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Impact of Productive Activities on Forest Cover Change in the Calakmul Biosphere Reserve Region: Evidence and Research Gaps

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Abstract

Background and Research Aims: Human activities seeking to satisfy various needs have resulted in deforestation and other forest cover change processes. The Natural Protected Areas are among the most efficient instruments to contain forest loss. The compensation from conservation is not sufficient to compete with land uses with higher economic rent, such as timber extraction and food production. This study summarizes the evidence and identifies research gaps on forest processes caused by productive activities in Mexico's Calakmul Biosphere Reserve.

Methods: We systematically reviewed the scientific literature investigating forest processes caused by the productive activities in the Calakmul, including the transition zone. We calculated the frequencies of codes on forest processes and productive activities in the entire sample (53), evaluated each code's significance in the qualitative synthesis and interpretation, and summarized the measurements of forest processes considering only the primary studies (46).

Results: Deforestation was the most commonly investigated process. Traditional agriculture initially caused deforestation, while livestock and conventional agriculture became more dominant recently with the agricultural intensification policies. Few articles investigated forest degradation experiencing a steady increase from fallow shortening and selective logging. Also, few studies identified forest recovery resulting from long fallows and core zone delimitation. No publications evaluated the forest cover impact of sustainable initiatives.

Conclusion: The tendency to quantify deforestation on a regional scale masks presence of other forest processes. The rural development programs in Calakmul did not include the environmental perspective, while participation in sustainable initiatives was low. The understanding of productive activities at the local level will allow differentiation of the long-term from temporary forest dynamic.

Implications for Conservation: To assure resilient and inclusive growth in Calakmul, the reduced-impact logging, sustainable agricultural intensification, improved fallows, and beekeeping should be supported with monetary resources that cover the transaction costs of unsustainable livestock breeding and industrial agriculture.

Keywords

land use, systematic review, sustainable rural development, REDD+, Campeche, Mexico

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Introduction

Throughout history, human activities seeking to satisfy various needs have resulted in deforestation and other forest cover change processes (Williams, 2006). A historically exceptional rapid and extensive forest clearing occurred between 1950 and 1980 (Ramankutty et al., 2010). In the 1990s, the annual rate of global deforestation started to slow down, from 7.84 million ha in 1990–2000 to 4.74 million ha in 2010–2020 (FAO, 2020a). Nevertheless, recent global estimates suggest that forest degradation (no change in land use) emits 40%–212% more carbon dioxide than deforestation (Baccini et al., 2017; Pearson et al., 2017). Currently, forest degradation is more widespread than deforestation in tropical regions (Trondoli et al., 2020) and contributes to one-fourth of the total forestry sector emissions (Griscom et al., 2009; Pearson et al., 2017).

Given the urgency to reach at least net-zero CO_2 emissions to limit the rapid and intense global climate change and its adverse effects, we must consider regional modulations for planning adaptation strategies (IPCC, 2021). As a response, 141 countries, including Mexico, signed the Declaration on Forest and Land Use in 2021 as the culmination of a chain of efforts from global environmental governance. This declaration urges humanity to limit climate change, achieve resilient and inclusive growth, and stop and reverse forest loss and land degradation through a sustainable land use transition (UNFCCC, 2002). This change may propel human activities that result in positive examples of forest cover change processes, such as forest succession and recovery (Keenan et al., 2015; Lambin & Meyfroidt, 2011).

In Mexico, the forest area decreased from 70 million ha in 1990 to 65 million ha in 2020 (FAO, 2020a). The direct cause of forest loss in 88% of cases was the expansion of both rainfed agriculture for subsistence and intensive commercial agriculture (GFW, 2020). Recent studies suggest that the annual net forest loss has decreased from −0.32% (1990–2000) to −0.19% (2010–2020) (FAO, 2020a). From 2001 to 2013, 392,920.49 ha of forest were lost in the state of Campeche to livestock breeding (59%) and mechanized agriculture (30%) for the most part, which represents an annual net deforestation rate of −0.39% (Ellis et al., 2015). However, the forest degradation rate has not been evaluated with precision yet, and the evaluations reported to the FAO range from 22,800 to 300,000 ha/year (2000–2015) (CONAFOR, 2020; Madrid, 2020). In Mexico, the land extension affected by forest degradation was more significant than the affected by deforestation in the last decades (CONAFOR, 2017a).

The establishment of Natural Protected Areas (NPAs) has been one of the most efficient instruments to reverse the forest loss and contain the advance of the agricultural frontiers (Humphreys, 2006). However, the pressure against protected forests remains strong because the economic compensation from forest conservation or sustainable productive initiatives is not sufficient to compete with land uses with higher economic rent, such as wood extraction, food, fodder, and biofuels production, and mining (Bezaury-Creel & Gutiérrez Carbonell, 2009; Fitzherbert et al., 2008; Ramírez et al., 2015). Therefore, we need to continue analyzing the productive activities, and their impacts on the forest cover change processes in the NPAs and promote local sustainable practices.

There are currently 183 federal NPAs in Mexico, including 42 with the category of Biosphere Reserve (BR) (CONANP, 2022), a model proposed by the United Nations Educational, Scientific, and Cultural Organization's Man and Biosphere Program (UNESCO MAB). BRs are natural areas of international importance due to their biological and cultural diversity and the potential to implement sustainable rural development initiatives within them (UNESCO, 2017). Each BR has three zones: core, buffer, and transition (Bridgewater, 2016; UNESCO, 1996). Core zones are dedicated to conservation, and only selected non-destructive and low-impact research and education activities are allowed. Buffer zones surround or adjoin the core areas. Their primary function is to host the development and exploration of cooperative and ecologically sound activities, such as ecotourism, recreation, and basic research. Finally, transition zones are spaces between the BRs and the surrounding areas where the local population may develop sustainable productive activities. The outer limits of the transition area are not legally determined. Still, they can be defined by natural phenomena (forest edges, rivers, lakes, etc.) or by human-made forms (roads, railroads, borders, etc.) (UNESCO, 2021). In the Mexican model of BR, the legally determined buffer zone includes the activities allowed in the transition zone (Halffter, 1984).

We selected the Calakmul Biosphere Reserve (CBR) as our study area, which is administratively located within the boundaries of the state of Campeche in the Yucatan Peninsula in southeastern Mexico. Since its establishment in 1989, the CBR has attracted many conservation and development projects and numerous research groups, resulting in multiple publications. However, only one review article has been published that analyzes primary research publications about deforestation caused in the last 50 years in the entire Yucatan Peninsula (Ellis, Hernandez Gomez, & Romero-Montero, 2017).

Therefore, a literature review is necessary given Mexico's adoption of the Reducing Emission from Deforestation and forest Degradation, plus promoting conservation, sustainable management of forests, and enhancement of forest carbon stocks (REDD+) (CONAFOR, 2017b). REDD+ is an international forest and climate change policy designed to financially reward reduction in land use based emissions through carbon markets or conventional financial aid (UNFCCC, 2010). Despite the critique of its technical complexity, economic inefficiency, and potential negative social and environmental impacts on local indigenous people (e.g., Bayrak & Marafa, 2016; Osborne et al., 2014), REDD+ is being implemented in many developing countries under different policy design.

REDD+ in Mexico is planned as a set of productive and conservation activities from forestry and agriculture to promote sustainable rural development. It implies the improvement of social welfare and economic activities while guaranteeing natural resources conservation within territorial units defined by environmental boundaries (e.g., hydrological basins, biological corridors) (CONAFOR, 2017b). Therefore, CBR, including its broader transition zone, was included as one of the priority areas for the early REDD+ activities (ATREDD+) (2010–2015) (CONAFOR, 2015).

To summarize the evidence of forest cover change processes caused by productive activities in the study area, clarify controversies, and identify learnings and research gaps, we systematically reviewed the existing publications (sensu Haddaway et al., 2015). We asked the following question: Which positive and negative forest cover change processes caused by productive activities have been identified, described, and evaluated in the Calakmul Biosphere Reserve and its transition zone?

Methods

Study area

The Calakmul Biosphere Reserve in the southeastern state of Campeche is the largest forested area in the Yucatan Peninsula (722,000 ha). CBR is part of the Maya Forest, that is the second-largest neotropical forest after Amazonia spanning southern Mexico, Belize, and Guatemala, and a biodiversity and deforestation hotspot. In addition, CBR is part of the Mesoamerican Biological Corridor, which is the largest bioregional conservation initiative in Central America (Eaton & Lawrence, 2009).

CBR's core and buffer zones are mainly located in the municipality of Calakmul. Its transition area spreads to the adjacent municipalities both in the states of Campeche and Quintana Roo. However, we focus only on the broader CBR area in Campeche, which includes the municipalities of Hopelchén, Escárcega, Candelaria, and Champotón (Figure 1). This is because different development, agricultural, and forestry policies are implemented at the state level in Mexico (CONAFOR, 2017a). In addition, the five selected municipalities have had the highest forest loss to agriculture in the state of Campeche from 2001 to 2013 (Ellis et al., 2015).

The dominant land tenure in the region is the *ejido*—a type of social land ownership unit gained in the 1910s Mexican Peasant Revolution when the nation granted customary rights to landless farmers to meet their subsistence needs (García-Barrios et al., 2009). Usually, one part of the *ejido* land is managed in common (mostly forests), while the rest is divided between the *ejido* members (*ejidatarios*) and is used for agriculture. In most cases, the *ejidatarios* have to work the parceled lands to keep their land rights, which they can transfer only to one of their descendants (Ley Agraria, 2018). The CBR core area is within the territories of *ejidos*; however, it is managed by the National Commission of Protected Areas

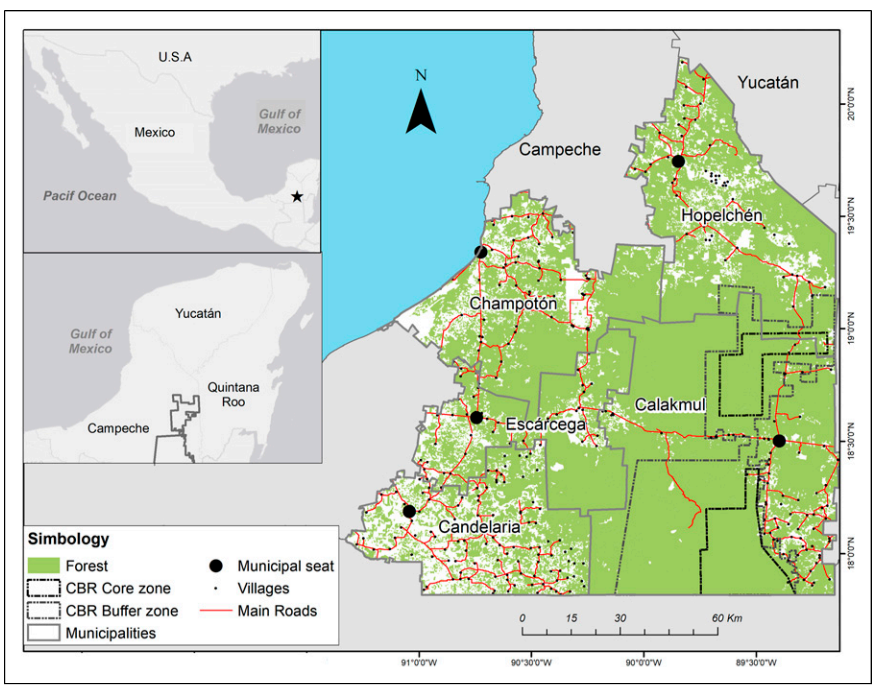

Figure 1. Study area: transition zone of the Calakmul Biosphere Reserve, including limits of the municipalities of Hopelchén, Escárcega, Candelaria, and Champotón neighboring the municipality of Calakmul where the core and buffer zone of CBR lay.

(CONANP). Some private lands are located predominantly in buffer and transition CBR zones (Klepeis, 2003).

The total study area, including the five selected municipalities, is 3,747,585 ha, and it is inhabited by 293,640 people, 70% of whom live in poverty (CONEVAL, 2020; INAFED, 2022; INEGI, 2020). The dominant ethnic groups in the study area are the Yucatec Maya, Chol, Tzeltal, Tzotzil, and Chontal indigenous people, along with the mestizo population (both indigenous and Spanish ancestry) that migrated to the study area from the Mexican states of Chiapas, Tabasco, Veracruz, Oaxaca, and Michoacan (Alonso Velasco, 2020). In addition, there are Mennonites (a religious group of industrial farmers of European descent) that immigrated to the study area from the states of Durango, Chihuahua, Zacatecas, and Tamaulipas (Ellis, Romero Montero, et al., 2017; Roy Chowdhury & Turner II, 2006; Porter-Bolland et al., 2007).

The climate is sub-humid warm tropical, with a mean annual temperature of 25°C and marked by dry and rainy seasons with hurricanes (Eaton & Lawrence, 2009; Porter-Bolland et al., 2007). The topography is karst with underground drainage and no superficial flows. The dominant soil type is rendzina, whose main characteristic is low fertility. Our study area hosts different tropical forests, including the low deciduous and sub-evergreen forest, the medium subdeciduous and sub-evergreen forest, the high sub-evergreen forest, and various associations of hydrophytes (Geoghegan et al., 2010).

The forest ecosystems are rich in precious timber and melliferous species that have historically favored beekeeping and forest management for timber production (Porter-Bolland et al., 2007). The landscape is composed of mature forests (*montañas*), secondary forests in different stages of succession (*acahuales*), and agricultural areas that include shifting agriculture, livestock, and mechanized agriculture (Krylov et al., 2018; Porter-Bolland et al., 2007). In addition, the numerous and well-preserved archeological sites with Mayan ruins host many cultural and ecotourism activities. In 2014, CBR became a Mixed World Heritage (UNESCO, 2014).

Articles selection

We consider local productive activities as those of the primary economic sector involved in the extraction and production of natural resources for subsistence or commercial purposes, such as agriculture, livestock breeding, beekeeping, and forestry (Pérez & Merino, 2016). Productive activities are the direct human causes of forest cover changes and their underlying factors. They act as demographic and economic stressors (e.g., globalization and market liberalization) and the accompanying mounting demand for food (crops and livestock) and energy (oil crops, fossil fuel extraction, and mining), and the resulting public policies (Lambin et al., 2003). Our review method follows systematic review principles, such as systematic searching, screening, and critical appraisal, which increase transparency, objectivity, replicability, and reliability (Haddaway et al., 2015, 2020).

First, we tested our review question by evaluating the presence of main PICo elements (P—Problem or Population affected; I—a phenomenon of Interest, Intervention, or exposure; and Co—Context, geographical, economic, political, or biological) (Haddaway et al., 2015). Our P stands for positive and negative impacts on forest cover (see Table 1 for a definition of each process). Our I represents productive activities from the primary economic sector that are supported by governmental, nongovernmental, or private actors (see Table 2 for a definition of each activity). Finally, our Co is CBR, our geographic study area. After assuring our question is researchable through a review, we wrote the review protocol and generated a search string.

The search string is composed of a combination of terms corresponding to each of the PICo elements and their synonyms: *(deforestation OR "forest degradation" OR "forest loss" OR "land$use change" OR "forest transition" OR "forest disturbance" OR "forest restoration" OR regrowth OR revegetation OR reforestation OR "forest recovery" OR "forest fragmentation" OR "forest succession") AND (activities OR agriculture OR livestock OR cattle OR harvesting OR logging OR management OR beekeeping OR apiculture OR pasture OR milpa OR agroforest* OR silvopastoral OR agrosilvopastoral OR orchard OR plantation OR cultivation) AND (Calakmul OR Campeche OR Yucatan).* We performed our search in English in April 2021 and found 190 (Web of Science-WoS) and 158 (Scopus) scientific publications. We translated the string into Spanish and used it in the Scielo academic database, finding 98 publications. We screened all search results to determine whether or not a publication was relevant to the review. At this point, we applied no time or document type restrictions. However, the selection of search databases limited our sample to academic publications, excluding gray literature, such as reports and thesis. In addition, we only considered documents in English and Spanish.

We then evaluated publications for inclusion at three successive levels. First, we assessed them by title. We selected 149 publications after checking their titles and excluding duplicates. Then, we evaluated the abstract of each publication that was potentially relevant based on the title. This procedure reduced the number to 74 publications that we analyzed in total. The final sample included only those studies that complied with the following three criteria: (1) they investigate variables for identification and/or quantification of forest cover change processes, such as land cover and change, carbon stocks, emissions, and biomass, (2) they do so concerning the activities of extraction and production of raw materials for subsistence or commercialization, and (3) they focus on the broad transition area of the CBR within the borders of the state of Campeche.

Relevant articles included qualitative and quantitative studies of forest conditions relating to productive activities

Table 1. Definition of forest cover change processes considered in the review.

Process	Definition	Example Quotes
Deforestation	It refers to the direct human-induced conversion of forests to non-forested land for agricultural, mining, infrastructure, or urban development purposes, among others; as well as the long-term reduction of forest cover due to legal and illegal clear-cut logging for timber (FAO, 2007; Hosonuma et al., 2012; Laurance, 2015)	"By 2000 the net increase in open lands within the core, buffer, and non-reserve areas was 0.04%, 0.12%, and 0.49%, respectively (Table 2), recalling that deforestation began previous to 1987/88" (Vester et al., 2007, p. 993)
Forest degradation	It implies some degree of forest disturbance without a change in land use. It occurs through poorly regulated or managed extractive activities carried out at a small scale by many actors giving way to selective and excessive logging, shifting cultivation, over-collection of fuelwood and non-timber forest products, overgrazing of understory by livestock, and uncontrolled forest fires (Hosonuma et al., 2012; Skutsch et al., 2009). Forest degradation may or may not lead to deforestation of the same area (Angelsen, 2008)	"However, after the strike of the hurricane winds, these areas may be more degraded in case of forest fires, because they are fire-sensitive ecosystems" (Rodríguez-Trejo et al., 2011, p. 606)
Forest fragmentation	It is a type of forest degradation where interrelated forest cover change processes have formed an intricate mosaic of small patches of forest, degraded soils, and non-forests land uses (Arroyo-Rodríguez & Dias, 2010). It occurs, for example, when deforestation results in the degradation of the neighboring areas receiving more considerable pressure as remaining standing forests or when illegal logging makes way for intensive agriculture (Morales-Barquero et al., 2014); or even when authorized logging is carried out inadequately (Navarrete et al., 2011)	"The number of low biomass outliers are an indication of the level of forest fragmentation in high biomass areas" (de Jong, 2013, p. 614)
Forest recovery	It represents a net increase in tree cover or tree density through natural successional processes on abandoned lands (i.e., passive recovery without human intervention) or through deliberative tree establishing activities through planting, seeding, or the human-induced promotion of natural seed sources (i.e., active recovery or restoration or reforestation) (Honey-Roses et al., 2018; Keenan et al., 2015; Lambin & Meyfroidt, 2011)	"The current fallow period in the Yucatán is often less than 12 years (Turner et al., 2001), half the time needed to recover 90% of mature forest levels" (Eaton & Lawrence, 2009, p. 956)
Conservation	In this case refers to the permanence of forest quantity and quality, that is, undisturbed forest continues to be present on the same land area (Humphreys, 2006). Besides its interpretation as no land-cover change, it includes the areas designated and managed for biodiversity conservation within the protected area (FAO, 2020b)	"Interestingly, parcels belonging to households that have registered larger areas under NGO or state-subsidized green projects such as agroforestry/reforestation or agricultural sedentarization involving green fertilizers (the RPS program) were more likely to undergo deforestation over 1987–1996. Most individuals that captured such opportunities for state/NGO assistance tended to also be longer-established ejidatarios that greater proportions of their parcels deforested during the time period modeled, but the tenancy variables control for such factors, throwing into question the utility of 'green' projects for forest preservation on land parcels" (Roy Chowdhury, 2006, p. 145)
Forest transition	It represents forest recovery at larger geographical scales (state, country, or region), being the result of a phenomenon of long-term changes from net deforestation to net forest increase related to overarching socio-economic trends (economic development, industrialization, and urbanization) (Mather & Needle, 1998; Rudel et al., 2005)	"It is too early, however, to declare a forest transition as more than incipient or emerging for at least two reasons: (1) the variance in forest recovery by ejido and (2) the investment of remittances in pasture" (Schmook & Radel, 2008, p. 905)

Table 2. Definition of selected productive activities present in our study area.

Activity	Definition	Example Quotes
Traditional agriculture	Agricultural production using a traditional system, for example, slash and burn, *milpa* (intercropping of maize—*Zea mays* L., beans—*Phaesolus vulgaris* L., and squash—*Cucurbitace*), with or without agroecological principles (Moreno-Calles et al., 2016). It also includes shifting or rotational agriculture when a forest is cyclically cut and burned to be cultivated for 2–4 years, followed by 10–15 years long fallow. In this case, it also includes nontraditional systems without irrigation (rainfed) or use of farm machinery (only manual or animal power) (Ellis, Navarro Martínez, et al., 2020), called short-term agriculture, as it is likely to revert to a forest in the near future (Keys, 2005)	"Households with more male labour also had a higher proportion of their holdings in crop and less in fallow" (Abizaid and Coomes, 2004, p. 79)
Conventional agriculture	Agricultural production that includes either the use of farm mechanization for agricultural intensification (e.g., tractors, irrigation), and/or application of agrochemicals, and/or the establishment of monoculture of hybrid and genetically modified varieties of commercial crops (Otero, 2014). It is also called long-term agriculture and represents more permanent changes that are unlikely to revert to a forest in the near future (Keys, 2010)	"Mechanized agriculture for producing maize, soy and sorghum for commercial markets are characteristic mostly in the north and central parts of the municipality (mostly under Mennonite cultivation)" (Ellis et al., 2017a, 2017b, p. 476)
Big livestock breeding	Conventional cattle production systems that include clearing forests to induce pasture in large areas using or not agrochemicals (Thornton, 2010)	"Investigating land subject to individual household agricultural use, we find that pasture creation for cattle ranching acted as the main driver of deforestation in the 1997–2003 time period when deforestation is defined as land under agricultural use whether clearance of primary or secondary forest was cleared" (Busch & Geoghegan, 2010, p. 191)
Small livestock breeding	Conventional sheep, goats, pigs, and poultry production systems, such as commercial farms sometimes landless (most of the feed coming from outside of the farm) where animals are raised in a limited land area or in an air/temperature-controlled environment (Salaheen & Biswas, 2019); also, traditional sheep, goats, pigs and poultry production systems, such as pastoralism	"Another couple also plans to invest in land improvement for agriculture: "We want to put in grass and sheep with the little money we will have…" (Radel & Schmook, 2008, p. 72)
Traditional beekeeping	Traditional intensive management of native bee species of the subfamily *Meliponinae*, particularly a stingless bee *Melipona beecheii* Bennette (Porter Bolland, 2003)	"Several projects were promoted, such as beekeeping with honey bees of the genus *Apis* that was adopted in the early 1970s by traditional Melipona (stingless bee) honey producers" (translated from Spanish) (Porter-Bolland et al., 2008, p. 73)
Commercial beekeeping	Honey production with Africanized varieties of honeybees (*Apis melifera* L.) predominantly for commercialization (Porter Bolland, 2003)	"Many of the farmers that were interviewed engaged in apiculture, and maintained apiaries near or in successional forests, because several of the flowering trees that are found in such sites are valued for the quality and profusion of their pollen" (Chowdhury, 2007, p. 13)
Forest harvesting	Extraction of timber or non-timber products from a forest. When organized, it is done according to an authorized forest management plan (10–20 years) that includes annual extraction from delimited cutting areas of timber whose volumes and species composition were previously assessed (Ellis et al., 2019)	"These differences could be due in part to the type of machinery used and the way the skid trails are opened. In Caobas, logs are mainly skidded with a modified agricultural tractor (Table 1), necessitating the manual cutting of only smaller trees to cut a path that allow the tractor to skid logs. Smaller width and weight of the modified tractor notably causes less forest biomass impacts than a conventional skidder (locally known as Tree Farmer) which was used by 20 de Noviembre for all skidding operations" (Armenta-Montero et al., 2020, p. 9)

(continued)

Table 2. (continued)

Activity	Definition	Example Quotes
Productive reforestation	Planting high-value trees in the fallow or other degraded or abandoned areas for its harvesting (e.g., fruits, timber), such as *acahuales* management, an enriched or improved management of secondary forest that is part of *milpa* cycle (also type of agroforestry) (Soto Pinto et al., 2011)	"Many of the trees from early projects are now generating a financial return to select households, particularly the fruit trees. In the case of the hardwoods (primarily cedar and mahogany), tree maturity is eagerly awaited by households, as a mature mahogany, for example, can bring up to 5000 Mexican pesos (US$500)" (Radel & Schmook, 2008, p. 72)
Agricultural/livestock-forestry systems	*Agroforestry* (AF) includes both traditional and innovative productive systems in which trees and crops coexist (FAO, 2017), for example, traditional Maya home gardens (*solares* y *parcelas*), predominantly for subsistence. Still, sometimes fruit, timber, or other products are commercialized on a small scale. Although agroforestry systems can be created following agroecological principles, this is not the only way to do so (Moreno-Calles et al., 2016)	"Aside from planted tree species such as cedar, mahogany, allspice and fruit trees, farmers often preferentially maintain other naturally occurring trees species for their economic value. These include palms, naturally occurring allspice (*pimienta*), chicozapote (*Manilkara zapota*), and other tree species that provide material for thatching, lesser-known timber species or nontimber forest products" (Chowdhury, 2007, p. 12–13)
	Silvopastoral (SSP) includes traditional and innovative productive systems in which the forestry component is combined with animal beading (Chará et al., 2020), with or without agroecological principles	"Ramón Corona in Campeche state is among the few communities that have collectively implemented and participated in pilot silvopastoral and conservation agriculture projects, demonstrating REDD+ success in a high deforestation municipality" (Ellis et al., 2020a, 2020b, p. 22)
	Agrosilvopastoril (AFSP) includes traditional and innovative systems in which crops, trees, and animals interact under productive logic (Choocharoen et al., 2014), with or without agroecological principles	"Among the direct causes of deforestation are the natural resources practices that imply a change from the forest land use to agricultural uses, with the exception of agrosilvopastoril systems" (translated from Spanish) (Porter-Bolland et al., 2008, p. 66)

considered as causes of positive or negative changes. They provided original data or referred to other studies containing supplementary information. The studies citing other primary field studies helped to check the comprehensiveness of our sample. Due to the focus on forest cover change as a proxy measure of carbon emissions from the forestry sector, we did not take into account ecological studies evaluating the impact of productive activities on other ecosystem services, such as forest structure and composition, invasive species, biodiversity, nutrients, or biomass in soil, microclimate and water flow regulation. Furthermore, we did not consider the environmental history studies that investigated periods before the 20th century or those evaluating the governance of CBR.

On the other hand, we included all the studies that investigate our study area even when performed at a different scale of analysis, for example, studies comparing CBR and other national or international case studies. We discarded 21 publications during the full-text revision phase (see Appendix 1). Our final sample counts 53 publications, including 51 journal articles and two book chapters. These were written by 31 different first authors and published in 33 journals and one book (see Appendix 2 for the final sample metadata).

Data analysis

We used a coding technique in MaxQDA software to organize and extract data. We assigned the predetermined codes based on the review question elements to specific units of analysis (paragraphs, sentences, or words) (Saldana, 2015). We organized our list of codes in two general categories: (1) forest cover change process (listed in Table 1), including terms, definitions, and numerical or qualitative measurements; (2) productive activities (listed in Table 2), including socio-economic, ecological, cultural or political reasons to adopt/increase or quit/decrease them, as well as related practices (specific actions used by local actors in the production process, e.g., fallowing) and policies (programs, projects, and initiatives promoted by government or other actors). Both practices and policies were coded as positive or negative depending on how the authors identified them: either as avoiding/decreasing or causing/increasing deforestation and/or forest degradation.

The coding technique organized the data and allowed its interpretation. An important step in the qualitative content analysis was calculating the code frequencies to identify their prevalence. Additionally, we evaluated the significance of each code in the qualitative interpretation analysis, which allowed us to ponder, organize, connect, and synthesize the results from different studies (Saldana, 2015). We calculated the relative frequency distribution of assigned codes to evaluate their relative representation in the entire sample. Finally, we calculated the frequency of study focus and performed qualitative synthesis and interpretation, focusing only on the primary studies (46) (Grant & Booth, 2009) (primary and secondary studies are marked with * and ** in the References list, respectively).

We used the segments containing numerical data about measurements of forest cover processes from primary studies to construct a summary table (Appendix 3). The studies using quantitative criteria and indicators to measure the forest processes did so at different geographical and temporal scales, which does not allow for generalization or calculation of the rates for the entire study area. However, we observed some general trends in forest cover change processes attributable to each productive activity from the results of primary studies.

We grouped and extracted segments containing textual data assigned with the same code in specific documents that we used to construct the narrative synthesis (Grant & Booth, 2009). We organized the synthesis around the productive activities and policies and grouped them based on their impact on forest cover (deforestation, forest degradation, forest recovery and transition, and forest conservation). We critically appraised the methodological rigor of each primary research article during the information interpretation process.

Results

Relative frequency distribution of codes

The code frequency (78%) shows that data concerning negative forest cover change processes were dominant in our sample (Figure 2). When looked at separately, the most frequently mentioned negative changes were deforestation (45%) and forest loss (10%), both of which represent the same process. Although forest degradation is the third most frequently mentioned process, it has only 6% of the codes assigned. The reason may be that degradation is more difficult to observe and measure than deforestation. Conversely, the information on positive processes was less frequent (only 22% of the assigned codes), which indicates their occurrence in the region. The most frequently mentioned positive changes were forest succession and recovery, which represent the same process related to traditional fallowing, agricultural abandonment, and productive reconversion to agroforestry.

Analyzing the frequency of codes assigned to practices associated with each activity, traditional agriculture, big livestock breeding, and forest harvesting (51%, 24.5%, and 10%, respectively) were associated with negative forest cover changes. However, forest harvesting was also the most frequently related to positive forest cover changes (53%). Forest harvesting does not include the total removal of the forest or the land-use change, and forest authorities regulate it. In addition, public policies implemented in the study area caused adverse effects on traditional agriculture and big livestock. However, some public policies promoting traditional agriculture, agroforestry, and beekeeping were factors of positive changes in forest cover also (Figure 3). The following section will discuss in further detail the relation between productive practices and policies and forest cover change processes.

Frequency of primary study focus

Among the studies with primary data (46), deforestation was the most investigated process (11), with commercial agriculture and cattle ranching as their primary concern (Table 3 and Appendix 4). Deforestation was referred to with various terms, including forest loss, clearance, conversion, and land-use change. Only five articles

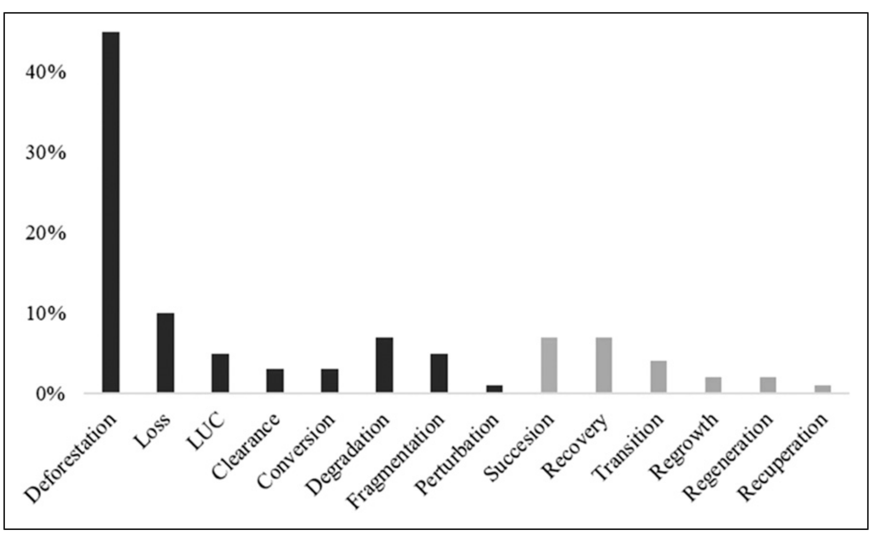

Figure 2. Frequency of codes on positive (dark gray) and negative (light grey) forest cover change processes.

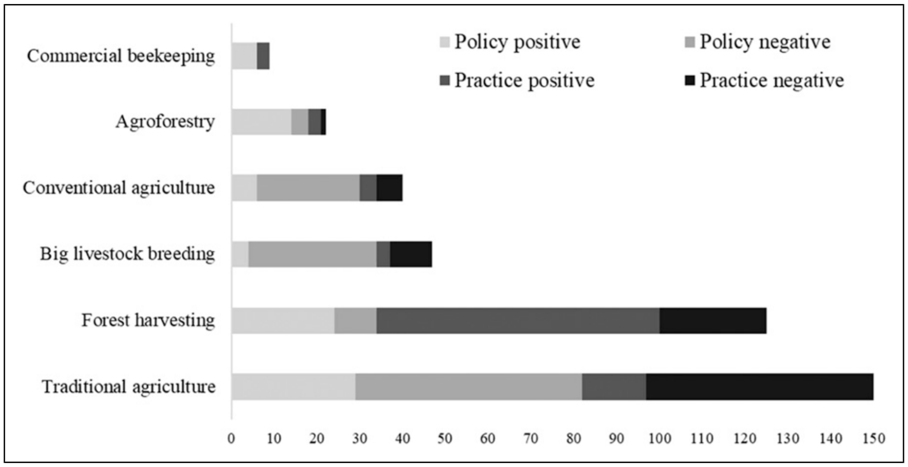

Figure 3. Frequency of codes on positive and negative practices and policies concerning productive activities.

Table 3. Number of primary studies investigating negative and positive forest cover change processes in relation to productive activities (the intensity of gray shades corresponds to the number of articles).

Process	Negative—Forest cover/quality loss			Positive—Forest cover/quality gain or maintenance				
Activity	Deforestation	Degradation	All negative	Recovery	Conservation	Transition	All negative and positive	Total activity
Traditional agriculture	1	1	0	3	0	0	1	**6**
Conventional agriculture	1	0	0	0	0	0	0	**1**
Big livestock breeding	2	0	0	0	0	0	0	**2**
Small livestock breeding	0	0	0	0	0	0	0	**0**
Traditional beekeeping	0	0	0	0	0	0	0	**0**
Commercial beekeeping	0	0	0	0	0	0	0	**0**
Agricultural/livestock-forestry systems	0	0	0	0	0	0	1	**1**
Productive reforestation	0	0	0	0	0	0	0	**0**
Forest harvesting	0	2	1	0	0	0	0	**3**
Agriculture and big livestock	3	2	3	1	0	1	4	**14**
All	4	0	6	1	1	1	6	**19**
Total process	**11**	**5**	**10**	**5**	**1**	**2**	**12**	**46**

investigated forest degradation caused by shifting cultivation and forest harvesting in CBR. As for the positive forest cover change processes, most articles (5) investigated passive forest recovery, including forest succession and regeneration. An important number of investigations (12) focused on several negative and positive processes associated with a selected group of productive activities presented in the area.

A narrative synthesis of qualitative data

Negative forest cover change processes. Most primary studies in our sample investigated individual negative forest cover change processes concerning productive activities (26), while an additional twelve did so by grouping them with positive processes.

Deforestation. Although traditional agriculture establishment was the main deforestation driver in the first period, big livestock breeding and conventional agriculture were the leading causes of deforestation within the study area in the more recent periods (Table 4).

The process of pasture expansion starts with forest clearance; it is then followed by land use for traditional agriculture for a few years to finally end with seeding pasture (Porter-Bolland et al., 2008; Busch & Geoghegan, 2010).

Table 4. Primary studies' results on land-cover and land-use changes recognized as deforestation resulting from the establishment and expansion of productive activities (e.g., pasture, traditional crops, commercial crops, bare land).

Period	Study area[1]	Percentage of land Area	Change rate	References
Traditional agriculture				
1969–1987	SY	/	+471%	Turner et al., 2001
1987–1997		/	+33%	
1995–1996	CBR	3.22%	/	García Gil et al., 2001
1978–2000	CBR	/	+6%	Díaz-Gallegos et al., 2008
2000	SY	14%	/	Geoghegan et al., 2010
1997–2003	SY	/	−1.60%	Busch & Geoghegan, 2010
2000–2012	Campeche	/	+30%	Krylov et al., 2018
Big livestock				
1978–2000	CBR	/	+7%	Díaz-Gallegos et al., 2008
1995–1996	CBR	0.25%	/	García Gil et al., 2001
1997–2003	SY	/	+4%	Busch & Geoghegan, 2010
2000–2012	Campeche	36%	/	Krylov et al., 2018
Big livestock and agriculture				
1969–1987	SY	/	+71%	Turner et al., 2001
1987–1997		/	+19%	
1987–1996	SY	/	+2.34%/yr (sec. For.)	Roy Chowdhury, 2006
		/	+0.36%/yr (mature for.)	
1995–1996	CBR	3.51%	/	García Gil et al., 2001
2000	SY	5.8%	/	Geoghegan et al., 2010
Conventional agriculture				
1997–2003	SY	/	−0.07%	Busch & Geoghegan, 2010
1986–2015	Hopelchén	/	+2.1%/yr	Ellis, Romero Montero, et al., 2017
2005–2015		/	+3.1%/yr	
Agriculture				
1987	SY	2.7%	/	Roy Chowdhury, 2006
1992		4.1%	/	
1996		3.4%	/	
2000–2012	Campeche	8%	/	Krylov et al., 2018
2005	La Montaña	4%	/	Porter-Bolland et al., 2007
All activities				
1978–2000	CBR	/	+0.6%/yr	Díaz-Gallegos et al., 2008
1987–1994	SY	/	+0.4%/yr	Vester et al., 2007
1987–1997	Calakmul	19%	+2.6%/yr	Reyes-Hernández, 2003
1987–2000	SY	2.36%	+0.34%	Vester et al., 2007
1988–2000	La Montaña	6.2%	/	Porter-Bolland et al., 2007
2000–2005		7%	/	
1988–2000	La Montaña	/	+0.3%/yr	Ellis & Porter-Bolland, 2008
2000–2005		/	+0.7%/yr	
1990–2006	SY	/	+0.12%/yr	Ramírez-Delgado et al., 2014
1990–2000		/	+0.15%/yr	
2000–2006		/	+0.06%/yr	
2002–2011	Campeche	/	+1.42%	Porter-Bolland et al., 2015

[1]Study areas names and land extensions: SY (South Yucatán region) = 2,200,000 ha; Campeche (state) = 5,792,400 ha; Calakmul (municipality) = 1,383,900 ha; Hopelchén (municipality) = 746,000 ha; CBR (Calakmul Biosphere Reserve) = 722,000 ha; La Montaña (region in Hopelchén) = 473,336 ha.

Since pasture is its final use, even those areas considered unsuitable for *milpa*, such as lowland flooded forests, have now been deforested (Porter-Bolland et al., 2008). The *milpa* and the areas under irrigated agriculture were transformed into the pasture, for example, rice fields supported by governmental agricultural mechanization programs in the 1970s were abandoned in the 1980s due to weed invasion, disease, and inadequate water control (Porter-Bolland et al., 2008). Pastures have experienced a steady increase since they were introduced through governmental policies, despite the limitations such as soil type, water scarcity, and distance to market centers (Busch & Vance, 2011).

Livestock development in the area does not follow an idealized, long-term development logic of a yearly increase in pasture areas and cattle. Due to the cash and labor constraints, farmers build pasture and ranching infrastructure (e.g., fences, artificial ponds) over several years, often without owning livestock (Busch & Vance, 2011). In addition, the fact that producers sell cattle does not necessarily mean that their farms have reached a minimum level of operational development but may only indicate that they need emergency money. The studies concur that raising cattle also fulfills a security function as a wealth accumulation and savings strategy (Busch & Geoghegan, 2010; Schmook & Vance, 2009).

Despite these shortcomings and barriers, and the fact that pasture brings a relatively modest return to the household economy, extensive livestock farming provides the highest profit per day of labor invested, and it is considered an economically beneficial alternative by small producers (Busch & Geoghegan, 2010; Busch & Vance, 2011). Pasture maintenance requires less labor (in smaller areas), and it is less vulnerable to soil infertility and climate extremes than maize and jalapeño chili peppers. In other words, cattle are more likely to survive hurricanes and, unlike irrigating crops, can be brought water in case of droughts (Busch & Geoghegan, 2010; Busch & Vance, 2011). Another reason for pasture increase may be that it maintenance is considered a relatively cheap way to keep the land under production as required by agricultural programs (Schmook & Vance, 2009).

Pasture can be grown almost permanently if properly maintained and under a moderate stocking rate. However, bracken fern (*Pteridium aquilinum*) invaded large sites of former pastures in the Calakmul municipality (Roy Chowdhury, 2006; Reyes-Hernández et al., 2003; Schmook & Radel, 2008; Schmook et al., 2011; Turner et al., 2001; Vester et al., 2007). This process proves the potential reversibility of pasture thanks to its abandonment or improper management in some cases. Additionally, given that it was not economically viable for local farmers to reestablish pasture in areas invaded by bracken fern, new forest areas were open for livestock production, contributing to the overall deforestation of the area (Busch & Geoghegan, 2010; Turner et al., 2016).

Owning pasture for renting or animal production and sale increased the farmers' economic capacity to open additional forest areas for agricultural use. Furthermore, cattle ranching freed up labor for other income-generating activities, such as migration. In turn, the remittances allowed for the enlargement of pasture areas despite the outflow of people, following a *hollow frontier* pathway (Busch & Vance, 2011; Radel, Schmook, & Chowdhury, 2010). Market closeness, larger land area, higher average rainfall, government subsidies, farmer's education level, and greater wealth increased pasture adoption. Greater wealth is related to the sum of years that the household had grown jalapeño chili peppers (*Capsicum annuum* L.) and to the migration status of the male household head (Busch & Geoghegan, 2010; Roy Chowdhury et al., 2006; Radel, Schmook, & McCandless, 2010).

Chili producers earned more money than most other farmers, allowing them to use more land (Busch & Vance, 2011). According to Keys (2010), chili was the most crucial income generator for the majority (85%) of the region's farmers in 2000. Chili holds second place after the *milpa* in the area devoted to it. Chili production in the southern CBR (municipality of Calakmul) takes two forms—swidden (70% of farmers), which is similar to the *milpa* cycle, and mechanized (30%). Mechanized plots are less likely to be converted back into the forests. Those farmers with mechanized land tend to cultivate more land, while those without it expressed a desire to mechanize their land. However, chili production demands a large amount of labor and external inputs of agrochemicals (both fertilizers and pesticides). This crop requirement is why farmers cleared primary, old-growth forests with high soil nutrient content to cultivate jalapeño chili. Chili was, therefore, a significant deforestation factor mainly in the first period of its establishment (1987–1992). However, in the subsequent period (1992–1997), chili production did not significantly impact deforestation, probably because the *ejidos* with the largest deforested area had to direct their efforts toward their mechanization to produce enough to pay back government credits (Reyes-Hernández et al., 2003).

In Hopelchén in the 1980s, the government-supported mechanized agriculture for commercial crops (maize, soy, and sorghum) was performed mainly by the experienced Mennonites migrants. They were expected to teach modern agriculture to Maya communities. *Ejidos* progressively adopted agricultural mechanization and currently either cultivate their land or rent it to Mennonites (Ellis, Romero Montero, et al., 2017). This replacement of traditional *milpa* with permanent mechanized plots contributed to the deforestation in the municipality (1986–2015). In addition, contamination from agrochemicals and pollen of genetically modified crops used in mechanized commercial agriculture has negatively affected local honey production.

Forest degradation. The shifting cultivation, agricultural use of fire, and selective logging were the productive activities that caused forest degradation and whose impact has steadily increased over the investigated period (see Table 5).

The shifting cultivation cycle typically involves a few years of clear-cut and burned forest land use followed by fallow periods characterized by natural regeneration of the secondary forest. However, currently, the shifting cultivation cycle in the Yucatan Peninsula includes shorter fallow periods (6–11 years), which prevents full recovery of aboveground and soil carbon stocks (less than 66% of mature forest stocks) (Eaton & Lawrence, 2009). Shorter fallows keep the biological wealth of forest permanently diminished, including

Table 5. Primary studies' results on land-cover and land-use changes recognized as forest degradation resulting from the maintenance of productive activities (e.g., secondary forest, secondary growth, burnt areas, bracken fern).

Period	Study area	Percentage of land area	Change rate	References
Agriculture and big livestock				
1987–2000	SY	9.62%	+2.42%	Vester et al., 2007
2000–2012	Campeche	/	+23%	Krylov et al., 2018
2005–2010	Campeche	63%	+2%	Mascorro, Coops, Kurz, & Olguín, 2016
All activities				
1987	SY	4.9%	/	Roy Chowdhury, 2006
1992		4.5%	/	
1996		7.4%	/	
2000	SY	14%	/	Geoghegan et al., 2010
2005	La Montaña	10%	/	Porter-Bolland et al., 2007
Forest harvesting				
2000–2012	Campeche		+>1%	Krylov et al., 2018

the propagation of invasive species, such as sunflower goldeneye (*Viguiera dentata*), locally known as *tajonal* (Keys, 2010). However, the mean combined carbon stock tends to be larger in young and old secondary forests (only 22% of the old forest stocks), while it is the lowest in middle-aged secondary forests. This difference in carbon stock is because of the decline of soil organic carbon during the first 5–10 years of regrowth, followed by an increase (Eaton & Lawrence, 2009). However, those *ejidatarios* who practice longer fallow hold more agricultural areas, supplying resting sites by opening new ones each year.

Besides forest age, the number of cultivation-fallow cycles negatively affected the aboveground biomass carbon stocks, experiencing a decrease of approximately 64% from one to four cycles (Eaton & Lawrence, 2009). Each cultivation cycle begins with cutting and burning secondary forests to remove residual biomass and enrich the soil. Therefore, it is not surprising that the most significant number of fire hot spots occurred in secondary fallow forests, followed by pasture, and *milpas*, where farmers deliberately initiate fires that sometimes last several days (Cheng et al., 2013). The fire danger index was "medium-low" to "high" for most of our study area. Although a more extended perimeter of agricultural areas increases fire risk in the neighboring fire-sensitive medium tropical forests, the hurricanes reach them with reduced strength, resulting in fewer forest fuels (Rodríguez-Trejo et al., 2011). However, fallen dead trees can be a source of local income through charcoal production, a fire prevention measure (Schramski & Keys, 2013).

The precious wood species, in particular mahogany (*Swietenia macrophyla* King) and cedar (*Cedrela odorata* L.) (Klepeis, 2003), were depleted in the extractive forest concessions during the first half of the 20th century. As a result, some authors no longer considered timber harvesting a primary livelihood strategy. Most forest *ejidos* in the study areas hold government permits to harvest timber of lesser-known species such as chacáh (*Bursera simaruba* (L.) Sarg.) and granadillo (*Platymiscum yucatanum*) (Porter-Bolland et al., 2007). Selective logging, or the removal of commercially valuable trees, is a dominant timber harvesting practice in the Yucatan Peninsula. However, some carbon emissions (37%) originate from felling, skidding, and construction of log landings and logging roads (Ellis et al., 2019).

Although the impact of selective logging on carbon emission rates in the investigated area is low compared to other regions of the world, implementing reduced-impact logging (RIL) practices could still reduce it even further. These practices include directional felling, planning of logging and skid trails, mapping and marking of harvested trees, pre-cutting of lianas and vines, and the use of modified tree farmer tractors. However, even when the investigated *ejidos* in our study area had low logging intensity, they did not implement the RIL practices and, therefore, had high carbon impacts. Only one *ejido* implemented the RIL practices as part of the Forest Stewardship Council (FSC) forest certification process (Ellis et al., 2019). Although several actors promoted certification, including the Rainforest Alliance, CONAFOR, The Nature Conservancy (TNC), and United Nations Development Program (UNDP), only those *ejidos* with larger harvest volumes and better-managed operations could afford it. Community Forestry Management (CFM) helps overcome the lack of direct access to timber and non-timber forest products' market, local and inter-*ejido* conflicts, and the need to carry out logging activities without a formal management plan (Armenta-Montero et al., 2020). However, there is a lack of government support for CFM. In other words, since 2010, REDD+ has been a central forest policy in Mexico, and it focuses principally on payment for ecosystem services.

Positive forest cover change processes

Eight primary studies in our sample investigate positive forest cover change processes concerning productive activities,

Table 6. Primary studies' results on land-cover and land-use changes recognized as forest succession and recovery (e.g., regrowth, older secondary forest, increase of mature forest) resulting from the abandonment of productive activities.

Period	Study area	Percentage of land area	Change rate	References
All activities				
1988–2000	La Montaña	2.6%	/	Porter-Bolland et al., 2007; Ellis & Porter-Bolland, 2008
2000–2005		3.9%	/	
1987–1992	SY	47%	/	Roy Chowdhury, 2006
1992–1996		41%	/	
1987–1996		/	+9.93%	
1994–2000	SY	/	+0.1%/yr	Vester et al., 2007

while only four measured related land-cover and land-use changes (Table 6). Many others only mention the need to promote these activities in the region.

Forest recovery and transition. Shifting cultivation can be considered a biodiversity-friendly agricultural system, but only if long fallows come after short cultivation periods to allow secondary forest regeneration from accumulated tree seeds. Secondary forests are important carbon stocks, and trees in the early stages of succession capture and store a significant amount of carbon. The secondary succession of tropical forests varies depending on the biophysical conditions and the disturbance that initially caused the forest loss. In our study area, it takes between 12 and 25 years after the abandonment of agriculture to recover half of the biomass of mature forests and 35 years to recover nearly 85% of the basal area of mature forests (Read & Lawrence, 2003). According to Turner et al. (2001), a forest takes between 25 and 30 years to reach its maturity again. Fully recovering carbon stocks takes approximately 85 years, while regaining biomass levels before first cultivation would take more than 125 years (Aryal et al., 2014). However, shorter or interrupted traditional agriculture cycles do not allow forest carbon stocks to recover completely. Furthermore, while some areas are cleared for pastures and agriculture, others are left or abandoned, allowing secondary succession. Some studies suggest that the southern part of the study area (in the municipality of Calakmul) shows the characteristics of an initial stage of forest transition because the recovery of secondary forest from cropland occurred in large areas (Busch & Geoghegan, 2010; Roy Chowdhury, 2010; Schmook & Radel, 2008). These studies assume that increasing revenues from commercial crops and cattle ranching provoked the outflow of people through international work migration.

Forest conservation. CFM, Mayan Community Forest Reserves, beekeeping, and agroforestry systems are productive activities that propitiate the conservation of forests (Casey & Caviglia, 2000; Levy-Tacher et al., 2019; Porter-Bolland et al., 2015). Timber harvesting with CFM, including local norms and traditional practice, preserved 80% of forest cover in an ecological state similar to an unmanaged forest and reported more tree species (Levy-Tacher et al., 2019). CFM also ensured the connectivity of the forest landscape. During the first half of the 20th century, the extraction of chewing gum resin from chicle trees (*Manilkara zapota* L.), a non-timber forest product, was an economically significant activity that favored forest conservation in the study area (Abizaid & Coomes, 2004). Mayan Community Forest Reserves provide firewood, fruits, and construction material to local people and nectar to the bees; they also regulate microclimates and protect from fire and hurricanes (Levy-Tacher et al., 2019).

Beekeeping with honeybees of the genus Apis was adopted in the 1970s by traditional Maya beekeepers and is another low-intensity productive activity (Porter-Bolland et al., 2008; Rodríguez-Solorzano, 2014). As a result, government and non-governmental organizations (NGOs) promoted apiculture, which currently represents one of the primary sources of income for communities, including honey exportation. In addition, agroforestry systems in the study area that are part of the Maya tradition combine fruit, forage, and medicinal plants and trees and have received strong support from NGOs (Casey & Caviglia, 2000).

Policies and actors

The spatial and temporal forests cover dynamic responds to the social processes and public policy presented in the study area. However, only a few primary studies measure the impacts of policies and actors on forest cover change processes. In contrast, many others only recognized policies and actors as important factors that promoted particular land uses in the region (Table 7).

Agriculture programs. With chicle extraction being no longer profitable after World War II and the rapid exploitation of marketable precious wood species in the 1980s that led to the decline in forestry activity, the Mexican government moved rapidly to target the region for agricultural development (Klepeis, 2003). Since the 1970s, the deforestation of the primary forest has occurred under state-promoted policies (see Table 4). These included colonization policies (construction of highway, the extension of *ejido* land grants, and the sale of state-owned land to Mennonites) and commercial agriculture and

Table 7. Productive activities, their impacts on forests, promoting actors and policies, and reversibility measures suggested in the reviewed articles.

Practice	Land-use/Land cover change processes and associated impacts	Actors	Policies (+/− impact on forests)	Reversibility measures	Source[1]
		Big livestock			
-Pasture establishment -Pasture expansion	*Deforestation* -Carbon emissions -Forest loss -Natural ecosystems loss	-Rural households -*Ejidos* -Federal and state government -Mennonites -Local groups (intra- and inter-*ejido* productive unions) -Regional Agrosilvocultural and Services Council of X-pujil (CRASX) -Mestizo immigrants -NGOs -CONA FOR	(−) PROCAMPO (−) Alianza para el cCmpo (−) Livestock policies (−) Agricultural sedentarization program (+) REDD+ (+) Conservation initiative (+) Non-timber forest products (NTFP) initiatives (beekeeping and allspice) (+) Program for forestry, agroforestry, and tree plantations	-Silvopastoral activities -Non–forest-extractive based activities (beekeeping) - NTFPs initiatives	3, 4, 5, 6, 7, 8, 10, 25, 31, 39, 40, 43
-Pasture maintenance with fire -Pasture abandonment	*Forest degradation* - Impact on carbon stocks -Fire occurrence frequency -Reduction of aboveground living biomass -Invasion of bracken fern	-Cattle ranchers -Rural smallholding households	(−) Colonization and agrarian distribution government programs (−) PROCAMPO (+) PES (+) REDD+	/	15, 19, 20, 21, 22, 24
-Land use diversification (extensive subsistence, intensive commercial crops and pasture, and agroforestry, reforestation, and conservation agriculture)	*Forest transition* -Policy drivers for conservation and productive activities	-*Ejidos* in the municipality of calakmul	(+) Conservation initiative (+) Agroforestry/ reforestation small scale programs (+) *Roza-pica-siembra* (RPS or zero-burn agriculture)	/	33

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Table 7. (continued)

Practice	Land-use/Land cover change processes and associated impacts	Actors	Policies (+/− impact on forests)	Reversibility measures	Source[1]
		Traditional and conventional agriculture			
-Agricultural expansion -Agricultural mechanization -Increasing adoption of chili cultivation	*Deforestation* -Forest loss -Tree cover loss	-Government -The Municipal council of Sustainable Rural Development -NGO -*Ejidos* -Mennonites -Monsanto corporation -Maya indigenous movement -TNC -Local groups (intra- and inter-ejido productive unions) -Regional Agrosilvocultural and Services Council of X-pujil (CRASX) -Mestizo immigrants -NGOs	(−) Agricultural intensification policy (−) Crédito a la Palabra (−) Alianza para el Campo (−) Forest concessions (−) National Deforestation Program (−) Colonization programs (−) Agricultural sedentarization program (−) Intensive agriculture programs (−) Government programs for rice production (+) Conservation initiative (+) REDD+ (+) PES (+) Forest management (+) NTFPs initiatives (beekeeping and allspice) (+) Forestry, agroforestry, and tree plantations (+) Ecotourism initiatives	-Agroforestry -Agroecological alternatives -Beekeeping policies -Ecotourism initiatives	1, 2, 5, 6, 7, 8, 9, 10, 11, 19, 31, 35, 39, 40, 41, 45, 46
-Agricultural intensification -Fallow shortening -Commercial crops	*Forestdegradation* -Carbon stock reduction -Biomass loss -High forest fire risk	-*Ejidos* -Agricultural producers -Rural smallholding households	(−) PROCAMPO (+) The Mexican Forest Code of Law for Sustainable Forestry Development (LSFD) (+) PES (+) CBR	-Management of secondary forest (*acahuales*)	12, 16, 18, 20, 23, 37, 38
-Agricultural abandonment -Traditional fallow	*Forest recovery* -Recovery of basal forest area -Aboveground live biomass increase	-*Ejidos* -State and federal government -Migrants from other states -Local farmers	(+) Conservation incentives (+/−) Migration policies (+) PROCAMPO, *roza-pica-siembra* (RPS or zero-burn agriculture) (+) Local agroforestry (+) Reforestation programs	/	27, 28, 29, 30

(continued)

Table 7. (continued)

Practice	Land-use/Land cover change processes and associated impacts	Actors	Policies (+/− impact on forests)	Reversibility measures	Source[1]
-Mayan community forest reserves	*Forest conservation* -Land planning -Preservation of tree richness and diversity	-Local peasants and Mayan leaders -Communities in CBR -Farmers	(+) Forest conservation governmental policies	/	32, 43
-Agricultural abandonment due to out-migrations	*Forest transition* -Forest cover recovery at larger area	-Regional Agrosilvocultural and Services Council of X-pujil (CRASX)	(−) PROCAMPO (+) ONG projects for non-timber forest products	/	34
		Agricultural/ livestock-forestry systems			
-Adoption of agroforestry land use	*Forest recovery* -Reduced deforestation - Secondary succession	-Farmers -Researchers	(+) Agroforestry programs (+) Small scale reforestation programs (+) PET	/	36, 45
		Productive reforestation			
-Tree planting (fruit and commercial-grade hardwood)	*Forest recovery* - Active restoration	-Rural households	(+) Program of temporary employment (+) State and private conservation (tree planting) programs	-Tree seedlings free of charge	31
		Forest harvesting			
-Regulated forest use -Charcoal production	*Deforestation and forest degradation* -Forest loss -Biomass loss -Carbon stock reduction	-*Ejidos* -SEMARNAT -Municipal authorities -Political leaders -Intermediaries	(+) Rainforest Alliance (+) National forest harvest policy (+) CONAFOR (+) Forest Management Plan (+) Forest certification (+) REDD+ (+) Community Forestry Management (CFM) (+) Sustainable Forest Management (SFM)	-Reduced logging impact (RIL) practices	13, 14, 17

[1]See Appendix 4 for authors of each references.

tock production programs to exploit resources for macroeconomic development under the North American Free Trade Agreement (NAFTA) and to provide small farmers with subsistence (Krylov et al., 2018). The National Deforestation Program (PRONADE) provided credit to smallholders who cleared upland forests to establish pasture and cropland (Klepeis, 2003; Velasco & Torres, 2019).

In 1975, three independent producers initiated chili production in one village. This activity spread rapidly to other communities through the market intermediaries (Keys, 2010). The National Solidarity Program (PRONASOL) "Crédito a la Palabra," supported the production of the jalapeño chili for commercialization among small producers (2–3 ha) (Reyes-Hernández et al., 2003). The funds of the Program of Direct Support to the Countryside (PROCAMPO) were available to large and small farmers (min. 1 ha) that cultivated on the same plot of land maize and other staple crops, such as beans, wheat, soybeans, sorghum, rice, and cotton. PROCAMPO's primary aim was the sedentarization of swidden agriculture and the intensification of commercial crops (Roy Chowdhury et al., 2006). Since 1995, PROCAMPO has included finance for establishing pastures, acquiring rural equipment and development, and procuring agricultural mechanization. The farmers' credits ("Alianza para el campo" program) and subsidies for equipment helped overcome startup costs, which incentivized the establishment of pasture in anticipation of future government subsidies for cattle ranching (Reyes-Hernández et al., 2003).

Both PROCAMPO and Alianza were positively associated with increased, cultivated areas of mainly pasture. In the municipality of Calakmul, PROCAMPO directly caused forest area loss as a consequence of the compensation that local producers made for removing the cultivated plots from the swidden agriculture cycle (Díaz Gallegos et al., 2001; Schmook & Vance, 2009). Reyes-Hernández et al. (2003) suggested that the *ejidatarios* that received more funding from PROCAMPO caused less deforestation because they used this money to cover their basic needs. This program did not influence deforestation in neighboring Hopelchén. Two studies coincide that the Alianza program was not associated with further deforestation. This program included technical assistance, a flexible design, specific activities, and land area selection; it also provided nonmonetary support (equipment and seeds).

Agroforestry, agroecology, and other sustainable activities. Some NGOs promoted the establishment of agroforestry parcels (e.g., *Pimenta dioica*—allspice), agroecological demonstration plots, and organic farming as alternatives to commercial crop production principally in the Calakmul municipality (Casey & Caviglia, 2000; Chowdhury, 2007; Roy Chowdhury et al., 2006). However, the above-mentioned sustainable initiatives failed to recruit farmers except for the introduction of velvet bean (*Mucuna pruriens L.*), a nitrogen-fixing legume, and the productive reforestation of secondary forests because they considered other sustainable activities as risky as chili cultivation (Keys, 2010). Other programs promoted agricultural intensification by subsidizing the use of tractors, as well as non-forest-extractive land uses like organic beekeeping and ecotourism. However, none of the identified studies investigated the impact of these sustainable initiatives on forest cover.

Conservation and forest policies. Some authors suggested that the establishment of CBR led to an increase in deforestation in the newly established *ejidos* because of their need to assure claim over the land (Abizaid & Coomes, 2004; Reyes-Hernández et al., 2003; Rueda, 2010). However, others demonstrated that the biosphere reserve slowed deforestation rates in the study area (Klepeis, 2003; Neeti et al., 2012; Vester et al., 2007) (Table 4) and even provoked an increase in the forest recovery area after 1989 (Roy Chowdhury, 2006) (Table 6). As mentioned previously, REDD+ is the central forest policy in Mexico, and it combines forestry and agricultural activities for sustainable rural development. Since 2010, REDD+ has been implemented in the Yucatan Peninsula by the forest owners (predominantly *ejidos*) through the government forestry programs and international NGO pilot projects (e.g., Alianza MREDD+).

Ellis, Sierra-Huelsz, et al. (2020) found that the REDD+ interventions were the most effective in reducing deforestation in those municipalities and communities where timber harvesting was combined with traditional agriculture for subsistence. The *ejidos* that perform livestock breeding as their dominant activity or combine it with mechanized agriculture for commercial crops and forestry harvesting had the lowest REDD+ effectiveness. Those predominantly cattle ranching municipalities in the southern part of our study areas (Calakmul and Candelaria) that share a border with Belize and Guatemala are also experiencing illicit logging, drug trafficking, and migration. A net forest cover loss in the municipality of Calakmul is particularly concerning because it hosts the entire core and majority of the buffer zone of CBR and has received a significant share of national REDD+ investments. The municipality of Champotón was the second with the most REDD+ initiatives, and together with Escárcega, it has an essential role in the state's forestry sector, and both experienced the positive effect of REDD+. Although REDD+ interventions did not reduce forest cover loss in the municipality of Hopelchén, some communities implementing silvopastoral and conservation agriculture projects did experience a positive trend in deforestation rate.

Discussion

We used a literature review with key criteria from a systematic review (Haddaway et al., 2015, 2020) to analyze which forest cover change processes caused by productive activities were identified, described, and evaluated in the Calakmul Biosphere Reserve, including its broader transition area. Most investigations in our study area focused on deforestation, which was evident by the highest frequency of codes assigned to this process in the entire sample. Also, the majority of primary studies focused on deforestation. Although they are sometimes recognized as present in the dynamic CBR forest landscape, other forest cover change processes were less evidenced in the literature. The majority of the studies use a quantitative methodology to evaluate the changes in the forest cover. They do so at a scale of the Southern Yucatán region, which includes the municipality of Calakmul and the southeast portion of Quintana Roo (Turner, 2010), and consider productive activities only as one of the land uses. Nevertheless, the heterogeneity in spatial and temporal scales between studies did not allow for a meta-analysis.

The tendency to document deforestation is common in the global tropics (Borda-Niño et al., 2020). This trend can be explained by the alarming global forest loss (Gibbs et al., 2010; Keenan et al., 2015). However, the focus on deforestation can mask the presence or importance of other forest cover change processes, such as forest degradation in particular. According to a study performed in the neighboring state of Quintana Roo by Ellis, Navarro Martínez, et al. (2020), forest degradation might be the most dominant process in our study area too. The authors acknowledge that besides more precise remote sensing methods, the understating of agricultural activities at the local level allowed them to differentiate the long-term (deforestation) from temporary forest losses (degradation).

In other words, in shifting cultivation, deforestation and forest succession are part of a single cycle that is considered sustainable if the optimal balance between cropping and fallow time is maintained (Altieri & Toledo, 2005). However, the shortening of fallow resulting from population increase and agricultural intensification in the study area (Dobler-Morales et al., 2020; Porter-Bolland et al., 2008) pushed forests toward degradation. This occurs when the ecosystem does not have time to recover minimal levels of biomass, biodiversity, and nutrients necessary for its normal functioning (Ghazoul et al., 2015). Similarly, pasture establishment truncates the succession cycle in the area that could potentially grow in secondary forests, moving this way from forest degradation to deforestation.

Although productive activities might cause both negative and positive forest cover change processes, the investigations in our study area focused more on the former. They analyzed commercial agriculture and big livestock breeding as the cause of deforestation and selective logging and subsistence agriculture as the cause of forest degradation. In addition, the studies showed that pasture abandonment did not result in forest recovery but in another negative forest process instead: *arrested succession*, that is, an invasive species-dominated ecosystem remaining a long time in an early succession state (Thrippleton et al., 2018).

However, many other identified activities and practices concerning forest degradation were not empirically documented. In particular, the misuse of fire in livestock activity that can be considered a driver of degradation was not documented. More severe forest fires might also provoke more permanent land-use changes. Similarly, high-impact logging practices aggravate degradation more immediately, but the associated road infrastructure might encourage deforestation for commercial agriculture expansion. However, forest degradation not always has negative repercussions. For instance, shorter fallows result in an abundance of invasive species of sunflower goldeneye that is an essential source of nectar for honey production in the region (Cázares et al., 2016), which in turn incentivizes forest conservation.

Although much less evidenced in the studies, forest conservation and recovery occur parallel to the negative forest cover change processes. The large forest areas in the CBR region bear witness to this. The forest preservation has to do with Calakmul's status as BR, which includes zones obeying more or less restrictive rules. Biosphere reserves in Mexico have particularly complex zoning because they are usually established on historically occupied land under social ownership, which restricts local owners' use of forest resources (Durand & Jímenez, 2010). The establishment of CBR in 1989 implied a series of agreements, rearrangements, and conflicts in land-use planning and the regulation of productive activities (Levy-Tacher et al., 2019; Oliva et al., 2020). The CBR zoning resulted in the 'humanless' core zone experiencing the recovery of mature forests (Porter-Bolland et al., 2015). In contrast, the intensification of productive activities resulted in negative forest cover change processes in buffer and transition zones (Schmook & Vance, 2009). In addition, the government promoted the eco-archaeo-tourisms projects as compatible with conservation policies and agricultural incentives (Manson, 2006). However, the tourist influx increases the probability of forest fires and contamination from waste accumulation in open garbage dumps (Rada et al., 2015). In addition, the economic gains from tourism might not be sufficient to outweigh monetary and cultural losses due to restrictions on traditional productive activities (Quadri-Barba et al., 2021; Turner et al., 2003).

Agricultural intensification was considered a viable solution for achieving both conservation and productive objectives of CBR. Consequently, subsidies and regulations incentivized these activities (Dobler-Morales et al., 2020). Therefore, it is not surprising that more than 90% of the revised publications focus on the period after the 1970s when the green revolution had already been going on in Mexico for three decades (González, 2006). The main drivers of deforestation in the municipality of Calakmul were subsistence and the commercial production performed by *ejidos*. In Hopelchén, in contrast, the most deforestation was reported in private property land owned by Mennonite industrialized farmers. In both cases, the intensified commercial agriculture did not manage to spare forest cover. Instead, the prospect of more profit prompted the *ejidos* to expand mechanized agriculture to flat areas of forest extension allotted to them in the past to support traditional shifting agriculture and timber harvesting activities that were once the most dominant (Cantún & Pat, 2012).

Despite the expansion of cattle-raising, this activity is performed largely for commercialization, and the local population continues to be dependent on meat hunting for subsistence (Roy Chowdhury et al., 2006). Hunting can negatively impact the forest when it includes the use of fire (Rada et al., 2015). On the other hand, agricultural development could also affect hunting, for less (dense) forest means less habitat for the wildlife species (Escamilla et al., 2000).

Despite its great importance in assuring the achievement of the BR objectives, our sample investigated the transition zone to a smaller extent. This zone is also called the area of influence, which explains well the bidirectionality of impact between BR (core and buffer) and surrounding (transition) areas under public policies and non-policy factors identified in the literature. However, except for the municipality of Calakmul, there is a lack of initiatives to develop local institutions that could promote productive activities compatible with conservation in the other four municipalities that host the CBR transition area (see Porter-Bolland et al., 2008).

In addition, and according to Klepeis (2003), during a large part of the 20th century, local people played only a passive role in land management decisions in the study region. Although the current design of the REDD+ recognizes local forest owners as direct implementers and beneficiaries of forestry programs, the federal government designed and implemented them with national and international money. Furthermore, REDD+ has predominantly focused on reducing deforestation through payments to traditional farmers for ecosystem services (Kelly, 2020). However, industrial farmers are the main forest loss drivers (Skutsch & Turnhout, 2020).

With or without REDD+, the traditional small farmers contribute to forest conservation and succession processes through their traditional productive systems. Traditional agroforestry and beekeeping are well-known for their adaptability to changing socio-economic conditions (Bareke et al., 2021; Jose, 2019). The heterogeneity of forest covers and the diversity of practices are observed at the *ejido* scale (Rueda, 2010). However, in our study area, positive forest cover change processes were investigated as coupled with negative processes at state and regional scales. Therefore, those positive processes occurring at the local scale stay unperceived. Future investigations should focus on sustainable activities related to positive forest cover change processes at the local level to fill this research gap.

Implications for Conservation

Since the 1960s, the Mexican government has targeted the broader Calakmul area for rural development (timber harvesting, agriculture, livestock breeding) and conservation activities (Biosphere Reserve). However, the design of development programs did not include an environmental perspective. Although many *ejidos* have valid governmental permits, timber harvesting is considered unprofitable. This productive activity is currently performed only by a few *ejidos*, the same who can afford RIL practices to reduce forest degradation. Governmental policies should consider monetary resources and technical assistance supporting RIL practices, and CFM in forest *ejidos* should be promoted to increase local timber competitiveness in the national and international market.

Even though the latest agricultural programs focus on intensification to yield more from less land, they continue contributing to deforestation because they do not include in their design low-impact organic inputs (e.g., green compost) and technology (e.g., small tractors), nor do they account for other important local socio-economic factors, such as land and labor availability. The shortening of fallows can be addressed by either targeting its biological efficiency (weed control and soil fertility improvements) or by increasing its economic value (commercial species), also known as improved fallows (*manejo de acahuales* in Spanish), a local agroforestry practice (Soto Pinto et al., 2011).

REDD+ promoted silvopastoral systems and conservation agriculture, which significantly reduced deforestation when combined with productive forestry (Ellis, Sierra-Huelsz, et al., 2020). To make these activities more attractive to farmers, their design should be based on the traditional agrosilvopastoral systems, and they should grant enough payments to cover transaction costs and leave net benefits. In addition, beekeeping as an economically viable activity should be supported by providing equipment and helping revive beekeepers' associations.

However, the Mennonites' pressure that makes unsustainable agriculture more profitable to *ejidos* may diminish these efforts. The unsustainable behaviors of industrial farmers should, thus, be controlled with stricter implementation of environmental and agrarian laws and by their inclusion in participatory spaces where sustainable rural development of the broader Calakmul area is discussed.

Finally, more empirical studies are needed to make forest conservation and development efforts visible. For example, longitudinal mixed-methods studies should be performed (e.g., Dobler-Morales, 2019 in; Dobler-Morales, 2021) to evaluate non-conventional agricultural activities and forest regeneration and reforestation efforts, including the newest governmental agroforestry development program *Sembrando Vida* (Planting Life) that was launched in 2018. These studies will allow learning from the experience and promote public policy instruments' design for resilient and inclusive growth in the Calakmul Biosphere Reserve's broader area.

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Supplemental Material

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