondary organizations of producers and companies, both with (n=9). In Transformation, the largest number of nodes were cooperatives (n=4), companies, secondary producer organizations and intensive producers, all of them with (n=3). In Commercialization companies had the largest number of nodes (n=27), traders (n=21) and conventional producers (n=7) (Fig.

4). Besides, Production had the greatest number of links (n=120), followed by Commercialization (n=84) and Transformation (n=24).

The highest versatility per degree in Production was found in secondary producer organizations (n=0.260), agroecological producers (n=0.211) and intensive producers (n=0.117). In Transformation, the highest values were found by government agencies (0.536), and civil associations and intensive producers, both with (n=0.143). In Commercialization, the most central by degree were civil associations (n=0.636), secondary producer organizations (n=0.545) and conventional producers (n=0.442). The values are similar in versatility by eigenvector, where the most central actors in Production were also secondary producer organizations (n=0.243), conventional producers (n=0.158) and intensive producers (n=0.148). In Transformation, the highest values were found by government agencies (n=0.500), producer cooperatives (n=0.194) and secondary producer organizations, both with (n=0.178). To see complete statistics, consult Appendix 1.

On the other hand, the number of connected components (Table 3) was high: in Production there were 5 connected components with 62 nodes making it up. In Transformation there were 5 components connected with 57 nodes and in marketing there were 7 components connected with 15 nodes. In addition, the density of all networks was closed to 0 which supported a lower connectivity (Table 3).

4.2 Second period, 2010-2020. In this decade, more complex networks were observed, although this complexity varies with respect to each level of the system (Fig. 3). The number of nodes significantly increased (Table 3), as well as the type of collective nodes and the number of links, in all layers (Table 3, Fig. 4). Diversity significantly increased based on the number of collective nodes and the high values of degree centrality; besides, we observed that international, national, regional, and local companies, civil associations and government agencies were present in this decade, as well as "social organizations" founded by producers (such as companies and civil associations). This high diversity was observed at the Production and Transformation subsystems; however, in Marketing, companies and traders predominated, being the subsystem with the least diversity (See Appendix 2). Regarding connectivity, the best-connected subsystems were Production and Commercialization, specifically Information and Trading layers, respectively, and less connected was Transformation in all its layers.

Fig. 3 Multiplex networks of the coffee AFSES, 2010-2020

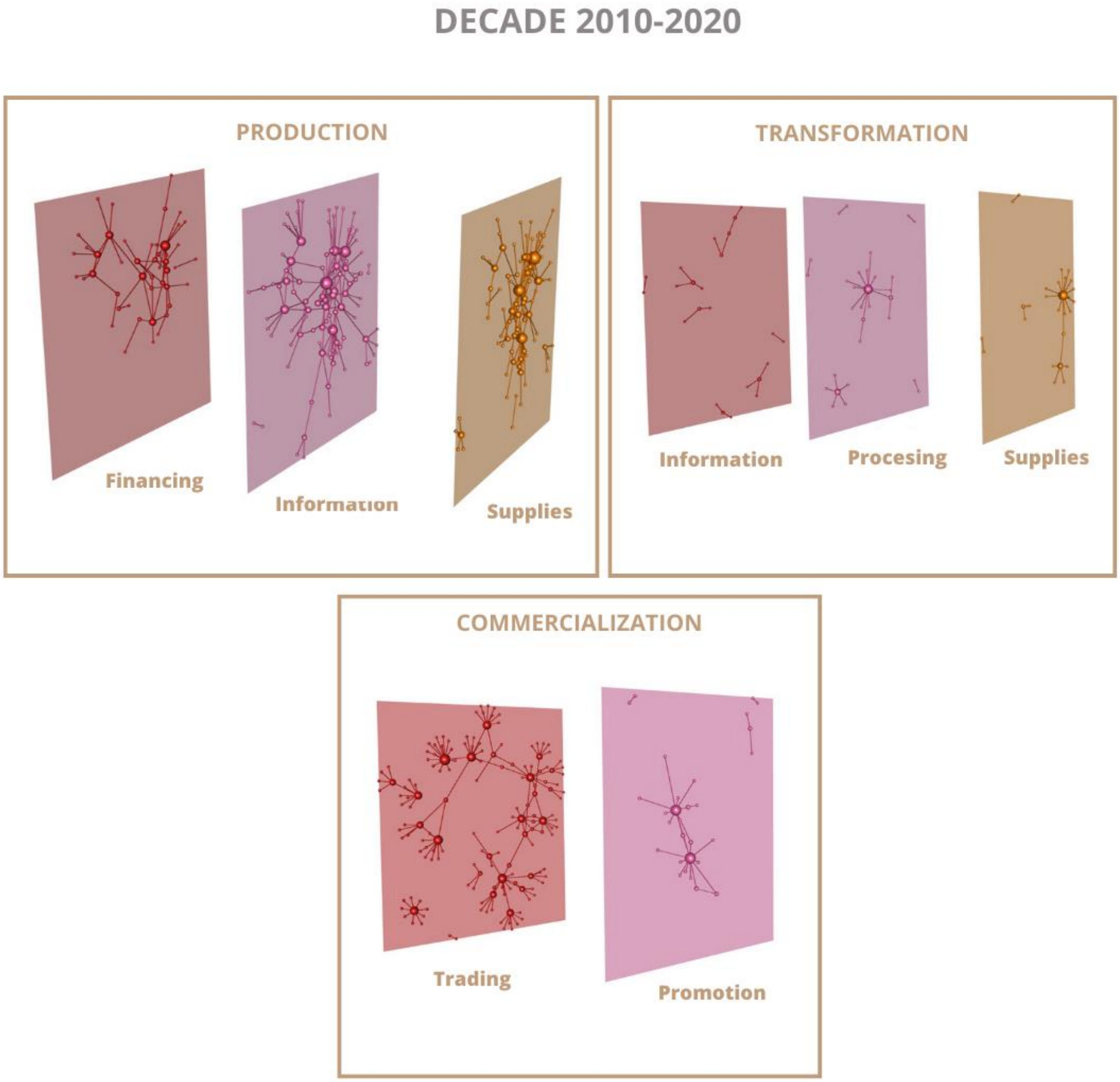


Figure 3 Graphic representation of the three multiplex networks of the coffee AFSES for the 2010-2020 period. Nodes represent actors which participated in the activities (layers) related to each subsystem of the AFSES (production, transformation and commercialization). Nodes which interacted in a layer are connected by links (see Table 1 for activity definitions) and their size is proportional to their relevance to connect other nodes. Nodes which did not interact in a layer are omitted. Layers in each multiplex are shown in different colors and node position is kept the same across layers. Interlayer links are omitted for clarity.

On the other hand, peripheral nodes were reduced in Production and Commercialization but not in Transformation where subgroups increased in comparison to the previous decade (Fig. 3). Therefore, the fragmentation in all networks decreased, improving connectivity in Production and Marketing subsystems. In the case of Transformation despite of low connectivity, this subsystem continued to operate, even improving its performance since several producers were able to access this stage that was difficult to enter in previous years. Additionally, central actors in Production and Commercialization were secondary producers organizations, cooperatives, government agencies, cooperatives and intensive producers. In Transformation were government agencies, secondary producers organizations and cooperatives.

Regarding Production the largest number of nodes were concentrated in government agencies (n=32), companies (n=22), and civil associations (n=14). On the other hand, centrality degree was concentrated in secondary producers organizations (n=0.228), followed by intensive producers (n=0.210) and cooperatives (n=0.182). In contrast, for the eigenvector centrality, intensive producers had the highest value (n=0.281), followed by secondary producers organizations (n=0.233) and conventional producers (n=0.192). Respecting to the number of connected components it was reduced during this period from (n=6) to (n=2) which 140 nodes making it up. However, although there were a greater number of central nodes that connect a greater number of peripheral nodes and less connected components, remain some disconnected nodes (Fig. 3).

In Transformation, government agencies concentrated the highest value (n=0.274) of degree centrality (Fig. 3), followed by companies (n=0.148) and intensive producers (n=0.143). Regarding to eigenvector centrality, government agencies also had the highest value (n=0.217), followed by secondary producers organizations (n=0.215) and cooperatives (n=0.205). The number of nodes increased and especially was concentrated in companies (n=15), cooperatives (n=13), and government agencies and civil associations all of them with (n=6) nodes. The small number of central nodes to link subgroups and disconnected nodes continued as well as the disconnection of peripheral nodes, mainly in the Information layer. To complement this scenario, the number of connected components increased from (n=5) to (n=7) compared to the first decade, reflecting low connectivity.

In Commercialization, secondary producers' organizations had the highest value (n=0.354) of degree centrality followed by cooperatives (n=0.344) and conventional producers (n=0.295). In the same way, the secondary producers organizations have an eigenvector centrality of (n=0.455), followed by government agencies (n=0.258) and civil associations (n=0.245). The number of nodes also increased, and the number of the main nodes was divided in companies (n=80), traders (n=18) and individuals (n=16). Although the number of central nodes increased, this subsystem continued to maintain star shapes. To complete this observation, the number of connected components decreased from (n=7) to (n=5) respect to the first decade but remained density values close to 0 indicating disconnected networks with low exchange and collaborative capacity.

4.3 Collective nodes. Another relevant finding is that collective nodes became the most relevant in terms of eigenvector versatility (Fig. 3). In descending order, these were secondary producer organizations (Production 0.233; Transformation 0.215; Commercialization 0.455), government agencies (Production 0.103; Transformation 0.217; Commercialization 0.258), and cooperatives (Production 0.063; Transformation 0.205; Commercialization 0.123). With less preponderance were the research centers (Production 0.097; Transformation 0.011; Commercialization 0.185), civil associations (Production 0.026; Transformation 0.028; Commercialization 0.245), and companies (Production 0.033; Transformation 0; Commercialization 0.084). At the individual level, the most important nodes were intensive producers who stood out in the Production (0.281) and Commercialization (0.241), while agroecological producers stood out in the Transformation level (0.061) (See Appendix 1).

Table 3. Diversity and Connectivity Indicators

2000-2010

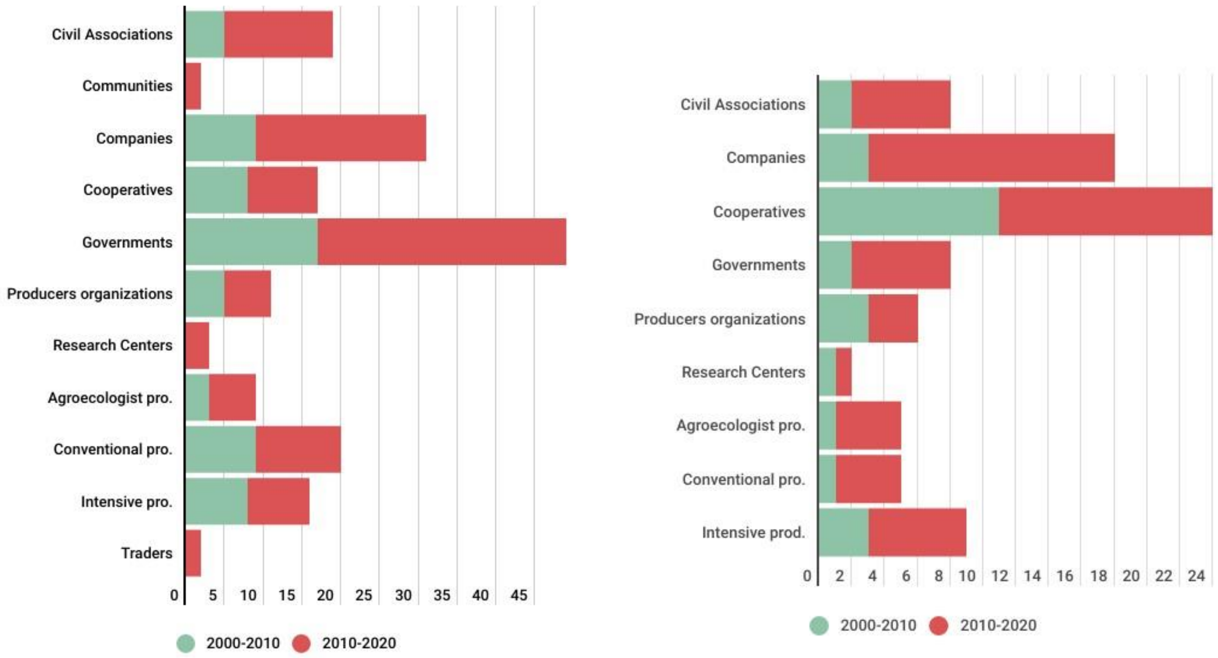
Multiplex name	Number of layers	Layer name	Number of nodes	Number of collective nodes	Number of edges	Density	Number of connected components*	Number of nodes in the largest connected component**
Production	3		123	59	120	0.02	6	62
		Financing	28	13	28	0.07	3	24
		Information	60	30	61	0.03	5	50
		Supplies	35	16	31	0.05	7	21
Transformation	2		31	24	24	0.07	5	15
		Information	9	5	6	0.17	3	4
		Supplies	22	19	18	0.08	4	15
Commercialization	1		86	35	84	0.02	7	57
		Trading	86	35	84	0.02	7	57

2010-2020

Multiplex name	Number of layers	Layer name	Number of nodes*	Number of collective nodes*	Number of edges	Density	Number of connected components*	Number of nodes in the largest connected component**
Production	3		236	120	290	0.01	2	140
		Financing	47	19	53	0.05	2	45
		Information	102	56	136	0.03	4	96
		Supplies	87	45	101	0.03	5	74
Transformation	3		80	53	63	0.03	7	45
		Information	23	14	16	0.06	7	5
		Processing	30	18	24	0.06	6	16
		Supplies	27	21	23	0.07	4	20
Commercialization	2		187	108	191	0.01	5	160
		Promotion	29	22	28	0.07	4	129
		Trading	158	86	163	0.01	5	22

Table 3. Network metrics for the three multiplexes of each period. See Table 2 for network definitions.

Figure 4 Number of nodes type



Production *Transformation*

Commercialization

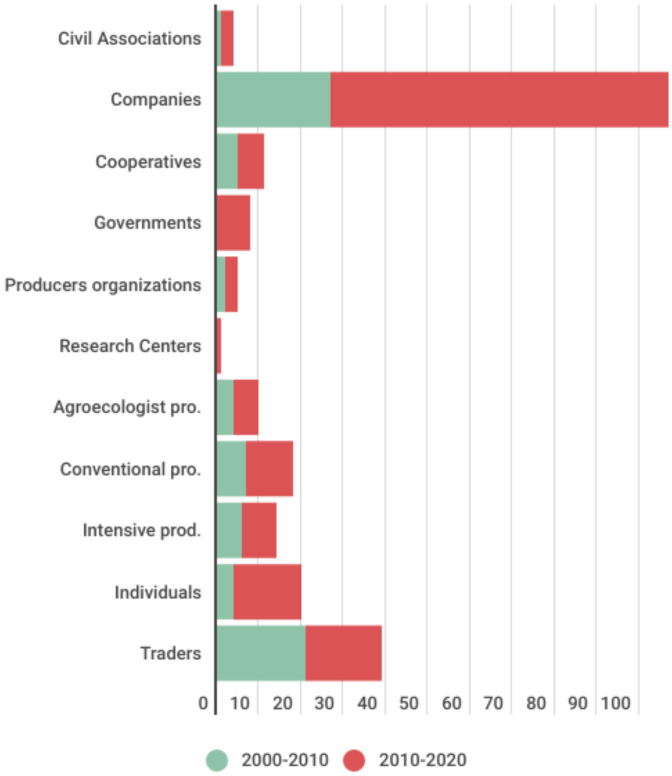


Figure 5 Eigenvector versatility according to node type

Figure 4. This figure represents the change in average eigenvector versatility per node type for the two time periods. Normalized values were plotted to improve their comparison and readability with respect to the centrality by degree shown in Appendix 2.

5. Discussion

5.1 Diversity and connectivity for adaptive capacity. The results show that the multiplex network approach was useful to assess how the diversity and connectivity of social interactions influence the adaptive capacity of the AFSES over two decades. Via multiplex metrics we observed that diverse and well-connected social interactions allow access to different capacities to adapt. The combination of these two attributes took place simultaneously among three semi-autonomous subsystems that influenced each other, and changes at one subsystem drove changes in the others. However, not all subsystems had the same diversity and connectivity. The Production subsystem was the most diverse and most connected, followed by Marketing, which had less diversity but regular connectivity. While the Transformation subsystem had the least connectivity of all despite having greater diversity than Marketing. This suggests that the combination of attributes to promote adaptive capacity depends on the activities carried out in each subsystem. Also, we found that despite the relevance of the diversity of actors, the most outstanding attribute was connectivity, since an actor has access to information or resources useful for adaptation through their links. Therefore, interaction patterns are fundamental for resilience.

On the other hand, despite the fact that other studies (Baird et al., 2019; Cabel & Oelofse, 2012; Soriano et al., 2023) have indicated that a low diversity (high number of low connections) avoids a single node essential for the system and this favors flexibility to face local changes; in this study, in the three subsystems a higher diversity of node types (which meant higher institutional diversity) was an important factor to promote innovation and collaboration for adaptation.

Regarding the different characteristics of connectivity at each subsystem (in Production there were more central nodes and less fragmentation; in Transformation there were few central nodes and a lot of fragmentation; and in Commercialization there were more central nodes, disconnected components and therefore a regular fragmentation), it could be different because subsystems are not identical, and the socioecological processes taken in each one interacting at different scales. Even though each subsystem has specific functions, specializations, and objectives, each one depends on the other for the supply of resources, information, or services. Consequently, connectivity is stronger between those levels that have strong relationships of interdependence and vice versa (Biggs et al., 2012).

Regarding the change in adaptive capacity over time, we found that it was greater in the second decade. In the decade 2000-2010, the system had the capacity for adaptation and resistance to face the instability of world coffee prices and the decline in coffee production in the AFSES. However, compared to the second period, the social networks formed between subsystems were dispersed, fragmented, and very centralized. In contrast, in the second decade (2010-2020) the system faced the coffee rust plague (Hemileia vastratrix), the decrease of government subsidies, and the effects of climate change, mainly, which exerted greater pressure. The social networks formed between the subsystems with the characteristics of diversity and connectivity analyzed here were crucial to maintain the production and sale of coffee.

For example, in the Production subsystem, producers had the resources to apply more nutrients to the coffee tree, introduce varieties resistant to rust and high temperatures, and improve post-harvest processes. In the Transformation subsystem, coffee growers individually decided to form other organizations (included in the collective nodes) to participate in the processing and marketing processes to add value to their production, which favored groups of producers affiliated with certain cooperatives and associations of producers could access this stage of the value chain. This was crucial to facilitate marketing and increase their income since for many years they had been limited to their role as farmers without having bargaining power in the following stages. Regarding the Marketing subsystem, the commercial exchange of coffee was carried out under more equitable conditions because producers could connect directly with consumers and roast houses.

5.2 The role of key actors for resilience. The most important node type to foster the adaptive capacity were collective nodes which, in general, were secondary producer organizations, government agencies, and cooperatives. These kinds of actors played pivotal roles as influential actors within individual layers while also serving as critical connectors across layers. The secondary producer organizations and cooperatives were constituted by coffee farmers in both decades; additionally, were relevant civil associations and companies founded by coffee farmers during the second decade. These collective nodes lead the formation of subgroups and bridge the transit of information and resources. Although, the formation of new collective actors was triggered by conflicts between members of secondary producer organizations that caused the segmentation of a cohesive union during the international coffee crisis in the 1990s. Various coffee farmers identified at the individual level (who began the formation of new organizations) were local and regional leaders and recognized as such by private and governmental organizations.

Therefore, part of the history of the organizations was part of the individual story of farmers, and they were feedback mutually. This situation invites us to reflect on the formation of collective nodes as part of an individual identity that revealed, in this case, the importance of the vision and capabilities of individual producers to trigger the auto-organization. The relevance of coffee farmers at the individual scale was different according to subsystem (intensive producers were the most relevant in Production and Commercialization, while agroecological producers were relevant in the Transformation level), which suggests that producers have their own subgroups and paths inside each one, but all have points of coincidence via collective organizations. Thus, in the AFSES the structures and mechanisms of feedback were determined by historical paradigms that shape them and give them identity and change slowly. Finally, these collective nodes had widespread effects, making them essential leverage points for promoting stability and adaptability in the coffee AFSES (Bacsi et al., 2023; Yuniarti Widayat et al., 2023)

5.3 The future of the coffee AFSES. In this study, coffee farmers and other relevant actors were able to organize themselves to confront change and uncertainty. However, resilience is context-dependent and social arrangements that are considered resilient today may not be so in the future; even short-term resilience can reduce long-term resilience (Cabel & Oelofse, 2012). The results invite us to reflect about what will be the effects of the actual social interactions in the future. The current conditions of the AFSES have allowed the general resilience of the system but in a zoom at specific activities at each subsystem, we ask if the role played by leaders of coffee farmers and collective nodes until now will be viable in the future. For example, the actual structure of the Transformation subsystem could favor only some producers to get the most out of entering the activities of this level, which would create conditions of inequality and exclusion in the long term. Similarly, at the Commercialization subsystem where the most relevant and powerful nodes have been those collective actors who connect to companies and traders limiting the bargaining capacity of individual coffee farmers. Therefore, it is important to maintain the diversity and the connectivity of type nodes to sure the availability of multiple options to maintain the habitual functions of the AFSES during stable periods and to react in case of emergence.

It is important to encourage the presence of governmental agencies to support the activities at all subsystems because has been a regulator and a provider. Likewise, it is important to strengthen the formation of different organizations for producers, not only cooperatives or secondary producers organizations but also commercial companies to sell or to process in conditions of equity as well as to enhance transparency among their members. Also, it is important to maintain diversity in approaches and strategies among organizations while establishing effective mechanisms for coordination and collaboration among them to coordinate coherence and complementary actions which maximize the benefits of connectivity.

6. Conclusions

In general, the combination of high diversity and high connectivity in social interactions in a coffee system were attributes that drove adaptive capacity over twenty years. The combinations of these attributes were different (high diversity-high connectivity; medium diversity-high connectivity; high diversity-low connectivity) due to the functions and needs of each subsystem and according to the time. It was evident that in the decade 2010-2020, diversity and connectivity increased significantly in all subsystems compared to the first decade. Therefore, we maintain that the combinations found allowed the system to maintain its productive capacity despite the changes faced over time. However, although having diverse actors contributed to adaptation, connectivity patterns were key to strengthening adaptive capacity and collective actors (government agencies, producer organizations, and civil associations) were the connectors. However, there is a possibility that maintaining current social interactions will not contribute to resilience in the future.

Acknowledgments

We acknowledge the National Council for Science and Technology (CONACYT) and the French National Agency for Research (ANR-France) for funding project 290832 ANR-CONACYT “Trajectories of Social-Ecological Systems in Latin American Watersheds: Facing Complexity and Vulnerability in the context of Climate Change (“TRASSE”)”. In addition, The National Autonomous University of Mexico awarded grants through the PAPIIT-IN302720 and PAPIIT-IV300123 projects and PASPA-DGAPA. Finally, special recognition to Bruno Locatelli for his invaluable support at the beginning of this research.

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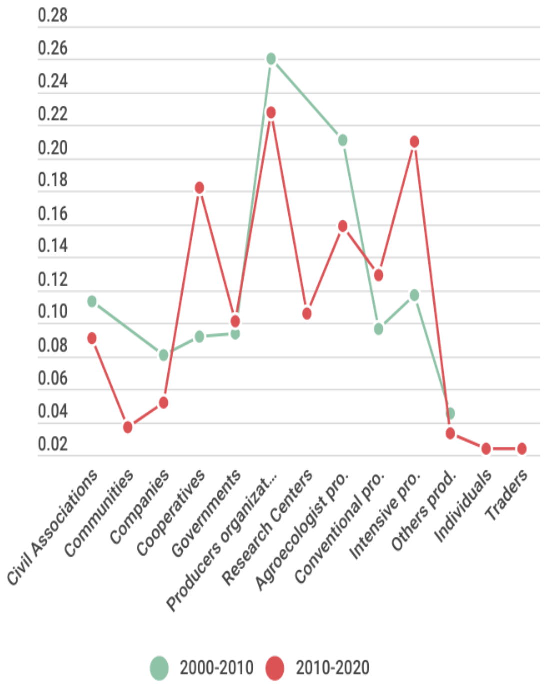
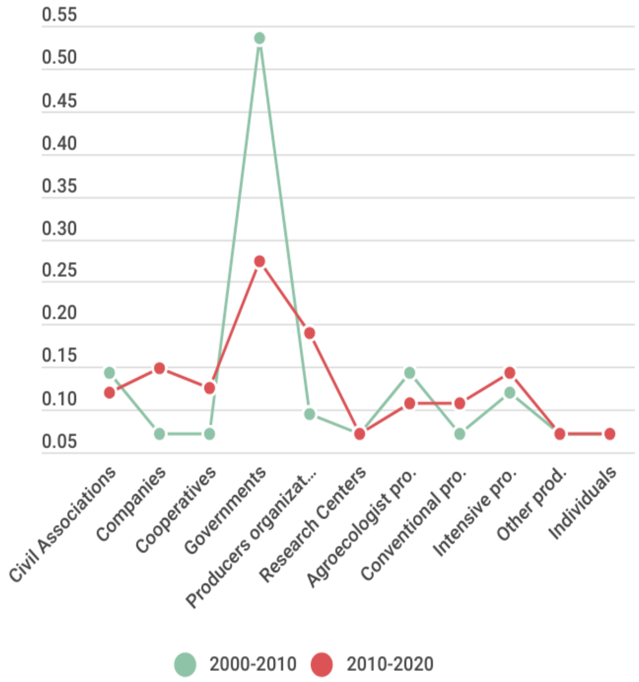
APPENDIXES (Supplementary information).

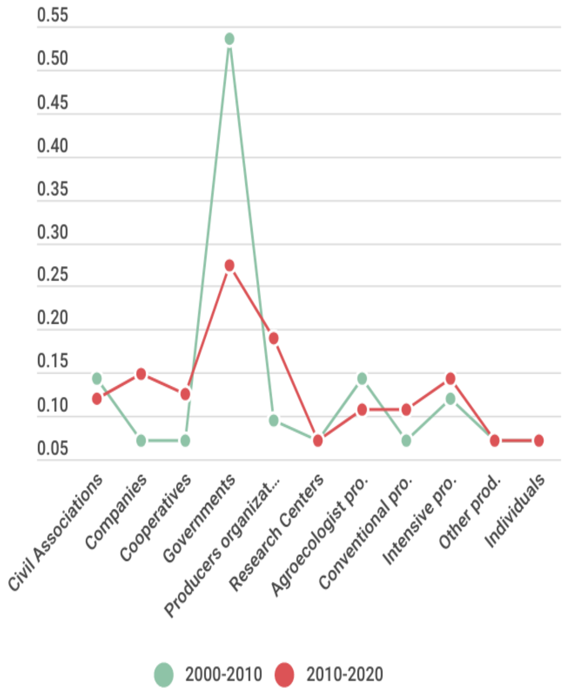
Appendix 1. Degree versatility according to node type



Production



Transformation



Commercialization

Appendix 2. Descriptive statistics regarding versatilities

PRODUCTION - Descriptive statistics - First Decade 2000-2010

	Degree versatility				Eigenvector versatility			
Node type	Mean	Standard Deviation	Maximum	Minimum	Mean	Standard Deviation	Maximum	Minimum
Civil Associations	0.113	0.161	0.400	0.033	0.018	0.027	0.066	0.000
Companies	0.081	0.087	0.300	0.033	0.038	0.038	0.096	0.000
Cooperatives	0.092	0.056	0.200	0.033	0.014	0.017	0.050	0.000
Governments	0.094	0.102	0.467	0.033	0.075	0.113	0.481	0.000
Producers organizations	0.260	0.420	1.000	0.033	0.243	0.426	1.000	0.000
Agroecologist pro.	0.211	0.195	0.433	0.067	0.091	0.081	0.157	0.000
Conventional pro.	0.096	0.059	0.200	0.033	0.158	0.130	0.363	0.000
Intensive pro.	0.117	0.093	0.300	0.033	0.148	0.159	0.364	0.000
Others prod.	0.045	0.017	0.067	0.033	0.058	0.089	0.220	0.000

PRODUCTION - Descriptive statistics- Second Decade 2010-2020

	Degree versatility				Eigenvector versatility			
Node Type	Mean	Standard Deviation	Maximum	Minimum	Mean	Standard Deviation	Maximum	Minimum
Civil Associations	0.091	0.098	0.390	0.024	0.026	0.033	0.108	0.003
Communities	0.037	0.017	0.049	0.024	0.013	0.008	0.019	0.008
Companies	0.052	0.054	0.220	0.024	0.033	0.047	0.203	0.001
Cooperatives	0.182	0.219	0.707	0.024	0.063	0.095	0.307	0.000
Governments	0.101	0.161	0.854	0.024	0.103	0.197	1.000	0.001
Individuals	0.024	0.000	0.024	0.024	0.006	0.000	0.006	0.005
Producers organizations	0.228	0.391	1.000	0.024	0.233	0.360	0.906	0.006
Research Centers	0.106	0.141	0.268	0.024	0.097	0.159	0.281	0.005
Traders	0.024	0.000	0.024	0.024	0.023	0.010	0.030	0.016
Agroecologist pro.	0.159	0.148	0.439	0.049	0.084	0.064	0.158	0.000
Conventional pro.	0.129	0.062	0.244	0.049	0.192	0.099	0.331	0.034
Intensive pro.	0.210	0.055	0.317	0.146	0.281	0.151	0.458	0.032
Others prod.	0.033	0.013	0.073	0.024	0.030	0.045	0.143	0.000

TRANSFORMATION - Descriptive statistics - First Decade 2000-2010

Node Type	Degree versatility Mean	Standard Deviation	Maximum	Minimum	Eigenvector versatility Mean	Standard Deviation	Maximum	Minimum
Civil Associations	0.143	0.101	0.214	0.071	0.000	0.000	0.000	0.000
Companies	0.071	0.000	0.071	0.071	0.178	0.154	0.267	0.000
Cooperatives	0.071	0.000	0.071	0.071	0.194	0.125	0.267	0.000
Governments	0.536	0.657	1.000	0.071	0.500	0.707	1.000	0.000
Individuals	0.071	NA	0.071	0.071	0.000	NA	0.000	0.000
Producers organizations	0.095	0.041	0.143	0.071	0.178	0.154	0.267	0.000
Research Centers	0.071	NA	0.071	0.071	0.000	NA	0.000	0.000
Agroecologist pro.	0.143	NA	0.143	0.143	0.000	NA	0.000	0.000
Conventional pro.	0.071	NA	0.071	0.071	0.000	NA	0.000	0.000
Intensive pro.	0.119	0.082	0.214	0.071	0.089	0.154	0.267	0.000
Other prod.	0.071	NA	0.071	0.071	0.267	NA	0.267	0.267

TRANSFORMATION - Descriptive statistics - Second Decade 2010-2020

Node Type	Degree versatility Mean	Standard Deviation	Maximum	Minimum	Eigenvector versatility Mean	Standard Deviation	Maximum	Minimum
Civil Associations	0.119	0.087	0.286	0.071	0.028	0.050	0.129	0.000
Companies	0.148	0.210	0.857	0.071	0.085	0.119	0.360	0.000
Cooperatives	0.126	0.083	0.286	0.071	0.205	0.125	0.387	0.000
Governments	0.274	0.360	1.000	0.071	0.217	0.402	1.000	0.000
Individuals	0.071	0.000	0.071	0.071	0.002	0.003	0.006	0.000
Producers organizations	0.190	0.206	0.429	0.071	0.215	0.085	0.264	0.116
Research Centers	0.071	NA	0.071	0.071	0.011	NA	0.011	0.011
Agroecologist pro.	0.107	0.071	0.214	0.071	0.061	0.035	0.110	0.028
Conventional pro.	0.107	0.041	0.143	0.071	0.021	0.014	0.030	0.000
Intensive pro.	0.143	0.090	0.286	0.071	0.029	0.039	0.100	0.000
Other prod.	0.071	0.000	0.071	0.071	0.092	0.149	0.264	0.000

COMMERCIALIZATION - Descriptive statistics - First Decade 2000-2010

Node Type	Degree versatility				Eigenvector versatility			
	Mean	**Standard Deviation**	**Maximum**	**Minimum**	**Mean**	**Standard Deviation**	**Maximum**	**Minimum**
Civil Associations	0.636	NA	0.636	0.636	0.024	NA	0.024	0.024
Companies	0.104	0.033	0.182	0.091	0.015	0.032	0.120	0.000
Cooperatives	0.200	0.197	0.545	0.091	0.010	0.020	0.046	0.000
Individuals	0.091	0.000	0.091	0.091	0.024	0.048	0.095	0.000
Producers organizations	0.545	0.643	1.000	0.091	0.500	0.707	1.000	0.000
Trader	0.095	0.020	0.182	0.091	0.047	0.047	0.120	0.000
Agroecologist pro.	0.250	0.261	0.636	0.091	0.004	0.005	0.011	0.000
Conventional pro.	0.442	0.237	0.727	0.091	0.225	0.219	0.503	0.000
Intensive pro.	0.348	0.260	0.818	0.091	0.134	0.135	0.272	0.000
Other prod.	0.111	0.040	0.182	0.091	0.110	0.135	0.359	0.000

COMMERCIALIZATION - Descriptive statistics - Second Decade 2010-2020

Node Type	Degree versatility				Eigenvector versatility			
	Mean	**Standard Deviation**	**Maximum**	**Minimum**	**Mean**	**Standard Deviation**	**Maximum**	**Minimum**
Civil Associations	0.292	0.397	0.750	0.063	0.245	0.121	0.384	0.175
Companies	0.096	0.103	0.688	0.063	0.084	0.093	0.446	0.000
Cooperatives	0.344	0.246	0.688	0.063	0.123	0.078	0.272	0.052
Governments	0.234	0.300	0.750	0.063	0.258	0.357	0.889	0.000
Individuals	0.063	0.000	0.063	0.063	0.037	0.029	0.096	0.000
Producers organizations	0.354	0.452	0.875	0.063	0.455	0.472	1.000	0.175
Research Centers	0.125	NA	0.125	0.125	0.185	NA	0.185	0.185
Traders	0.063	0.000	0.063	0.063	0.048	0.034	0.096	0.005
Agroecologist pro.	0.156	0.201	0.563	0.063	0.058	0.073	0.207	0.023
Conventional pro.	0.295	0.170	0.563	0.063	0.126	0.154	0.411	0.000
Intensive pro.	0.344	0.322	1.000	0.063	0.241	0.203	0.684	0.028
Other prod.	0.070	0.021	0.125	0.063	0.076	0.080	0.278	0.000

Foto: Ramírez León, A. Diciembre 2021. Cuenca Copalita vista desde San Pedro El Alto, Oax.

CAPÍTULO 5. DISCUSIÓN Y CONCLUSIONES

5.1 Relación entre adaptación, resiliencia y sustentabilidad

Esta investigación respondió a la pregunta sobre cómo las interacciones sociales pasadas influyen en la capacidad de adaptación de un SSEAG de café para ser resiliente en el largo plazo ya que presentó evidencia histórica relevante sobre la influencia de las interacciones sociales en la trayectoria de un SSEAG de café y su capacidad de adaptación. Por un lado, el marco analítico-metodológico cumplió el objetivo general que consistió en conocer la trayectoria histórica del SSEAG de café localizado en las cuencas Copalita-Huatulco y el papel de las interacciones sociales en su adaptación y resiliencia a lo largo de 40 años. Este marco estuvo compuesto por dos etapas: primera, se realizó un análisis histórico de la trayectoria del SSEAG a lo largo de 40 años (1980-2020), que estuvo marcado por estresores y shocks políticos (desaparición del IMECAFE), económicos (crisis de precios internacionales de café) y ambientales (huracán Paulina y cambio climático), para entender a profundidad cómo esta trayectoria ha determinado las condiciones actuales del sistema. Esto se logró identificando los diferentes factores de cambio que han impulsado cambios en la trayectoria, la cual fue descrita y evaluada a través del Ciclo Adaptativo; esto permitió cumplir el primer objetivo específico. En la segunda etapa se analizaron las interacciones sociales del SSEAG a lo largo de 20 años (2000-2020) para identificar los arreglos entre conectividad y diversidad impulsan su capacidad de adaptación; esto se llevó a cabo a través de un análisis de redes multiplex cuya aproximación teórica permite analizar diferentes interacciones entre los mismos actores para realizar distintas actividades, las cuales a su vez tienen diferentes propósitos, pero una misma meta: mantener la oferta de café para su consumo. De este modo, se cumplió el segundo objetivo específico.

En el caso del análisis de la trayectoria, se encontró que los SSEAG no siempre cumplen con un proceso de sucesión como el que propone el Ciclo Adaptativo. Aunque este enfoque fue útil para identificar umbrales y transiciones, no fue suficientemente apropiado para identificar en qué condiciones se alcanzan umbrales que abran "ventanas de oportunidad" para impulsar la transformación del sistema hacia estados más resilientes. En este sentido, el Ciclo Adaptativo fue insuficiente para analizar las posibilidades de afrontar varias o diferentes trayectorias alternativas de un SSEAG. También se encontró que las estrategias de adaptación y afrontamiento pueden ser negativos dependiendo de la acumulación de sus efectos a lo largo del tiempo, lo que nos hace reflexionar en los límites que pueden tener la adaptación. Además, es importante profundizar el análisis de los *trade-offs* entre estrategias de adaptación y la capacidad de transformación para mejorar la resiliencia del sistema. La capacidad de transformación no se estudió profundamente en esta investigación y no es claro si el Ciclo Adaptativo es suficiente para su análisis; también queda pendiente entender cómo evoluciona la capacidad de resistencia hacia la capacidad de adaptación y sus desafíos.

Respecto al análisis de las interacciones, se encontró que la combinación de alta diversidad y alta conectividad en las interacciones sociales fueron atributos que impulsaron la capacidad de adaptación durante un periodo de veinte años (2000-2020). Se encontró que en la década 2010-2020 la diversidad y la conectividad aumentaron significativamente en todos los subsistemas en comparación con la primera década (2000-2010). Sin embargo, las combinaciones de estos atributos fueron diferentes (alta diversidad-alta conectividad; media diversidad-alta conectividad; alta diversidad-baja conectividad) debido a las funciones y necesidades de cada componente del SSEAG y según su evolución en el tiempo. Las combinaciones encontradas permitieron que el sistema mantuviera su capacidad productiva a pesar de los cambios enfrentados en el tiempo. Por otro lado, aunque la diversidad de actores contribuyó en la capacidad de adaptación, los patrones de conectividad fueron clave para fortalecer esta capacidad y los actores colectivos (agencias gubernamentales, organizaciones de productores y asociaciones civiles) fueron los articuladores y puentes en esa conexión. Sin embargo, existe la posibilidad de que mantener las interacciones sociales actuales no contribuyan a la resiliencia del SSEAG en el futuro, ya que hasta ahora el sistema ha resistido, pero no han mejorado sustancialmente las condiciones de vida de los cafeticultores.

Las evidencias que aportan los análisis de esta investigación muestran que, como se ha señalado en otros estudios en SAG (Abson et al., 2013, 2017; Bair, 2005; Pedreño et al., 2015), la resiliencia no es igual a la sustentabilidad. En primera instancia, las evidencias obtenidas muestran que la cadena de valor de café ha tenido la capacidad para gestionar y mitigar las perturbaciones que ha atravesado el SSEAG a lo largo de 40 años, principalmente gracias a las estrategias de afrontamiento y adaptación. Asimismo, el cultivo de café de sombra hoy en día provee diversos servicios ecosistémicos esenciales en el SSEAG. También es claro que hubo un proceso de aprendizaje que fue respaldado por las redes de colaboración y apoyo que se han construido entre los diversos actores presentes en el SSEAG. Sin embargo, según los propios testimonios de los informantes, la continuidad e intensidad de los factores de cambio que han afrontado les ha impedido recuperar la rentabilidad de la producción de café y en cambio ha generado nuevas condiciones que disminuyen la relevancia económica y social de la actividad cafetalera en la región. Esto demuestra que el SSEAG ha tenido la capacidad de persistir en el tiempo, pero difícilmente podrá evolucionar hacia un sistema más sustentable donde se mantenga y expanda el cultivo de café de sombra orgánico, agroecológico, o con bajo impacto ambiental, que mantenga la provisión de servicios ecosistémicos diversos, y que aumente los ingresos de los cafeticultores para mejorar sus medios de vida, principalmente entre los pequeños productores marginados.

Por otro lado, estudios como los de Lamine (2015) y Sinclair et al. (2017) sugieren que la diversidad de actores en un SSEAG puede derivar en conflictos y desacuerdos por la cantidad de intereses y decisiones que pueden contribuir a la imprevisibilidad de sus efectos a largo plazo. En cuanto a la conectividad, estudios como los de Cabel & Oelofse (2012) y Biggs et al. (2012) indican que a largo plazo es deseable evitar que un elemento del sistema sea esencial para el rendimiento general (resiliencia general) y en cambio es más recomendable mantener un elevado número de conexiones *débiles o bajas* (Cabel & Oelofse, 2012) a fin de fomentar la flexibilidad para responder ante una perturbación. Por tanto, estos estudios junto con las evidencias aportadas en esta investigación muestran que la diversidad y la conectividad son importantes para la resiliencia, aunque es difícil definir sus umbrales, los cuales van a cambiar dependiendo del contexto. En otras palabras, estos atributos de resiliencia pueden considerarse variables sistémicas que no serán iguales en todos los casos y no hay criterios absolutos para definir en qué condiciones son más positivas que en otras.

De este modo, se sostiene que el SSEAG es resiliente a escala general para continuar proporcionando los bienes y servicios que respaldan la producción de café. Si bien las estrategias para adaptarse, aprender y recuperarse de las perturbaciones tienden a favorecer la estabilidad de corto y mediano plazo, su efectividad a largo plazo puede estar comprometida. Esto coincide con otros estudios como los de Cabel & Oelofse (2012), Folke et al. (2010) y Meuwissen et al. (2019), que señalan que la resiliencia general puede ser contradictoria a la resiliencia específica. Es decir, las capacidades de resistencia, adaptación y transformación pueden ser diferentes para cada componente y generar *trade-offs* a nivel general. Otro tema pendiente es el papel de las interacciones sociales y cómo contribuyen a los procesos de gobernanza; dichas interacciones indudablemente se encuentran embebidas en procesos de gobernanza que no fueron analizados en esta investigación. Estudiar las trayectorias de un SSEAG impone un reto importante para la investigación en las ciencias de la sostenibilidad y el pensamiento resiliente, pues es indispensable averiguar cómo detonar la capacidad de transformación hacia un estado deseado del sistema, el cual deberían ser definido desde la transdisciplina para involucrar a los actores en la planeación y gestión del SEEAG. Así, es importante identificar puntos de equilibrio para que el sistema pueda ser flexible y tener estrategias de colaboración y políticas públicas eficaces a lo largo del tiempo.

5.2 ¿Cuál es el futuro del SSEAG de café?

Como se mencionó, desde hace más de 30 años el sector cafetalero mundial se ha expandido significativamente con un aumento en la producción en más del 65% (ICO, 2019). Este crecimiento ha sido impulsado por el aumento del consumo en las economías emergentes y los países productores de café: el 46% de la demanda mundial de café proviene de estos mercados, en comparación con el 29% a principios de los años noventa (ICO, 2019). Teniendo en cuenta las tendencias del crecimiento demográfico mundial y las tasas de consumo per cápita entre los países consumidores de café tradicionales y no tradicionales, existe un potencial significativo para el crecimiento del mercado mundial del café (ICO, 2019). Además, la demanda en los mercados tradicionales con un consumo per cápita alto se ha visto revitalizada por el crecimiento de segmentos de mercado de alto valor, como el café de especialidad, y como resultado de innovaciones de productos que brindan nuevos sabores y más comodidad a los consumidores (ICO, 2019).

A pesar del crecimiento general del sector, los precios del café han mantenido una tendencia continua a la baja desde 2016, cayendo un 30% por debajo del promedio de los últimos diez años (ICO, 2019). Los productores de café de todo el mundo están luchando por cubrir sus costos operativos a medida que los costos de insumos, cumplimiento y transacción continúan aumentando (ICO, 2019). En consecuencia, los ingresos agrícolas disminuyen y los medios de vida de los hogares productores de café, la mayoría de los cuales están encabezados por pequeños agricultores en países de ingresos bajos y medianos, están cada vez más en riesgo (ICO, 2019). La caída de los precios tiene graves consecuencias económicas y sociales para los países productores (ICO, 2019). A esta situación se le suman otro tipo de riesgos como los eventos climáticos extremos y las afectaciones por causa del cambio climático, que están haciendo mella en la producción de café en América Latina, donde la frecuencia e intensidad en los brotes de roya están asociados al aumento de temperatura (Avelino et al., 2015; Valencia et al., 2018).

Aunque el consumo mundial ha aumentado, la producción de café en México ha caído drásticamente a lo largo de 20 años: pasó de 6.2 millones de sacos en el ciclo 1999-2000 a 2.3 millones en 2010; con un leve repunte en 2017 (CEDRSSA, 2018). Son múltiples las causas de esta situación (como lo muestra la evidencia aportada por esta investigación) entre las que se encuentran: los efectos de la desaparición de los acuerdos internacionales del café, el desplome de los precios del grano, la baja rentabilidad, las condiciones climáticas, principalmente (CEDRSSA, 2018). Oaxaca es el cuarto productor de café a nivel nacional (Oaxaca, 2019), sin embargo, en 2018 registró una caída del 57% con respecto a su producción de 2010. Esto ha generado una disminución de los campesinos oaxaqueños que se dedican a su cultivo y que los municipios cafetaleros agudicen su condición de pobreza y abandono; no obstante, permanece como uno de los cuatro cultivos preferidos del estado (SAGARPA, 2017; Silva, 2015). Si bien los precios nacionales del café al cierre del ciclo agrícola en 2022-2023 mostraron una tendencia de crecimiento en el precio para el consumidor final, ni los caficultores ni la mano de obra ocupada en su producción reciben un pago justo. Por ejemplo, según datos publicados en Forbes en octubre de 2019, el precio por kilo de café mexicano fue de 37 pesos, equivalentes a 1,700 pesos por quintal. Ese precio debería aumentar en 50% para recuperar la inversión y en 100% para tener algún margen de utilidad (Castillo, 2019).

Según información de la Secretaría de Desarrollo Rural, se espera que en México haya un aumento en la demanda de café de 18% en 2030 con respecto a la producción de 2021 (Arguello Campos, 2022) lo que implica intensificar y expandir su producción. Sin embargo, el mayor factor de cambio de uso de suelo en las zonas cafetaleras con áreas naturales protegidas es la falta de rentabilidad (Arguello Campos, 2022), como en el caso de las cuencas Copalita-Huatulco. Esto se pudo observar en esta investigación, ya que desde la década de 1980 se inició un proceso de deterioro paulatino del SSEAG de café que, aunque ha logrado mantener su producción, esta es mucho menor que lo registrado en los años 70s cuando fue el auge cafetalero en la región de estudio. Con melancolía y nostalgia muchos de los entrevistados señalaron que a lo largo de 40 años no se volvieron a registrar las cosechas generosas que se conocieron en esos años. Asimismo, aunque han logrado adaptarse a los cambios en las condiciones climáticas, de mercado y en materia de políticas públicas, es claro que se requieren actividades económicas complementarias para sostener la producción del café. En aquellos casos de éxito donde sólo se cultiva café, los cafeticultores han implementado otras estrategias para incursionar en toda la cadena de valor para sostener la rentabilidad del café. También encontramos que han sido útiles otras estrategias como la formación de redes de colaboración entre actores en la cadena de valor y que estas logran proveer capacidades para adaptarse y ser resilientes.

Sin embargo, como ya se ha mencionado, los efectos a largo plazo de varias de las estrategias adoptadas para mantener la producción de café tienen efectos inciertos. Algunos ejemplos relevantes son la disminución de árboles de sombra en las plantaciones de café debido a requerimientos de cultivos comerciales o a la introducción de variedad robusta en sustitución de la variedad arábica (debido a que la variedad robusta tiene una mayor productividad, resistencia y rentabilidad). Otro ejemplo es la perturbación que podría generar el aumento de turistas en fincas cafetaleras que ya participan en proyectos de turismo rural y ecoturismo en la región. Asimismo, se desconoce si las redes actuales en el SSEAG serán eficientes para incrementar la producción y su rentabilidad en el futuro. Otros obstáculos relevantes que enfrentará la producción de café en el futuro, además de la volatilidad del precio, es la inversión que se requiere en activos para la productividad, la poca innovación y la falta de esquemas de gobernanza colaborativa entre actores en la cadena de valor.

En este contexto, se reitera que mantener las condiciones actuales para seguir produciendo café no es suficiente para la resiliencia y sustentabilidad futura del SSEAG. Para trazar una trayectoria sostenible de largo plazo, es importante mantener el cultivo de café de sombra, pero se necesita que esté vinculado a instrumentos de política pública innovadores u otras estrategias que sean capaces de: i) desalentar el cambio de uso de suelo; ii) aumentar la rentabilidad; iii) mejorar la provisión de servicios ecosistémicos; iv) proveer infraestructura e información para dar valor agregado al café cosechado; v) articular redes de colaboración entre cafeticultores y otros actores relevantes en la cadena de valor; y vi) ordenar el territorio de las cuencas Copalita-Huatulco para definir aquellas áreas propicias para hacer un reemplazo de variedades de café y donde se pueden introducir otros cultivos. En este sentido, hay que reconocer las capacidades de los cafeticultores que han sido líderes de opinión e innovación en la resiliencia del SSEAG y fortalecer sus habilidades para impulsar esquemas de gobernanza colaborativa de largo plazo. Es importante señalar que hay temas asociados a la equidad y justicia social pendientes de análisis que no fueron abordados, como el cambio generacional, el papel de la mujer, los niños y trabajadores migrantes en la cafeticultura, los salarios bajos entre los trabajadores agrícolas, entre otras. Finalmente, se debe reconocer que no se puede trazar una trayectoria sostenible sin la participación y opinión de los cafeticultores y demás actores involucrados.

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