THE IMPACT OF FOREST THINNING ON MICROCLIMATE
IN MONARCH BUTTERFLY (*DANAUS PLEXIPPUS* L.)
OVERWINTERING AREAS OF MEXICO

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RESUMEN

Se midió el efecto de la densidad boscosa sobre la temperatura mínima en varios cuadrantes de bosques de *Abies religiosa* ubicados en y cerca de colonias de la mariposa monarca (*Danaus plexippus*), en el Eje Neovolcánico de México. Análisis de regresión con densidad del bosque, altitud y fecha de los estudios, demuestran que la temperatura mínima es una función inversa de la densidad boscosa. La fecha de los estudios y la altitud también fueron componentes importantes del modelo. Las temperaturas más bajas en los bosques aprovechados (entresacados) se explican por la ausencia de estructuras arbóreas que eviten el escape de calor debido a radiación durante la noche. Utilizando la ecuación de regresión, podemos predecir que las temperaturas en los bosques que han sido entresacados radicalmente, serán más de un grado centígrado menos que en las zonas donde las mariposas han establecido sus colonias. Un decremento subsecuente en la temperatura de esta magnitud, que ya se encuentra en el límite mortal para las mariposas durante algunas tormentas invernales, seguramente aumentaría considerablemente la mortalidad en las colonias.

INTRODUCTION

The monarch butterfly's (*Danaus plexippus* L.) overwintering sites occur in high altitude coniferous forests of Mexico's transvolcanic belt which are dominated by the oyamel fir, *Abies religiosa* H. B. K. (Urquhart and Urquhart, 1976; Brower, Calvert, Hendrick and Christian, 1977). Butterflies aggregate here in enormous numbers estimated to be in the tens of millions and form roosting clusters on trunks and branches in the middle and lower portion of the tree crowns. The butterflies conspicuously avoid clearings and areas radically thinned by logging where the Moderating effect of the canopy on temperature extremes is reduced (Calvert and

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Brower, in press). Our experiments indicated that butterfly mortality through freezing is greatly increased in open areas (Calvert and Brower, l.c.). This raises the ominous possibility that even carefully controlled forest thinning may alter the microclimatic requisites in a way detrimental to the overwintering butterflies.

In the states of Michoacán and México where the butterflies, overwinter, government controlled forest management is practiced and includes selective marking and removal of trees on both communal and private property. There is little waste; large trunk sections are used for saw logs, intermediate sections for pulp, and branches and tops for firewood by the local population. When trees are removed, growth of those remaining is enhanced. However, since 1976, the level of exploitation has increased dramatically in forests near the most extensive overwintering area (designated Site Alpha; Brower *et al.*, 1977) and at one site in the 1978-79 overwintering season a heavy logging operation was carried out in the midst of a major colony.

We do not know whether butterfly behavior is flexible enough for them to shift their overwintering locations if their prime area is made ecologically less suitable by lumbering. Furthermore, since occasional winter storms kill millions of butterflies in these forests (Calvert, Zuchowski and Brower, in press), questions are raised of how the undisturbed forest protects them and how further thinning effects the forest's ability to dampen weather extremes. We therefore, initiated this study to investigate the effects of forest thinning on microclimate in the high altitude forests.

MATERIALS AND METHODS

Daily minimum temperatures were measured at ground level along transects laid down through the colony and through 3 nearby forest areas from January 22 to March 15, 1981. Two sequential transects were established through the center of the colony along its long axis, one in January and one in February. Two of 3 nearby forested areas were chosen for temperature comparisons because there, radically and moderately thinned plots existed side by side. One transect was laid down through the denser plot, another through the thinner plot. Measurements of minimum daily temperatures were replicated twice for each area. Extreme care was taken in locating transect lines to avoid effects of exposure on microclimate: transects in plots to be compared had identical compass azimuths, similar slopes (dip angles), and altitudes, and were never more than 100 m apart. One transect was also laid down through a third area where a small colony had existed earlier in the season.

Seven to 10 station points were established at 10 meter intervals along each transect. Each station served several functions: the locus for a maximum/minimum thermometer (Taylor or PSG; Forestry Supply), the point used to locate trees for distance determinations to be used in the computation of forest density (Cottam and Curtis, 1953), and the point from which a photo of the canopy and/or sky was made. All photos were taken with the long axis of the film perpendicular to the transect line with the camera lens pointed directly skward.

Forest density was computed by the point-centered quarter method using 8 to 10 stations per determination (Cottam and Curtis, l.c.). Percent cover was computed for each station by placing the 35 mm photo negative in a standard slide frame and projecting it *via* a mirror mounted at 45 degrees onto an Apple II electronic graphics table and electronically tracing the area represented by the foliage. The minimum temperature corresponding to each density and percent cover determination

Table 1. Relationship between nightly minimum temperature and forest density and foliar cover.

Replicate	Location	No. of Stations	Date	Altitude	Forest Density	Average % Cover	Average Min Temp (°C)	Temperature Difference	Conditions
a. Direct comparison of radically thinned and moderately thinned forests									
1	Mojonera Alta	7	Feb. 8	3283	279	—	— 1.37	2.92	Clear
		8			1076	—	1.55		
2	Mojonera Alta	8	Mar. 8		197	51.3	3.75	— 0.03	Fog
		8			1039	74.0	3.72		
1	Aserradero	7	Feb. 24	3266	131	29.4	— 0.92	2.45	Clear
		8			513	63.3	1.53		
2	Aserradero	8	Mar. 14		105	21.3	0.69	2.45	Clear
		8			653	60.6	3.14		
b. In forests occupied by colony and remnant colony									
1	Colony	10	Jan. 23*	3138	399	—	— 1.04	—	—
2	Colony	9	Feb. 11*		371	74.1	2.00	—	—
3	Colony	8	Mar. 2*		371**	74.1**	4.29	—	—
1	Remnant colony	8	Feb. 7	3120	731	—	3.86	—	Clear

* Middle dates for a 6 and two 7-day temperature record periods, respectively.

** Same transect as above.

of Tables 1a and 1b is the average of all minimum temperatures for all station points on the transect. Likewise percent cover is the average for all the stations on the transect.

A Statistical Analysis System (SAS version H, release 79.5, Anon., 1975) general linear regression program was used to establish the dependence of minimum temperature first, on forest density, date and altitude and second, on percent cover, date and altitude. A single forest density estimate was made for each transect. In contrast, percent cover was measured above each of the station points along the transects. Percent cover measurements were subjected to an arcsine transformation to meet the normality criteria. Finally minimum temperature was separately correlated with forest density and percent cover using a SAS non-parametric Spearman rank correlation procedure (Anon., 1979).

RESULTS

Radiations shielding of a single tree

To investigate the effect of coniferous foliage in retarding the escape of radiation at night, minimum temperatures at ground level were measured at various distances from an isolated fir tree into a small clearing. After a small initial rise, minimum temperature declines steadily with distance out to 12 m from the tree except for one station at meter 10 (Fig. 1). The occurrence of warmer temperatures here was

Figure 1. Minimum ground temperature in relation to the distance from the tree.

caused by the presence of a small clump of herbaceous plants (*Penstemon gentianoides* Don.). The warmest temperature recorded was at 2 m where overhanging fir foliage was thickest and lowest. At meter 14 temperatures began to rise again as the influence of the trees on the other side of the clearing begins to be felt.

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Radiation shielding of a forest

To investigate the shielding effect of an entire forest, minimum nightly temperatures were measured in the colony and at 3 nearby forest locations (Table 1a and 1b). At each of the two sites, Mojonera Alta and Aserradero, two contrasting transects were chosen to compare radically thinned and moderately thinned plots adjacent to each other. Ignoring for the moment replicate 2 at Mojonera Alta, an average density difference of 797 trees/ha results in an average minimum temperature difference of 2.92°C or a loss of 0.37°C for each 100 trees/ha density decline. At Aserradero the average density difference of 465 trees/ha (averaging differences for both replicates) results in an average temperature difference of 2.45°C or 0.53°C per 100 trees/ha density decline. The lack of this difference at Mojonera Alta on March 8th is explained by the presence of dense fog which is similar in effect to foliage in retarding radiation loss to the night sky (Geiger, 1965). Minimum temperatures during the night were the same in spite of large differences in forest density (Table 1a, replicate 2). Forests within and adjacent to the colony and remnant colony were uniform in density; therefore, no direct comparisons of the effects of density were possible. Minimum temperature differences here reflect the presence of different air masses in the area and a general increase in radiational influx with seasonal advance (Table 1b).

Using the data of Tables 1a and 1b (replicate 2 is excluded because of fog, see above) a regression analysis with forest density shows density ($t = 6.20$, $p < .0008$), date ($t = 7.04$, $p < .0004$), and altitude ($t = 6.58$, $p < .0006$) all to be important predictors of minimum temperature in these mountainous forests ($r^2 = .93$). These data were also analyzed using percent cover above each thermometer station as a predictor with date and altitude. A model with percent cover ($t = 4.32$, $p < .0001$), date ($t = 4.80$, $p < .0001$) and altitude ($t = 4.49$, $p < .0001$) is not as good ($r^2 = .60$) as the corresponding model with forest density. However, percent cover *per se* correlates better with minimum temperature (Spearman rank $r_s = .53$, $p = .0001$) than does density ($r_s = .34$, $p = .0003$).

DISCUSSION

High altitude tropical areas are unique ecosystems in that they are subject to extreme daily temperature fluctuations. Because they are located at tropical latitudes, and low levels of moisture prevail in the dry season, solar influx during dry winter months is extreme (Mosioño and García, 1974; Kimball and Hand, 1936). Because of their location at high altitudes and the low levels of moisture, nighttime radiational efflux is also extreme and temperatures at Site Alpha typically fall to freezing or below in forest clearings (Fig. 1, and unpublished observations). Surfaces cool at night because they lose heat by radiation to the atmosphere and the cosmic cold, or by convection to surrounding air and objects. Normally the interface between plant and sky is the active surface where most of the radiational cooling occurs. Consequently, in the absence of wind, air temperatures are stratified with the coldest being those closest to the interface surface (Geiger, 1965; Calvert and Brower, in press). Several factors affect radiational losses from active surfaces, *e.g.* water vapor absorbs and reradiates it back to the active surface. As a consequence, cloudy nights are warmer than clear ones and, as we found, temperatures during a foggy night were the same regardless of differences in forest density (Table 1a). Vegetation also absorbs radiation and reradiates it. Plant parts need not be directly above a radiating object to effects

its temperature. Thus, an isolated tree's influence is felt far beyond the reach of its branches (Fig. 1).

Within a forest this process of radiation, absorption and reradiation from ground to foliage and back and from foliage to foliage is in a dynamic equilibrium and hence, at night the forest is warmer than nearby clearings where radiation is lost directly to the atmosphere and cosmic cold and cooler by day because some incident radiation is reflected by the upper canopy. This effect was dramatically evident at Site Alpha between January 20 and February 28, 1979, where mean air temperatures in a clearing adjacent to the colony ranged from 3.1 to 13.6°C. In contrast mean minimum and maximum air temperatures within the forest were 5.3 and 12.6°C for the same time period, a 3.2°C difference in mean maximum-minimum temperature range (Calvert and Brower, unpubl. obs.).

Radically thinned forests have fewer plant parts to act as barriers to outgoing radiation as well as more gaps through which radiation may escape, hence minimum temperatures at ground level here are lower than those in denser forests (Hansen, 1938). This effect should be directly related to the amount of plant material above the thermometer station, and we in fact found percent cover of foliage to be a good predictor of minimum temperature ($r_s = 0.53$). Forest density also reflects the amount of foliage present to interface with radiation loss at night, but in a more general way since it indicates the general concentration of trees in the area rather than the specific amount of foliage above a point. Thus, density *per se* is a slightly less useful predictor of minimum temperature ($r_s = 0.34$) than percent cover, the more direct measure of radiation shielding. The fit of the regression with both cover and density are greatly improved when seasonal warming and altitude, a factor of special importance in these mountainous forests, are introduced into the model (multiple r^2 for multiple regression with density and percent cover are 0.93 and 0.60).

The three factors within the predictive model explain 93 and 60% of the data variance, respectively. The unexplained portion could be due to several factors, some of which interact with each other. Although seasonal warming accounts for the general increase in radiation as the sun moves northward from the equator, the effect of large air masses differing in temperature is superimposed on the general increase in temperature with date.

At a specific location in the forest stratified temperature profiles are determined mainly by radiational cooling and the specific pattern of foliage above. Wind may disrupt the stratified air and thereby introduce variance into the data. The effect of wind is expected to be the greatest in low density forests where impediments to air flow are at a minimum. Wind is not always present however, especially in the early predawn hours when nightly temperatures reach their minimum (Geiger, 1965). The lowest temperatures in low density forests were likely recorded in the absence of wind.

The general multilinear relationship for one dependent and 3 independent variables is described by:

$$Y = \alpha + \beta_1(\text{predictor 1}) + \beta_2(\text{predictor 2}) + \beta_3(\text{predictor 3}) + \text{error}$$

where α is the y intercept and β_{1-3} are the regression coefficients for the respective predictors. Using the data in Table 1 the computer generated the following equation:

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$$\text{Minimum temperature} = 63.8140 + 0.0047 (\text{density}) + 0.1061 (\text{date}) - 0.0217 (\text{altitude})$$

For a forest with a density and altitude of that the butterflies selected during the 1980-81 overwintering season and for January 24th, the coldest day of the year the predicted minimum temperature is 0.04°C:

$$\text{Minimum temperature} = 63.8140 + 0.0047(400) + 0.1061(24) - 0.0217(3138)$$

If this same forest were thinned to 150 trees/ha the predicted minimum falls to -1.15°C:

$$\text{Minimum temperature} = 63.8140 + 0.0047(150) + 0.1061(24) - 0.0217(3138)$$

Thus, the temperature in the thinned forest is expected to be 1.19°C lower than that in which the butterflies overwintered.

In January, 1981, a major storm enveloped the overwintering area bringing in, rain, snow and freezing temperatures and killing an estimated 2.5 million butterflies (Calvert *et al.*, in press). How many additional millions would have been killed if these forests had been thinned is only a matter of speculation. But temperatures during these storm periods are clearly at the killing threshold for these tropically adapted butterflies. Every tenth of a degree fall in temperature could cause the death of thousands of butterflies.

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