Quantitative Changes in Forest Quality in a Principal Overwintering Area of the Monarch Butterfly in Mexico, 1971–1999

LINCOLN P. BROWER,*†† GUILLERMO CASTILLEJA,† ARMANDO PERALTA,‡ JOSE LOPEZ-GARCIA,‡ LUIS BOJORQUEZ-TAPIA,§ SALOMON DIAZ,§ DANIELA MELGAREJO,§ AND MONICA MISSRIE**

*Department of Zoology, University of Florida, Gainesville, FL 32611, U.S.A.
†Endangered Spaces Program, World Wildlife Fund, 1250 24th Street NW, Washington, D.C. 20037, U.S.A.
‡Instituto de Geografia, Universidad Nacional Autonoma de México, México D.F., 06170, México
§Instituto de Ecologia, Universidad Nacional Autonoma de México, México D.F., Apartado Postal 70–725, México D.F. 06170, México
**Department of Conservation Biology, University of Minnesota, St. Paul, MN 55108, U.S.A.

Abstract: *Degradation of the oyamel fir-pine forest ecosystem in central Mexico is a threat to the overwintering and migratory phenomenon of the eastern North American population of the monarch butterfly (*Danaus plexippus*). Because a lack of quantitative data has hindered effective conservation policy, we photogrammatically analyzed the changing state of a major overwintering forest area. We analyzed stereographic aerial photographs of a 42,020-ha area taken in 1971, 1984, and 1999 with GRASS, a geographic information system. What in 1971 was a nearly continuous high-quality forest is now fragmented and severely degraded. Between 1971 and 1999, 44% of conserved forest (forest with >80% cover) was degraded, and the largest patch of high-quality forest was reduced from 27,115 ha to 5827 ha. The annual rate of degradation from 1971 to 1984 was 1.70%, and this increased to 2.41% during the next 15 years. At the latter rate, <10,000 ha of high-quality forest will remain in 20 years and <4,500 ha in 50 years. A subset of the analysis quantified changes in a 6596-ha area on the Sierra Chincua, Sierra Campanario, and Cerro Chivati Huacal massifs that were declared protected by presidential decree in 1986. Corresponding rates of degradation of these reserves more than tripled, from approximately 1.0% between 1971 and 1984 to more than 3% between 1984 and 1999. Passage of the 1986 decree failed to protect the forest. Our data provide irrefutable evidence that successful implementation of a more inclusive presidential decree issued in November 2000 will require (1) effective enforcement against logging within the oyamel-pine forest ecosystem and (2) restoration of areas that have been degraded. All indications are that the rate of logging is increasing throughout the area. The grandeur of the monarch butterfly overwintering phenomenon in this tiny area of Mexico is too great a cultural and biological treasure for this rampantly destructive process to continue.*

Cambios Cuantitativos en la Calidad del Bosque en un Área Principal de Hibernación de la Mariposa Monarca en México, 1971 a 1999

Resumen: *La degradación de los ecosistemas de bosque de oyamel-pino en México central es una amenaza para el fenómeno de hibernación y migratorio de la población de mariposa monarca (*Danaus plexippus*) de Norte américa oriental. Debido a que la carencia de datos cuantitativos ha limitado la aplicación de políticas efectivas, analizamos fotogramáticamente los cambios en un área de hibernación principal. Analizamos fotografías aéreas estereográficas de una superficie de 42,020 ha tomadas en 1971, 1984 y 1999 con GRASS, un sistema de información geográfica. Lo que en 1971 era un bosque de alta calidad casi continuo, actualmente esta fragmentado y severamente degradado. Entre 1971 y 1999, el 44% de bosque conservado (bosque*

††*Current address: Department of Biology, Sweet Briar College, Sweet Briar, VA 24595, U.S.A., email brower@sbc.edu*
Paper submitted December 26, 2000; revised manuscript accepted October 9, 2001.

Conservation Biology, Pages 346–359
Volume 16, No. 2, April 2002

con >80% de cobertura) fue degradado, y el fragmento mayor de bosque de alta calidad se redujo de 27,115 Ha a 5,827 Ha. La tasa anual de degradación de 1971 a 1984 fue de 1.70%, y se incrementó a 2.41% durante los 15 años siguientes. A esta tasa, <10,000 Ha de bosque de alta calidad permanecerán en 20 años y <4,500 Ha en 50 años Un subconjunto del análisis cuantificó los cambios en un área de 6,596 Ha en las cordilleras de Sierra Chincua, Sierra Campanario y Cerro Chívati Huascals que fueron declarades como protegidas por decreto presidencial en 1986. Las tasas de degradación de estas reservas se triplicaron, pasando de aproximadamente 1.0% entre 1971 y 1984 hasta más de 3% entre 1984 y 1999, El decreto de 1986 no protegió el bosque. Nuestros datos proporcionan evidencia irrefutable de que la instrumentación exitosa de un decreto presidencial más incluyente promulgado en noviembre de 2000 requerirá de (1) vigilancia efectiva contra la tala dentro del ecosistema de bosque oyamel – pino y (2) la restauración de las áreas que hansido degradadas. Todo indica que la tasa de deforestación en el área esta incrementando. La magnificencia del fenómeno de hibernación de la mariposa monarca en esta pequeña área de México es un tesoro cultural y biológico muy grande como para permitir que este proceso destructivo continúe.

Introduction

Each fall, the eastern North American population of 100–500 million monarch butterflies (*Danaus plexippus* L.) migrates to central México. Here they form dense wintering clusters on the boughs and trunks of trees growing in a high-elevation boreal-forest-like ecosystem dominated by the oyamel fir (*Abies religiosa*) (reviews by Brower 1995*a*, 1999*a*). Colonies, varying in size from about 0.5 to 5 ha, occur between 2400 and 3500 m on 12 mountain massifs in a small area of the central region of the transverse neovolcanic belt between latitudes 19° N and 20° N (L.B.-T. et al. and L.P.B. et al., unpublished data) (Fig. 1). The total forest area of the 30 or so known overwintering

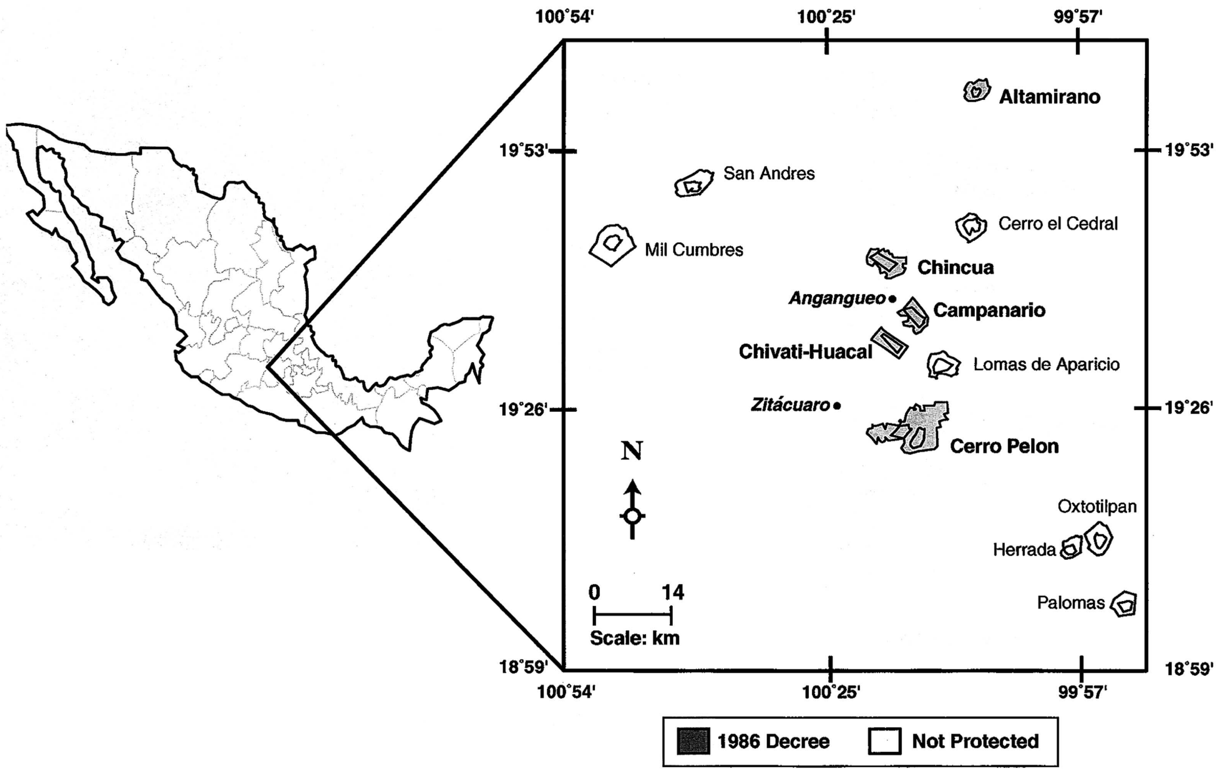


Figure 1. Locations of 12 mountain massifs on which monarch butterfly overwintering occurs in the oyamel-pine forest ecosystem of central Mexico. Total area shown is approximately 11,700 km^2. The five shaded polygons are overwintering areas protected by presidential decree in 1986 (16,100-ha). The unshaded polygons are seven additional overwintering areas that are currently unprotected. Inner polygons represent existing or proposed core zones in which no tree-cutting is allowed. Outer polygons represent buffer zones in which controlled cutting may be allowed. Topographic map references are those of Cetenal (1976, 1987).

sites varies annually from 10 to perhaps 25 ha, an area less than one-millionth that of the butterflies' spring and summer breeding ranges (Brower 1999*b*).

The fir ecosystem grades into pines at lower elevation and coincides with a 2400- to 3600-m cloud belt that forms around the peaks and enshrouds the forest with moisture during the summer wet season. Because this forest occurs within the tropics at high elevation, it provides a relatively stable microclimatic envelope that protects the butterflies from freezing due to radiational heat loss on clear, cold nights. The forest also protects the butterflies from severe rain, snow, and windstorms that occur when cold fronts penetrate the Tropic of Cancer. Adiabatic rainfall, together with fog condensation on the fir and pine boughs, provides moisture that prevents the butterflies from desiccating as the dry season advances during the 5-month overwintering season. Researchers have determined that the forest canopy must be relatively intact to maintain the microclimatic envelope that protects the butterflies from freezing, wind-buffeting, excessive wetting, and desiccation (Anderson & Brower 1996; reviews by Brower 1996, 1999*b*, 1999*c*).

Shortly after the overwintering forests were discovered in 1975 (Urquhart 1976; Brower 1995*a*, 1999*a*), numerous authors warned of their degradation due to industrial logging, charcoal production, domestic use, and the expansion of agricultural fields. Consequently, in 1980 President Jose Lopez-Portillo issued a proclamation declaring all overwintering areas of the monarch butterfly in Mexico as wildlife reserves and refuge zones that would be protected from all uses for an indefinite period of time (Lopez-Portillo 1980). Because of this proclamation's vagueness, Mexican federal agencies (Rodriguez 1984); scientists (Brower 1985; Calvert et al. 1989; Melo-Gallegos & Lopez-Garcia 1989); environmental organizations such as Monarca AC, The World Wildlife Fund, and The Group of 100 (in Aridjis 2000); and H.R.H Prince Philip, Duke of Edinburgh (Ogarrio 1984; Pyle 1984), called for a specific conservation plan. On 9 October 1986, President Miguel de la Madrid (de la Madrid 1986) issued a decree protecting 16,110 ha of forest on 5 of the 12 mountain ranges (Fig. 1).

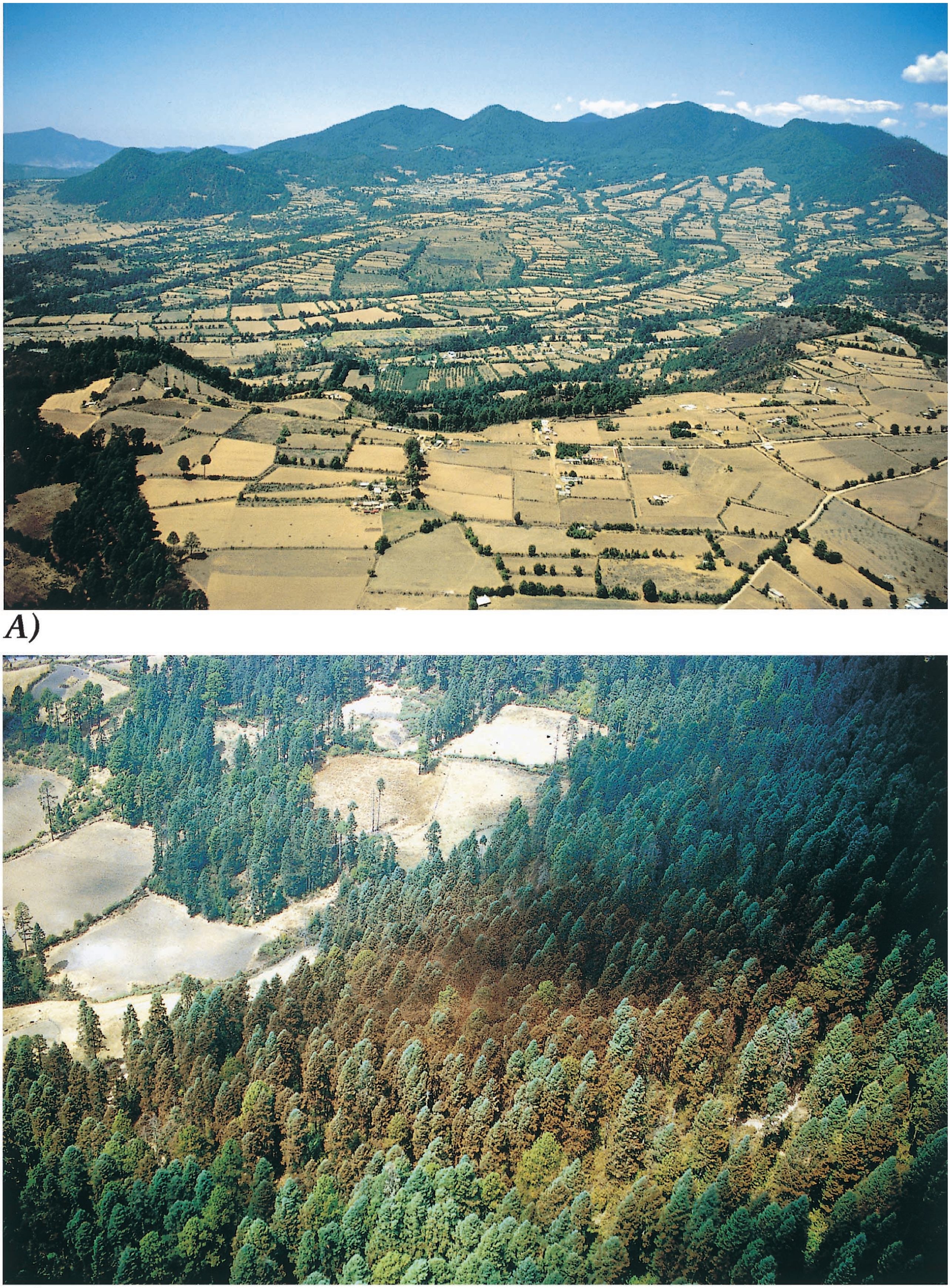
Although this decree was an important attempt to conserve the overwintering phenomenon, understanding of the ecological needs of the monarch was incomplete. Subsequently acquired data, for example, indicated that many colonies formed outside of the reserves, and large areas that were included in the reserves never hosted colonies (L.B.-T. et al., unpublished data). Of paramount importance from the biological point of view was the realization that the 1986 decree had not adequately protected the overwintering phenomenon in the context of the oyamel-pine forest ecosystem.

Moreover, the continued cutting of trees in and adjacent to the butterfly colonies elicited accusations of illegal logging, failure to enforce existing laws, and claims of the ineffectiveness of overlapping governmental-agency missions (Manzanos 1997; Hernandez & Vera 1999). Paralysis of conservation also resulted from pitting the economic needs of local human populations against the ecological requirements of the butterflies (Chapela et al. 1995; Hoth 1995 vs. Brower 1995*b*; Merino 1997, 1999; Merino & Alatorre 1997). Qualitative evidence of the general ineffectiveness of the earlier decree is evident in photographs, which show the general expansion of agricultural fields into the oyamel-pine ecosystem (Fig. 2a), specific encroachment onto the border of the Campanario Reserve (Fig. 2b), and time-documented deforestation on the southeastern border of the Chincua Reserve (Fig. 3a & 3b).

Recognizing the socioeconomic difficulties and the ecological inadequacies of the earlier decree, and under the auspices of the North American Free Trade Agreement (NAFTA), the governments of Mexico, Canada, and the United States authorized the North American Commission for Environmental Cooperation (CEC) to assemble academicians, artists, campesinos, educators, and journalists to address problems and search for solutions at an international symposium in Morelia, Michoacan, in November 1997 (Hoth et al. 1999*a*,1999*b*). The principal conclusion of the symposium was affirmation that forest exploitation, the needs of the local people (Alonso-Mejia & Alonso 1999; Barkin 1999; Hoth 1999; Masera et al. 1999; Merino 1999), and the biological requirements of the overwintering monarch butterflies (Anderson & Brower 1996; Alonso-Mejia et al. 1997) remain in severe conflict.

Following the Morelia meeting, the Mexican Ministry for the Environment, Natural Resources and Fisheries (SEMARNAP) requested the National Ecology Institute (INE) to review the social and ecological efficacy of the 1986 presidential decree. In February 1998, INE in turn asked World Wildlife Fund–Mexico (WWF) to assist in addressing the biological issues. This resulted in an international workshop in the Mexico City offices of the WWF during October 1998 that assembled monarch scientists from Canada, Mexico, and the United States. Our main charge was to synthesize up-to-date biological information and develop a revised conservation plan to assure the long-term survival of the monarch butterfly overwintering phenomenon in Mexico. An additional outcome of the workshop was recognition of the necessity to quantify the extent and rate of degradation of the oyamel-pine forest ecosystem.

World Wildlife Fund–Mexico therefore charged us to perform a geographic information system (GIS) analysis of deforestation. To do this, we analyzed aerial photographs taken during 1971, 1984, and 1999 of an area including the Chincua, Campanario, and Chivati Huacal overwintering reserves in the states of Michoacan and Mexico. We documented changes in forest quality that occurred over this 28-year period in the 42,020-ha area. We also analyzed a 6596-ha subset of the data that included these three reserves, supposedly protected by the 1986 presidential decree.



A)

B)

Figure 2. Aerial views of (a) agricultural expansion into the montane forest near the border of the states of Michoacan and Mexico, 23 March 1999, and (b) agricultural encroachment on the southwestern border of the Campanario monarch butterfly overwintering reserve, 26 February 1999. Photos are by L.P.B.

A) January 1985

B) March 1999

Figure 3. Deforestation in the protected southeastern buffer zone of the Chincua monarch butterfly overwintering reserve between (a) January 1985 and (b) March 1999. Photos are by L.P.B.

Methods

We analyzed conventional aerial photographs and digital images with standard photogrammetry and by GIS analysis in GRASS (Geographic Resources Analysis Support System, version 4.2, U.S. Army Corps of Engineers 1998). We used GRASS rather than other GIS programs because much of the original data were in this format.

We performed two separate analyses. The first digitized the data for a 42,020-ha (420.2-km^2) area photographed in 1971, 1984, and 1999. The area is bounded by the coordinates 19°43′47″ N, 100°20′38″ W and 19°30′00″ N, 100°10′15″ W, as shown on the 1:50,000 topographic maps for Angangueo (Cetenal 1987) and Ciudad Hidalgo (Cetenal 1976). The approximate elevational range within the area analyzed was 2100–3600 m. The second analysis, a 6596-ha subset of the first, included the data for three of the five 1986-decreed reserves in the Chincua, Campanario, and Chivati Huacal mountain massifs (Fig. 1) that occur in the center of the 42,020-ha region.

Aerial Images

Melo-Gallegos and Lopez-Garcia (1989) carried out a qualitative vegetation study that utilized 32 conventional black-and-white aerial stereographic photographs taken in 1971 and 1974. They did not cite the dates the photographs were taken; here we correct this omission (Table 1). They defined three deforestation categories (see below) that we used for the time periods in this study. We digitized and further analyzed their data following the procedures described below. Because most of the photographs were taken in 1971, we designated 1971 as the first time period in our study. We used the same methodology to analyze 47 aerial photographs taken of the same region in December 1983 (Table 1) and designated 1984 as the second time period in our study.

Table 1. Information on aerial photographs[a] taken in the 1970s (*n* = 32) and 1984 (*n* = 47) that were used in the analyses of Mexican forests where monarch butterflies overwinter.

Date	*Area*	*Film*	*Flight lines*	*Photo nos.*
1971[b]				
Feb	20A	2	6	1–6
Feb	20A	2	7	28–33
Feb	20A	2	8	2–9
Feb	20A	3	9	30–35
Mar[c]	20A	540	38	1–6
1983[d]				
	D.F. 151.96	—	307	Odd 85–113
	D.F. 151.96	—	308	Even 144–162
	D.F. 151.96	—	308	Even 288–298
	D.F. 151.96	—	309	Odd 261–279
	D.F. 151.96	—	309	Even 250–260

[a]*Photographs are 23 × 23 cm.*
[b]*From the federal Comision de Estudios del Territorio Nacional (CETENAL). Scale: 1:50,000.*
[c]*1974*
[d]*From the federal Instituto Nacional de Estudistica, Geografia Informatica (INEGI). Scale: 1:37,000. All were taken in December.*

For our third analysis, we obtained 334 digital images on 23 and 24 January 1999. Peralta (third author), together with his experienced crew, flew 10 paths with 60% longitudinal overlap and 30% overlap between lines to obtain stereo images with a Kodak DCS 420 digital camera. We fitted the camera with a Sigma 14-mm lens, set at F 3.5; manually focused it at infinity; set it to manual exposure, SP Program (effective film speed ISO = 100); and mounted it on a Cessna 206 aircraft outfitted for aerial photography. The plane was flown at approximately 80 knots and maintained at an altitude of 5600 m to obtain images at a scale of 1:15,000. Bubble levels mounted on the floor of the plane and on the camera ascertained that the images were taken when the plane was level; we suspended photography during turbulence. We downloaded the images from camera memory and numbered and labeled each with the flight line and direction (north to south or south to north). We color-adjusted all images in Adobe Photoshop version 3.0 and printed them on paper (12.9 × 19.5 cm) with a four-color ink-jet printer at 600-dpi resolution. We designated 1999 as the third time period in this study.

We set the area of our vegetation maps and the fragmentation analyses for all three dates to 42,020 ha. (i.e., the area approximately as mapped for 1971 by Melo-Gallegos & Lopez-Garcia 1989). All aerial images were taken during mid-dry season, when the likelihood of cloud cover and storm turbulence is minimal.

Creation of the GIS Data Layers

Quantification of the changes in the states of the forest involved four general steps: (1) Based on stereoscopic examination of the aerial images, we qualitatively designated three categories of forest status as conserved, semialtered, or altered. (2) We then circumscribed each patch of forest according to category with a closed, hand-drawn polygon on an acetate sheet that we overlaid on the aerial images. (3) We stereoscopically transferred the polygons onto a base topographic map. (4) We digitized the data.

We initially transferred the 20-m contour lines and UTM (Universal Transverse Mercator) coordinates onto base maps by making 40 × 40 cm negatives of the two 1:50,000 topographic maps. Paper or clear acetate maps were then printed from these at scales corresponding to scales of the original aerial images.

For each of the three dates, we sequentially numbered all overlapping aerial images taken along the parallel flight lines and covered each with a small, clear acetate sheet to allow inking of information with a fine-point felt marker. We determined the geometric center of each image as the point of crossing of diagonal lines drawn from corner to corner over the image. We then drew a third line through the geometric center point from left to right to allow stereo-alignment of sequential pairs of images along the parallel flight lines. A fourth line drawn perpendicularly to the flight line from the top to the bottom of each image through the center point allowed lateral alignment of the respective image pairs along the adjacent flight lines. We then used a Wild Mirror Stereoscope to stereoscopically view the overlapping sections of the aligned pairs of images. This allowed us to bound the areas of useful resolution so that distortion and inclination errors were minimized during restitution.

By stereo-viewing adjacent image pairs, we identified three categories of decreasing forest density as defined by Melo-Gallegos and Lopez-Garcia (1989): (1) conserved forest, patches in which the forest cover exceeds 80% (the forest was mostly closed and continuous but may have had small openings caused by natural or human disturbance); (2) semialtered forest, patches in which the forest cover was between 30% and 80%, with various degrees of deforestation, lower tree density, and considerable fragmentation; and (3) altered forest, patches in which the forest cover was <30% (i.e., severely deforested, with small, dispersed fragments of conserved or semialtered forest remaining). The third category included encroachments such as small human settlements, agricultural fields, and pastures.

Each discrete forest patch on the stereo-images was circumscribed with a felt marker, and each resulting polygon was numbered and designated as conserved, semialtered, or altered. Full contiguity of all polygons was mandatory, and all data code entries were verified.

We used Stereosketch (Hilger and Watts, New York) to restitute the polygons on the stereo sections of adjacent image pairs (i.e., to align them into correct geographic positions by projection onto the base map). This device allows simultaneous three-dimensional viewing of stereo pairs and monocular viewing of the base map with its 20-m contour lines and coordinates. We adjusted the stereo-image pairs to correct for inclination by using the center points and flight lines to facilitate alignment. The images were also corrected for variations in distance from the ground surface due to the mountainous topography. Once each polygon was restituted, we manually traced it onto the paper base map and indicated its vegetation category. All the data in our vegetation analyses were in a raster format; no vectorized data were used. We used a Summa Sketch III Professional digitizing tablet to register the UTM coordinates, the 20-m contour lines, the correctly positioned vegetation polygons, and their status as conserved, semialtered, or altered forest.

The next data layer, provided by Procuraduria Federal de Protección al Ambiente (PROFEPA) (Anonymous 1997), included the coordinates for the inner core and outer buffer-zone boundaries of the five reserves decreed in 1986: Altamirano, Chincua, Campanario, Chivati Huacal, and Cerro Pelon (five darkened concentric polygons in Fig. 1). The clear concentric polygons in Fig. 1 are core and buffer-zone boundaries that PROFEPA proposed for seven additional massifs where overwintering monarch colonies occur regularly. These seven polygons were unfortunately not included in the 1986 or 2000 decrees.

The final data layer compiled the coordinates of all monarch butterfly overwintering locations recorded by investigators over 22 wintering seasons from 1976–1977 through 1997–1998. The data are from Calvert and Brower (1986), PROFEPA (Anonymous 1997), and L.P.B. et al. (unpublished).

After displaying and correcting closure and other errors, we made color-coded printouts of the maps to verify the vegetation categorizations for the three time periods. Our ground-truthing was largely qualitative: none was done for the 1971 analysis, but we made qualitative ground checks with topographic maps during the summer of 1985. In May 1999 we returned to the area and verified 120 vegetation polygons with a Magellan 1500 global-positioning device and base and topographic maps. Based on this effort and overall stereo-image quality (Fig. 4), we are confident that our categorizations are accurate.

Once all the digital layers were corrected, we used a GIS to rasterize the information and manipulate the data mathematically, including changes in map scale and calculations of the areas occupied by conserved, semialtered, or altered forest for each time period. We used a subprogram of GRASS to analyze habitat fragmentation and calculate the numbers and areas of forest patches for the three time periods (Baker & Cai 1992).

The minimum area that can be mapped at any scale on our digitizing tablet was 0.5×0.5 cm (i.e., 0.25 cm^2). The scale of the printed aerial photographs for the 1971 study was 1:50,000, in which 1 cm = 500 m. At this scale, 0.5×0.5 cm is equivalent to 250×250 m (62,500 m^2; i.e., the minimal polygon size we could digitize represented 6.25 ha). The photographs for the 1984 study were printed at a scale of 1:37,000, in which 1 cm = 370 m, so that the minimum area represented by 0.25 cm^2 was 185×185 m (34,225 m^2; i.e., the minimal polygon size was 3.42 ha). In contrast, the scale of the 1999 digital images was 1:13,000, in which 1 cm = 130 m, so that the minimum area represented by 0.25 cm^2 was

Figure 4. Examples of analyzed aerial images showing changes in forest cover. Black lines are buffer and core boundaries decreed in 1986. For (a) Chincua, the cleared central area in the 1999 image is the same as in Fig. 3b. Most of (c) Chivati Huacal was clear-cut after the 1986 decree. Some (d) deforested areas showed recovery through time (three white arrows). White Cs point to monarch colonies on 23 January 1999. White dots are colony positions recorded for several years prior to 1986.

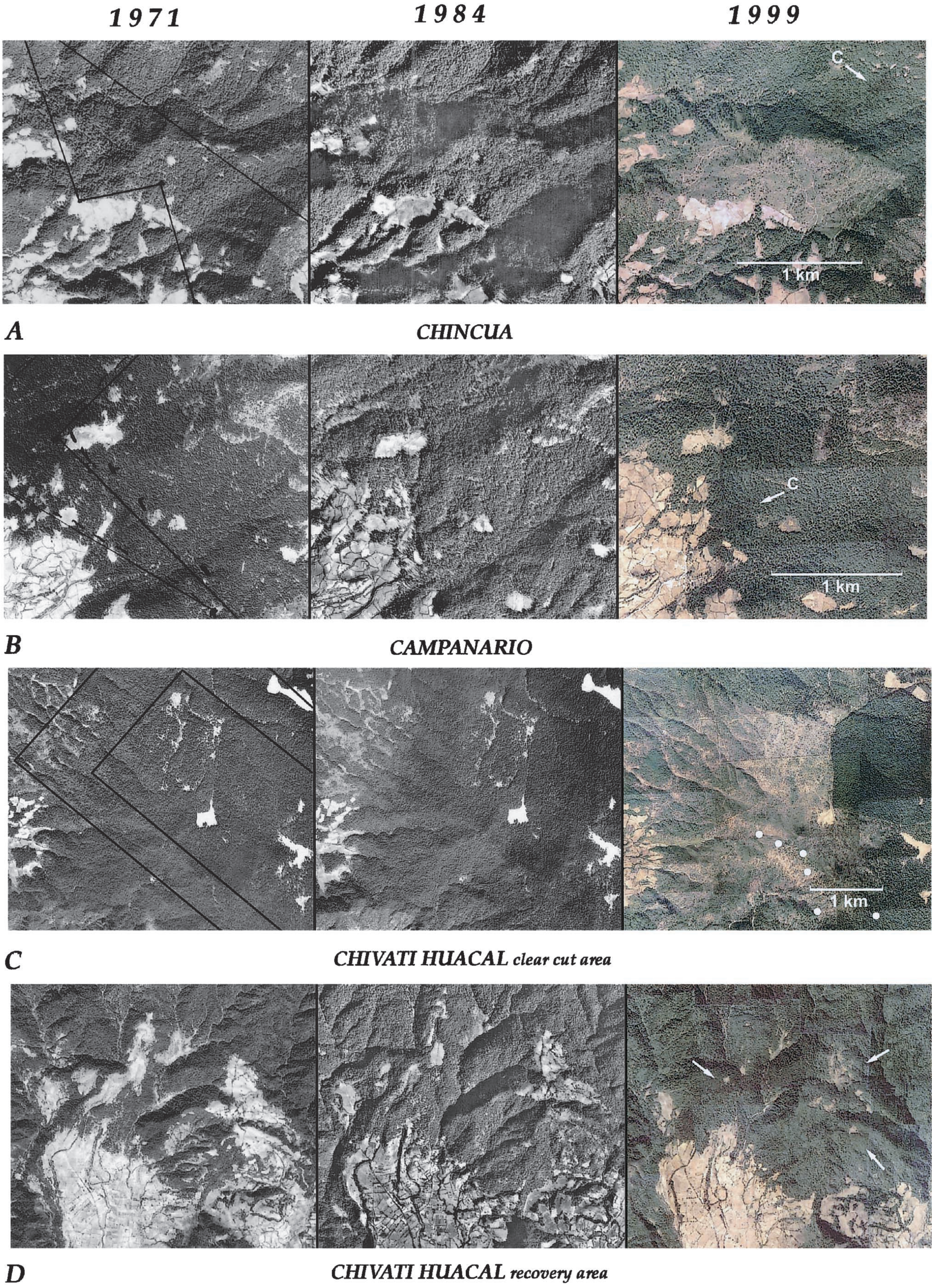

1971
1984
1999
C
1 km
A
CHINCUA
C
1 km
B
CAMPANARIO
1 km
C
CHIVATI HUACAL clear cut area
D
CHIVATI HUACAL recovery area

Table 2. Fragmentation of the forest: temporal changes in sizes (ha) and numbers of patches in three forest categories.

*Region**	*Forest category*	*Total area (ha)*	*No. of patches*	*Maximum size (ha)*	*Mean size (ha)*
42,020-ha area	conserved				
	1971	27,485	13	27,115	2,114
	1984	22,000	32	20,489	688
	1999	15,260	60	5,827	254
	semialtered				
	1971	3,975	45	628	88
	1984	6,520	121	321	54
	1999	8,220	139	603	59
	altered				
	1971	10,560	71	2,756	149
	1984	13,500	97	4,316	139
	1999	18,540	79	9,186	235
The Chincua, Campanario, and Chivati Huacal reserves	conserved				
	1971	6,101	3	2,570	2,034
	1984	5,332	9	2,227	592
	1999	3,291	13	1,802	253
	semialtered				
	1971	311	6	167	52
	1984	670	20	153	34
	1999	1,258	32	223	39
	altered				
	1971	184	8	59	23
	1984	594	22	98	27
	1999	2,047	29	1,009	72

**Both regions are shown in Fig. 5.*

65 × 65 m (4225 m^2; i.e., the minimal polygon size was 0.4225 ha). Therefore, the base resolution of the 1999 digital images was 8.1 and 14.8 times more detailed than the 1984 and 1971 aerial photographs, respectively (i.e., 3.42 ha and 6.25 ha, divided by 0.4225 ha).

The higher resolution and better stereo-imaging capability of the 1999 digital photographs allowed us to define forest-quality categories in much more detail (26 vegetation states) than in the 1971 and 1984 photographs. But to avoid errors in estimating changes in the areas of the vegetation in the three categories and in the extent of fragmentation, we used a GIS to adjust the 1999 and 1984 resolutions downward to the lower 1:50,000 1971 scale and analyzed only the three original vegetation states. We also excluded all forest patches that were <10 ha before plotting the polygon data. Thus, our data (Table 2) and map comparisons for the 3 years (Fig. 5) are conservative and underestimate the extent of both forest fragmentation and degradation. We saved all three maps as bitmap files and printed them from Adobe Photoshop.

Rates of Reduction of the Conserved-Forest Category

We calculated the mean annual rates of conversion from the conserved forest category to the semialtered and altered categories from 1971–1984, 1984–1999, and the entire period 1971–1999. Arithmetic mean rates (R) were calculated as follows, where N is the number of years between the two intervals:

$$R = 1/N(\text{area at time 1} - \text{area at time 2})/\text{area at time 1}). \quad (1)$$

To project these rates into the future, we recalculated them using the geometric-decay function of Dirzo and Garcia (1992). Accordingly, the geometric rate of deforestation (r), where n is the number of years between two successive measurements, was calculated as

$$r = 1 - [1 - (\text{area at time 1} - \text{area at time 2})/\text{area at time 1})]^{1/n}. \quad (2)$$

We then used r as derived from Eq. 2 to predict the area of forest remaining (AFR) at time t in the future:

$$AFR^t = \text{original area}(1 - r)^t. \quad (3)$$

Results

Qualitative Description of the Changing States of the Forest

The results of the three aerial surveys spanning the period from 1971 through 1999 indicate severe forest degradation (Fig. 5). The 1971 panel reflects the rationale for the boundaries of the three monarch butterfly overwintering reserves decreed in 1986. Conserved, high-quality forest predominated in the Chincua, Campanario and Chivati Huacal reserves. Extensive areas of conserved forest surrounded and interconnected the three

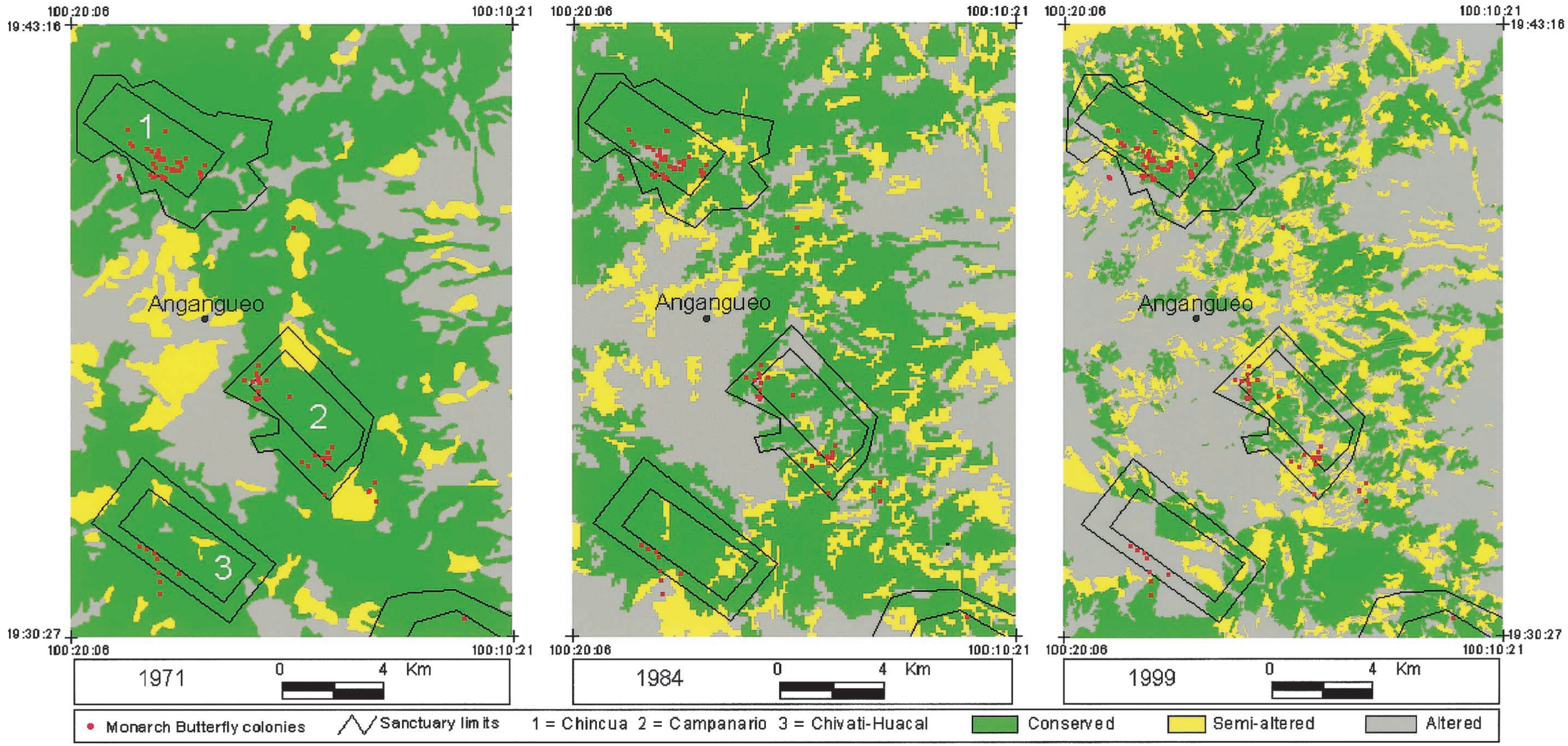


Figure 5. Changes in forest cover from 1971 to 1984 to 1999 in a 42,020-ha region of central Mexico that includes three of the 12 known massifs that serve as overwintering areas for the monarch butterfly. Three categories of forest quality are shown: conserved forest cover >80%; semialtered forest cover 30–80%; altered forest cover <30%. Numbers are the (1) Chincua, (2) Campanario, and (3) Chivati Huacal reserves depicted in the center of Fig. 1. These three reserves occupy 6596 ha. The concentric black polygons are the core (internal) and buffer (external) zones as defined by the 1986 presidential decree. A portion of the Lomas de Aparacio massif, proposed as a sanctuary by Procuraduría Federal de Protección al Ambiente (PROFEPA) (Fig. 1), is also shown (unnumbered, lower right). Red dots indicate all recorded locations of overwintering colonies from January 1977 through March 1998; they do not represent colonies that form each year.

reserves, and there was minimal forest fragmentation. Semialtered and altered forests were limited to the environs surrounding the mining town of Angangueo and the heavily inhabited area on the southwestern side of the Campanario Reserve.

Between 1971 and 1984, widespread forest alteration occurred in the areas adjacent to and between the reserves (Fig. 5). Large contiguous areas that had been semialtered were degraded to altered, and several areas within the intact forest were thinned, resulting in substantial shifts from continuous conserved forest to fragments of semialtered forest (Diaz 1996). Substantive incursions took place in the eastern part of the Chincua reserve. Both the core and buffer zones of the Campanario Reserve were subject to patchy harvesting (Fig. 5). Major harvesting on the southern flanks of the Chivati Huacal Reserve occurred, and some reduction from conserved to semialtered forest occurred within the eastern core zone. Considerable reduction from conserved to semialtered forest and fragmentation of the forest corridors between the three reserves occurred.

Between 1984 and 1999 (Fig. 5), severe forest alteration occurred both within and adjacent to the three reserves, notwithstanding the decree mandated on 9 October 1986. Clearing in the buffer zone along the southern border of the Chincua reserve reduced most of the conserved forest to altered forest (Fig. 4a), and there was substantial thinning within the core area in and adjacent to the known locations of butterfly colonies. Much of the conserved forest in the Campanario Reserve was degraded to semialtered patches. Major clearcutting in and adjacent to the Chivati Huacal Reserve removed the forest that had hosted nearly all the former butterfly overwintering sites (Fig. 4c). Comparison of the 1984 and 1999 maps documented extensive degradation of the previously conserved forest corridors that connected the three reserves. This comparison also revealed severe forest fragmentation and degradation on the eastern side of the butterfly overwintering massifs. Partial forest recovery in some areas also occurred—for example, immediately south of the Chivati Huacal Reserve (Figs. 4d & 5).

Quantitative Analysis of the Changing Forest Quality

Between 1971 and 1984, in the 42,020-ha area there was a 20% reduction (5485 ha) in the conserved-forest category, and between 1984 and 1999 a further 6740-ha were thinned and cleared (Table 2). Thus, over the 28-year period, 44% (12,225 ha) of the conserved forest was converted to the semialtered or altered categories. Deterioration of the conserved forest over the 28-year period was also indicated by the increasing number of patches and by their changing maximum and mean sizes (Table 2). During this time, the number of conserved-forest patches increased from 13 to 60, and their mean size decreased from 2114 to 254 ha. Maximum patch size also changed from 27,115 to 5827 ha, a decrease of >75%. As the conserved category was diminishing, the number of semialtered patches tripled. This magnitude of change was also indicated in the altered-forest category: mean altered patch size increased from 149 to 235 ha, and the maximum altered patch size increased more than three-fold, from 2756 to 9186 ha. The number of patches in the altered-forest category increased from 1971 to 1984, but then decreased between 1984 and 1999 because of their merging into larger, continuous areas of altered forest.

The changes in landscape in the three reserve areas that were decreed as protected in 1986 were similar to those in the entire area (Table 2). Both the mean and maximum size of the conserved-forest patches dwindled as altered patch size increased. Simultaneously, the numbers of patches in all three forest categories increased over time. Forest degradation accelerated after the decree was enacted. Thus, from 1971 to 1984, 769 ha (13%) of conserved forest were degraded, and from 1984 to 1999, 2041 ha (38%) were degraded, averages of 59 and 136 ha per year, respectively.

Rates of Reduction of the Conserved-Forest Category

The annual geometric rate of loss of the conserved forest in the 42,020-ha region was 1.70% between 1971 and 1984 and increased to 2.41% between 1984 and 1999 (Table 3). For the three reserves, the geometric rates for the same periods more than tripled, from 1.03% to 3.17%. These values reinforce our finding that, since the 1986 decree was enacted, more forest degradation has occurred in the reserve areas than in the general region.

Actual and Projected Reduction of the Conserved-Forest Category

The first three points of the two lines in Fig. 6 are data from Table 2 for the number of hectares in the conserved-forest category for 1971, 1984, and 1999. We used the geometric decay equation (equation 3) to project the decreases of conserved-forest from 1999 through 2050 (Fig. 6). If current practices continue in

Table 3. Annual rates of decrease (percent per year) of the conserved-forest category for the three time periods, calculated as mean annual arithmetic rates and as geometric-decay rates.[a]

	Region (42,020 ha)		*Three reserves[b] (6,596 ha)*	
Period	*arithmetic*	*geometric*	*arithmetic*	*geometric*
1971–1984	1.54	1.70	0.97	1.03
1984–1999	2.04	2.41	2.55	3.17
1971–1999	1.59	2.08	1.64	2.18

[a] *Rates are shown for the region and for the three reserves.*
[b] *Chincua, Campanario, and Chivati Huacal.*

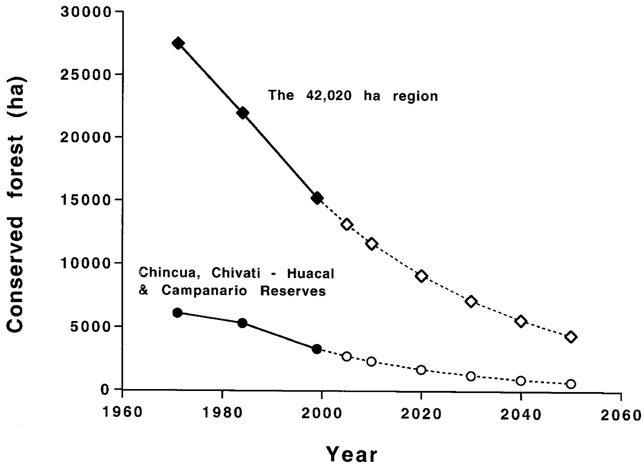


Figure 6. Actual and projected loss of conserved forest from 1971 to 2050 for the 42,020-ha region and for the 6596 ha in the three reserves of Chincua, Campanario, and Chivati Huacal. The data for 1971, 1984, and 1999 (from Table 2) are indicated by closed symbols and solid lines. The projections, based on the geometric rates of loss (from Table 3) of 2.41% for the region and 3.17% for the three reserves, are indicated respectively by open symbols and dotted lines.

the region, the remaining 15,260 ha of conserved forest will dwindle to 9144 ha by 2020 and to 4399 ha by 2050 (i.e., losses from 1971 of 67% and 84%, respectively). In the three reserves, the current 3291 ha of conserved forest will dwindle to 1675 ha by 2020 and to 638 ha by 2050 (i.e., losses from 1971 of 63% and 90%, respectively).

Discussion

A quantitative breakdown of the various causes of this forest degradation has not been made, but they include conversion of forest to agriculture and pastures, excessive commercial logging (legal and illegal), uncontrolled harvesting of wood for domestic use, charcoal production, and damage from periodic agricultural fires escaping into adjacent forests (Snook 1993; Brower & Missrie 1998). Illegal browsing and grazing by cattle and sheep add to the deterioration by preventing forest regeneration (Rendon-Salinas 1997).

Our projected rates of forest degradation are undoubtedly underestimates, because qualitative observations in the area indicate that logging rates are sharply increasing. Helicopter reconnaissance in February and March 1999 and ground reconnaissance through the fall of 2000 found extensive logging activities, numerous new sawmills, and accelerating industrial production. For example, Rexcel, a major particleboard and laminate wood company, has a manufacturing plant located in the heart of the overwintering area along Highway 15 south of Angangueo and west of Zitacuaro. Its current wood consumption is >350,000 m^3 per year, and consumption is predicted to increase (Rexcel 2000, unpublished data). Although this plant is said to purchase most of its wood from other regions of Mexico, it constitutes a virtually unlimited buyer of wood chips.

For eight states in southern Mexico, Cairns et al. (2000) estimated a mean annual deforestation rate of 1.9% between 1977 and 1992. We determined that the oyamel-pine forest ecosystem in the major area of monarch butterfly overwintering is being degraded even faster, at the rate of 2.41% in the general area and 3.17% in the three 1986-decreed reserves. Over the past 15 years, 31% and 38% of the high-quality forest in the region and three reserves, respectively, have been degraded.

Our findings reflect the limitations of mandated protection decrees as deterrents to habitat degradation. Liu et al. (2001) found a similar degradation in the Wolong giant panda reserve in southwestern China, where the rate of habitat loss and fragmentation accelerated after creation of the reserve. As in the monarch butterfly reserves, this degradation is associated with continued uncontrolled extractive activities by local communities after the reserve was created. Examples such as these two "flagship" reserves demonstrate the need for conservation schemes that take into account land and resource tenure by local communities. Studying 92 protected areas in 22 countries, Bruner et al. (2001) demonstrated that the effectiveness of protected areas in the tropics is largely a function of enforcement, boundary demarcation, and direct compensation to local communities.

Our results demonstrate quantitatively what has been qualitatively evident since 1977, namely that wood harvesting in the oyamel-pine forest ecosystem of central Mexico is extensive and accelerating. Our new data provide compelling evidence that the microclimate characteristics of the oyamel-pine forest ecosystem are in imminent danger of unraveling. The overwintering phenomenon of the monarch butterfly in Mexico will deteriorate and possibly collapse totally if this ecosystem is not effectively protected and restored.

Finally, as reported on 12 September 2000 in the *New York Times* (Yoon 2000) and in *Reforma* (Millan 2000), our data convinced SEMARNAP to revise and extend the areas that had been defined as protected under the 1986 presidential decree. Shortly thereafter, on 9 November 2000, most aspects of our proposal under the World Wildlife Fund–Mexico for a new ecosystem-based reserve (L. B.-T. et al., unpublished data) were decreed as law by President Ernesto Zedillo (Medina 2000; Zedillo 2000). This new decree expanded the monarch butterfly reserve system from 16,110 to 56,259 ha. In addition, the government approved and will help implement a new multimillion-dollar trust fund, the interest from which will be used to compensate local inhabitants for relinquishing their wood rights and to help them shift to conservation-based economies.

However good this news may seem, we end with a caveat: signing additional presidential decrees per se is insufficient. What is required is a consensual but binding agreement on limits to the extraction and use of forest products and effective enforcement linked with appropriate compensation to local communities. Field observations (Bruner et al. 2001) suggest that once anthropogenic pressure is reduced to a minimum, the oyamel-pine forest could be capable of naturally restoring most of its original structure and function in a matter of decades. The grandeur of the monarch butterfly overwintering phenomenon in this tiny area of México is too great a cultural and biological treasure for the current rampantly destructive process to continue.

Acknowledgments

We are grateful for support from The Wildlife Conservation Society of New York, The Rufford Foundation–UK, the World Wildlife Fund (WWF)-Canada, The Monarch Butterfly Sanctuary Foundation, Scion Natural Science Association, Universidad Nacional Autonoma de México, The University of Florida, and Sweet Briar College. We also thank K. Reinhold, P. Reinhold, and an anonymous donor for generous support. For manuscript critiques, we are grateful to L. Fink of Sweet Briar College, D. Perault of Lynchburg College, P. Sanchez-Navarro Russell of WWF–México, and three anonymous reviewers. Special thanks are due J. Carabias, former Minister of the Environment, and J. de la Maza, formerly of the Secretaria de Medio Ambiente, Recursos Naturales y Pesca (SEMARNAP), both of whom served under President Zedillo's administration, for their cooperation and provision of helicopter reconnaissance. Procuraduria Federal de Protección al Ambiente (PROFEPA) provided coordinates of the five 1986 butterfly reserves, several overwintering sites, and their recommended conservation areas on the seven other overwintering massifs shown in Fig. 1.

Literature Cited

Alonso-Mejia, A., and L. E. Alonso. 1999. Scientific research and social investigation priorities for the Monarch Butterfly Special Biosphere Reserve: recommendations. Pages 183–193 in J. Hoth, L. Merino, K. Oberhauser, I. Pisanty, S. Price, and T. Wilkinson, editors. Paper presentations: 1997 North American Conference on the monarch butterfly. The Commission for Environmental Cooperation, Montreal.

Alonso-Mejia, A., E. Rendon-Salinas, E. Montesinos-Patino, and L. P. Brower. 1997. Use of lipid reserves by monarch butterflies overwintering in México: implications for conservation. Ecological Applications **7:**934–947.

Anderson, J. B., and L. P. Brower. 1996. Freeze-protection of overwintering monarch butterflies in México: critical role of the forest as a blanket and an umbrella. Ecological Entomology **21:**107–116.

Anonymous. 1997. Cuenta patrimonial del recurso suelo y monitereo de la mariposa monarca 1996–1997 en la Reserva de la Biosfera Mariposa Monarca [compact disk]. Procuraduria Federal de Proteccion al Ambiente (PROFEPA), Secretaria de Medio Ambiente, Recursos Naturales y Pesca (SEMANARP) y World Wildlife Fund-México. Coyoacan, México City.

Aridjis, H. 2000. Flight of kings. The Amicus Journal **22:**26–29.

Baker, W., and Y. Cai. 1992. The v.le program for multiscale analysis of landscape structure using the GRASS geographical information system. Landscape Ecology **7:**297–302.

Barkin, D. 1999. Dos milagros: monarcas y campesinos. Pages 205–210 in J. Hoth, L. Merino, K. Oberhauser, I. Pisanty, S. Price, and T. Wilkinson, editors. Paper presentations: 1997 North American Conference on the monarch butterfly. The Commission for Environmental Cooperation, Montreal.

Brower, L. P. 1985. Biological rationale for the conservation of the overwintering sites of the monarch butterfly, *Danaus plexippus* L., in the states of Michoacan and México. Pages 66–88 in Primer simposium internacional de fauna silvestre. Secretaria de Desaarrolo Urbano y Ecologia (SEDUE), México City.

Brower, L. P. 1995*a*. Understanding and misunderstanding the migration of the monarch butterfly (Nymphalidae) in North America: 1857–1995. Journal of the Lepidopterist's Society **49:**304–385.

Brower, L. P. 1995*b*. Revision a los mitos de Jurgen Hoth. Ciencias **39** (July–September)**:**50–51.

Brower, L. P. 1996. Forest thinning increases monarch butterfly mortality by altering the microclimate of the overwintering sites in México: Decline and conservation of butterflies in Japan III. Pages 33–44 in S. A. Ae, T. Hirowatari, M. Ishii, and L. P. Brower, editors. Proceedings of the international symposium on butterfly conservation, 1994. The Lepidopterological Society of Japan, Osaka.

Brower, L. P. 1999*a*. Para comprehendar la migracion de la mariposa monarca (1857–1995). Instituto Nacional de Ecologîa, México, D.F.

Brower, L. P. 1999*b*. Biological necessities for monarch butterfly overwintering in relation to the oyamel forest ecosystem in México. Pages 11–28 in J. Hoth, L. Merino, K. Oberhauser, I. Pisanty, S. Price, and T. Wilkinson, editors. Paper presentations: 1997 North American conference on the monarch butterfly. The Commission for Environmental Cooperation, Montreal.

Brower, L. P. 1999*c*. Oyamel forest ecosystem conservation in México is necessary to prevent the extinction of the migratory phenomenon of the monarch butterfly in North America. Pages 41–50 in Proceedings of a symposium on Animal Migration, 1997. United Nations Environment Program and Convention on the Conservation of Migratory Species of Wild Animals, Bonn and The Hague.

Brower, L. P., and M. Missrie. 1998. Fires in the monarch butterfly sanctuaries in México, Spring 1998. Que Pasa (Toronto) **3:**9–11.

Bruner, A. G., R. E. Gullison, R. E. Rice, and G. A. B. da Fonseca. 2001. Effectiveness of parks in protecting tropical biodiversity. Science **291:**125–128.

Cairns, M. A., P. K. Haggerty, R. Alvarez, B. H. J De Jong, and I. Olmsted. 2000. Tropical México's recent land-use change: a region's contribution to the global carbon cycle. Ecological Applications **10:**1426–1441.

Calvert, W. H., and L. P. Brower. 1986. The location of monarch butterfly (*Danaus plexippus* L.) overwintering colonies in México in relation to topography and climate. Journal of the Lepidopterists' Society **40:**164–187.

Calvert, W. H., S. B. Malcolm, J. I. Glendinning, L. P. Brower, M. P. Zalucki, T. Van Hook, J. B. Anderson, and L. C. Snook. 1989. Conservation biology of monarch butterfly overwintering sites in México. Vida Silvestre Neotropical **2:**38–48.

Cetenal. 1976. 1:50,000 topographic map. Carta topographica, Ciudad Hidalgo. E14A25. México y Michoacan. Escala 1:50,000. San Antonio de Abad no.124, México, D.F.

Cetenal. 1987. 1:50,000 topographic map. Carta topographica, Angangueo. E14A26. México y Michoacan. Escala 1:50,000. 3rd impression. San Antonio de Abad no.124, México, D.F.

Chapela, G., Y. Mendoza, and D. Barkin. 1995. Mariposas y campesinos. Estrategia de desarrolo sustenable en el oriente de Michoacan. Centro de Ecologia y Desarrollo, A.C., México, D.F.

de la Madrid, M. 1986. Decreto por el que por razones de orden publico e interes social, se declaran areas naturales protegidas para los fines de la migracion, invernacion y reproduccion de la mariposa Monarca, asi como la conservacion de sus condiciones ambientales la superficie de 16,110-14-50 hectareas, ubicadas en los municipios que se indican, pertenecientes a los Estados de Michoacan y del Estado de México. Diario Oficial 9 Octubre **398(27):**33–41. Organo del Gobierno Constitucional de los Estados Unidos Mexicanos, México, D. F.

Diaz, N. 1996. Landscape metrics. Journal of Forestry **94:**12–16.

Dirzo, R., and M. C. Garcia. 1992. Rates of deforestation in Los Tuxtlas: a Neotropical area in southeast México. Conservation Biology **6:**84–90.

Hernandez, M. A. B., and A. D. C. Vera. 1999. Analisis critico del manejo de la Reserva Especial de la Biosfera Mariposa Monarca. 1997 North American conference on the monarch butterfly. Pages 315–322 in J. Hoth, L. Merino, K. Oberhauser, I. Pisanty, S. Price, and T. Wilkinson, editors. Paper presentations: biology, conservation, sustainability and development, environmental education. Commission for Environmental Cooperation, Montreal

Hoth, J. 1995. Mariposa monarca, mitos y otras realidades aladas. Ciencias **37:**19–28.

Hoth, J. 1999. Introduction. 1997 North American conference on the monarch butterfly. Pages 197–204 in J. Hoth, L. Merino, K. Oberhauser, I. Pisanty, S. Price and T. Wilkinson, editors. Paper presentations: biology, conservation, sustainability and development, environmental education. Commission for Environmental Cooperation, Montreal.

Hoth, J., L. Merino, K. Oberhauser, I. Pisanty, S. Price, and T. Wilkinson, editors. 1999*a*. Roundtable discussions and priority actions. Pages 1–36 in 1997 North American conference on the monarch butterfly. U.S. Fish and Wildlife Service, Office of International Affairs, Washington, D.C.

Hoth, J., L. Merino, K. Oberhauser, I. Pisanty, S. Price, and T. Wilkinson, editors. 1999*b*. 1997 North American conference on the monarch butterfly. Paper presentations: biology, conservation, sustainability and development, environmental education. Commission for Environmental Cooperation, Montreal.

Liu, J., M. Linderman, Z. Ouyang, L. An, J. Yang, and H. Zhang. 2001. Ecological degradation in protected areas: the case of Wolong Nature Reserve for giant pandas. Science **292:**98–101.

Lopez-Portillo, J. L. 1980. Decreto por el que por causa de utilidad publica se establece zona de reserva y refugio sylvestre los lugares donde la mariposa conocida con el nombre de Monarca hiberna y reproduce Presidential decree protecting the monarch in all parts of México. Diario Oficial (México, D.F.) **25 Marzo:**106–107.

Manzanos, R. 1997. La PROFEPA desecha las denucias de Aridjis sobre los santuarios de la mariposa Monarca, aunque reconoce ineficiencia en el manejo de recursos. Proceso **1091(**28 September**):**70–71.

Masera, O., D. Masera, and J. Navia. 1999. Conservacion y restauracion forestales: retos y oportunidades a partir de un estudio sistémico de la demanda de productos forestales. Pages 289–303 in J. Hoth, L. Merino, K. Oberhauser, I. Pisanty, S. Price, and T. Wilkinson, editors. Paper presentations: 1997 North American Conference on the monarch butterfly. The Commission for Environmental Cooperation, Montreal.

Medina, M. E. 2000. Triplican superficie de reserva monarca. Reforma, 10 November:17a.

Melo-Gallegos, C., and J. Lopez-Garcia. 1989. Contribucion geografica al programa integral de desarrollo mariposa monarca. Pages 9–26 in Boletin 19. Instituto de Geografia Universidad Nacional Autonoma de México, México City.

Merino, L. 1997. El manejo forestal comunitario en México y sus perspectivas de sustenabilidad. Universidad Nacional Autonoma de México, México City.

Merino, L. 1999. Reserva especial de la Biosfera Mariposa Monarca: problematica general de la region. Pages 239–248 in J. Hoth, L. Merino, K. Oberhauser, I. Pisanty, S. Price, and T. Wilkinson, editors. Paper presentations: 1997 North American conference on the monarch butterfly. The Commission for Environmental Cooperation, Montreal.

Merino, L., and G. Alatorre. 1997. Los requerimientos de la conservación y el manejo de los recursos forestales: los ejidos de El Paso y Ocampo, Michoacán. Pages 76–88 in L. Merino, editor. El manejo forestal comunitario en México y sus perspectivas de sustentabilidad, Universidad Nacional Autonoma de México, Secretaria Mexicana de Agricultura, Recursos Naturales, Agua y Pesca, Consejo Mexicano para la Silvicultura Sostenible. World Resources Institute.

Millan, D. 2000. Pierde su terreno mariposa monarca. Reforma 12 September:9a.

Ogarrio, R. 1984. Development of the civic group, Pro Monarca, A. C., for the protection of the monarch butterfly wintering grounds in the Republic of México. Atala **9:**11–13.

Pyle, R. M. 1984. International efforts for monarch conservation, and conclusion. Atala **9:**21–22.

Rendon-Salinas, E. 1997. Diagnostico de las mariposas monarca hibernantes que intentaron alimentarse y la estructura del rodal del bosque donde se agroupo la colonia del Llano del Toro en la Sierra Chincua, Mich., durante la temporada de hibernacion 1993–1994. M. S. thesis. Universidad Nacional Autonoma de México, México City.

Rexcel, S. A. de C. V. 2000. Planning for growth. http://www.worldwidewood.com/archive/tech/latin00/rexcel.htm (accessed 5 December 2000).

Rodriguez, J. J. R. 1984. Mariposa monarca. Atala **9:**9–10, 31–32.

Snook, L. C. 1993. Conservation of the monarch butterfly reserves in México: focus on the forest. Pages 363–375 in S. B. Malcolm and M. P. Zalucki, editors. Biology and conservation of the monarch butterfly. Los Angeles County Museum, Los Angeles.

U. S. Army Corps of Engineers. 1998. GRASS (Geographic Resources Analysis Support System). Version 4.2. Construction Engineering Laboratory, Champaign, Illinois.

Urquhart, F. A. 1976. Found at last: the monarch's winter home. National Geographic **150:**160–173.

Yoon, C. K. 2000. Monarch butterflies lose much of their wintering grounds. New York Times 12 September:D1, D4.

Zedillo, E. 2000. Decreto por el que se declara área natural protegida, con el carácter de reserva de la biosfera, la región denominada Mariposa Monarca, ubicada en los municipios de Temascalcingo, San Felipe del Progreso, Donato Guerra y Villa de Allende en el Estado de México, asi coo en los muncipios de Contepec, Senguio, Angangueo, Ocampo, Zitácuaro y Apor en el Estado de Michoacán, con una superficie total de 56,259-05-07.275 hectáreas. Secretaria Mexicana de Agricultura, Recursos Naturales, Agua y Pesca, México, D. F. Diario Oficial Gazette, 10 November 2000:6–29.