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SPATIAL MODELS OF MICROCLIMATE AND HABITAT SUITABILITY: LESSONS FROM THREATENED SPECIES

Knowledge of the spatial distribution of microclimate is essential for determining habitat suitability of rare and endangered species, and for responsible design of biological reserves. Threatened overwintering populations of monarch butterflies (*Danaus plexippus*) in California and Mexico are limited to unique forest microsites that provide suitable shelter and thermal regimes. Similarly, population levels of the threatened Bay checkerspot butterfly (*Euphydryas editha bayensis*) in California grasslands are limited by the availability of unique microsites that provide food plants for larvae. For Bay checkerspot butterfly populations, a microclimate model predicts population persistence based on effects of local temperature and moisture regimes on food plant availability and larval development. A generalized, spatially-based habitat model of microclimate distribution relates habitat diversity to biodiversity. We are investigating the application of this habitat model to predict biodiversity in tropical forests. GIS techniques allow us to organize databases and to apply such habitat models to design biological reserves that optimize biodiversity.

INTRODUCTION--HABITAT DIVERSITY AND POPULATION PERSISTENCE

Effective design of biological reserves must consider the resource and habitat requirements of species that are most vulnerable to habitat loss and fragmentation (Ehrlich and Ehrlich 1981). Because most species require a relatively narrow range of climatic conditions, the spatial distribution of microclimates strongly influences long-term population viability and, in a broad context, biodiversity. Conservation biologists face the challenge of protecting sufficient habitat diversity to ensure population persistence of sensitive species. Basic landscape features, such as elevation, aspect, and tilt, can serve as first-order predictors of habitat suitability. The fundamental principles of environmental biophysics that determine microclimate are universally applicable in ecological systems, from temperate zone butterfly populations to complex tropical forest communities (Geiger 1965). Geographical information systems (GIS) can provide the appropriate technology to organize and analyze the complex spatial data necessary for a more complete understanding of species habitat requirements.

FOREST GAPS AND OVERWINTERING MONARCH BUTTERFLIES

Each winter, millions of monarch butterflies, *Danaus plexippus*, migrate from throughout North America to overwintering sites in Mexico and California. The butterflies aggregate in protected forest groves and roost in groups that often number hundreds of thousands of individuals. Only certain roost sites within particular groves of trees provide appropriate combinations of habitat characteristics that allow the butterflies to survive the winter. In California, these overwintering sites are situated near the ocean, where the forest groves provide protection from wind and rain, while at the same time maintaining moderate temperature and humidity regimes. Throughout the range, the overwintering habitat is being threatened by encroaching human development.

For conservation planning it is important to be able to predict whether a microsite is likely to serve for overwintering. Habitat suitability can potentially be predicted from detailed maps of tree locations and heights, by detailed measurements of temperature and humidity made with sensors held on poles in the forest canopy, from hemispherical photographs taken in sampling arrays. Weiss *et al.* (1991) used hemispherical photography to demonstrate that the butterflies select microsites that provide both a moderate degree of overall canopy openness and sufficient openings along the path of the sun. Hemispherical photography involves analysis of photographs taken through an extreme wide angle (fisheye) lens pointed upward from beneath the forest canopy (Rich 1990, Rich *et al.* 1991). The photographs were analyzed using video image analysis to determine the potential solar radiation penetration from all sky directions and along the path of the sun. The study showed that the forest canopy must be sufficiently closed to protect against wind and excessive solar radiation; yet the canopy must be sufficiently open to provide some penetration of sunlight. Too much solar radiation increases metabolism so as to valuable fat reserves, while too little solar radiation prevents the butterflies from warming up sufficiently to fly when they need to.

Hemispherical photography, used in combination with video image analysis and GIS, can allow us to understand and monitor simple habitat indicators that are excellent predictors of a suite of important habitat characteristics, including temperature, humidity, wind, and solar radiation regimes. Using the technique, it is also possible to model how changes in the habitat, for instance due to tree removal, are likely to affect habitat suitability. This example illustrates that for many species it is necessary to measure habitat characteristics over short spatial scales, on the order of 1 to 10 m.

SUN, SLOPE, AND CHECKERSPOT BUTTERFLIES

All landscapes exhibit ranges of microclimates created by topographic variation. These microclimates, or more specifically “topoclimates”, are primary determinants of the ability of species to persist within a geographic area. Because many species persist only in relatively narrow climatic conditions, analysis of topoclimates across the distribution of an endangered species can provide primary information about habitat requirements. Quantification of topoclimatic variation using calculated clear sky insolation on tilted surfaces has proven useful in untangling the roles of weather, topoclimate, and larval hostplant availability in the population dynamics of the threatened Bay checkerspot butterfly, *Euphydryas editha bayensis* (Weiss *et al.* 1988, Murphy and Weiss 1988a).

Climate plays a key role throughout the life cycle of the Bay checkerspot butterfly. Adult butterflies mate and lay eggs in March and April, toward the end of the winter rainy season. The eggs hatch and the young larvae feed on hostplants until the plants senesce following the end of seasonal rains. The vast majority of young larvae starve to death because they are too small to enter diapause, a dry season hibernation state. Those larvae that do survive through diapause enter a postdiapause growth phase when the next rainy season begins. At the end of the postdiapause growth phase, the larvae undergo metamorphosis and emerge as adult butterflies that mate and lay eggs. Rapid development of postdiapause larvae enables early emergence of adults, thus reducing mortality of the subsequent generation of prediapause larvae.

Weather and topographic position (aspect and tilt) play important roles in determining both how quickly postdiapause larvae develop and when hostplants senesce. Rainy and cloudy weather slow larval development, whereas sunny weather facilitates rapid growth. On grassland slopes where larvae develop, the local microclimate is highly dependent on aspect and tilt. For example, postdiapause larvae on warm south-facing slopes can reach adulthood more than a month earlier than larvae on cool north-facing slopes. Similarly, larval hostplants may senesce three or four weeks earlier on south-facing slopes than on north-facing slopes. The temporal phase relationship between adult flight and hostplant senescence--the primary determinant of survival rates of prediapause larvae--therefore exhibits high variability across the habitat because of variations in aspect and tilt.

Topoclimatic diversity in Bay checkerspot habitat is important because it allows populations to persist through stressful growing seasons. During droughts, hostplants senesce rapidly and most prediapause larvae survive only on cool slopes, thus causing populations to decrease in size. After favorable rainy seasons, with much winter sunshine for rapid larval growth and sufficient spring rainfall to keep hostplants green, prediapause larvae may survive on a wider variety of slopes. Such changes in larval distributions have been tracked for one population since 1985, using a stratified sampling scheme based on aspect and tilt (Murphy and Weiss 1988b).

Topographic maps were analyzed and the habitat divided into topoclimatic strata based on clear-sky insolation. Larval densities have been sampled yearly, and stratum-specific densities are multiplied by the area in each stratum. To date, these procedures have been done manually, however data management with a GIS will greatly facilitate this ongoing monitoring.

Such information on spatial patterns of habitat use is critical for conservation planning for the Bay checkerspot, especially because most populations border rapidly expanding urban areas. By understanding the topographic determinants of microclimate, with its direct relation to habitat suitability, conservation planners have a powerful and direct means for mapping key habitats. This type of topographic analysis can form the basis for predicting population viability from basic climatic and topographic data (Murphy *et al.* 1990).

TOWARD A SPATIALLY-BASED HABITAT MODEL

Our experiences with monarch and Bay checkerspot butterflies suggest a generalized model that relates climatic variation through time to climatic variation across landscapes. Landscape features predictably modify weather conditions to form mosaics of distinct microclimates. Solar exposure, wind, rainshadows, and cold air drainage all have a profound effect on local climatic conditions. Climate maps at the landscape level are valuable tools for ecological investigations and land-use planning (Geiger 1965). We hope to be able to use long-term climatic data in conjunction with topographic data to quantify local variations in climate that control the distribution and abundance of organisms. These large, spatially-based data sets are best managed in a GIS format.

As in the cases of monarch and checkerspot butterflies, spatial relationships between microclimate may provide a mosaic of suitable habitats for any particular species. During stressful climatic events, populations may contract to a limited habitat range, surviving only in refugia; whereas, during favorable periods, populations may expand into marginal habitats. By the same principles, global climate changes will shift habitat ranges as a direct consequence of rearrangement of microclimates. Predictions of such range shifts can only reasonably be accomplished using GIS.

CHARACTERIZING TROPICAL FOREST HABITATS

Tropical forests harbor a bewildering diversity of species (Wilson 1988). Various systems have been devised to classify tropical regions into broad life zone groups based on climate (Holdridge 1967); however, fine scale microclimatic variation within the tropics has been more difficult to approach. Present emphasis on gap dynamics and biotic interactions has directed attention away from the physical determinants of microclimate and their direct role in maintaining biodiversity. The same basic topographic determinants of microclimate in temperate zones (e.g., elevation and solar exposure) also the distribution and abundance of tropical species (Janzen 1967, Stevens 1989). Basic studies that relate topography to biodiversity are few in comparison to similar temperate zone studies. Recent studies using remote sensing and GIS in tropical systems have begun to approach spatial variation in species diversity and productivity (e.g., Sader *et al.* 1990, Luval *et al.* 1990).

The complexities of tropical systems--high species diversity and relatively subtle differentiation of microclimates--pose great challenges to reserve design and management. GIS is the natural tool for organizing and analyzing the volumes of data from topographic maps, ground-based studies, and remote sensing. Criteria for the existence of a particular climate zone, such as that leading to cloud forest (windward slopes at a particular elevation), could be established, and likely occurrences of that vegetation type within a reserve could then be identified from maps. These predictions may then be tested by remote sensing and ground surveys. With the use of GIS, it is thus possible to make first-order assessments of physical determinants of biodiversity before overlaying important, but often confusing, effects of history and biotic interaction.

CONCLUSION--GIS NEEDS FOR CONSERVATION BIOLOGY

GIS is the ideal tool for planning biological reserve systems because it provides the means for organizing and analyzing large data sets. Site-specific information on climate and species diversity are essential for developing predictive models of population persistence. GIS allows us to link climate and habitat suitability at many spatial scales, from the scale of individual trees, to grassland slopes, to whole tropical mountain ranges. The success or failure of biological conservation will ultimately be determined by the spatial distribution of protected natural habitats across the landscape.

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REFERENCES

Ehrlich, Paul R. and Anne H. Ehrlich. 1981. Extinction: the causes and consequences of the disappearance of species. Random House, New York, NY.

Geiger, R. 1965. The climate near the ground. Harvard University Press, Cambridge, MA.

Holdridge, Leslie R. 1967. Life Zone Ecology. Revised edition. Tropical Science Center, San Jose, Costa Rica.

Janzen, Daniel H. 1967. Why mountain passes are higher in the tropics. American Naturalist 101:223-249.

Luval, Jeffrey C., Diana Lieberman, Milton Lieberman, Gary S. Hartshorn, and Rodolfo Peralta. 1990. Estimation of tropical forest canopy temperatures, thermal response numbers, and evapotranspiration using an aircraft-based thermal sensor. Photogrammetric Engineering and Remote Sensing 56:1393-1401.

Murphy, Dennis D., Kathy E. Freas, and Stuart B. Weiss. 1990. An environment-metapopulation approach to population viability analysis for a threatened invertebrate. Conservation Biology 4:41-5 1.

Murphy, Dennis. D. and Stuart B. Weiss. 1988a. Ecological studies and the conservation of the Bay checkerspot butterfly, *Euphydryas editha bayensis*. Biological Conservation 46:183-200.

Murphy, Dennis D. and Stuart B. Weiss. 1988b. A long-term monitoring plan for a threatened butterfly. Conservation Biology 2:367-374.

Rich, Paul M. 1990. Characterizing plant canopies with hemispherical photography. In: N.S. Goel and J.M. Norman (eds). Instrumentation for studying vegetation canopies for remote sensing in optical and thermal infrared regions. Remote Sensing Reviews 5:13-29.

Rich, Paul M., David B. Clark, Deborah A. Clark, and Steven F. Oberbauer. 1991. Long-term study of light environments in tropical wet forest using quantum sensors and hemispherical photography. Submitted to Agricultural and Forest Meteorology.

Sader, Steven A., Thomas A. Stone, and Armond T. Joyce. 1990. Remote sensing of tropical forests: an overview of research and applications using non-photographic sensors. Photogrammetric Engineering and Remote Sensing 56:1343-1351.

Stevens, George C. 1989. The latitudinal gradient in geographic range: how so many species coexist in the tropics. American Naturalist 133:240-256.

Weiss, Stuart B., Dennis D. Murphy, and Raymond R. White. 1988. Sun, slope, and butterflies; topographic determinants of habitat quality for *Euphydryas editha*. Ecology 69:1486-1496.

Weiss, Stuart B., Paul M. Rich, Dennis D. Murphy, William H. Calvert, and Paul R. Ehrlich. 1991. Forest canopy structure at overwintering monarch butterfly sites: measurements with hemispherical photography. Conservation Biology 5(2) in press.

Wilson, E.O. (ed). 1988. Biodiversity. National Academy Press, Washington, DC.