



Trends in Deforestation and Forest Degradation after a Decade of Monitoring in the Monarch Butterfly Biosphere Reserve in Mexico

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Abstract: We used aerial photographs, satellite images, and field surveys to monitor forest cover in the core zones of the Monarch Butterfly Biosphere Reserve in Mexico from 2001 to 2012. We used our data to assess the effectiveness of conservation actions that involved local, state, and federal authorities and community members (e.g., local landowners and private and civil organizations) in one of the world's most iconic protected areas. From 2001 through 2012, 1254 ha were deforested (i.e., cleared areas had <10% canopy cover), 925 ha were degraded (i.e., areas for which canopy forest decreased), and 122 ha were affected by climatic conditions. Of the total 2179 ha of affected area, 2057 ha were affected by illegal logging: 1503 ha by large-scale logging and 554 ha by small-scale logging. Mexican authorities effectively enforced efforts to protect the monarch reserve, particularly from 2007 to 2012. Those efforts, together with the decade-long financial support from Mexican and international philanthropists and businesses to create local alternative-income generation and employment, resulted in the decrease of large-scale illegal logging from 731 ha affected in 2005–2007 to none affected in 2012, although small-scale logging is of growing concern. However, dire regional social and economic problems remain, and they must be addressed to ensure the reserve's long-term conservation. The monarch butterfly (*Danaus plexippus*) overwintering colonies in Mexico—which engage in one of the longest known insect migrations—are threatened by deforestation, and a multistakeholder, regional, sustainable-development strategy is needed to protect the reserve.

Keywords: federal government, habitat loss, illegal logging, payment for ecosystem services

Tendencias en la Deforestación y la Degradación de Forestal después de una Década de Monitoreo en la Reserva de la Biósfera de la Mariposa Monarca en México

Resumen: Usamos fotografías aéreas, imágenes satelitales y muestreos de campo para monitorear la cobertura forestal en las zonas núcleo de la Reserva de la Biósfera de la Mariposa Monarca en México de 2001 a 2012. Usamos nuestros datos para estudiar la efectividad de las acciones de conservación que involucran a autoridades locales, estatales y federales, así como a miembros de la comunidad (p. ej.: propietarios locales de tierras y organizaciones privadas y civiles), en una de las áreas protegidas más icónicas del mundo. Desde 2001 y hasta 2012, 1254 hectáreas fueron deforestadas (es decir, áreas en las cuales el dosel del bosque cubría <10%), 925 hectáreas fueron degradadas (es decir, áreas en las cuales el dosel del bosque disminuyó) y 122 hectáreas fueron afectadas por condiciones climáticas. Del total de 2179 hectáreas afectadas, 2057 hectáreas fueron afectadas por tala ilegal: 1503 hectáreas por tala a gran escala y 554 hectáreas por tala a pequeña escala. Las autoridades mexicanas efectivamente hicieron cumplir los esfuerzos para proteger la reserva monarca, particularmente de 2007 a 2012. Esos esfuerzos, junto con el apoyo económico de una década por parte de filántropos y empresarios mexicanos e internacionales para generar ingresos alternativos y empleos locales, resultaron en la disminución de la tala ilegal a gran escala de 731 hectáreas afectadas en el período 2005–2007 a ninguna en el 2012, aunque la tala a pequeña escala es una preocupación creciente.

*Sin embargo, en la región persisten problemas sociales y económicos severos que deben ser atendidos para asegurar la conservación a largo plazo de la reserva. Las colonias de mariposa monarca (*Danaus plexippus*) que pasan el invierno en México, que participan en una de las migraciones más extensas conocidas de insectos, están amenazadas por la deforestación y se requiere una estrategia regional de desarrollo sustentable y con la participación de todos los interesados para proteger la reserva.*

Palabras Clave: gobierno federal, pago por servicios ambientales, pérdida de hábitat, tala ilegal

Introduction

For decades, scientists and conservationists have advocated the establishment of protected areas that conserve ecosystems and biological diversity as a primary goal but that also benefit local inhabitants. However, few long-term examples are available with which to assess the effectiveness of conservation actions within these areas and, in particular, those that document the complex interactions among local people, authorities, civil-society organizations, and private donors. The Monarch Butterfly Biosphere Reserve in Mexico offers a useful case study on the local socioeconomic conditions and the political realities leading to an impressive decline in deforestation in an iconic protected area.

Traveling over 4000 km from the Great Lakes region east of the Rocky Mountains in Canada and the United States to central Mexico (Urquhart 1976; Calvert & Brower 1986; Alonso-Mejía et al. 1997), the eastern North American population of the monarch butterfly (*Danaus plexippus*) performs one of the longest migrations of all known insects (Pence 1998; Anderson 2009). The overwintering sites of this butterfly were discovered by scientists in Mexico in 1975 (Urquhart 1976).

The monarch's overwintering concentrations have passed through 3 different protection schemes and federal decrees of the Mexican government (Galindo-Leal & Rendón-Salinas 2005). First, in 1980, a reserve and wildlife refuge zone was established to protect the overwintering sites, but exact locations were not specified and logging was restricted only during monarch hibernation season (November–March) (Diario Oficial de la Federación 1980). Second, in 1986, 5 isolated protected areas were established, and jointly called Special Monarch Butterfly Biosphere Reserve, in Sierra Chincua, Sierra El Campanario, Cerros Huacal, Chivatí, Pelón, and Altamirano located in the municipalities of Ocampo, Angangueo, Zitácuaro, Contepec (Michoacán state), Donato Guerra, Villa de Allende, and Temascalcingo (Mexico state). The total area protected was 16,110 ha. Within this area were 4491 ha of core zone (all extractive activities prohibited, only conservation and scientific research allowed) and 11,619 ha of buffer zone (sustainable extractive activities permitted) (Diario Oficial de la Federación 1986). Indigenous communities protested this decree by setting forest fires (Galindo-Leal & Rendón-Salinas 2005). Third, the Monarch Butterfly Biosphere Reserve, as it is

known today, was established in 2000 to protect 56,259 ha of temperate forest along the mountains of the Trans-Mexican Volcanic Belt between the states of Michoacán and Mexico state (42,707 ha in 2 buffer zones and 13,552 ha in 3 core zones) (Fig. 1) (Calvert 1994; Rendón-Salinas 1997; Diario Oficial de la Federación 2000; Brower et al. 2002; Galindo-Leal & Rendón-Salinas 2005). Forest cover was mostly oyamel fir (*Abies religiosa*), pine (*Pinus* spp.), pine-oak (*Pinus* and *Quercus*), oak, and white cedar (*Cupressus*). The new reserve united all 5 areas from the previous decree to ensure better protection of the reserve's ecological processes. In 2008, the monarch reserve became a World Heritage site (UNESCO 2008).

The reserve's core zone (composed of 3 core zones) contains the majority of the monarch's sanctuaries (Galindo-Leal & Rendón-Salinas 2005): a northern zone (558 ha) includes Cerro Altamirano; a central zone (9671 ha) includes Sierra de Chincua, Sierra El Campanario, and Cerro Chivatí-Huacal; and a southern zone (3339 ha) includes Cerro Pelón (Fig. 1). One of us, (E.R.-S., unpublished) recorded 16 overwintering colonies in Mexico between 2004 and 2012, 11 inside the reserve and 5 outside the reserve. The 3 core zones include parts of the land of 38 communities and are surrounded by 2 buffer zones that provide connectivity. In the core zone, logging permits on 17 properties were rescinded when the reserve was established (Galindo-Leal & Rendón-Salinas 2005).

There are 3 primary threats to the monarch butterfly in its range in North America (Brower et al. 2011a): deforestation and degradation of forest by illegal logging of overwintering sites in Mexico; widespread reduction of breeding habitat in the United States due to land-use changes and the decrease of this butterfly's main larval food plant (common milkweed [*Asclepias syriaca*]) associated with the use of glyphosate herbicide to kill weeds growing in genetically engineered, herbicide-resistant crops; and periodic extreme weather conditions throughout its range during the year, such as severe cold or cold summer or winter temperatures. These threats combined are responsible for the dramatic decline over the last decade in the number of monarch butterflies in the hibernation colonies in Mexico, which reached a 20-year low during the 2012–2013 season (E.R.-S., unpublished). From 1971 through 1999, 44% of the high-quality overwintering forest in the monarch reserve (in 1986 the reserve protected 16,110 ha) was estimated to have been

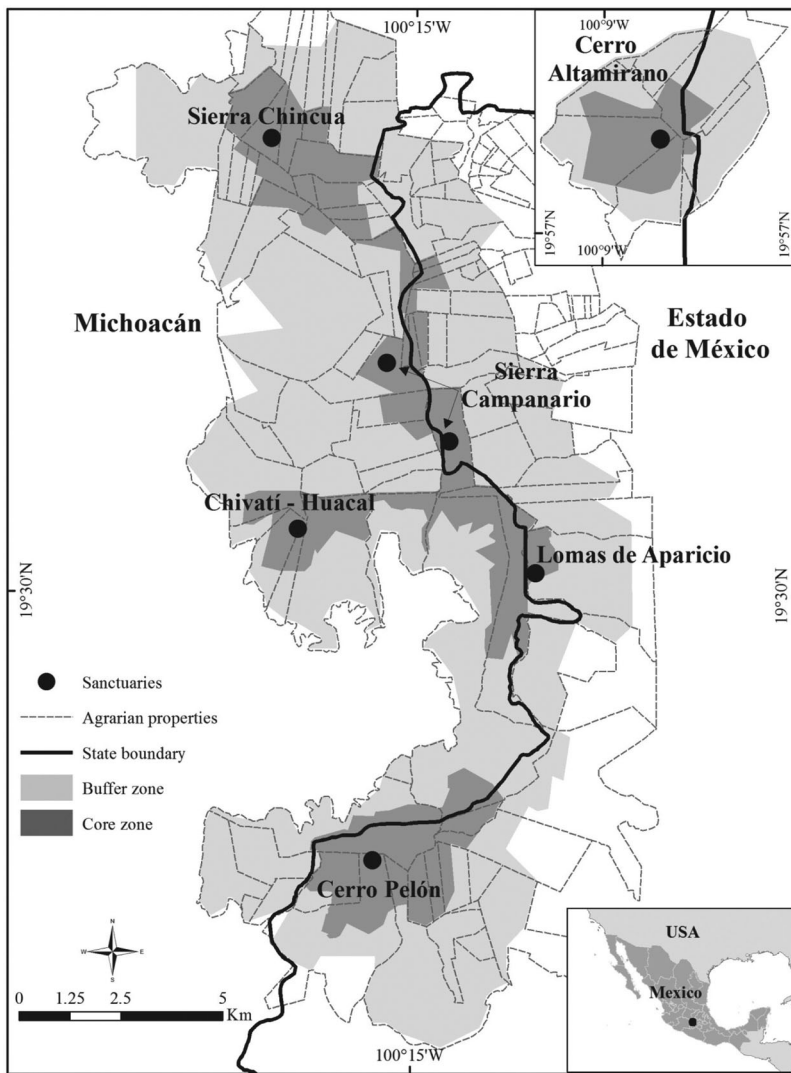


Figure 1. Overwintering sites (sanctuaries) of the monarch butterfly in Mexico.

degraded by illegal logging (Brower et al. 2002). As a result, several colonies either disappeared completely or the number of butterflies in them decreased substantially, including colonies near Cerro Pelón (Ramírez et al. 2008), Sierra Campanario (Brower et al. 2008), Cerro Altamirano, Rosario, and Sierra Chincua (Brower et al. 2011a). After 1999, increased production of genetically modified glyphosate-resistant soy and maize resulted in a significant reduction of milkweed and the loss of monarch breeding habitat in its eastern North American breeding range (Pleasants & Oberhauser 2012). Extreme weather conditions, which kill large numbers of butterflies and have become much more frequent and intense over the last few years, have severely reduced the number of butterflies migrating to Mexico in the autumn (E.R.-S., unpublished).

Following the reserve's establishment in 2000, the World Wildlife Fund (WWF) and the Mexican Fund for Nature Conservation (FMCN)—with financial support from the David and Lucile Packard Foundation, the then Mexican Secretariat of the Environment, Natural

Resources and Fisheries (SEMARNAP), and the states of Michoacán and Estado de México—established the 6.5 million monarch butterfly conservation trust fund to provide economic incentives to the landowners who lost their rights to log the forests (all monetary units are U.S. dollars unless otherwise specified). Currently, this fund has a capital of nearly 8 million, and the interest provides the money for payments to those communities that protect their forests. As trustors of the monarch fund, WWF is responsible for monitoring forest cover as the basis for providing economic incentives to the communities, and FMCN manages the trust's capital and ensures transparent and efficient disbursement. As of 2012, 34 of 38 agrarian communities participate in the monarch fund and have thus agreed to conserve their forests in exchange for economic incentives. Owners of 17 properties have wood-exploitation permits (i.e., they were legally logging their forests before the reserve was established in 2000) and received \$18/m³ of wood not logged from 2001 to 2009. In 2009, these payments were discontinued as specified in the monarch fund when it

was established, and since 2001 all agrarian properties received \$12/ha owned for conducting conservation activities such as fire control, soil restoration, and reforestation (Honey-Rosés 2009). As of 2012, the monarch fund has paid about 4.5 million directly to landowners (FMCN 2012).

We documented changes in forest cover in the reserve's core zones from 2001 to 2012 and provide recommendations for conserving the habitat of this butterfly in Mexico to ensure this unique migratory phenomenon continues.

Methods

In general, we followed the methods of Brower et al. (2002) for taking and analyzing aerial photographs and specialized digital satellite images, for geographical information system (GIS) data comparisons, and for the analyses of changes in forest cover in the reserve's core zones. We conducted biennial analyses of photographs and images obtained from 2001 to 2012, which we used to determine large (abrupt) changes in forest cover caused by large-scale illegal logging (i.e., massive logging carried out by organized groups). We compared photographs and images obtained in 2001 with photographs taken in 2011 to determine small-scale (i.e., logging of a few trees by individuals from local communities) changes that could not be detected in the biennial analyses due to the small number of trees taken each year. For example, if one hectare of mature oyamel forest has on average 500 trees and if every year 25 trees are cut, the absence of those trees cannot be detected by the biennial analyses, but this absence can be detected in a comparison of photographs taken at longer time intervals.

Aerial photographs and satellite images of the core zone were taken mostly in January or February 2001, 2003, and 2005–2012 (Supporting Information). No photographs were available for 2002, 2004, or 2007. Data for 2001 came from a limited series of photographs that covered most of the central core zone (9671 ha; Sierra de Chincua, Sierra El Campanario, and Cerro Chivatí-Huacal), and the remaining data came from a panchromatic Landsat satellite image. For the comparative analyses of 2005–2007 and 2007–2009, we used a 2007 SPOT5 satellite image that combined the multispectral image with the panchromatic image to produce a 3 m/pixel image, which we visually compared with the aerial photographs from 2005 (0.4 m/pixel) and 2009 (0.3 m/pixel). We used 2003 as our baseline for the comparative biennial analyses, which ended with the 2009–2011 comparison. We analyzed the 2012 photographs to determine whether any additional logging had occurred since the 2009–2011 period. Each year we took 200–250 photographs with small digital cameras from small

airplanes at 5332 m above sea level (Supporting Information) along the same transects (i.e., 11 paths covering all the core zones). All photographs were printed at a scale of 1:10,000 and were analyzed with a stereoscope to determine the category of forest stands (i.e., percentage of canopy). The comparative analyses were conducted visually in digital format and with a stereoscope to determine changes in forest cover (2001–2003, 2003–2005, and 2009–2011) and only visually in digital format for the analyses of photographs plus satellite images (partial in 2001–2003, total in 2005–2007 and 2007–2009).

Once the stands for each year were delimited, we digitalized them on the basis of an orthophoto corrected mosaic (prepared with Erdas Imagine geospatial data-authoring system) with aerial photographs for 2003. We then represented the orthophoto corrected mosaic in a GIS for the biennial analyses. To estimate the biennial forest changes, we overlapped the maps of forest stands with ArcGis (version 9.2). Then we superimposed a map of the agrarian properties (including *ejidos* [common land, which in Mexico is land expropriated from owners of large tracts and redistributed for use as communal farmland, especially to poor populations], indigenous community property, and private property) on the maps of forest stands to show forest changes per property. Results from aerial photographs and satellite images were validated each year in the field by a team of the local forest owners and scientific personnel from WWF, the National Commission on Protected Areas (CONANP) of the Secretariat of the Environment and Natural Resources (SEMARNAT), and the monarch fund.

For the purposes of this paper, *deforestation* refers to areas with <10% of canopy cover in a forest stand and *degradation* refers to areas for which the category of canopy forest cover changed to a category with less cover. Deforested and degraded areas are referred to collectively as *affected*. The 5 canopy-cover categories were closed (75–100% of forest cover), semiclosed (50–74.9%), semiopen (25–49.9%), open (10.1–24.9%), and deforested (0–10%).

Results

A total of 2179 ha of forest of the core zones was affected between 2001 and 2012: 1254 ha were deforested and 925 ha were degraded (Tables 1 & 2; Fig. 2). Of this, 2057 ha were affected by illegal logging (1503 ha by large-scale logging and 554 ha by small-scale logging) and 122 ha by floods, strong winds, drought, and fire (Fig. 3 & Supporting Information). In 2012, for the first time since we began monitoring the reserve in 2001, our aerial surveys detected no degradation or deforestation by large-scale illegal logging. During field visits from 2011 to

Table 1. Deforestation and degradation^a by agrarian property in the Monarch Butterfly Reserve 2001–2012.

| State | Municipality | Agrarian property ^b | Large-scale logging | | | Small-scale logging | | | Climate-related | | | Total |
|----------------------|-----------------------------|--------------------------------|---------------------|-------------|----------|---------------------|-------------|----------|-----------------|-------------|----------|--------|
| | | | deforestation | degradation | subtotal | deforestation | degradation | subtotal | deforestation | degradation | subtotal | |
| Estado de México | San José del Rincón | Ejido El Depósito | 6.59 | 14.48 | 21.07 | 4.15 | 2.05 | 6.20 | 21.07 | 2.91 | 23.99 | 27.27 |
| | | Ejido La Mesa | 45.34 | 33.64 | 78.98 | 19.61 | 11.75 | 31.35 | 21.07 | 2.91 | 23.99 | 134.32 |
| | Villa de Allende | P.P. Catingo III | | | | | | | 1.32 | | 1.32 | 1.32 |
| | | P.P. Catingo I y II | | | | | | | 0.12 | | 0.12 | 0.12 |
| | | P.P. Catingo IV | | | | | | | | 0.23 | 0.23 | 0.23 |
| | | P.P. Rancho Verde | 1.11 | 2.59 | 3.71 | 0.39 | 0.97 | 1.36 | | | 0.23 | 5.06 |
| Donato Guerra | In dispute 1 | 22.02 | 10.85 | 32.87 | 57.30 | 5.42 | 62.72 | | | | 95.59 | |
| | C. I. San Pablo Malacatepec | 4.16 | 0.91 | 5.07 | 0.86 | | 0.86 | | | | 5.93 | |
| | P.P. Cañada Seca | | | | 0.07 | | 0.07 | | | | 0.07 | |
| | Ejido El Capulín | 0.31 | 1.04 | 0.31 | 0.55 | | 0.55 | 0.41 | | 0.41 | 1.27 | |
| | P.P. Los Saucos | 1.38 | 2.42 | 2.42 | 0.31 | | 0.31 | 0.14 | 1.87 | 2.00 | 4.74 | |
| | C. I. San Juan Xoconusco | 0.12 | 2.29 | 2.41 | 0.50 | | 0.50 | | | | 2.91 | |
| Michoacán | Estado de México | Subtotal | 81.02 | 65.81 | 146.83 | 83.42 | 20.51 | 103.93 | 23.06 | 5.01 | 28.06 | 278.83 |
| | | Federal property | 22.53 | 51.73 | 74.27 | 2.70 | 4.98 | 7.68 | 1.62 | 5.15 | 6.77 | 88.71 |
| | | Ejido Hervidero y Plancha | 9.17 | 0.42 | 9.59 | 0.60 | 9.04 | 9.64 | 0.68 | 0.05 | 0.74 | 19.96 |
| | | Ejido Santa Ana | 0.39 | 1.28 | 1.66 | 3.44 | 0.49 | 3.94 | 4.74 | 7.45 | 12.18 | 17.79 |
| | | State property | | 6.87 | 6.87 | 0.96 | 0.32 | 1.29 | 2.97 | 3.07 | 3.07 | 11.22 |
| | | Ejido Jesús de Nazareno | 0.31 | | 0.31 | 3.51 | 2.14 | 5.66 | 1.02 | | 1.02 | 8.93 |
| | | Ejido Anganguco | | | | 1.21 | 1.49 | 2.70 | 1.78 | 4.13 | 5.91 | 8.61 |
| | | Ejido Los Remedios | 5.40 | 3.96 | 9.37 | | | 0.00 | | | | 9.36 |
| | | Ejido El Asoladero | 1.10 | 2.94 | 4.04 | 10.61 | 5.05 | 15.67 | 17.13 | 27.56 | 44.69 | 49.30 |
| | | In dispute RRV | 0.95 | 0.36 | 1.31 | 1.01 | 2.29 | 3.30 | | | | 4.97 |
| | | Ejido El Rosario | | | 0.00 | 1.06 | 0.64 | 1.70 | | | | 7.75 |
| | | Senguio | C. I. San Cristóbal | 1.76 | 4.29 | 6.04 | 0.45 | 3.76 | 4.21 | | | 1.67 |
| Ejido Cerro Prieto | 2.73 | | 1.96 | 4.69 | | | | | | | 7.03 | |
| Ejido Senguio | 0.29 | | | 0.29 | | | 0.00 | | | | 0.29 | |
| Ejido Chincua | | | 1.17 | 1.17 | 0.27 | 2.36 | 2.63 | | | 3.23 | 7.03 | |
| Ejido El Calabozo II | 0.63 | | 0.38 | 1.00 | 0.14 | 2.41 | 2.55 | 0.57 | 4.03 | 4.60 | 8.16 | |
| Ejido El Calabozo I | 449.27 | | 366.31 | 815.58 | 75.55 | 40.78 | 116.33 | 1.03 | | 1.03 | 932.94 | |
| Zitácuaro | C. I. Crescencio Morales | 32.69 | 58.21 | 90.90 | 4.92 | 1.66 | 6.58 | | | | 97.48 | |
| | C. I. Francisco Serrato | 255.11 | 53.24 | 308.36 | 126.33 | 111.48 | 237.81 | 5.75 | | 5.75 | 551.91 | |
| | C. I. Nicolás Romero | 7.45 | 7.22 | 14.67 | | | | | | | 14.67 | |
| | Ejido Nicolás Romero | 2.08 | 3.63 | 5.71 | 1.38 | 11.50 | 12.88 | | | | 18.59 | |
| Subtotal Michoacán | C. I. Donaciano Ojeda | | | | 2.26 | 0.62 | 2.88 | | | | 2.88 | |
| | C. I. Curunguo | | | | 0.44 | 7.43 | 7.87 | | | | 7.87 | |
| | C. I. San Felipe los Alzati | 791.85 | 563.99 | 1355.84 | 236.86 | 213.40 | 450.26 | 37.29 | 56.34 | 96.63 | 1899.73 | |
| Total core zones | Subtotal | 872.87 | 629.80 | 1502.67 | 320.28 | 233.91 | 554.19 | 60.35 | 61.35 | 121.7 | 2178.56 | |
| | Total core zones | | | | | | | | | | | |

^a Areas for which the category of canopy forest cover changed to a category with less cover.

^b Abbreviations: P.P., private property; C.I., indigenous community.

Table 2. Changes in canopy cover in the Monarch Butterfly Reserve 2001–2012.

| Type of forest effect and canopy cover category | Affected forest area (ha) | | | | | |
|---|---------------------------|-----------|-----------|-----------|-----------|-----------|
| | 2001–2003 | 2003–2005 | 2005–2007 | 2007–2009 | 2009–2011 | 2011–2012 |
| closed to semiclosed | 36 | 62 | 33 | 18 | 5 | 0 |
| closed to semiopen | 28 | 69 | 71 | 25 | 8 | 2 |
| closed to open | 2 | 32 | 107 | 23 | 6 | 1 |
| semiclosed to semiopen | 20 | 39 | 45 | 14 | 20 | 3 |
| semiclosed to open | 29 | 23 | 53 | 11 | 12 | 0 |
| semiopen to open | 21 | 23 | 44 | 21 | 6 | 1 |
| Subtotal | 136 | 248 | 354 | 112 | 58 | 7 |
| closed to deforested | 23 | 43 | 153 | 32 | 21 | 0 |
| semiclosed to deforested | 18 | 19 | 57 | 17 | 14 | 0 |
| semiopen to deforested | 63 | 62 | 93 | 40 | 23 | 0 |
| open to deforested | 49 | 93 | 75 | 36 | 4 | 0 |
| Subtotal | 153 | 216 | 378 | 125 | 62 | 0 |
| Total | 289 | 464 | 731 | 237 | 120 | 7 |

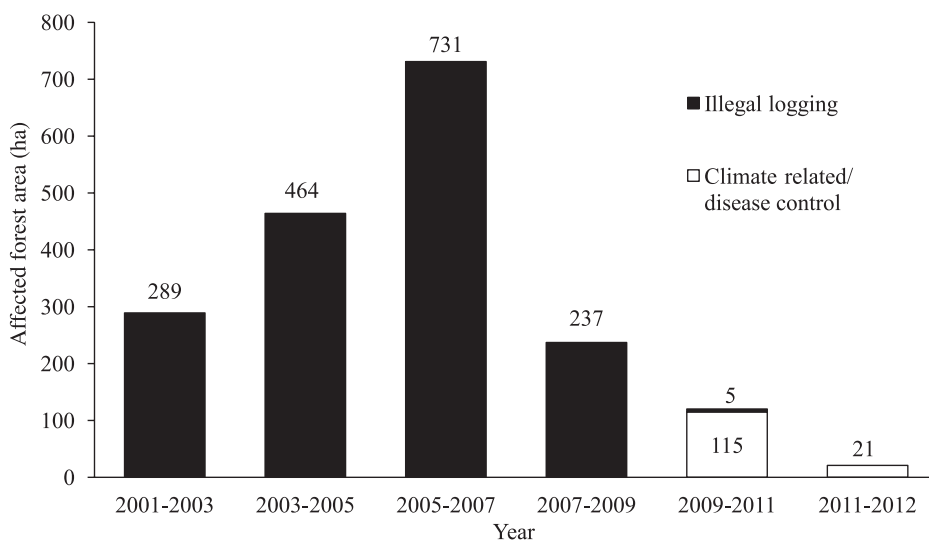


Figure 2. Areas of forest affected biennially in the core zones of the Monarch Butterfly Reserve (2001–2012). We used data for 2003 as our baseline, and hectares shown as affected in subsequent periods include areas from previous periods that were further degraded plus those additionally affected in a particular period (numbers above bars, total hectares affected by large-scale illegal logging; 115 and 21 are hectares affected by climate-related events and tree removal for disease control).

2012, we detected 21 ha affected by drought and parasitic plants (*Arceuthobium* spp. and *Psittacanthus calyculatus*) (14 ha) and by tree removal for disease control (7 ha).

Most (88%) forests affected by illegal logging were in Michoacán state (1356 ha by large-scale logging and 450 ha by small-scale logging), primarily on the agrarian properties of Crescencio Morales (816 and 116 ha, respectively), Nicolás Romero (323 and 238 ha), and Francisco Serrato (91 and 6 ha) indigenous communities and on federal land (74 and 8 ha) (Table 1, Fig. 3). In Mexico state, 251 ha (12% of total) were affected by illegal logging, mainly at ejido La Mesa (79 and 31 ha) and an agrarian property with internal land conflicts in San Jose de Villa Allende (33 and 63 ha) (Table 1 & Fig. 3). Deforestation and degradation of forest have been extensive in some locations such as Crescencio Morales, Nicolás Romero, Francisco Serrato, La Mesa, In dispute 1, and the federal land, as documented by aerial photographs (Supporting Information).

Discussion

One hundred fifteen hectares of forest were affected by floods, strong winds, droughts, and fires from 2009 to 2011, and 21 ha more were affected by drought and parasitic plants in 2012. From 2008 to 2011, the monarch reserve was affected by extreme drought (Comisión Nacional del Agua 2013) and, as a result, trees were probably subjected to stress, which renders them more susceptible to disease. Whether these anomalous weather conditions are the result of human-induced global climate change is unknown, but they represent a major threat to this butterfly throughout its range (Harvell et al. 2002; Oberhauser & Peterson 2003; Batalden et al. 2007).

Illegal logging substantially affected the core zones up to 2009, the major cause being large-scale logging to which the majority of law enforcement and surveillance efforts by both federal and state authorities have been devoted. This type of logging is probably the main cause of the disappearance of the small monarch colony on

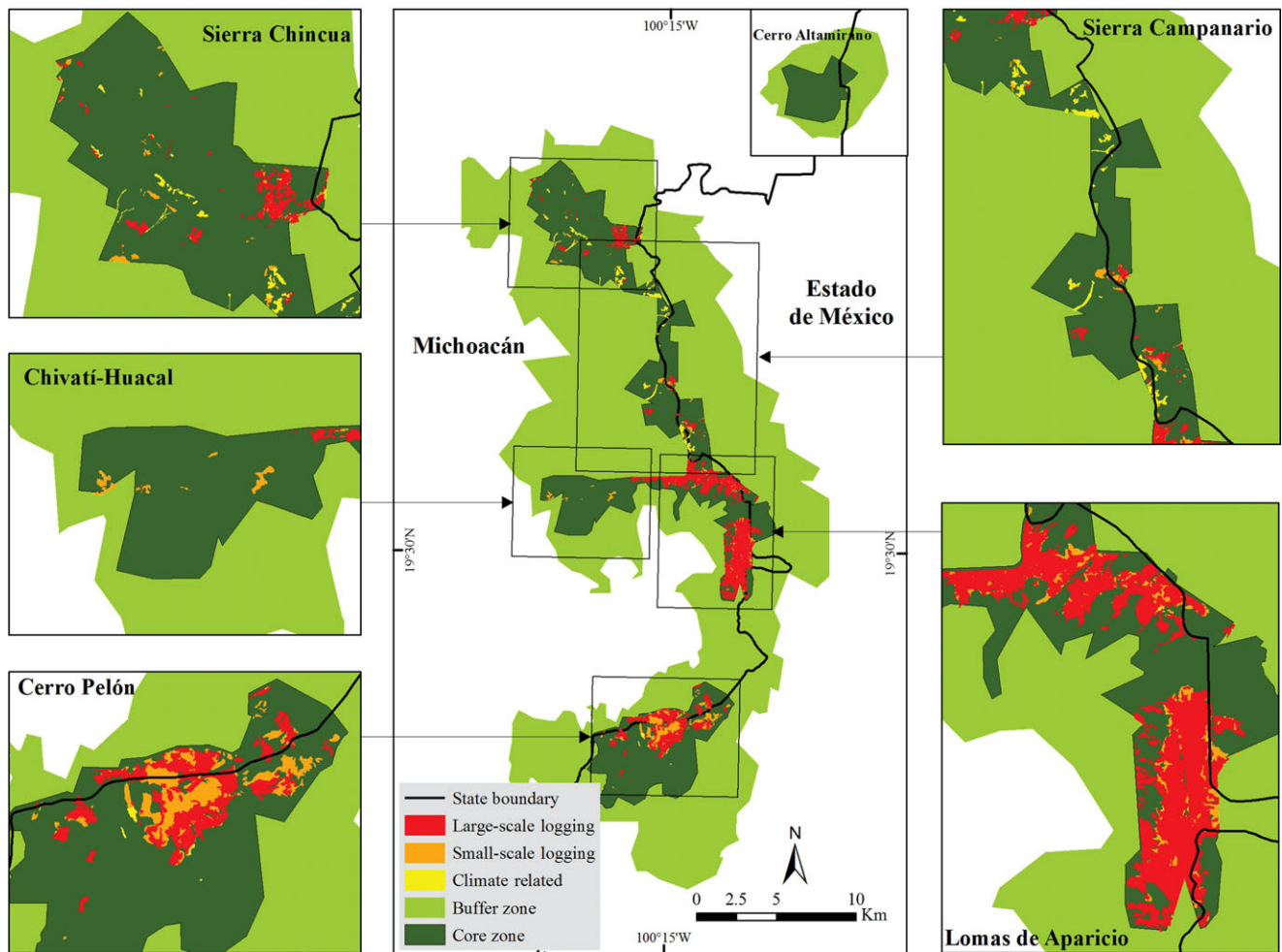


Figure 3. Large-scale and small-scale logging and climate-related events that decreased forest cover 2001–2012 in the core zone of the Monarch Butterfly Reserve.

the property of Crescencio Morales, where during the 2004–2005, 2005–2006, and 2006–2007 overwintering seasons we documented overwintering butterflies. None have been recorded in this area since 2007–2008 because the forests where they used to hibernate are gone (E.R.-S., unpublished). However, unchecked small-scale illegal logging for subsistence represents over one-fourth of the total forest affected and has thus severely affected the core zones.

We believe that the trend of reduced large-scale illegal logging that began in 2007 (Fig. 2) is a direct result of the stringent law enforcement by federal authorities, the government's payment for environmental services, and the financial support from Mexican and international philanthropists and businesses that helped to create alternative incomes and employment for local communities. We further believe that the monarch fund, in particular, played a key role by providing incentives for the communities to protect their forests.

Tackling large-scale illegal logging is challenging. As demonstrated by records from Mexico's Federal Attorney

for Environmental Protection (PROFEPA), illegal logging in the monarch reserve is a profitable activity (e.g., PROFEPA 2002, 2003, 2006–2010; Presidencia de la República 2011) (Table 3). For example, in just 2 d PROFEPA reported having seized 6000 m³ (5 December 2007) and 9475 m³ (4 December 2008) of wood.

Large-scale illegal logging was concentrated in a few indigenous communities, primarily Crescencio Morales, Nicolás Romero (both the ejido and the indigenous community), and Francisco Serrato in Michoacán and ejido La Mesa in Estado de México. Crescencio Morales alone had 45% of the total deforestation and degradation in the entire core zones between 2001 and 2009. When the monarch fund was originally designed in 2000, this community refused to participate and thus did not receive any economic incentives to protect its forests. Logging was large scale and its effects were exacerbated by internal agrarian conflicts (Rendón-Salinas 2012). In 2007, WWF engaged Crescencio Morales's authorities to convince them that protecting their forest could return better and longer economic benefits than logging them. In 2009,

Table 3. Illegal wood seized by Mexican authorities in the monarch region 2002–2011 (PROFEPA 2002, 2003, 2006–2010; Presidencia de la República 2011).^a

| Year | Volume (m ³) | Monetary value (US\$) ^b |
|-----------|--------------------------|------------------------------------|
| 2002 | 5428 | 626,300 |
| 2003 | 6402 | 738,700 |
| 2004–2006 | 4765 | 550,000 |
| 2007 | 17,000 | 1,960,000 |
| 2008 | 9475 ^c | 108,460 |
| 2009 | 1614 | 186,230 |
| 2010 | 3995 | 460,960 |
| 2011 | 1798 | 207,460 |
| Total | 41,942 | 4,838,000 |

^aFigures for volume and monetary value are minimums because large amounts of illegal wood are likely not detected or seized by authorities before entering the local market or being transported outside the region.

^bEstimated by the authors on the basis of local market price (Mex\$1500 or US\$115) per cubic meter of wood processed into wooden planks.

^cThis number was not found in the PROFEPA reports we examined, but PROFEPA officials told Mexican newspaper *La Jornada* (4 December 2008) that this wood was seized from 12 sawmills that same day (<http://www.jornada.unam.mx/2008/12/05/index.php?section=estados&article=037n1est>).

this community finally decided to join the monarch fund, and also received economic support for economic alternatives and employment (e.g., establishment of communal nurseries trees) from WWF and its partners, which promptly resulted in a sharp and steady decline in illegal logging in the core zones (Table 1, Fig. 2). A similar situation in Nicolás Romero contributed to illegal logging there, which accounted for 27% of total deforestation and degradation in the core zones between 2001 and 2009. Federal land (which is uninhabited) was also heavily affected by illegal logging.

Small-scale logging is a serious and growing concern for the conservation of the monarch sanctuaries and the reserve. Its dynamics need to be better understood so as to devise a strategy to curtail it. It was not until 2012, when we compared photographs from 2001 with those from 2011, that the considerable effect of this activity became evident, mainly in Crescencio Morales and Nicolás Romero indigenous communities. Primarily pine and oyamel fir are logged, and their wood is used mainly for local housing construction and firewood. The wood is sold locally.

In 2010 about 27,000 people lived in 93 agrarian communities within the reserve's buffer zones, 40 (38 agrarian communities, one federal property, one state property) of which were located primarily in 10 municipalities, including Angangeo, Contepec, Ocampo, Zitácuaro, Donato Guerra, San Jose del Rincón, and Villa de Allende. More than 1 million people live around the reserve, many of them are from the Mazahua and Otomí ethnic groups. Formerly based on mining and forestry, the economy of the monarch butterfly region faces seri-

ous economic challenges, mostly in the form of scarce and poorly paid jobs that encourage many to migrate seasonally to neighboring Mexican states and the United States (Galindo-Leal & Rendón-Salinas 2005) or even to pursue illegal logging as a short-term option to cope with the dire economic conditions, particularly in Michoacán. Basic services are concentrated in town centers and many villages lack electricity and water and use firewood as their main source of fuel. Local people work in agriculture, livestock production, and forestry sectors. Many also benefit from monarch-associated tourism: 87,335 people visited (November to March) the different colonies in 2002–2003, 133,263 in 2003–2004, 126,896 in 2004–2005, 54,515 in 2011–2012, and 72,591 in 2012–2013 (F. Martínez, personal communication).

Mexican federal and state authorities are to be commended for the important enforcement, as well as financial (through payment for environmental services by the National Commission on Forests of SEMARNAT) efforts to protect the monarch reserve, in particular from 2007 to 2012. Their efforts and the strategic, uninterrupted, decade-long financial support for generation of alternative income and employment (e.g., communal tree nurseries, ecotourism, community-based surveillance, and making and selling of handicrafts) by committed Mexican and international philanthropists and businesses have dramatically reduced large-scale illegal logging in recent years. In 2012 we found no forest changes caused by large-scale logging. However, more needs to be done to address the region's social and economic problems and to ensure the long-term conservation of the reserve. The forests in the buffer zones have been, and continue to be, degraded significantly by unsustainable forest exploitation, fires, grazing, and agricultural expansion (J.L.-G., unpublished), all of which would eventually play a key role in further degrading the already degraded and particularly vulnerable core zones.

Selective logging, such as both large-scale and small-scale illegal logging within the monarch reserve, usually removes only the larger and most valuable trees (Lawson & McFaul 2010). Even small openings in the forest canopy may cause a lessening in the temperature buffering provided by the oyamels at mid-heights of the forest, which are the heights where monarch butterflies form their clusters (Brower et al. 2011b). Selective logging also increases edge effects through which forest fragmentation and disturbance increase the ratio of edge-to-forest area. The long-term risks associated with this effect include increased susceptibility to wildfire, tree mortality, changes in plant and animal species, and increased human use of the land (Broadbent et al. 2008).

We believe the best conservation strategies to augment the capacity of the monarch butterfly to respond to unpredictable and changing climate-related conditions are to protect its habitat from direct human disturbances, such as illegal logging in Mexico and habitat loss and

degradation in the United States and Canada, and to restore its habitat in the 3 countries. We think a strategy needs to be devised and implemented as a matter of urgency to address the socioeconomic and environmental problems and opportunities of both the monarch reserve and the region as a whole. We suggest a substantive increase and more focused and coordinated action with regards to the payments for environmental services to the local communities and ejidos by the federal and state authorities as part of a long-term investment in sustainable economic activities, such as ecotourism and production of trees. Those investments should be better coordinated with the financial support provided by private donors and the monarch fund. Simultaneously, federal, state, and municipal authorities should implement a year-round and effective on-the-ground surveillance and law-enforcement strategy to avoid the resurgence of large-scale logging and to stop small-scale logging. Finally, we suggest implementation of a comprehensive, regional plan to create (and maintain) new and better job opportunities, improve and expand basic education for children and youth, improve basic services (e.g., sanitation, electricity, and water), all of which should be in partnership with the people living in the region and take full account of their needs and aspirations.

Municipal, state, and federal governments need to work together to ensure this region follows a path toward sustainable development. The role of the private sector and national and international organizations is also crucial. These entities need to augment their efforts and investments and strengthen their collaboration with the authorities and the local communities. Although the concentrated nature of monarch use of wintering habitat makes it easy to quantify the loss of this habitat, it is important to remember that the majority of monarchs that winter in Mexico depend on habitat in the United States and Canada for breeding and migrating. Concomitant with overwintering habitat loss, there have been large losses of breeding and migrating habitat. The direct relation between the loss of milkweed host plants in agricultural areas in the United States and the number of monarchs wintering in Mexico was recently documented by Pleasants and Oberhauser (2012). Thus, it is important that citizens; local, state, and federal government agencies; nonprofit organizations; and private donors in the United States and Canada restore and protect habitat within their own territories.

Acknowledgments

We dedicate this paper to C. Slim Helú, who constantly challenged us to look carefully at the socioeconomic dimensions of nature conservation. His engagement and support to protect the monarch reserve over the last decade is deeply appreciated. We also thank the indige-

nous communities and ejidos of the monarch reserve, H. Slim, D. Hajj, M. Velasco, J. Rocher, J. Franco, C. Galindo, C. Roberts, J. Elvira, E. Peña-Nieto, L. Cárdenas-Batel, L. Fueyo, J. Pérez, J. Rickards, P. Cendón, M. A. Álvarez, CONANP, SEMARNAT, Dirección General de Asuntos del Personal Académico at Mexico's National Autonomous University, and FMCN. The WWF's work in the reserve was possible thanks to the generous financial support of Telcel, Telmex, Carlos Slim Foundation, Yves Rocher México/France, the David & Lucile Packard Foundation, WWF-UK, WWF-US, and Altos Hornos de México. Figures 1 and 3 were prepared by A. Martínez and R. Pérez. This paper greatly benefited from the critical review and comments of E. (Eddy Joe) Pfeiler, V. Radeloff, K. Oberhauser, E. Main, and an anonymous reviewer.

Note Added in Proof

Analyses completed by the authors in July 2013 showed that 16.6 ha of forest (5.3 ha in Mexico state and 11.3 ha in Michoacán state) were degraded in the reserve's core zones in 2013: 5.02 ha by large-scale logging, 3.96 ha by small-scale logging, 3.95 ha by drought, and 3.69 ha by tree removal for disease control.

Supporting Information

Information on techniques used to monitor forest cover (Appendix S1) and aerial photographs of illegal logging in the Monarch Butterfly Reserve (Appendix S2) are available online. The authors are responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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