Butterfly Mortality and Salvage Logging

from the March 2016 Storm in the Monarch Butterfly Biosphere Reserve in Mexico

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A severe late spring storm in central Mexico in March 2016 that struck the Monarch Butterfly Biosphere Reserve was unique because it was accompanied by high-velocity winds that eliminated the normal thermal protection provided by the Oyamel fir forest. Temperatures throughout the forest merged with the colder open-area ambient temperatures. The storm was in effect a rain and snow storm sandwiched within a powerful and sustained wind storm, followed by lethal freezing that killed 31–38% of the butterflies in the Sierra Chincua and Cerro Pelón overwintering colonies. Several lines of evidence point to greater than 40% mortality of monarchs in the Rosario colony. Our estimates are a five-fold increase over the 7.4% mortality reported by the press. Tens of thousands of trees were blown down and subjected to extensive salvage logging in the Core Zone of the Reserve. This loss of canopy cover will diminish the normal microclimatic protection provided by the intact forest. The unexpected effects of this storm may take place at greater frequency in an era of changing climate.

Research summarized in Williams and Brower (2015) has shown that the intact Oyamel forest ecosystem provides microclimatic protection of the overwintering monarch butterflies (*Danaus plexippus* L.) by acting as a blanket that holds heat beneath the forest canopy, as an umbrella that reduces wetting of the butterflies clustering on the tree boughs, and as a heat source from the tree trunks radiating warmth that protects the butterflies clustering on the trunks from freezing. Although several past winter storms have struck the overwintering area (Calvert et al. 1983, Marriott 1996, Taylor et al. 2000, Brower et al. 2004, Taylor 2004, Brower et al. 2009), the March 2016 storm was exceptionally severe, with intense and continuous wind in combination with rain, snow, and lethally cold temperatures. In this paper, we describe this storm and how the severe wind obliterated the microclimatic protection by homogenizing sub-freezing temperatures throughout the Oyamel fir forest ecosystem and the effect this had upon the butterflies. We also provide the first quantitative estimate of butterfly mortality caused by the storm, and we describe and address potential effects of the authorization to permit the salvage logging of tens of thousands of trees blown down by the storm.

Historical Decline in the Numbers of Overwintering Butterflies

Over the past 24 years, the numbers of monarch butterflies overwintering in Mexico, as measured by the combined area of forest occupied by all known colonies, declined by 90%, from a high of 18.2 hectares during the 1996–1997 overwintering season to a low of 0.67 hectares in 2013–2014 (Brower et al. 2012, Vidal and Rendón-Salinas 2014, Rendón-Salinas and Tavera-Alonso 2014). In the 2014–2015 season, the numbers increased slightly to 1.13 ha, but that was still the second lowest number in the historical record (Rendón-Salinas et al. 2016). The severe

Fig. 1. Snow on 10 March 2016 on the northeastern face (in the background) of the Sierra Chincua along the border of the Monarch Butterfly Biosphere Reserve near Palo Amarillo (photo by Raul Zubieta).

Fig. 2. Lethally threatening rime ice on Oyamel firs the morning after the storm (11 March 2016) on the Llano de los Villalobos near the overwintering colony on the Sierra Chincua (photo by Isabel Ramírez).

decline resulted in widespread press coverage (Partlow 2014, Stevenson 2014, Wade 2014, Wines 2014) expressing concern that the migration and overwintering phenomenon might be on the verge of extinction, as had been predicted by Brower and Malcolm (1991). The dwindling population was formally addressed on 26 August 2014 in a petition to the U.S. Fish and Wildlife Service to designate the monarch butterfly migration as a threatened phenomenon (Center for Biological Diversity et. al. 2014). Following that, a multidisciplinary study concluded that the eastern North American population of the butterfly is at substantial risk of extinction (Semmens et al. 2016). Modeling the overwintering numbers over a 22-year period (1993–2014), the authors pointed out that the historical fluctuations and the precipitously small recent number of hectares occupied by the butterflies have resulted in the eastern North American population approaching what they termed "a quasi-extinct population," defined as a population with so few individuals remaining that recovery becomes impossible. Their model predicted that if the overwintering area declined to between 0.01–0.25 hectares, a quasi-extinction probability over 20 years would reach 11–57%. The study concluded that reducing the probability of extinction by 50% over the next two decades will depend on increasing the size of the breeding population in the U.S. and Canada, in turn leading to an increase in the area occupied in Mexico by up to at least 6 ha, with a goal of doing so by 2020.

The 2015–2016 overwintering season heralded moderately good news: on 26 February 2016, World Wildlife Fund–Mexico together with two Mexican government agencies, SEMARNAT (The Secretary of the Environment and Natural Resources) and CONANP (The National Commission of Protected Natural Areas), reported that the area measured during the second half of December 2015 had increased from 1.13 ha in December 2014 to 4.01 ha (Rendón-Salinas et al. 2016). The press (Burnett 2016) responded to the positive news, quoting Daniel Ashe (Secretary, U.S. Fish and Wildlife Service): "Our task now is to continue building on that success" (see also Associated Press 2016a). Williams (2016) immediately responded to the optimism by urging caution in interpreting the increase, warning that it was for one year in a general 20-year downward trend, and that "the challenges facing monarchs remain." Two weeks later (7–11 March 2016), a severe and unusually late winter storm struck the overwintering area and, with speculation on the likely mortality, was reported as a "heartbreaking development" (Cave 2016).

Here, we describe the 7–11 March 2016 storm and analyze weather data recorded on the Sierra Chincua that indicate that the intensity and seeming uniqueness of the storm had heretofore unseen effects on the microclimatic protection that the Oyamel fir forest ecosystem normally provides the overwintering butterflies (Williams and Brower 2015). Based on our weather data and the known freezing resistance physiology of monarchs, we estimate the mortality that the storm might have caused. We then present field censuses of mortality in the Pelón and Chincua overwintering colonies and estimate that mortality was higher in the Rosario colony. Finally, we address the official decision to allow extensive post-storm salvage logging and the likely negative impact it will have on the microclimate of the Reserve.

Qualitative Description of the 7–11 March 2016 Storm

Personal and press reports (Rangel 2016, Romero 2016) stated that the four-day storm in Angangueo (the town located near the center of the Reserve at 2,630 m elevation) began with winds early in the morning of 7 March that built to a maximum in the afternoon of 9 March and ended early in the morning of 11 March. Rain commenced on the afternoon of 8 March, continued for at least 16 hours through the afternoon of 9 March, and changed to snow at higher elevations (Romero 2016; Zubieta, pers. comm.). Severe west-to-east winds caused widespread damage to rooftops, power lines, power transformers, and trees. Sleet and 4–5 cm hail fell on Angangueo, and up

Fig. 3. Downed Oyamel fir tree in the Arroyo Hondo adjacent to the monarch colony on the Sierra Chincua, 17 March 2016, one week after the storm (photo by Abbid Hernández).

to 10 cm of sleet fell below the entrance to the Rosario overwintering colony area. At higher elevations, snow was widespread, including on the Sierra Chincua (Figs. 1, 2), the Sierra Campanario, Cerro Pelón, and the San Andrés massif to the west of the Reserve (Rangel 2016; Romero 2016; Zubieta, pers. comm.; pers. observation).

A result of the storm was a widespread downing of trees. Local observers reported that after it cleared, "trees of all sizes were toppled everywhere" (Sharp 2016) near the Cerro Pelón, Sierra Chincua (Figs. 3–6), and Rosario monarch overwintering colonies. Major winds downed about 11 huge Oyamel firs adjacent to the Rosario butterfly colony (Fig. 7), and the violent winds stripped small and large fir and pine branches that littered the ground (Figs. 5, 6). On 5 ha in Zitácuaro, Michoacán, 30 white cedar trees 30 to 35 years old and up to 1.1 m in diameter were felled by "50 km/hr west-to-east winds during the day and night of 9 March" (Span, pers. comm.). The extent of the storm is emphasized by the fact that this location is at substantially lower elevation and 23 km southeast of Angangueo (19.4275°N, 100.3804°W; 1,835 m elevation). The subsequent cold nights led to the persistence of sleet, hail, and snow for about a week. Numerous estimates were made about the severity of the storm and the damage it had caused. On 11 March, a local community spokesman for the Rosario overwintering area said that up to 35 cm of snow had fallen, that heavy winds had blown down about a thousand trees, and that 5% of the butterflies had been killed (Mendez 2016). Local forest rangers familiar with the Cerro Pelón butterfly colony estimated that 25% of the butterflies were killed (Sharp 2016). On 23 August, World Wildlife Fund and Fondo Monarca (2016) reported

Fig. 4. Downed Oyamel fir trees along the ridge above the Arroyo Hondo monarch colony on the Sierra Chincua, 11 March 2016; tree falls are from west to east (photo by Isabel Ramírez).

Fig. 5. Tangle of Oyamel firs downed in the Arroyo Hondo overwintering area of the monarch butterfly on the south face of the Sierra Chincua, 28 March 2016 (photo by David Kust).

that trees in 54 hectares of forest in 28 communities in the Core Zone of the Reserve had been blown down. On 23-24 August, the Associated Press (Stevenson 2016, Associated Press 2016b, Ciudadanía Express 2016) cited Alejandro del Mazo (Commissioner for Natural Protected Areas), saying "the storm also appears to have frozen or killed about 6.2 million butterflies, almost 7.4 percent of the estimated 84 million butterflies that wintered in Mexico." Through 1 April 2017, no quantitative counts of the butterfly mortality nor of fallen trees had been published.

Quantitative Description of the Storm

Weather Stations. We recorded weather parameters from 5–16 Mar 2016 and compared temperatures in an open clear area with those beneath the adjacent Oyamel fir forest canopy. Our weather station (WeatherHawk Model 232, Logan UT; new in fall, 2012) was located on the eastern side of the Sierra Chincua in a level, open, grassy area of the El Llano de las Papas Field Station (19.6617ºN, 100.2681ºW) at an elevation of 3,160 m (Brower et al. 2009). The area is surrounded by Oyamel fir forest, is within the altitudinal range of the overwintering colonies on the Sierra Chincua, and is 2–4 km ESE of where monarch colonies have formed almost every year since first discovered in 1975 (Fig. 2 in Brower et al. 2016b). The WeatherHawk recorded weather parameters hourly with a stated temperature accuracy of ±0.5ºC. Data were also available from a nearby Mexican government weather station (Model FTS, Servicio Meteorológico Nacional 2016; http://smn.cna.gob.mx/es/variables-meteorologicas) located 1.4 km northwest of Chincua Station on a hill (Llano de los Villalobos) at 19.6708ºN, 100.2775ºW, at an elevation of 3,255 m (95 m higher than Chincua Station). Solar averages were converted to clearness values following Liu and Jordan (1960).

Fig. 6. Fir branches and debris on forest floor in Arroyo Hondo adjacent to the Sierra Chincua monarch colony on 17 March 2016, one week after the storm (photo by Abbid Hernández).

Fig. 7. Oyamel fir blown down along the trail leading up to the Rosario overwintering colony on 13 March 2016 (photo courtesy Journey North).

iButtons. We used small (1.57 x 0.67 cm) digital temperature recording devices (Model DS1921G-F50 Thermochron/Hygrochron iButtons, Maxim Integrated Products, Dallas Semiconductor, Embedded Data Systems LLC, Lawrenceburg, KY, USA) to measure the ambient temperatures in and adjacent to the forest at Chincua Station. These sensors recorded air temperature each hour in 0.5ºC increments with a stated accuracy of ±1ºC for thermochrons and ±0.5ºC for hygrochrons. One iButton hygrochron was positioned on the Chincua weather station and nine iButtons (8 thermochrons, 1 hygrochron) were placed on Oyamel fir trees beneath the surrounding forest canopy. The forest iButtons were installed on 10 cm posts on the north side of the tree trunks at 2 m height (Brower et al. 2009). All nine trees were still intact after the 2016 storm, even though several nearby Oyamels had been blown down. The first forest iButton was in the forest about 80 m from the Chincua weather station, and the rest were placed at intervals along an 800 m transect leading upslope in a north-northwest direction from approximately 3,180 to 3,280 m (further details in Brower et al. 2011).

Measurements of the Storm

Temperature in the clearing and beneath the forest. On 5–6 March, before the storm began, the normal winter clear weather thermal pattern prevailed, with the temperature in the clearing dropping below freezing in the early morning and rising to nearly 20ºC by midday (Fig. 8A). The temperatures within the forest show the same daily pattern but are warmer (above freezing) during the early morning and cooler during midday. On 7–8 March, the temperatures between the clearing and inside the forest began to merge, remaining above freezing and with minimal increase during midday. Then the difference in forest and clearing temperatures virtually disappeared from 8 March through the early morning of 11 March, as wind reached high speeds (Fig. 8C). On the night of 11 March, following clearing, the temperature in the open clearing ranged from -5.2º to -5.9ºC from approximately 04:00 to after 07:00. Most of the forest temperature readings were below -4.0ºC for four hours. We have not previously measured this merging of clearing and forest temperatures, and we attribute it to the increasingly strong and sustained wind speed from 7–11 March (Fig. 8C).

Thus, the wind obliterated the thermal blanket protection of the butterflies that is normally provided by the forest microclimate. It is likely that water on the butterflies wetted by the 8–10 March rain (Fig. 8B) began to freeze late on 10 March, frosting (but not yet killing) the butterflies through the early hours on 11 March. Immediately following the deep freeze on the clear morning of 11 March, the temperature began recovering to the normal cyclical pattern of daily highs and nightly lows and regaining the typical strong daily difference between the temperatures in the open compared to those beneath the forest canopy.

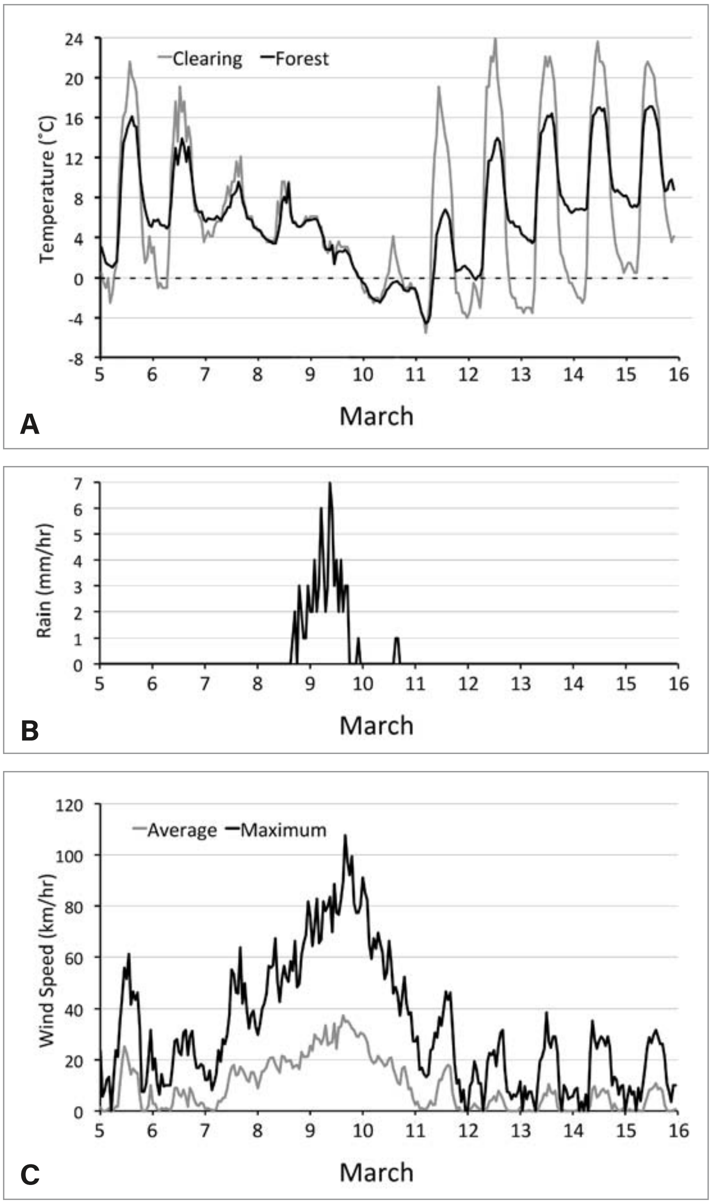

Fig. 8A–C. Weather before (5–6 Mar), during (7–11 Mar), and after (12–15 Mar) the March 2016 storm, showing (A) ambient temperatures recorded each hour in an open clearing near the Sierra Chincua colony and beneath the adjacent fir forest canopy; (B) rainfall in the clearing; and (C) the maximum and average wind speeds recorded each hour in the clearing. The forest temperature is the average of 9 different sensors under the canopy.

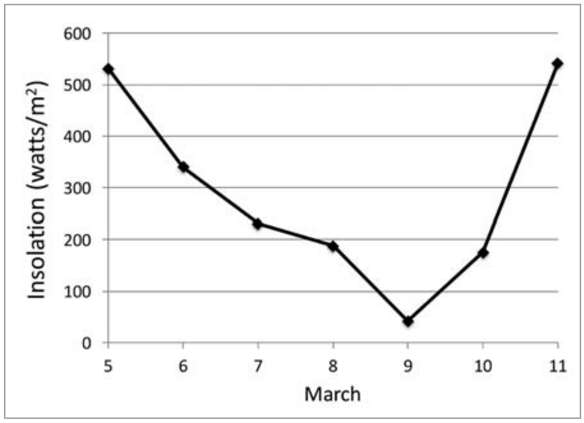

Fig. 9. Solar insolation before, during, and after the storm. The solar average on 9 March (42 watts/m^2) was 8% of that on 11 March (541 watts/m^2) after clearing.

Rain, snow, and rime ice. Cumulative rainfall from 1 January until 8 March was minimal (6 mm). As the wind was building up on 8 March, rain began that afternoon and fell almost continually through the afternoon of 9 March, accumulating a total of 78 mm (Fig. 8B) and heavily wetting the butterflies. With conditions below freezing, snow and rime ice occurred widely at the elevation of the butterfly colonies (Fig. 2; Besame 2016). Rain on the Sierra Chincua turned to snow during the morning of 10 March (R. Zubieta pers. comm., Fig. 1), and we witnessed 10–12 cm of snow at and near Chincua Station on 11 March (Fig. 2). Snow also occurred on the west face of Cerro Pelón (Sharp 2016). This precipitation should be added to the rain measured by the WeatherHawk. Ten centimeters of snow is equivalent to 7 mm of rain if dry and 12.5 mm if wet (Snowfall to Rainfall Calculator, www.csgnetwork.com/snowraincvt.html). The forests in all the overwintering butterfly colony areas in the Reserve and San Andrés massif were coated with rime ice (Fig. 2) that accumulated before the snow commenced on 10 March.

Wind speed. Wind speeds were moderate before the storm (32 km/hr on 6 March), but built to 82 km/hr during 8 March and then peaked at 108 km/hr at 1500 on 9 March, during the height of the storm (Table 1; Fig. 8C). Following the peak, wind speed decreased on 11 March. Interestingly, the intense four-day (8–11 March) wind storm began before and ended after the two-day precipitation period, in effect creating a rain and snow storm surrounded by a sustained high-velocity wind storm. This combination of weather events was the likely cause of so many downed trees. The wind speed and pattern on 8-11 March exceeded all other storm events for which we have WeatherHawk data at Chincua Station, dating back to 20 November 2004.

Direction of wind and tree fall. The wind on 5 March before the storm was predominantly from the east-northeast, and it shifted back to northeast after the storm (Table 1). However, from 8–11 March, during the height of the storm, the wind blew predominantly from the west, with heavy rain accumulating on 9 March. During the low temperatures from 9–11 March, the wind remained consistently from the west-southwest. The storms of both March 2016 and January 2002 came west-southwest from the Pacific (see Fig. 20.1 in Brower et al. 2004) rather than from the north. The combined soaking of the ground and high speed winds of 9–10 March led to trees being blown down. During our field visits from 11–28 March, we noted that most of the treefalls near and in the butterfly colonies on Cerro Pelón and the Sierra Chincua were oriented in a south-to-north direction. Both overwintering colony areas were on steep southwest-facing slopes.

Cloud cover and clearness. The intensity and duration of the storm are indicated dramatically by the cloud cover on 5–11 March (Fig. 1 and Fig. 9). Daily averages of daytime incoming solar radiation document a continuous decrease

Table 1. Summary of weather parameters before, during, and after the March 2016 storm measured at the Sierra Chincua weather station. For each 24-hour day, the range of the average hourly wind speed is shown along with the maximum recorded speed for that day and the time at which the maximum occurred. Wind direction is the median value of each day's hourly wind measurements.

Date	Cloud Cover	Rain (mm)	Min. Temp. (°C)	Time of min temp.	Wind speed (km/h) min to max	Time of max wind speed	Prevailing wind degrees	Prevailing wind direction
5 Mar	Clear	0	- 3.2	05:00	0 - 61	13:00	76	ENE
6 Mar	Partly Cloudy	0	- 1.4	04:00	7 - 32	15:00	235	SW
7 Mar	Cloudy	0	+ 3.0	00:00	8 - 64	16:00	246	WSW
8 Mar	Cloudy	13	+ 3.4	07:00	30 - 82	23:00	254	WSW
9 Mar	Heavy Clouds	62	+ 1.1	12:00	64 - 108	16:00	266	W
10 Mar	Cloudy	2	- 2.8	09:00 * ††	27 - 91	00:00	259	W
11 Mar	Clear	0	- 5.9	06:00 ** †	0 - 46	14:00	252	W
12 Mar	Clear	0	- 4.9	07:09 ***	0 - 32	16:00	225	SW
13 Mar	Clear	0	- 4.3	07:12	0 - 39	12:00	226	SW
14 Mar	Clear	0	- 2.6	05:24	1 - 35	09:00	45	NE
15 Mar	Clear	0	+ 0.3	05:30	0 - 32	14:00	203	SSW

* Below 0° all day

** Below 0° from 04:00 – 07:00

*** Below -3° most of night

† From midnight to 09:00 the relative humidity dropped from 95% to 8% indicating clearing with the resultant early morning temperature plunge.

†† Rain turned to snow during the morning of 10 March and ceased around 12:00 (Zubieta, l.c.)

from a nearly clear-sky day on 5 March to the peak of the storm on 9 March, when daily insolation was only 8% of clear-sky values (Fig. 9). At this time, a thick layer of clouds blocked nearly all incoming sunlight. Extreme cloudiness on 9 March was combined with rapidly decreasing temperature, increasing rainfall, and winds as high as 108 km/hr (Fig. 8A–C). Under these circumstances, the effect on the butterflies was potentially severe.

Relative humidity. The heavy precipitation during the storm was accompanied by high relative humidity on 9–11 March that would have prevented the wetted butterflies from drying. Relative humidity was 99% early on 9 March, remained high until the afternoon of 10 March, when it dropped to 52%, and then rose again to 94% that night. Finally, relative humidity dropped to 8% the morning of 11 March. These measurements indicate clearing through the night that led to the dangerously low temperatures for the butterflies in the early morning of 11 March. In short, the butterflies were buffeted by the wind, soaked by the rain, frosted, and then subjected to dangerous subfreezing temperatures when clearing occurred in the early morning of 11 March.

Predicted Mortality in the Colonies Based on Physiological Experiments

In physiological experiments with monarch butterflies collected from the Sierra Chincua overwintering area, Anderson and Brower (1996) determined that when monarch butterflies are wet, slight differences in sub-freezing temperatures produced very large differences in mortality. Fink et al. (unpublished data) also determined that the butterflies lose part of their physiological freeze resistance from January to March, so that if similar freezing temperatures occurred in mid- versus late winter, mortality would be substantially higher in March. During the March 2016 storm, the wetted butterflies were subjected to several hours of freezing temperatures. In the early hours of 11 March, the temperatures at Chincua station were ≤-4ºC for at least 2 hr, and measurements within the forest recorded a similar minimum of -5ºC.

Fink et al. also determined that, when butterflies collected in March 2004–2006 were experimentally wetted and then held at -4ºC, -5ºC, and -6ºC, 43%, 83%, and 100% (respectively) were dead within 90 minutes. These laboratory freezing experiments demonstrated that the 11 March 2016 temperature plunge had the potential to cause monarch butterfly mortality between 40% and 80% in the overwintering colonies. The experiments also determined that the probability of freezing is accelerated with very small drops in temperature below -4ºC. Had the nighttime blanket protection of the forest not been obliterated by the wind on 9–11 March, the minimum temperatures under the forest would have been about six to nine degrees warmer, i.e., well above freezing, as they were on the nights of 13–15 March (Fig. 8A). In that case, the mortality would have been 0% for the butterflies on 11 March. Thus, microclimatic homogenization to these critically low temperatures likely caused the mortality in the Pelón and Chincua colonies as well as in the Rosario colony.

Implications for the Rosario Colony

Although we do not have temperature records for the Rosario colony, photographs (Figs. 10, 11) indicate that

Fig. 10. Carpet of dead monarchs in Rosario overwintering colony, 31 March 2016 (photo courtesy of Journey North).

the minimum temperature on the morning of 11 March caused severe mortality. Of additional relevance is the fact that the Rosario colony on 4 March 2016 was located (19.5969°N, 100.2631°W) on the west-southwest-facing slope above the Llano de los Conejos; the colony was 130 m higher in elevation than Chincua Station, where our temperature measurements were made. Based on the known thermal gradient of 0.6°C decrease for every 100 m (Fig. 1.12 in Ramirez 2001), the temperature in the Rosario colony is estimated to have been approximately 0.8°C lower than that recorded at Chincua Station. While this difference is small, it would have added nearly a negative degree and pushed the temperature perilously close to -5°C. Based on the data of Fink et al., this would have caused 80% mortality in less than 1.5 hr.

Storm Damage at the Cerro Pelón and Sierra Chincua Colonies

During 24–28 March, we surveyed the Pelón and Chincua colonies, observing butterfly mortality and recording the colonies' geographic locations, elevations, and total areas using Garmin GPS instruments. In handling the butterfly samples, we found that the dead Pelón butterflies were moister than those in Chincua, which had drier and more brittle wings and abdomens. The difference likely was due to the more open Chincua forest and to the fact that the bottom of the Chincua colony abutted the exposed 10 ha area that had been illegally clearcut in the spring of 2015 (Brower et al., 2016a).

Pelón. On 24–25 March 2016, the Cerro Pelón colony was centered at 19.3877°N, 100.2585°W, elevation 3,200 m. The colony area was 0.13 ha and located in a steep-sided ravine on a south-southeast-facing slope with sheer relief (>35°) about 0.5 km upslope from the Llano de los Tres Gobernadores. The colony occupied a patch of young Oyamel firs in a heavily forested area with the presence of cedars (*Cupressus lusitanica* Mill.). We determined that the colony remained the same size and in the same location as measured by Rendón-Salinas et al. (2016) in December, before, during, and after the storm. The Pelón colony mortality counts therefore measure the cumulative mortality from mid-December

Fig. 11. Mostly dead monarch butterflies on top of snow in the Rosario overwintering colony at 16:00 on 12 March 2016 (photo by Jaime Rojo).

Fig. 12. Dead monarchs among storm debris on the forest floor in the Cerro Pelón overwintering colony, 25 March 2016 (photo by David Kust).

through 24 March (and possibly from when the colony formed in November).

Storm damage was extensive, with many broken branches strewing the forest floor as in the Sierra Chincua colony. Mortality (Fig. 12) was greatest around the bases of the trees, and many dead butterflies were buried, still clinging to the branch debris. The ground was also littered with dead monarchs enclosed in and clinging to clods of mosses and lichens that had been blown off the Oyamels. Macabre clusters of 90–100 dead butterflies were clinging to the north faces of about 30 tree trunks; these likely froze *in situ*. However, in contrast to the Chincua and Rosario colony areas, fewer trees had been blown down, likely because the south-southeast slope exposure provided some protection when the intense wind was mostly from the west (Table 1). We saw no live butterflies.

Chincua. On 19 January 2016, we found the Sierra Chincua colony centered at 19.67239°N, -100.29517°W, elevation 3,303 m, on the south-facing slope in the Arroyo Hondo. On 2 March, the colony had moved downslope and was adjacent to the upper boundary of the illegally logged area at 19.67108°N, -100.29831°W, elevation 3,150 m, as shown in Brower et al. (2016a); it was in the same location on 28 March. We measured 38 GPS locations and determined that the colony was centered at 19.67089°N, 100.29925°W and ranged in elevation from 3,110 to 3,179 m. In accordance with this measurement, the colony area was 0.10 ha, only one-ninth of the 0.89 ha that it had been when measured in December (Rendón-Salinas et al. 2016). Since the colony had moved approximately 500 m downslope and 153 m lower in elevation from the position it occupied on 19 January (Brower et al. 2016a), and because the dead butterflies tallied on 28 March were fresher than those we noted while walking through the prior January colony location, our Chincua counts are mainly of butterflies killed by the storm and did not represent cumulative winter mortality, as was the case on Pelón. Whereas the Pelón colony was mostly in shade, the Chincua colony was more exposed, with fewer but larger trees than Pelón.

Many large and small branches littered the ground (Figs. 5, 6) and numerous trees were uprooted and lying in a north-south direction. On the west edge of the colony, extensive butterfly mortality was visible. The greatest and most dense mortality was at the bases of the larger trees. Many of the sample areas had layers of debris (Figs. 5, 6) including conifer needles, branches, and leaves mixed in with the butterflies (Fig. 12). There was no mortality on the tree trunks at Chincua as at Pelón. There were no deep layers of butterflies, as was the case after the 2002 storm (Brower et al. 2004). Both the Chincua and Pelón colonies were orientated similarly on slopes that faced mainly south; both were steep, but Pelón was extremely steep.

Estimating Butterfly Mortality

To measure the butterfly mortality, we used stratified random sampling (Green 1979; Brower et al. 2004). We counted the numbers of live, moribund, and dead butterflies in 30 cm × 30 cm (0.09 m^2) plots beneath where the Cerro Pelón and Sierra Chincua colonies had been when the storm hit. Pelón mortality was estimated from five plots collected from each of four transects from 15 m to 42 m in length. Chincua mortality was similarly estimated from eight samples along each of four transects that ranged from 27 m to 56 m. Thus, there were 20 samples from Pelón and 32 samples from Chincua. Individual butterflies were categorized as alive, dead with evidence of predation, dead from other causes (attributed to the storm), and "other" (parts of wings, heads, or abdomens). Predation was assessed based upon sliced or missing abdomens, due to orioles and grosbeaks, respectively (Fink and Brower 1981), and missing or clipped wings. Sexes were also recorded.

In our analyses, we combined the data for both sexes because there was little difference between them. We estimated the number dead per square meter, per hectare, and per colony. To calculate the mortality in each colony, we assumed the comparatively low density of ten million per ha because of our and others' observations that colony densities as well as the colony areas are both in decline (Williams and Brower 2016).

Mortality in the Pelón and Chincua colonies. The monarch mortality in the Pelón and Chincua colonies was, respectively, 38% and 31%, with over 307,000 dead in the Chincua colony and with nearly a half a million dead in the Pelón colony (Table 2). As expected, the Pelón mortality was higher because it represented the cumulative mortality from December and possibly November through the storm, whereas the Chincua measure is of solely storm-caused mortality. The mortality estimates are within a range of values predicted by the laboratory freezing physiology experiments. Comparable mortality values for the Chincua and Rosario colonies after the 2002 storm were 2,628 and 7,283 per m^2, i.e., eight to nearly 24 times greater than in 2016. The overall estimate from the 2002 storm was 75% mortality (Brower et al. 2004). The large difference in mortality numbers is likely due to the decline in cluster density, which has yet to be quantified (Williams and Brower 2016; Thogmartin et al. 2017).

Mortality in the Rosario colony. The original estimate of 7.4% mortality in the Reserve reported by the press was based on anecdotal speculation from the Rosario colony (Stevenson 2016). Despite the lack of quantitative data from Rosario, personal communications from two photographers with experience in the Reserve both reported extensive mortality. Numerous dead butterflies were lying on the surface of the snow (Fig. 11). The most direct evidence of severe mortality in Rosario was a photograph taken on 31 March that shows a carpet of dead monarchs (Fig. 10), an image reminiscent of the 75% mortality caused by the 2–4 January 2002 storm (Brower et al. 2004). Thus, our measured mortality in the Chincua and Pelón colonies (Table 2), the photographic evidence, the climate data, previous physiological experiments, the Brower et al. (2004) mortality census in 2002, and the thermal lapse rate, all support the conclusion that the March 2016 storm mortality in Rosario was substantially greater than 40%, at least five and possibly as high as ten times the 7.4% value reported in the press.

Fig. 13. Photo taken about 1 May 2016 of salvage-logged Oyamel and pine trees accumulated in the parking lot below the Rosario overwintering colony (photo courtesy of Journey North).

Salvage Logging

In addition to causing butterfly deaths, the 2016 storm led to a salvage logging process of downed trees that further damaged the already disturbed ecosystem. On 23 August, World Wildlife Fund–Mexico and Fondo Monarca (2016) published a GIS analysis stating that the storm had blown down trees in 54 hectares in 28 locations within the Core Zone of the Reserve, including the Cerro Pelón, Sierra Chincua, and the Rosario overwintering areas. The report mapped locations of the blowdowns but gave no data on the number or volume of the trees downed and did not mention salvage logging.

Due to concerns about the possibility of fires or insect damage in the downed timber, the federal government authorized salvage logging of downed and damaged trees in the Reserve, initially from 1 April through 31 October

Table 2. Mortality of monarch butterflies in the Cerro Pelón and Sierra Chincua colonies after the March 2016 storm.

Colony	Samples (N)*	Mean dead butterflies/m^2	Mean dead/hectare (in millions)	Colony area (ha)	Total dead/colony	Mortality (%)**
Cerro Pelón	20	381.0 [a]	3.810	0.13***	495,300	38.1
Sierra Chincua	32	307.3 [b]	3.073	0.10***	307,313	30.7

[a] sd = 404; range = 78 - 1722

[b] sd = 184; range 11 - 767

* Based on 30 × 30 cm (0.09m^2) samples.

** Assumes colonies have 10 million monarch butterflies per ha.

*** In the second week of December, 2015, colony areas were 0.13 for Pelón and 0.89 ha for Sierra Chincua (Rendón Salinas et al., 2016).

Fig. 14. Salvaged Oyamel and pine logs along the roadside below the Rosario parking lot (photo taken around 1 May 2016)

Fig. 15. Cleared area of salvage-logged trees showing one uprooted and several cut Oyamel stumps on 10 May 2016 in the Rosario overwintering colony area (photo by Moises Acosta).

2016, a span that was later extended. In preliminary reports, authorities associated with the Reserve pointed out that the volume of wood approved for removal was about 60,000 m^3. Much of the wind damage of the storm was in the critical Core Zone of the Reserve, but a strong argument can be made from the known negative effects of salvage logging (Lindenmayer et al. 2008) that the logging should have been restricted to the Buffer Zone only, while allowing the downed trees in the Core Zone to decompose naturally to enrich the Reserve ecosystem. No distinction was made between the two zones, however, about where salvage logging was authorized.

Once permission had been given, extensive salvage logging began. Although there is no way to distinguish between trees that had been salvaged and those that might have been cut illegally, the removal of logs from the Reserve was conspicuous by mid-2016. Many trees were removed even from the monarch colony areas, and large piles of mature tree trunks cut to commercial length (approx. 2.7 m) were seen in visitor parking areas, along the nearby roads, and while being transported (Figs. 13–16). To obtain a rough estimate of the number of trees extracted, we measured the diameter of each log from four truckloads (avg. 58 logs/truck, see Fig. 17). Diameters

Fig. 16. Salvage logging of Oyamel firs downed during the March 2016 storm in the Arroyo Hondo overwintering area of the monarch butterfly on the south face of the Sierra Chincua, 24 May 2016 (photo by Moises Acosta).

Fig. 17. Logging truck loaded with 41 logs with diameters ranging from 20 to 80 cm, near Zitácuaro, 29 October 2016 (photo by Pablo Jaramillo).

ranged from 20-80 cm, which, according to the volume per tree estimated from previous forest inventories in the reserve (Tapia and Navar 2011, Gutiérrez et al. 2013, Navarrete et al. in press), contain from 0.3 to 12 m^3 per tree. The average log size was 44 cm diameter (SD ±14), with an average volume of 2.6 m^3 per tree (SD ±2). We are waiting to hear an official report of the volume of wood approved for removal, but the preliminary figure of 60,000 m^3 would be equivalent to many thousands of trees.

Whatever the authorized volume, extensive removal of trees from throughout the Reserve would seriously thin the forest's protective canopy (Williams and Brower 2015), while the process of salvage logging would further degrade the forest environment (example in Fig. 18). The management decision in the Core Zone favors logging interests over the mandated priority of preserving natural processes (LGEEPA 2003) and lessened the opportunity for the forest to return towards ecological maturity (Navarrete et al. in press) and provide a safe haven for the butterflies.

Lessons Learned from the March 2016 Storm

Our analysis of the March 2016 storm determined that strong winds can lead to the homogenization of the more severe weather conditions in open areas mixing with the normally moderated microclimatic conditions beneath the forest. We have previously shown (summarized in Williams and Brower 2015) that forest thinning reduces the microclimatic buffering provided by the forest canopy during the winter season, thus increasing the mortality risk to the overwintering monarchs. As a result of this unique storm, we now also realize that the forests surrounding the overwintering colony areas must serve as a screen that protects the colonies from severe wind, and that they are of major importance in sustaining the long-term microclimatic protection of the butterfly overwintering phenomenon in Mexico. This kind of storm, along with its unexpected effects, may take place at greater frequency in an era of changing climate. A survey of the logged areas should be done soon to quantify the effects of the storm and subsequent logging on the Reserve.

The March 2016 storm also produced a management challenge: when protected forests are damaged by a large-scale disturbance, should trees that are blown down or otherwise harmed be salvage-logged and removed from the ecosystem, or left in place to undergo natural decomposition and rebuild the soil? Extensive literature indicates that salvage logging is almost always profoundly disturbing and detrimental to the environment (Lindenmayer and Noss 2006; Lindenmayer et al. 2008). As is often the case, neither the local managers nor the scientific community were prepared for the devastating effects caused by these extreme meteorological events.

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Fig. 18. Habitat damage due to dragging out salvaged logs adjacent to the Rosario monarch butterfly overwintering colony, 10 May 2016 (photo by Moisés Acosta).

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