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Avocado Cover Expansion in the Monarch Butterfly Biosphere Reserve, Central Mexico

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Abstract: Avocado cultivation has reduced the extent of forest ecosystems in central Mexico, even in natural protected areas such as the Monarch Butterfly Biosphere Reserve (MBBR) where information on the extent and expansion dynamics of avocado cover is scant. This study aimed to identify avocado plantations within the MBBR through photo interpretation for the 2006–2018 period. Change rates of the avocado cover extent were calculated for the northern, central, and southern zones of the MBBR, and topographic attributes such as elevation, soil type, slope, and slope aspect were identified. A total extent of 958 ha is covered by avocado plantations within the MBBR. The southern zone hosted the largest area under avocado cultivation (570 ha), but the northern zone had the highest change rate between 2006 and 2018 (422%). Most avocado orchards have been established mainly in Acrisol soils, south-facing slopes, on steep hillsides, and in elevations between 2050 and 2800 m. The conversion from traditional agricultural lands has been the main mechanism for the establishment of avocado orchards. However, 40 ha under avocado cultivation derived from deforestation, mainly in the central zone. The expansion of avocado plantations could trigger environmental impacts, even threatening the overwintering habitat and the migratory phenomenon of the monarch butterflies.

Keywords: biological conservation; land-use change; Michoacán; natural protected area

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1. Introduction

Land-use change has been a relevant source of environmental degradation worldwide, a process strongly correlated with the expansion of pasture and agricultural lands, urban areas, and mining [1]. Land-use change reduces biodiversity [2], modifies the physicochemical properties of soils [3], alters hydrology [4], and increases greenhouse gas emissions [5]. The global expansion of new markets and the consumption of high-demand products, such as oil palm and soybean, have promoted land-use changes in southeastern Asia and Latin America, where these crops have been established on a massive scale in export-oriented intensive plantations [6,7].

During the last two decades, the consumption of avocados (*Persea americana* Mill.) has increased worldwide due to its known nutritional properties, as well as its potential medicinal and industrial applications [8]. Mexico is the major avocado producer in the world and supplies 66% of the global demand [9]. The state of Michoacán, located in central Mexico, provides 80% of the national production on a surface of approximately 170,000 ha [10]. Massive avocado plantations have been established in western and central Michoacán in a region known as the "Avocado strip", characterized by temperate climate and volcanic soils rich in organic matter, and is covered mainly by pine-oak forests [11]. These agro-climatic conditions allow four annual yields of avocados, producing up to 25 Mg ha^{-1} [12].

Due to the economic success of the Mexican avocado, governmental policies have prioritized an increase in production through incentives and credits, food safety programs, and support for producers to gain access to international markets [13]. At a regional level, the expansion of avocado cultivation has contributed to the reduction of poverty, social margination, and emigration indices [14]. The Mexican government intends to increase production volume up to 67% by 2030 [15], which necessarily implies the opening of new areas for avocado cultivation.

However, the expansion of the "green gold" has triggered the loss of 33% of the oak-pine forest in the Avocado strip of Michoacán, equivalent to 146,700 ha between 1990 and 2006 [16]. During that period, the land-use change rates for the establishment of avocado orchards reached 690 ha yr^{-1} [17]. A large number of avocado orchards have been established illegally, in which forest fires have been intentionally induced as a way to justify the recovery of burned areas through avocado cultivation [13,18]. The expansion of avocado cover has affected mainly oak and pine forests, whose natural distribution coincides with the optimal areas for the growth of avocado plantations [19,20].

Avocado orchard expansion has reached the region near the Monarch Butterfly Biosphere Reserve during the last 25 years. This natural protected area is located in the Mexican States of Michoacán and Mexico, where the monarch butterflies (*Danaus plexippus* Lindley) overwinter each year in montane conifer forests [21]. Avocado cultivation in the region began in 1995 when some municipalities of western and central Michoacán obtained the phytosanitary certification to export avocado to the United States, which encouraged many farmers in the state to replace their traditional crops, such as maize and bean, with avocado orchards [14], particularly after the implementation of the North American Free Trade Agreement (NAFTA) in 1994. It caused the reduction of the market price of these traditional crops and, at the same time, enhanced the exportation of avocado from Mexico and its consumption in the United States [22].

In 2018, the municipalities of Zitácuaro, Ocampo, and Angangueo, where part of the MBBR is located, obtained a phytosanitary certification for exportation [23]. Therefore, it is predictable that a substantial increase in avocado cultivation will ensue. Field-based observations suggest that avocado orchards have been established within the boundaries of the MBBR, mainly in low-elevation hillsides. However, little is known on the total extent covered by avocado orchards, as well as the spatiotemporal dynamics of their establishment and the topographic conditions on which avocado plantations grow.

Interpretation of satellite imagery is a common source for the detection, quantification, and mapping of land-use changes at a high spatial resolution [24]. Hence, this study aimed to (a) identify and estimate the area under avocado cultivation in the MBBR, (b) to assess the dynamics of avocado orchards expansion between 2006 and 2018, and (c) to identify topographic conditions such as elevation, soil type, slope, and slope aspect, on which avocado orchards are located.

2. Materials and Methods

2.1. Study Area

The MBBR is located in the boundaries of the states of Mexico and Michoacán in central Mexico, between the coordinates 19.3088° N, −100.1519° W and 19.7408° N, −100.3738° W. This natural protected area belongs to the Trans-Mexican Volcanic Belt and is formed by three montane ranges: Sierra Chincua in the northern zone, Sierra Campanario-Chivati-Huacal in the central zone, and Sierra Cerro Pelón in the southern zone. In addition, there is an external portion called "Cerro Altamirano", located northeast from the main polygon, between the coordinates 19.9914° N, −100.1661° W and 19.9515° N, −100.1114° W [25] (Figure 1).

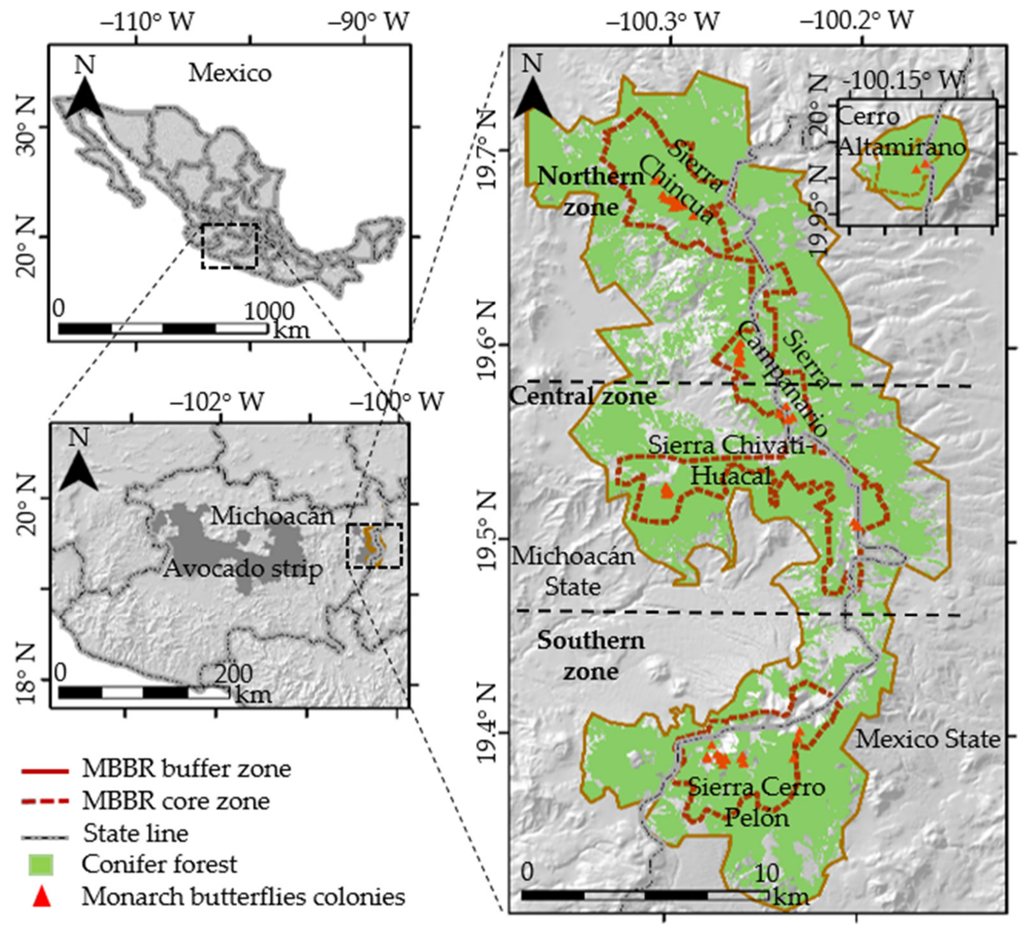

Figure 1. Location of the Monarch Butterfly Biosphere Reserve, central Mexico.

The orography of the MBBR is rugged, shaped by volcanic cones and montane plains in elevations between 2200 and 3640 m [26]. The climate is temperate subhumid in the southern zone and semi-cold subhumid in the central and northern zones. Mean annual temperature ranges, according to the zone, between 8 and 22 °C, and mean annual precipitation between 700 and 1250 mm, with rains from July to October [27]. Conifer forests are the most representative vegetation type and are dominated by sacred fir (*Abies religiosa* Schlecht et Cham) forests in elevations between 3150 and 3300 m, mixed-conifer forests co-dominated by *A. religiosa* and *Pinus pseudostrobus* Lindley (smooth-bark Mexican pine) between 2850 and 3150 m, and *P. pseudostrobus* forests below 2850 m [28]. Other vegetation types with less extent are oak forests, tropical montane cloud forests, and montane grasslands [29].

The MBBR was decreed in 1986, initially covering 16,110 ha of sacred fir forests in polygons surrounding the monarch butterfly colonies located at the highest mountain peaks, but a subsequent decree in 2000 increased the total extent to 56,256 ha, extending the polygon to lower elevations covered by mixed-conifer and pine forests, and dividing the main polygon into core and buffer zones [30]. In the core zones, productive activities such as commercial logging are not allowed. In the buffer zone, several productive activities are permitted under environmental restrictions such as commercial logging, firewood collection, mining, livestock grazing, and agriculture [25].

The land is owned by 59 *ejidos*, 13 indigenous communities, and a federal property [30]. The *ejidos* and indigenous communities have a social land property, in which management decisions are reached in assemblies [31]. Approximately 27,000 people inhabit the MBBR polygon, mainly in small rural settlements [32]. During the last two decades, illegal logging has affected sacred fir and mixed conifer forests in the core zone [33], whereas forest fires are common disturbances throughout the reserve, associated with logging, agricultural burns, and campfires [34].

2.2. Polygonization of Avocado Plantations

Landsat imagery from the years 2006, 2009, 2012, 2015, and 2018 of the MBBR main polygon was obtained from Google Earth Pro version 7.3.2 [35]. For each year, the fragments covered by avocado plantations within the MBBR were delimited through photo interpretation at a scale of 1:10,000, identifying avocado orchards according to the texture of the image shown in Figure 2. Avocado orchards were distinguished from forest plantations due to the spacing, which is usually 6 m in the former and 3 m in the latter [36].

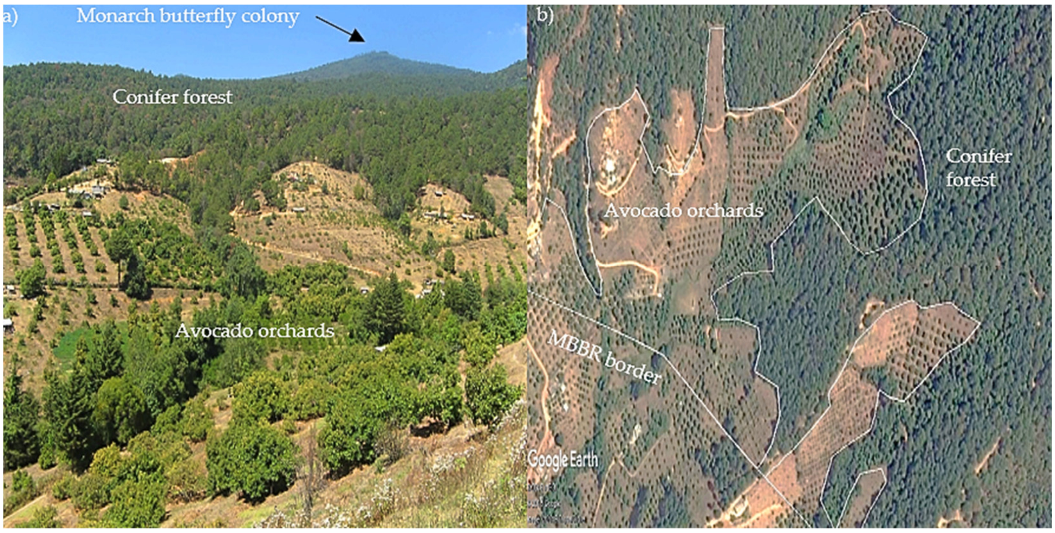

Figure 2. (**a**) Avocado orchards within the MBBR border; (**b**) polygons covered by avocado orchards seen from satellite imagery.

Photo interpretation was validated through ground-truthing of 30 georeferenced points distributed randomly over fragments classified as “avocado orchards” along the MBBR. Analysis of area under the curve (AUC) and a partial-ROC (Receiver Operator Classification) were carried out by using 50% of field-verification points as validation data, bootstrapping of 1000 replications, and an omission error less than 5%, in the Nichetoolbox [37]. Values of AUC > 0.7 and partial-ROC close to two indicate map models with a high predictive capacity [38,39]. A Z-analysis was made to evaluate whether the values of the partial-ROC differed from random, in the R software version 3.4.3 [40]. The extent of the avocado cover was estimated for each study period and zone. From the shape of the avocado cover of 2018, the elevation, soil type, slope, and slope aspect were identified. The proportion of avocado cover derived from agricultural lands or deforestation was also estimated.

2.3. Data Analysis

The land-use change rate was estimated through the following equation developed by FAO [41]:

$$t = -1 + \left[1 - \frac{S_1 - S_2}{S_1}\right]^{1/n} \quad (1)$$

where:

t = change rate;

S_1 = extent in the year 1;

S_2 = extent in the year 2;

n = number of years between S_1 and S_2.

3. Results

The map model reached an AUC = 0.94 and a partial-ROC = 1.88, values significantly different from random (df = 999, Z = 767.3, $P < 0.05$). Areas covered by avocado orchards were found along the MBBR polygon in the southern, central, and northern zones, occupying a total extent of 958 ha (Figure 3).

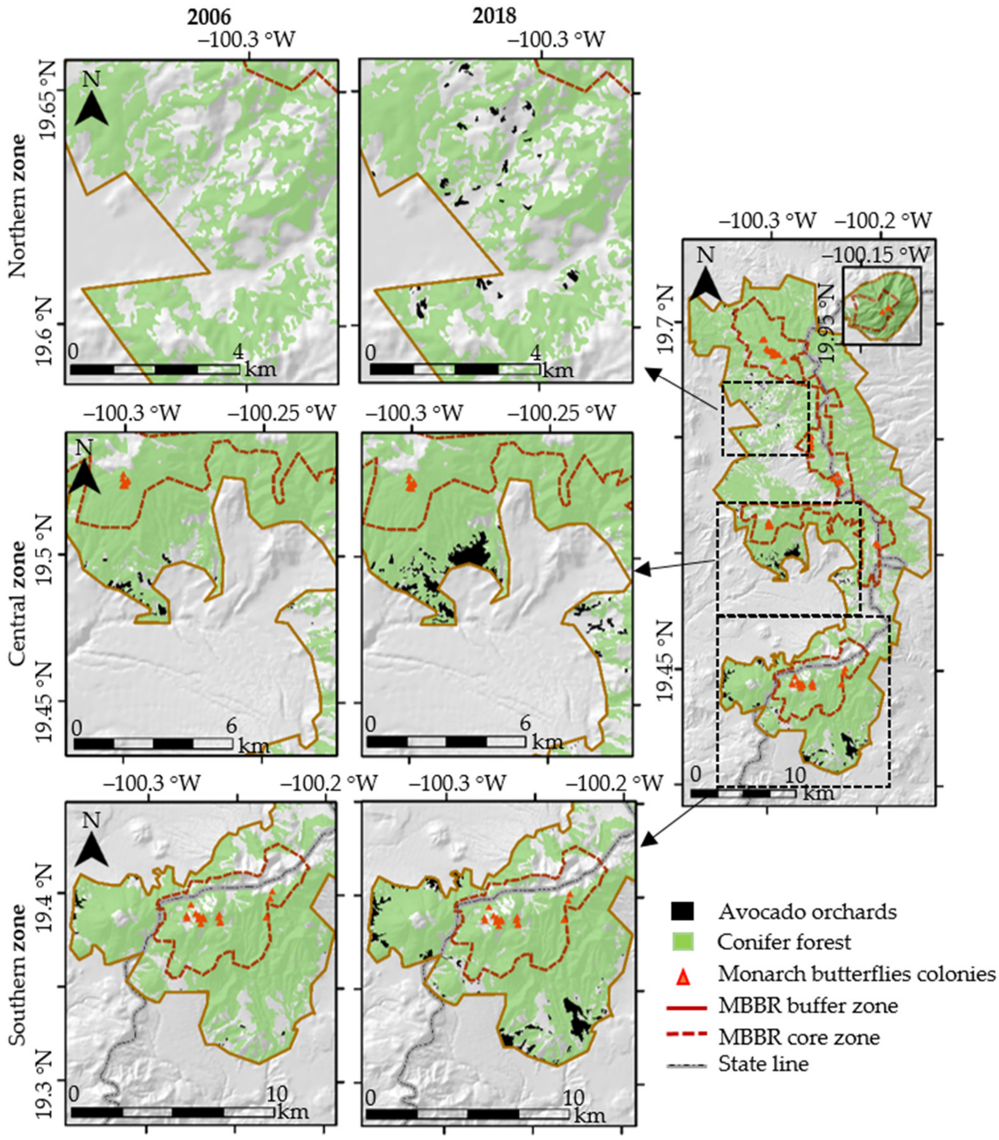

Figure 3. Expansion of avocado cultivation between 2006 and 2018 in the northern, central, and southern zones of the MBBR.

All avocado orchards were found in the buffer zone of the MBBR. By 2006, 118 ha covered by avocado plantations were identified, an extent that grew linearly in the following years (Figure 4a), whereas the change rate reached 101% between 2006 and 2018. The highest change rate was recorded between 2006 and 2009 (44%).

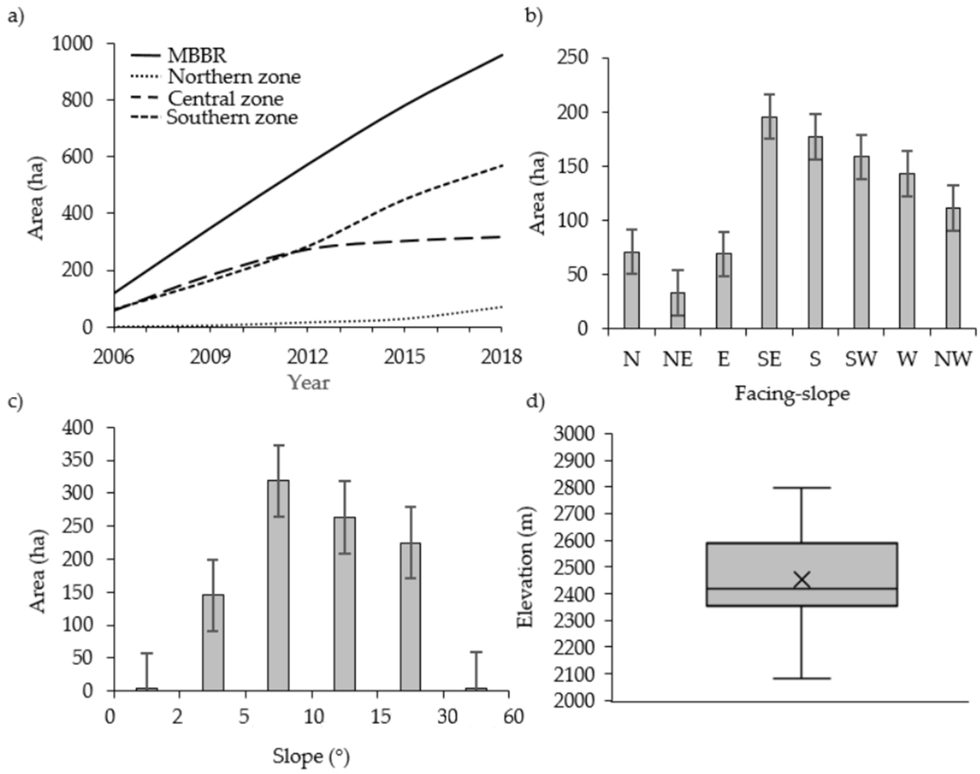

Figure 4. Area under avocado cultivation according to (**a**) year, (**b**) slope aspect, (**c**) slope, and (**d**) elevation in the Monarch Butterfly Biosphere Reserve, central Mexico.

By 2018, the southern zone had 570 ha of avocado orchards, equivalent to 59.5% of the avocado cover along the MBBR (Table 1). In this zone, the increase of avocado cover showed a linear pattern and a general change rate of 112% between 2006 and 2018 (Figure 4a). The central zone had 57.4 ha by 2006, an area that increased to 316.6 ha by 2018, with a sigmoidal pattern of avocado cover growth and a change rate of 77% between 2006 and 2018. The northern zone had the highest change rate between 2006–2018 (422%), although it had the lowest extent of avocado cover (70.8 ha). In all three zones, the highest change rates took place between 2006–2009, with 40%, 47%, and 105% in the southern, central, and northern zones, respectively.

Table 1. Area under avocado cultivation and change rates in the northern, central, southern, and all of the MBBR between 2006 and 2018.

	Area (ha)					Change Rate (%)				
Zone	2006	2009	2012	2015	2018	06–09	09–12	12–15	15–18	06–18
Southern	60.1	163.3	283.9	451.3	570.4	40	20	17	08	112
Central	57.4	182.6	273.3	302.3	316.6	47	14	03	02	77
Northern	0.5	4.2	15.7	28.3	70.8	105	55	22	36	422
MBBR	118.0	350.1	572.9	781.9	957.8	44	18	11	07	101

Most avocado orchards have been established on Acrisol (687%), followed by Andosol (29.8%) and Luvisol (1.5%) soils, as well as in Southeast- (20.3%), South- (18.4%), and Southwest-facing slopes (16.5%) (Figure 4b). Besides, 33% of the avocado cover occupied steep hillsides (slopes between 5–10%), 27.4% was found in very steep hillsides (10–15°), and 23% in rugged slopes (15–30°) (Figure 4c). The elevation ranged from 2050 to 2800 m, in which 25% of the area occupied elevations between 2050 and 2350 m, 50% of the avocado cover was found between 2350 and 2600 m, and 25% between 2600 and 2800 m (Figure 4d).

The establishment of new avocado plantations (84.3% of the avocado cover) derived from the replacement of former agricultural lands, human-induced grasslands, and areas without vegetation. Only 4% of the total extent of avocado plantations was conifer forest, equivalent to 40.2 ha. The rest of the area was avocado plantations in 2006. The highest land-use change from forest to avocado orchards happened in the central zone (24.3 ha), representing 60.5% of the deforested surface, a process that became stronger since 2015. In the northern zone, deforestation began until the 2015–2018 period, with 7 ha (Table 2).

Table 2. Area converted from forests to avocado orchards in the northern, central, southern, and all the MBBR between 2006–2018.

Zone	2006–2009 (ha)	2009–2012 (ha)	2012–2015 (ha)	2015–2018 (ha)	2006–2018 (ha)
Southern	0.8	0.5	0.3	7.2	8.9
Central	3.8	1.3	9.1	10.0	24.3
Northern	0	0	0	7.0	7.0
MBBR	4.6	1.8	9.4	24.2	40.2

4. Discussion

The photo interpretation revealed that areas under avocado cultivation have been present within the MBBR since 2006, currently occupying almost 1000 ha in the buffer zone. This area represents only 1.7% of the total extent of the MBBR (56,259 ha). However, it is the first indication of a land-use change process that could increase exponentially, as has happened in other natural protected areas in central Mexico such as the Tancítaro Peak, where the avocado plantations occupy wide areas in its buffer zone [42]. Therefore, it is imperative to stop the advance of the avocado orchards into the MBBR.

The southern zone includes 60% of the avocado cover, possibly due to the fact that it is the zone where the first avocado orchards were established in 1995 [43], and since it is warmer than the central and northern zones of the MBBR, with less frost frequency, and fertile soils (Acrisols) which provide suitable conditions for the growth of avocado plants and other crops [19,27]. The optimal conditions for agriculture in the southern zone have stimulated the opening of large agricultural fields, mainly in hillsides of *ejidos* and indigenous communities located near Zitácuaro, a city from which avocados are packed for national and international markets [43].

Although semi-cold climate conditions offer suboptimal conditions for avocado growth [44], it has not been a barrier to the establishment of avocado orchards in the central and northern zones of the MBBR. The central zone stood out by the largest extent of avocado plantations established in former forests, whereas the northern zone experienced the highest change rates. Before 2000, both zones experienced a rapid conversion from forests to agricultural lands, particularly in the lowest elevations [45]. Currently, with the expansion of avocado plantations, it is likely that in both zones there will be a second landscape transformation, from traditional crops such as maize and bean to monoculture of avocado, including new orchards at higher elevations.

The optimal elevation gradient for avocado cultivation ranges from 1600 to 2400 m since avocado plants are very sensitive to low temperatures [19,44]. However, 75% of the avocado cover is located in elevations higher than 2350 m (that is, above the optimal elevational range). Indeed, 25% of the avocado cover is already located between 2600 and 2800 m under semi-cold conditions, particularly in the central and northern zones.

Due to global warming, an increase by 1.5° of mean annual temperature is expected by 2030 in the MBBR [46], which implies that the optimal area for avocado growth also could show an increase in elevation [20]. This suggestion is consistent with observations that, in low-elevation orchards in western Michoacán, avocado trees have shown signals of severe hydric stress [47]. Therefore, an eventual elevational increase of avocado plantations would mean the replacement of current pine-oak forests, tropical montane cloud forests, mixed pine-fir forests, and even fir forests, which would imply habitat loss for the monarch butterflies and native fauna and flora. The loss of natural vegetation could also reduce the populations of endemic and vulnerable species, as well as reducing species richness in the MBBR [29].

The establishment of extensive avocado plantations could have negative effects on hillside stability. Most avocado plantations have been established in steep hillsides, which promotes adequate drainage and reduces susceptibility to root decay [36]. However, the Andosol and Acrisol soils of the MBBR are very vulnerable to hydric erosion, an issue that could worsen by establishment of avocado orchards since a common practice is a total clearing of the herbaceous layer through mechanical and chemical methods [48].

The erosion of soils in areas covered by avocado plantations ranges from 10–20 Mg ha^{-1} yr^{-1}, whereas in locations covered by preserved forest it decreases to 2 Mg ha^{-1} yr^{-1} [49]. The intensification of soil loss would increase the vulnerability to landslides, processes that have been frequent in hillsides of the MBBR, as occurred in February 2010 when an atypical rainfall event and depleted soils by illegal logging derived in massive landslides, devastating human settlements such as the towns of Angangueo and Tuxpan [50].

The conversion of agricultural lands has been the main mechanism for the establishment of avocado orchards, which is a common trend in central Mexico, where the cultivation of traditional crops, such as maize and bean, has been gradually replaced by avocado plantations [22]. Currently, deforestation has been marginal. Nonetheless, in the following years, this process could become more relevant, as has occurred in western Michoacán, where small and fragmented forests remnants are surrounded by a landscape matrix dominated by extensive avocado plantations [51]. The loss of forest cover would also reduce carbon stocks [52], as well as timber and non-timber forest resources for the inhabitants of the MBBR.

The expansion of avocado plantations within the MBBR could have other mid-term environmental impacts. On the one hand, avocados are a high water-demanding crop since they requires 90 l day^{-1} $tree^{-1}$ and 750 l kg^{-1} of fruit [53]. The high demand for water for irrigation of avocado orchards has already caused conflicts between its agricultural and domestic use in some localities south of the MBBR [54]. On the other hand, the excessive use of chemicals and organic fertilizers in avocado orchards increases the risk of diffuse pollution of aboveground and underground water reservoirs, as well as the acidification of soils [55].

In addition, the immoderate use of persistent and toxic pesticides, such as malathion and paraquat, could seriously threaten the health of day laborers [56,57]. The continuous use of pesticides has also reduced the abundance of pollinator fauna and herbaceous vegetation near avocado orchards in Michoacán [48], which could represent a direct effect on the monarch butterflies and the herbaceous plants that provide food for them, particularly during their annual arrival and departure from the MBBR. The use of anti-hail cannons has acquired relevance in avocado orchards; although their impact on fauna has not been assessed, they could disturb monarch butterflies due to the continuous detonations and shockwaves released into the atmosphere [58].

The expansion of avocado plantations in the MBBR represents a serious risk for the integrity of the forests and the migratory phenomenon of the monarch butterflies. Unfortunately, it is expected that the establishment of new avocado orchards will expand, due to the incentives received from governmental agricultural policies oriented at maintaining the first place in avocado production worldwide without taking into consideration the environmental impacts triggered by avocado expansion.

More research is needed on the environmental impacts that the expansion of avocado plantations could trigger in the MBBR, as well as the inclusion of sustainable practices of avocado production in the current production areas. Furthermore, it is necessary to implement programs of monitoring and prevention of land-use change for agricultural production in the buffer zones of the MBBR. This research represents the first effort to highlight the potential environmental impacts of the expansion of avocado plantations in a natural protected area that hosts the overwintering habitat of an emblematic species, not only for Mexico but also for the whole of North America.

5. Conclusions

The cultivation of avocados has shown sustained growth since 2006, reaching a current total extent of 958 ha in the buffer zone, particularly in the southern zone of the MBBR, which includes 60% of the avocado cover. Our data also suggest an elevational shift of avocado orchards into sites with semi-cold climatic conditions, found in the central and northern zones, although they are not suitable for avocado growth The main mechanism for the establishment of avocado orchards has been the replacement of traditional croplands. However, deforestation has taken place since 2015. The massive establishment of new avocado orchards could trigger environmental impacts on forests, hydrology, soils, and biodiversity, including the integrity of the monarch butterfly's migration.

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