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Recent Forest Cover Loss in the Core Zones of the Monarch Butterfly Biosphere Reserve in Mexico

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The Monarch Butterfly Biosphere Reserve (MBBR) in central Mexico was established in 2000 to protect monarch butterfly (*Danaus plexippus*) overwintering colonies and contribute to the conservation of the monarch migratory phenomenon. The MBBR has faced forest cover losses due to illegal logging and climate-related factors. Here we report forest cover losses from 2012 to 2018 in the core zones of the MBBR where most monarch overwintering colonies perch. We used aerial ortho-photographs and satellite images complemented with field validation for temporal comparisons. During this period, 163.44 ha of forest cover were affected, 125.44 ha due to climate-related factors (rain and wind), 25.86 ha due to large-scale illegal logging, and 12.14 ha due to small-scale illegal logging. The core zone of the MBBR located in the State of Michoacan showed the highest forest cover loss values with 94.07 ha lost due to climate-related factors, and 38.0 ha lost due to illegal logging. Our study also showed a substantial decrease of ∼98% in large-scale illegal logging in the core zones of the MBBR compared to previous reported forest losses from 2001 to 2012. Forest cover loss was similar, yet the periods of the two studies differed, one 12 years in length, this one 6 years. The decrease of forest cover during the period studied suggests that factors elsewhere rather than forest cover loss in the monarch butterfly's winter habitat have strongly contributed to the dramatic population declines observed in monarch overwintering colonies since 2010.

Keywords: biosphere reserves, climate-related factors, forest cover loss, monarch butterfly, illegal logging, overwintering colonies, population declines

INTRODUCTION

Protected areas are a cornerstone for conserving biodiversity worldwide (Margules and Sarkar, 2007). Most protected areas were decreed *ad hoc* for protecting scenic values, as refuges of cultural heritage, or to conserve specific places based on political criteria. Other protected areas have been decreed in areas that are biodiversity hotspots thereby contributing to their conservation (Room et al., 2000; Saura et al., 2018). Protected areas are also important for human well-being when they provide many environmental services, serve as areas of resilience to ameliorate negative impacts of climate change and other global change factors, and serve as refugia for the cultural heritage of

local communities (Carey and Stolton, 2000; Hockings, 2003). Forest cover loss and fragmentation of habitats, illegal hunting, extraction of species, and overexploitation of their natural resources threaten the viability of protected areas worldwide (Hockings, 2003; Miranda et al., 2016). An increasing awareness of the importance of conservation and surveillance of protected areas has been recognized in many countries, and supported by national and international agencies, NGOs and academic institutions (Sánchez-Cordero et al., 2009; Saura et al., 2018).

The Monarch Butterfly Biosphere Reserve (MBBR) was decreed in 2000 to protect the monarch butterfly (*Danaus plexippus*) overwintering colonies in Mexico and to contribute to the conservation of the monarch migratory phenomenon (SEMARNAT, 2001; Vidal and Rendón-Salinas, 2014). The MBBR has been internationally recognized as an essential component of strategies for the conservation of the monarch butterfly migratory phenomenon due to the importance of its forests in which monarch overwintering colonies perch (Calvert et al., 1983; Alonso-Mejía et al., 1997; UNESCO, 2008; Vidal and Rendón-Salinas, 2014). However, the MBBR has faced continuous forest cover losses (Rendón-Salinas et al., 2005; Vidal et al., 2013; Vidal and Rendón-Salinas, 2014; Sarkar, 2017). Specifically, illegal logging, forest fires, and diseases causing damage to trees in the reserve are severe problems directly affecting forest cover that have negative impacts on monarch overwintering colonies. Further, the high demand for legal logging by local communities is also affected by these factors and has created social tensions between stakeholders from local communities and external agents participating in illegal activities (Honey-Rosés, 2009; Vidal et al., 2013; Vidal and Rendón-Salinas, 2014; Ramirez et al., 2015).

Forest cover loss has negative impacts on environmental services, ecotourism, opportunities for legal logging and wood extraction, and soil erosion. In addition, watersheds can be irreversibly harmed, contributing to potentially deleterious changes in microclimate (Rendón-Salinas et al., 2005; Vidal and Rendón-Salinas, 2014). In response to these problems, several conservation initiatives have been implemented with respect to the MBBR. For example, the Monarch Butterfly Conservation Trust (also known as the Monarca Fund) established in 2000, was created by the World Wildlife Fund (WWF) and the Mexican Fund for Nature Conservation (FMCN) with the financial support from the David and Lucile Packard Foundation, the former Mexican Secretariat for the Environment, Natural Resources and Fisheries (SEMARNAP), and the States of Michoacan and Estado de Mexico. It consists of a management tool based on economic incentives for the protection of the MBBR core zone forest habitats and is owned by stakeholders who have accepted restrictions on their exploitation rights and promoted conservation programs and ecotourism (Rendón-Salinas et al., 2005; Vidal and Rendón-Salinas, 2014). In 2016, the Mexican Federal Government established an initiative supporting the conservation and monitoring of the MBBR that included participation by governmental authorities, federal police, NGOs, and academic institutions (Honey-Rosés et al., 2009). Finally, the trinational initiative promoting the conservation of the monarch butterfly migratory phenomena sponsored by the Commission for Environmental Cooperation, was launched in 2015 by the Presidents of Mexico and the United States of America and the Prime Minister of Canada to ensure the conservation of the monarch butterfly migratory phenomenon (Trudeau et al., 2016). This initiative involved the creation of a trinational scientific working group for coordinating academic, governmental, and NGOs activities related to the conservation of the monarch butterfly migratory phenomenon.

In this study, we examined whether forest cover loss decreased since commencement of these initiatives. Specifically, we quantified recent forest cover losses in the core zones of the MBBR from 2012 to 2018 using satellite images and aerial orthophotographs complemented with field validation for temporal comparisons. Our goals were to (1) compare recent forest cover loss due to climate-related factors (wind and rain), and large-scale and small-scale illegal logging between years, and (2) analyze long-term forest cover losses in the core zones of the MBBR by comparing a previous study (2001–2012, Vidal et al., 2013) with our study (2012–2018).

MATERIALS AND METHODS

Study Area

The MBBR is located in the border between the States of Michoacan and Mexico along the Transvolcanic Belt in central Mexico. It was decreed in 2000 and consists of 56,259 ha (SEMARNAT, 2001). The MBBR is composed of three core zones in which most monarch overwintering colonies occur (Calvert and Brower, 1986; Rendón-Salinas et al., 2005; Galindo-Leal et al., 2009). A northern core zone is located in Cerro Altamirano (558 ha), a central core zone (9,671 ha) is located in Sierra de Chincua, Sierra El Campanario, and Cerro Chivatí-Huacal, and a southern zone (3,339 ha) includes Cerro Pelón (see Vidal and Rendón-Salinas, 2014). In these core zones use of natural resources is restricted. The MBBR includes two buffer zones in which sustainable use of natural resources is allowed, including supervised legal logging (SEMARNAT, 2001; Galindo-Leal et al., 2009; Vidal and Rendón-Salinas, 2014) (**Figure 1**). This protected area holds a high diversity of habitats, including pine forest (*Pinus* spp.), oyamel forest (*Abies religiosa*), pine-oak forest (*Quercus* spp), oak forest, and cedar forest (*Cedrus* spp), and has high biodiversity content including 493 species of vascular plants and 198 species of terrestrial vertebrates (SEMARNAT, 2001).

Forest Cover Loss

Overall, we followed the methods provided by Brower et al. (2002) and Vidal et al. (2013). This analysis was quantified using satellite Quickbird sensor images (for 2012) and orthophoto images from the core zones of the MBBR from 2012 to 2018. These images were ortho-rectified and georeferenced using ArcMap editing tools (see below). A total of 45 images were obtained biennially covering the core zones of the MBBR at a resolution of 30 × 30 cm for comparison with the orthophoto images. The orthophoto images (aerial photographs, with the Argeomatica company) were obtained annually from February 2012, 2013, 2014, 2015, and 2016, May 2017, and March 2018. The image for 2012 that was used came from a previous study

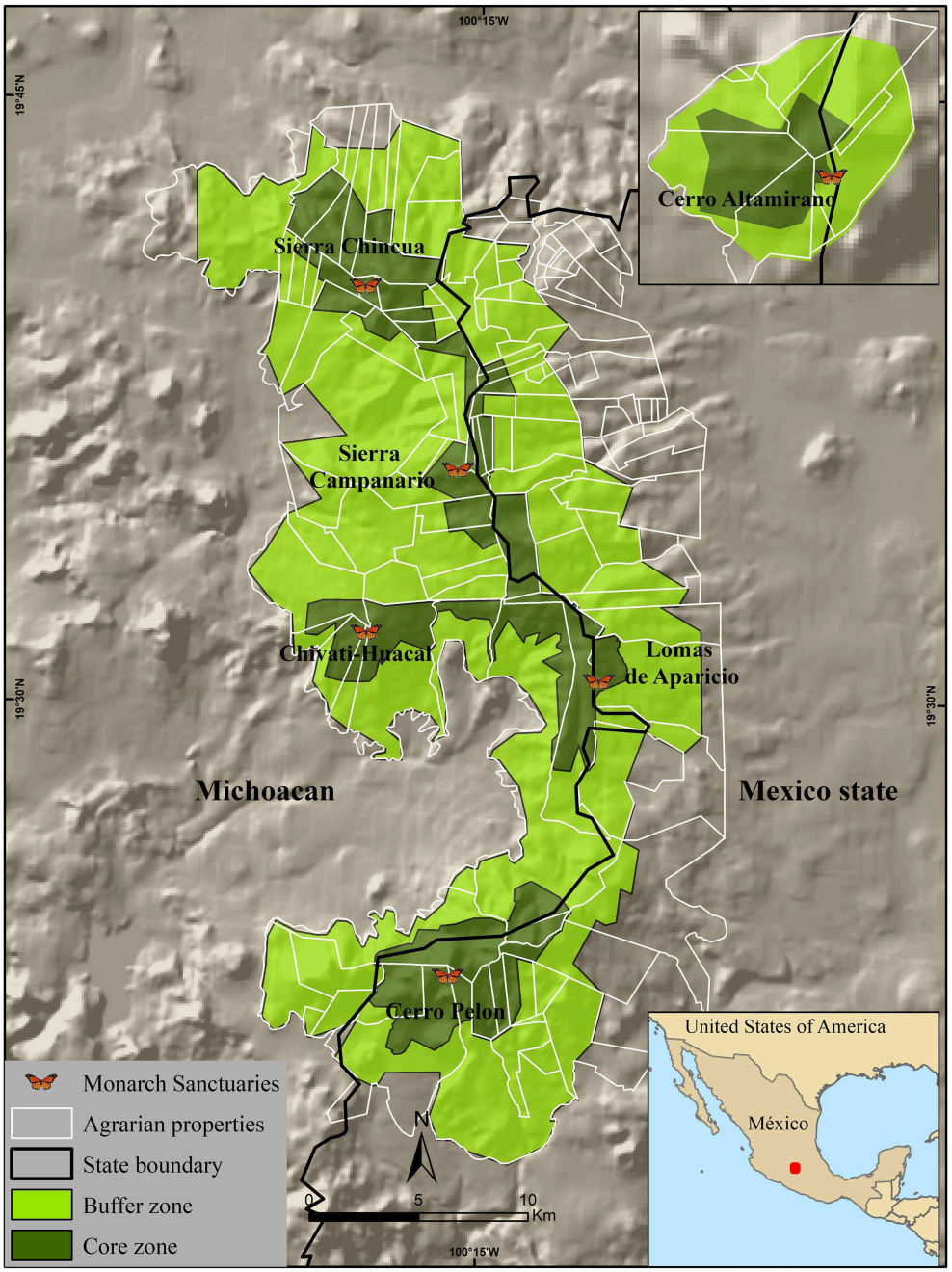

FIGURE 1 | Location of the Monarch Butterfly Biosphere Reserve (MBBR), along the border (thick line) of the States of Michoacan and Mexico. The buffer zones are depicted in light green, and include areas where sustainable use of natural resources is allowed by local communities. The core zones of the MBBR are depicted in dark green, and include areas where use of natural resources is restricted. Monarch overwintering colonies (monarch sanctuaries) are depicted as a red monarch logo. The polygons depicted in the buffer zones represent the agrarian properties owned by the stakeholders [Registro Nacional Agrario, Mexico 2018 (National Agrarian Records, Mexico 2018)].

(Vidal et al., 2013). This overlap of imagery allowed visualization of long-term trends in forest cover loss in core zones of the MBBR in a continuous year sequence (2001–2018) by combining both studies. Forest cover loss was recorded in a shapefile in ArcGIS (v.10.5), allowing calculation of the arithmetic difference of forest cover loss in different habitats (see Vidal et al., 2013; Vidal and Rendón-Salinas, 2014). A buffer of 300 meters surrounding the core zones of the MBBR was established in the GIS platform. We generated a grid of hexagons (16 ha) covering the core zones of the MBBR and buffer area to compare images biennially.

Visual interpretation was performed using ArcMAP editing tools, "Effects-Swipe," which allowed images to be superimposed

and compared. This tool facilitated the visual comparison of the two basic inputs to quantify forest cover loss. As a rule of interpretation, a screen scale was set to 1:3,000. This scale allowed a complete visualization of each hexagon of the grid, and ensured homogenization for the analyses (Vidal et al., 2013). Forest cover loss was estimated for the local communities and the core zones of the MBBR (**Figure 1**) (Vidal et al., 2013). Given our scale of analyses (1:3,000), other semi-automated tools in ArcMap can produce change detection errors, by the amount of topographic shadows that exist on the ground. We do believe that other ArcMap tools can be implemented in further priority studies of habitat loss at the MBBR. For example, including forest loss analyses of the remaining areas of the reserve.

Once forest cover loss was located and mapped, we proceeded with field validation using a GPS device configured with the exact route and position to the center of each affected polygon. Visits were made at least once to the 39 identified affected areas to record evidence of forest cover loss by climate-related factors (rain and wind) and illegal logging. Specifically, we classified forest cover loss into three categories: (1) climate-related factors due to wind and rain; (2) large-scale illegal logging due to massive logging carried out by organized delinquent groups; and (3) small-scale illegal logging due to logging of a few trees by individuals from local communities (see Vidal et al., 2013). Treefall due to illegal logging was easily detected as they showed clear marks of saw or axes in the stumps. Treefall due to climatic factors did not show evidence of human activities. The field trips included previously trained personnel to record tree fall according to our classification from the MBBR, World Wildlife Fund (WWF), Mexican Fund for the Conservation of Nature (FMCN), the National Forestry Commission (CONAFOR), the National Commission of Natural Protected Areas (CONANP), Forest Protector (PROBOSQUE), the Federal Office of Environmental Protection (PROFEPA), Institute of Biology, UNAM (IBUNAM), Science and Community for Conservation AC (CCC), and representatives of agrarian properties.

RESULTS

Forest cover loss totaled 163.44 ha from 2012 to 2018 in the core zones of the MBBR (**Figure 1**). Forest cover loss due to climate-related factors was 125.44 ha (77%), large-scale illegal logging, 25.86 ha (15%), and small-scale illegal logging, 12.14 ha (8%) (**Table 1**, **Figure 2**). Forest cover loss due to climate-related factors peaked at 81.75 ha between 2015 and 2017 in our study; in March 2016, strong winds and rains produced a peak in treefall (55.21 ha) in the core zones of the MBBR (**Table 1**, **Figure 3**). The State of Michoacan reached higher forest cover loss values due to climate-related factors (94.07 ha) from 2012 to 2018 compared to the State of Mexico (31.37 ha) (**Table 1**, **Figure 3**). These values represent 0.23 and 0.63% of the total area in the core zone of each State, respectively (**Table 1**).

Illegal logging caused moderate forest cover loss of 38.0 ha from 2012 to 2018, but peaked with 21.61 ha during 2013 to 2015. The State of Michoacan was the most affected with 25.86 ha compared to the State of Mexico, where no evidence of large-scale logging was observed (**Table 1**, **Figure 2**). Large-scale illegal logging decreased after 2015 in both States (**Figure 2**). Small-scale illegal logging resulted in low forest cover loss values during 2012 to 2018, although it reached a peak of 4.47 ha during 2015 to 2017 (**Figure 3**). Small-scale illegal logging was marginally present in the State of Mexico with 1.50 ha affected. Large- and small-scale logging represented 0.30% and 0.04% of forest cover loss in the core zones of Michoacan and the State of Mexico, respectively (**Table 1**). Although small-scale illegal logging continues, it has a minor impact compared to large-scale illegal logging in previous years. Over all, forest cover loss represented <1.0% and 0.30% in the core zones of Michoacan and the State of Mexico, respectively, and 1.21% in the core zones of the MBBR (**Table 1**, **Figures 2**, **3**).

DISCUSSION

Forest cover loss in the core zones of the MBBR showed a decreasing trend from 2012 to 2018. Climate-related factors caused the highest damage to the forest cover, as shown by the high forest cover loss values in the core zones of the MBBR (**Table 1**, **Figures 2**, **3**). Previous studies have suggested the importance and persistence of climate-related factors affecting the monarch overwintering colonies (Brower et al., 2004, 2012; Narayani et al., 2012; Vidal et al., 2013; Vidal and Rendón-Salinas, 2014). Climate-related factors such as rain, wind and low temperatures directly cause high mortality in monarch populations in addition to treefall, as monarchs are highly vulnerable to low temperatures and rain while perched on trees, and usually fall to the ground resulting in high mortality (Brower et al., 2004, 2017; Narayani et al., 2012). For example, we observed a high monarch mortality at El Rosario colony in January due to a heavy storm (pers. obs.). Brower et al. (2017) and Vidal et al. (2013) reported a peak of forest cover loss in 2009–2011 due to climate-related factors (**Figure 2**). Other natural factors such as disease or forest fires affecting trees can increase treefall. Thus, climate-related factors appear to play a crucial role affecting monarch overwintering colonies either by treefall due to strong wind and rain, diseases and forest fires, and causing high monarch mortality as well by exposure to adverse climatic conditions (Narayani et al., 2012; Vidal et al., 2013; Vidal and Rendón-Salinas, 2014; Ramirez et al., 2015).

Though the period of observations differed (12 years in Vidal et al., 2013, vs. 6 years in this study), the magnitude of forest cover loss from climate-related factors was similar (120 ha vs. 130 ha; **Table 1** and **Figures 2**, **3**) (Vidal et al., 2013). Previous studies have also reported adverse effects of climate-related factors on MBBR forest cover and on monarch overwintering colonies (Narayani et al., 2012). Climate-related factors as heavy wind and rain resulted in extensive forest cover loss and high mortality in monarch overwintering colonies at the MBBR in 1981 (Calvert et al., 1983) and in 1992 (Culotta, 1992). Brower et al. (2004) described a high number of mortality of monarchs due to climate-related factors, and Ramirez et al. (2015) suggested that forest cover loss is due to an additive effect

TABLE 1 | Recent forest cover loss (ha) due to climate-related factors (wind and rain), and large-scale and short-scale illegal logging in the core zones of the Monarch Butterfly Biosphere Reserve (MBBR).

Year	State	Climatic factors	Large-scale illegal logging	Small-scale illegal logging	Total	% loss in core zones
2012–2018	Mexico	31.37	0.0	5.37	36.74	0.27
	Michoacan	94.07	25.86	6.76	126.70	0.93
Total		125.44	25.86	12.14	163.44	1.21

Forest cover losses were quantified by comparing annually orthophoto images for the MBBR core zones from 2012 to 2018. The number of hectares is depicted by years and by State, and the percentage of forest cover loss in core zones of each State, and in the core zones of the MBBR, respectively, is included (see Methods for more details).

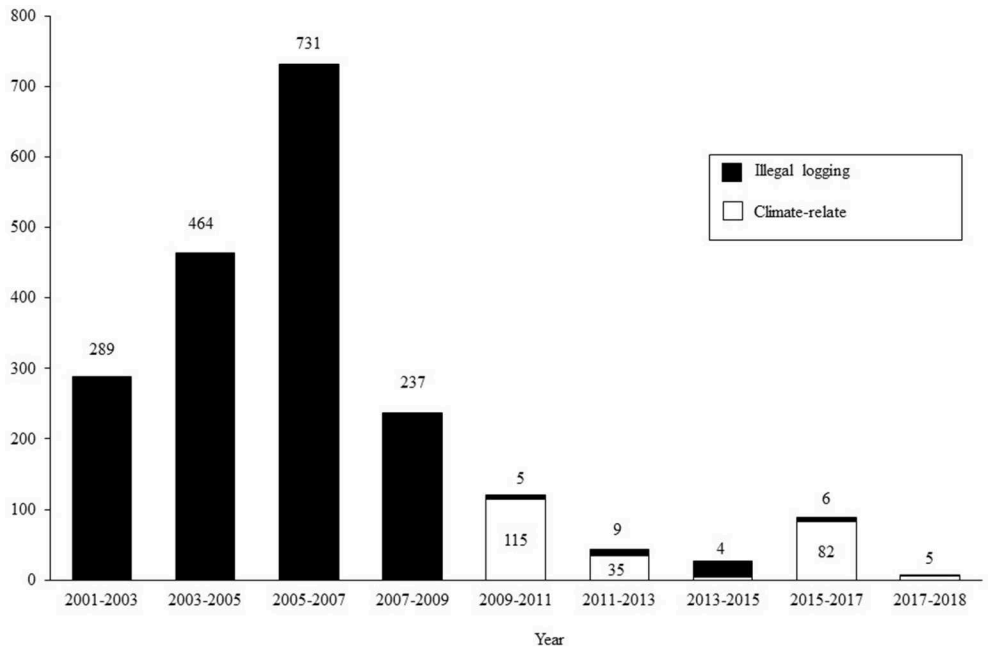

FIGURE 2 | Forest cover loss trends in the core zones of the MBBR from 2001 to 2018. Climate-related factors (rain and wind) are depicted in white bars; large-scale and small-scale illegal logging are depicted in black bars. The figure includes data from a previous study (2001–2012; see Vidal et al., 2013), and from this study (2012–2018) using similar methods.

of a poor land management and illegal logging, and climate-related factors. Vidal et al. (2013) reported a strong negative impact of climate-related factors on monarch overwintering colonies between 2005 and 2007, and Vidal and Rendón-Salinas (2014) observed the decreased of several overwintering colonies in the MBBR caused by climate-related factors between 2004 and 2007. The most recent damage occurred in March 2016, where MBBR was affected by climate-related factors (rain and snow storms) producing high damage to the Oyamel forests and consequently to the overwintering colonies from the sanctuaries of Sierra Chincua and Cerro Pelón showed a mortality of 31 and 38% respectively, while Sierra Campanario (El Rosario colony) showed a mortality of 40% (Brower et al., 2017). Further studies should also monitor the adverse impact of climate-related factors on trees and feeding plants not only in the MBBR, but along the monarch migratory route, as damage to trees and plants can strongly affect monarch's perching and feeding sites (Oberhauser and Peterson, 2003; Batalden et al., 2007; Lemoine, 2015).

Forest cover loss from large- and small-scale illegal logging was lower than from climate-related factors in the core zones of the MBBR. Moreover, large- and small-scale illegal logging decreased from 2012 to 2018. Large-scale illegal logging has been absent since 2015, and only small illegal logging is still marginally present. The State of Michoacan showed higher forest cover loss rates due to both large and small-scale illegal logging compared to the State of Mexico in the core zones of the MBBR. A decrease in forest cover loss due to illegal logging was observed between an earlier study (2001–2012) (Vidal et al., 2013) and our study (2012–2018). Vidal et al. (2013) reported a total of 2,057 ha forest cover loss by both large-scale and small-scale illegal logging in an 11-year period, while our study reported <50 ha in an 8-year period. These results indicate approximately a 98% reduction in illegal logging in the core zones of the MBBR in recent years. Conversely, forest cover loss due to climate-related factors was similar; 122 ha were reported from 2001 to 2012 (Vidal et al., 2013), and 125.44 ha in our study. Overall, forest cover loss due to

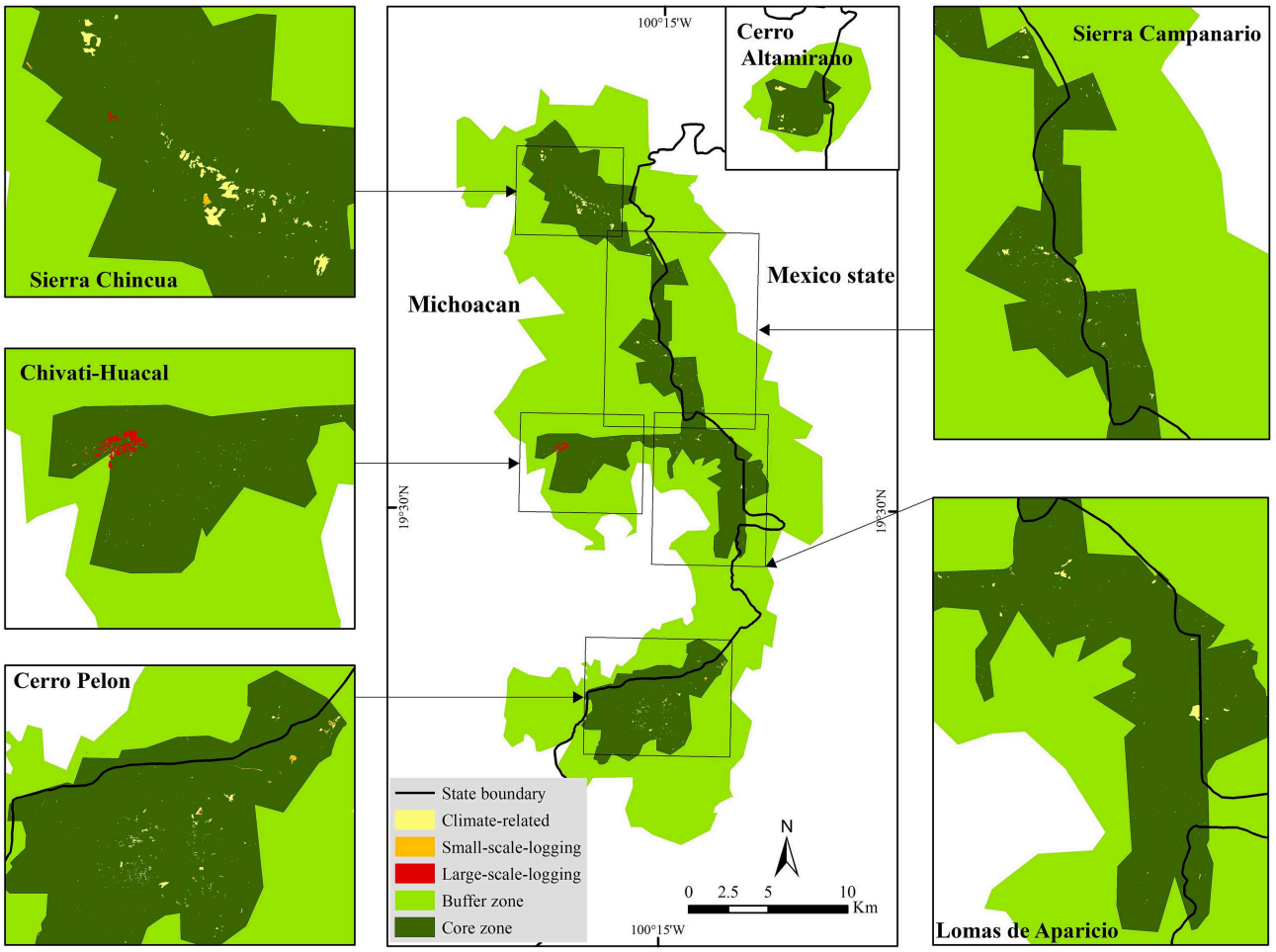

FIGURE 3 | Maps depicting forest cover loss due to climate-related factors (yellow), and large-scale (red), and small-scale (orange) illegal logging in the core zones of the MBBR (light green and dark green). Forest cover loss includes from 2012 to 2018.

both climate-related factors and illegal logging was lower in the cores zone of State of Mexico (0.27%) compared to Michoacan (0.93%), and only 1.21% in the core zones of the MBBR (see Brower et al., 2017) (**Table 1**).

The recent overall decrease of large and small-scale illegal logging is likely explained by a shared effort of stakeholders, Mexican government, NGOs, academic institutions, and philanthropists. Several actions have been implemented that have succeeded in preventing illegal logging in crucial areas of monarch overwintering colonies. For example, in 2016, the Mexican government established a program of a strict surveillance in the core zones of the MBBR involving environmental police in coordination with local communities, NGOs, and other stakeholders. This program is ongoing.

Further, the Mexican government continues to support stakeholders and local communities with specific conservation programs. The Federal Environmental Protection Agency (PROFEPA) continues a monitoring program for natural resources, and the Ministry of Environment and Natural Resources (SEMARNAT) maintains a program of payment for environmental services, which mitigates the overexploitation of the MBBR forests. Specifically, more than 330 programs were established between 2014 and 2018 supporting local communities located inside and in the vicinity of the MBBR. The subsidies granted as the Temporary Employment Program (PET), Conservation Program for Sustainable Development (PROCODES) and the Community Surveillance Programs (PVC) are examples of those that have benefitted local communities; 55% of the projects supported are aimed at the conservation and monitoring of the MBBR forests.

The role of NGOs has also been instrumental for conserving MBBR forests. World Wildlife Fund (WWF) is involved in the conservation of monarch overwintering colonies (Vidal et al., 2013; Vidal and Rendón-Salinas, 2014). It coordinates the development of forest protection programs, reforestation projects, development of production programs, and environmental monitoring with incentives to promote the conservation of the forests in the core zones of the MBBR. Other Mexican NGOs that are involved include the Monarch Fund, which grants payments to local communities for the protection

of forests, the Mexican Fund for the Conservation of Nature, AC, Alternare AC, and Monarch Butterfly Fund (MBF) aimed at protecting the forest in the core zones of the MBBR. The coordinated efforts involving the Mexican government, national and international NGO and agencies, and academic institutions have increased the surveillance and monitoring programs aimed at conserving forest in the MBBR, particularly in the core zones of the MBBR, where most monarch overwintering colonies perch and feed (Narayani et al., 2012; Vidal et al., 2013). Our study showed that illegal logging has substantially decreased in recent years in the core zones of the MBBR, indicating that these conservation efforts have been successful and should continue.

Recent studies have documented a dramatic reduction in monarch overwintering colonies of more than 90% in recent years (Vidal and Rendón-Salinas, 2014; Saunders et al., 2019). One question that continues to be debated is whether the decrease in monarch overwintering colonies is mainly due to forest cover loss in the core zones of the MBBR where monarch overwintering colonies occur (Brower et al., 2011). Other alternative proposals suggest that the dramatic decrease of monarch overwintering colonies is a combination of significant reductions of milkweed populations due to herbicides in extensive areas throughout the east and midwest US or that the decline is due to increasing mortality during the fall migration (Pleasants and Oberhauser, 2013; Agrawal, 2017; Sarkar, 2017; Thogmartin et al., 2017a; Saunders et al., 2019).

Our study contributes to understand monarch population declines by showing that, overall, forest cover loss in the core zones of the MBBR has substantially decreased in recent years and that this decrease is due to the prevention of large-scale illegal logging. Thus, problems generated by human activities in winter habitat are unlikely to be a determinative factor in the etiology of the population decline. In this context, it is important to highlight the success of the coordinated efforts of the Mexican government, NGOs, and national and international agencies and academic institutions in implementing the necessary conservation strategies. Forest cover loss in core zones of the MBBR due to climate-related factors needs continued monitoring and integrated to any conservation program that has been and will be undertaken. The conservation of the monarch migratory phenomena is a complex task and requires an internationally coordinated effort to address the challenges: prevent illegal logging in the core zones of the MBBR; increase milkweed populations and avoid toxic herbicides to ensure nectar availability to monarch butterflies throughout its migratory route and breeding areas, and restoring and maintaining habitats along the fall monarch migration (Brower et al., 2011; Agrawal, 2017; Thogmartin et al., 2017b). The trinational initiative between Mexico, the US and Canada aimed to conserve the monarch migratory phenomena can play an important role in promoting a shared responsibility that requires international coordination and cooperation on a continental scale.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

AUTHOR CONTRIBUTIONS

JF-M, VS-C, and ER-S conceived and designed the research, and conducted data analyses. All authors wrote the manuscript.

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