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Paul M. Rich  
Biological Sciences  
University of Kansas  
Lawrence, KS USA 66045  
Telephone: (913)864-7769  
FAX: (913)864-7789

Stuart B. Weiss  
Center for Conservation Biology  
Stanford University  
Stanford, CA USA 94305  
Telephone: (415)723-3237  
FAX: (415)723-5920

Diane M. Debinski  
Museum of Natural History  
University of Kansas  
Lawrence, KS USA 66045  
Telephone (913)864-4540  
FAX: (913)864-5335

John F. McLaughlin  
Center for Conservation Biology  
Stanford University  
Stanford, CA USA 94305  
Telephone: (415)725-9915  
FAX: (415)723-5920

## **PHYSIOGRAPHIC INVENTORY OF A TROPICAL RESERVE**

Design and implementation of GIS databases for tropical reserves can greatly facilitate conservation and scientific study of rapidly disappearing tropical forests. The task is especially difficult because of a paucity of reliable data on the distribution and abundance of species in the tropics. La Amistad Biosphere Reserve in Costa Rica and Panama is the focus of efforts by various conservation groups, including the Center for Conservation Biology (CCB), to study and protect one of the most extensive and least developed regions of Mesoamerican tropical forest, a region with high topographic, biological, and cultural diversity. Initial efforts to establish GIS databases for scientific and management purposes involve a physiographic inventory of two portions of La Amistad Biosphere Reserve: Hitoy Cerere Biological Reserve on the Atlantic slope of the Talamanca Mountains, and Las Tablas Protected Zone on the Pacific slope. First, basic coverages are being constructed for elevation, slope and aspect, streams and rivers, land use, life zones (Holdridge classification), site locations for biological collections, and potential solar radiation flux. From these coverages, a physiographic inventory is being conducted to delineate watersheds, classify and determine the extent of various habitat types, and develop a topoclimatic model that relates habitat diversity to species diversity. Understanding the physical determinants of habitat suitability will allow the projection of estimated biodiversity across broad areas where surveys would be impractical.

## INTRODUCTION

### *Overview*

La Amistad Biosphere Reserve includes the least-developed and least-explored parts of Costa Rica, and offers great topographic, biological, and cultural diversity. The Biosphere Reserve, so designated by United Nations Environmental, Scientific, and Cultural Organization (UNESCO) because of its global significance, comprises a series of administrative units that include biological reserves, indigenous people's reserves, buffer zones, and private inholdings. Recent designation of La Amistad International Park within the Biosphere Preserve has brought increased visibility, and has led to the involvement of government and private institutions in biodiversity inventories, conservation planning, and reserve management.

The Center for Conservation Biology (CCB) has taken this opportunity to develop a research program that will contribute directly to the management efforts of Costa Rican scientists and politicians. GIS will play a central role in this research program; this paper outlines our initial efforts to use ARC/INFO for an inventory of the physiography--including topography, climate, and stream networks--of La Amistad Biosphere Reserve.

### *Why a Physiographic Inventory?*

Most conservation planning aims to establish reserves that will encompass the full range of biodiversity in a landscape. Physiographic and field inventories of biodiversity can be thought of as a modern counterpart of more traditional biological exploration (e.g. Humboldt 1833, Darwin 1855). Though traditional tools such as specimen jars and plant presses must still play a key role, modern tools such as remote sensing imagery and sophisticated GIS computer systems can increase the efficiency of our field efforts (Aronoff 1989, Burrough 1986, Cowen 1988, Tomlinson 1987). Because of the rapid destruction of habitat, we must act quickly. By focusing at a broad landscape level, we can distinguish habitat units that are sufficient to maintain ecosystem integrity and maximize the preservation of biodiversity (Ehrlich and Ehrlich 1981).

GIS-based physiographic and field inventories will provide the detailed knowledge of species distribution and abundance that will enable us to determine and fill gaps in the biodiversity protection network. Such "gap analysis" (Scott et al. 1987, Scott 1989, Davis et al. 1990) involves GIS overlays of biological distributions on maps of protected areas. Filling in the gaps means preservation of unique habitats that are not currently in protected areas. Species oriented gap analysis requires detailed knowledge that is rarely available, even for the most ecologically conscious nations. In the tropics, where loss of biodiversity has reached alarming levels (Wilson 1988), Rapid Assessment (RAP) teams are scouting areas that appear to be most critical for immediate attention (Wolf 1991), while more detailed inventories such as those described here will provide an in-depth, long-term, and geographically extensive scientific baseline for conservation planning.

A physiographic inventory involves quantitative description of the underlying landscape features -- especially those features that affect local climatic conditions -- that determine the distributions of organisms. Ecologists have long appreciated the need to characterize the environmental and biotic conditions that limit populations (Schimper 1898, Whittaker 1967, Walter 1979). GIS is the clear choice to analyze the underlying determinants of habitat suitability (Stoms et al. 1989, Dunn et al. 1991, Rich and Weiss 1991, McLaughlin et al. 1992). Our initial effort involves hand-in-hand physiographic and field inventories of two reserves within La Amistad Biosphere Preserve: Hitoy Cerere Biological Reserve on the Atlantic slope of the Talamanca Mountains, and Las Tablas Protected Zone on the Pacific slope. In particular, the work described here is centered around Finca Las Alturas, private property lying partially within the Las Tablas Protected Zone.

The physiographic inventory is being used to explore three fundamental hypotheses concerning relations between of habitat characteristics and biodiversity.

1. Along elevational gradients in the tropics, distributional limits of organisms are determined by the extent of suitable habitat and predicted from a basic understanding of microclimate; low elevation biota would be expected to reach their highest elevational limits in the warmest microhabitats, whereas high elevation biota would be expected to reach their lowest elevational limits in the coolest microhabitats.
2. Habitat heterogeneity, as measured by microclimate heterogeneity, will be directly predictive of biodiversity; this correspondence is expected to hold for any level of biodiversity (genes, species, communities, and ecosystems).
3. Changes in community composition that might result from global climate change will be predictable as habitat shifts along environmental gradients.

### *The Study Site*

La Amistad Biosphere Reserve, situated between 80 and 100 N latitude, includes some of the largest remaining tracts of middle and high elevation forest in Central America. Lower forests on the Pacific Slope (1400-2000m) have been included in the Las Tablas Protected Zone, which is intended to serve as a buffer for La Amistad International Park. The protected zone is comprised of private lands, most of which support primary forest. Also included are some farms that are permitted to operate at their present size; residents are prohibited from clearing additional forest. The owner of one of these farms, Finca Las Alturas, has granted CCB a long-term lease to property adjacent to the Protected Zone. Here, CCB has constructed Las Alturas Biological Station and a trail system is currently under development. Forested portions of Finca Las Alturas lie within the Las Tablas protected zone, and are readily accessible by an all weather road.

The mixed land use in the protected zone presents conservation biologists with a valuable experimental arena. Large tracts of forest reaching from moist forest at 1,100 m to paramo at over 3,000 m enable access to a long elevational gradient in essentially pristine condition. The mosaic of human activity in a matrix of forest that is largely undisturbed offers a range of possibilities for the study of the impacts of agriculture and resource exploitation of natural ecosystems.

### **APPROACH**

#### *Integrated GIS Management Plan*

An integrated GIS management plan is essential for both scientific and administrative purposes. Development of a management plan is often best done in stages--the first stage serving as a realistic evaluation of what is needed and what is possible, and later stages serving to refine the plan. The preliminary GIS management plan for CCB work in La Amistad is modeled after similar plans for other reserves and long-term ecological research (LTER) areas. Our initial concerns for work at La Amistad include 1) explicit statement of scientific and administrative goals, 2) planning core data layers that will be assembled and maintained, 3) planning for immediate personnel and equipment needs, 4) developing protocols for data collection, entry, and quality control priorities, 5) accommodating information exchange with existing or planned databases at CCB, 6) planning for future personnel and equipment needs, and 7) deciding policy to facilitate data exchange and collaboration with other organizations and

individual researchers. Early planning has been especially important because GIS can be very resource intensive, both in money and time. The physiographic inventory for La Amistad was planned and initiated to serve as a pilot project with three purposes: 1) it enables assessment of realistic goals for the GIS management plan; 2) it provides core data layers (topography, streams, political boundaries, etc.); and 3) it guides the course of simultaneous field inventories.

### *Location of Resources*

For tropical regions, one of the greatest challenges can be location of reliable data. In the case of La Amistad, we are fortunate in that relatively high quality topographic maps and weather records are available; we are still in the process of assessing the quality of these data. Costa Rica's Instituto Geografico Nacional publishes a 1:50,000 map series covering the entire country. These are professionally produced topographic maps with a contour interval of 20m. While high resolution digital elevation models (DEMs) have been produced for Costa Rica (and much of the world) by the Defense Mapping Agency (DMA), they are unavailable to the general public. Recent software developments allow construction of DEMs from digital image stereo pairs at a relatively low cost (e.g. ERDAS Digital Ortho), which bodes well for future projects.

A weather station established by ICE (the national electric utility) has been maintained at Las Alturas since 1983, recording air temperature and humidity four times a day, and rainfall and evaporation daily.

### *Core Coverages*

A core of basic coverages must first be established to serve as the primary database for the GIS. For Las Alturas, we are constructing core coverages for 1) political boundaries (national boundaries, reserves, and private inholdings), 2) elevation (100 m contour intervals), 3) streams and rivers (both intermittent and perennial), 4) land use (primary forest, grazed land, etc.), and 5) site locations of biological field collections. From these coverages, we are calculating a variety of derivative core coverages including 1) slope and aspect, using a TIN surface model; 2) life zones, a classification of habitat that can be calculated based upon elevation, temperature, and rainfall (Holdridge 1967); and 3) clear-sky solar radiation flux, an estimation of flux based upon topography. For Las Akuras, we determined that 100 m intervals is more than sufficient for the initial core topography data layer (which covers hundreds of square kilometers and more than 2000 meters of elevation), construction of derivative core coverages, and conducting the physiographic inventory. Other desirable coverages include soils and underlying geology.

A variety of problems relating to data availability and quality have arisen in the course of this project. Obtaining reliable political boundaries has proven difficult for Las Alturas and other land units within La Amistad Biosphere Reserve. While the topographic maps are comparatively high quality, various inaccuracies have been apparent. In many cases there are no simple cross-checks of data reliability. However, to date, such problems have not been of a magnitude to prevent meaningful physiographic analysis. These considerations do underscore the need always be explicit about the sources and known limitations of map data.

### *Physiographic Inventory*

**Basic Physiography.** Though it is commonly held that tropical systems are shaped primarily by biotic interactions, physical factors such as microclimate and soils play profound roles at all levels of ecological organization. Distinct biotic assemblages are associated with different elevational zones in the tropics (Holdridge 1947, Richards 1952, Ashton 1969, Whitmore 1975). In comparison to temperate habitats, tropical habitats may be more finely divided into distinct climate zones, as a result of narrow temperature tolerances of tropical organisms (Janzen 1967, Stevens 1989).

The goal of a physiographic inventory is to provide a summary of the distribution and extent of land according to elevation, slope, and aspect. We expect that these topographic categories correspond closely to habitat types, as determined by such associated physical characteristics as temperature, rainfall, and solar radiation balance.

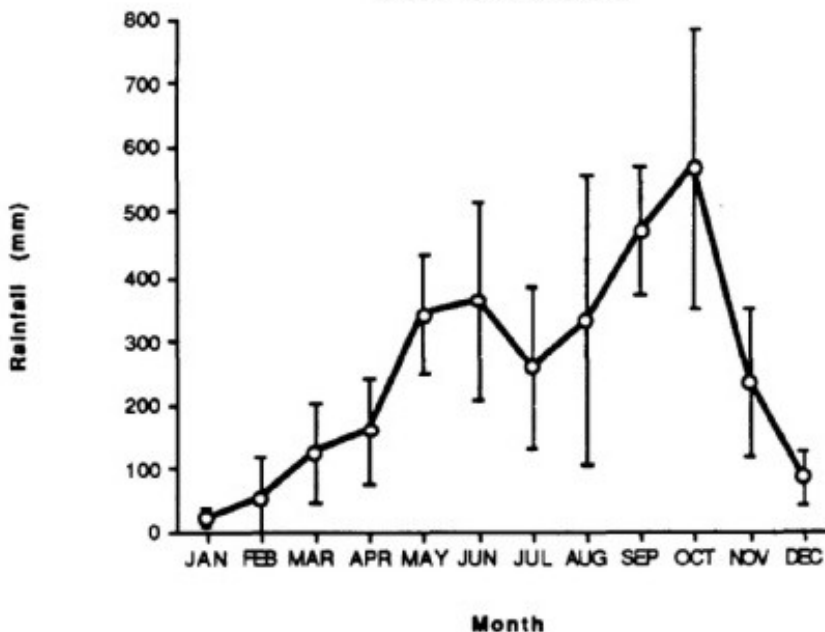
**Stream Networks.** The stream network is a primary resource of any reserve, providing aquatic habitats for numerous taxa, and, importantly, high quality water for downstream use. One of the major motivations for the establishment of La Amistad National Park and its buffer zones was protection of mountain watersheds that provide Costa Rica with the majority of its potential water supply and hydroelectric capacity. Water quality and quantity delivered to downstream users is one of the most tangible and valuable economic benefit afforded by the reserve: watershed protection is a powerful argument for protecting forests worldwide.

Analysis of the stream network at Las Amistad will include determination of length, order, elevation, and gradient of each reach in stream network, as well as boundaries and extents of watersheds. Stream reach characteristics can be used to predict aquatic species distributions. A network model may be applied to the stream systems, and in conjunction with climate data, provide the means to predict runoff and nutrient export.

**Modeling of Microclimate, Habitat, and Species Diversity**

**Macroclimate.** The average annual temperature at Las Alturas is approximately 19°C, and annual precipitation averaged close to 3000 mm over the eight years studied. The seasonality of rainfall is clearly seen in the monthly averages (Fig. 1). The drier season runs from December through March, sometimes starting in November or running into April. Rainfall in these drier months is variable (error bars show standard deviation); some dry seasons have virtually no rainfall for three months, while others are interrupted by intermittent heavy rains. There is as short break in the rainy season in July (the “veranillo” or little summer), and rainfall peaks in October.

**Fig. 1 Rainfall at Las Alturas (1983-89)  
Elev. 1340 Meters**

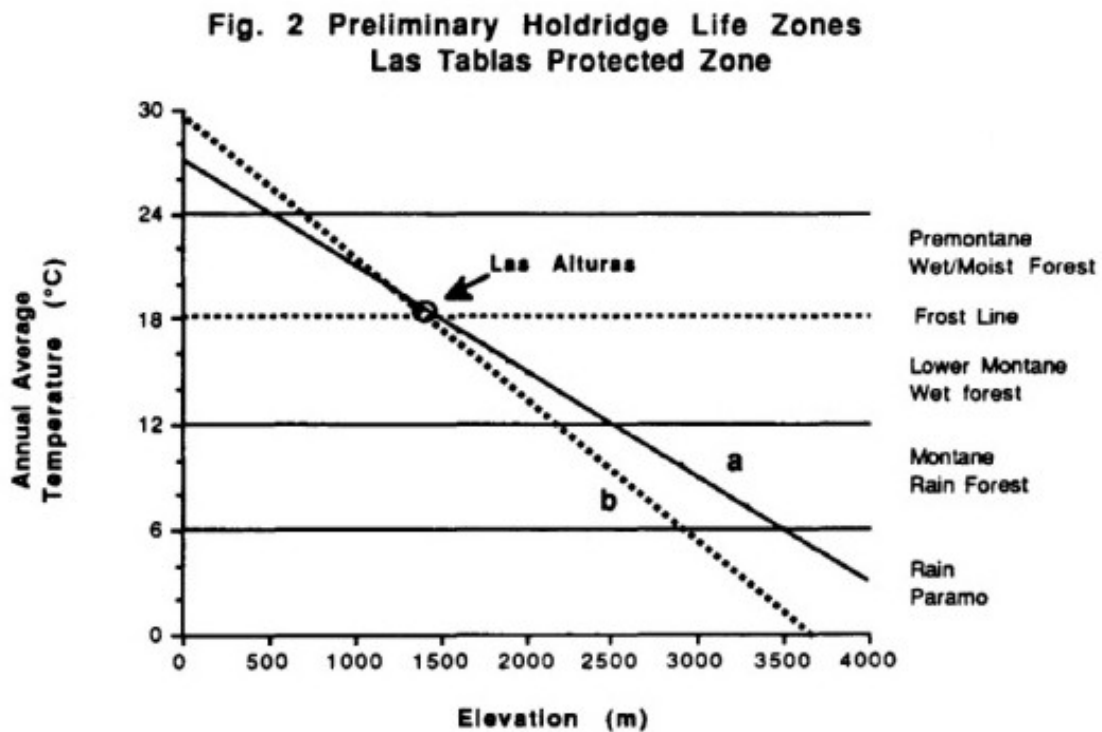


The seasonality in climate at Las Alturas presents the vegetation with a period of water stress that should be a limiting factor for numerous plant species. Indeed, the forest around Las Alturas is semi-deciduous, with a period of leaf fall soon after the onset of the dry season. Because the effective severity of the dry season will vary with physiographic variables such as elevation, slope, and aspect, the next step is to model the determinants of spatial variation in the climate.

**Holdridge Life Zones.** Elevation has a profound and predictable influence on both air temperatures and rainfall. The classic system for integrating elevational effects with vegetation types is the Holdridge Life Zone classification (Holdridge 1967). Temperature data are adjusted an adiabatic lapse rate (temperatures drop with elevation) and rainfall is adjusted by a similar relationship. Elevational belts are assigned to different life zones based on yearly average temperature and precipitation. The Holdridge system was developed and tested in Costa Rica itself, and has been widely applied across Central America, so it is a logical starting point for our study area.

The Las Alturas field station falls in the premontane-lower montane wet forest zone (annual precipitation 3000 mm, annual temperature 19°C). Interestingly, the station is situated close to the critical temperature isoline, or “frost” line -- a fundamental break where the frequency of frost limits frost sensitive species, such as coffee. The adjacent life zones include premontane moist forest, premontane wet forest, lower montane moist forest, lower montane rain forest, montane wet forest, montane moist forest, and montane rain forest. At the upper elevational extreme, rain paramo should appear.

Each of these life zones supports a characteristic vegetation physiognomy -- average canopy height, number of tree strata, degree of deciduousness, liana and epiphyte loads -- as well as characteristic species in virtually all taxonomic groups. Simply identifying proper Holdridge Life Zones provides a wealth of information on the distribution and abundance of species in this area.



Based on the wet adiabatic lapse rate of 6°C/1000 meters, the transition to montane rain forest should occur around 2500 meters, and rain paramo should appear at 3500 meters (Fig. 2, line a). We know from initial vegetation maps that rain paramo appears at about 3000 meters, so the lapse rate appears to need some adjustment. By setting the temperature threshold of rain paramo (6°C) at 3000 meters, we can generate a new lapse rate line somewhat steeper than previously, closer to the dry adiabatic rate (Fig. 3, line b). The new line suggests that the transition to montane rain forest occurs at about 2100 meters. This exercise is meant to illustrate methodology for converting elevational data into annual temperature through use of basic physical models. More sophisticated models that include both dry and wet lapse rates may also be used (MacArthur 1972). Las Alturas is effectively drier than might be expected based on the Holdridge classification, because of the pronounced dry season.

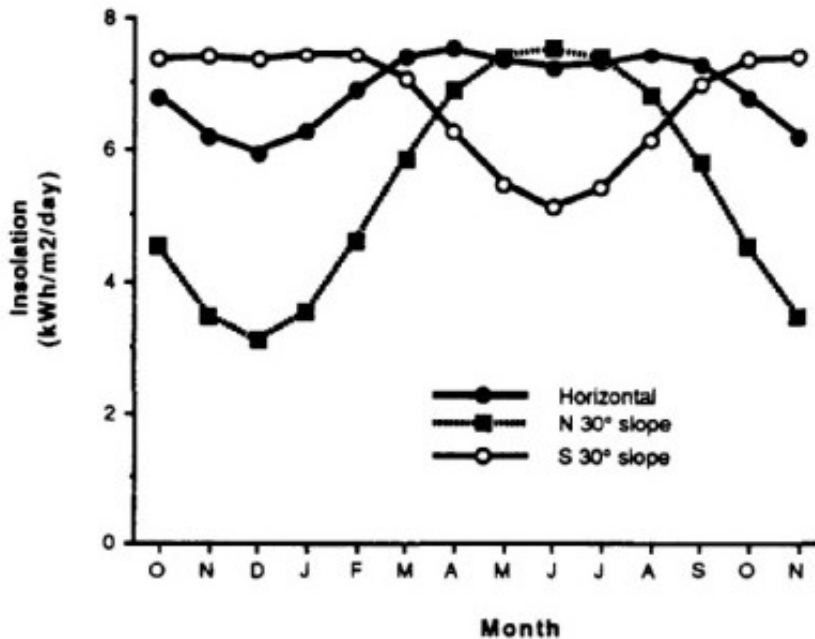
We can test and calibrate our lapse rate model in the field. Because of the small yearly amplitude in temperature, the actual lapse rate in tropical mountains may be directly measured by soil temperatures in the shade at a depth of about 50 cm (Walter 1979). Additionally, because each life zone has characteristic dominant tree species, these predictions may be tested in the field with vegetation sampling. We acknowledge that the Holdridge system is relatively coarse grained, and the reality of distinct life zones is under debate, but the Holdridge system provides a starting set of tested climatic benchmarks in Costa Rica.

**Solar Radiation Flux.** Solar exposure, determined by slope, aspect, and surrounding terrain, is the next factor that will affect local water balance (Geiger 1965). Solar exposure models have proven extremely useful in conservation planning (e.g. Weiss et al. 1988, Rich and Weiss 1991). Landscape-level solar radiation flux can readily be modeled based upon topography and estimates of radiation flux, as determined from simple models or weather records. The most basic starting point is calculation of a clear-sky solar radiation flux, the flux that would be expected under clear atmospheric conditions (i.e., with no weather) using topographic variables (slope, aspect, and shadows caused by topographic features), and calculated using daily and seasonal shifts of solar angle under clear-sky conditions (Dubayah et al. 1990). A climate-corrected radiant flux can be constructed by integrating monthly weather information and direct solar flux measurements with the clear-sky model. The climate-corrected radiation flux model can provide the basic input to ecosystem canopy radiation flux models.

Using a set of standard equations (Lunde 1980), we have calculated clear-sky insolation through the year on several different slopes at 10°N latitude (Fig. 3). These curves allow us to examine patterns of temporal and spatial variation in insolation across the landscape and generate hypotheses regarding seasonal effects on water balance -- i.e. identify dry and moist slopes and delineate a topographic moisture gradient. Temporal variation through the year differs between the slopes. On the horizontal surface, the minimum insolation is at the winter solstice, with two maxima when the sun is directly overhead in April and August. South-facing 30° slopes receive an almost constant high level of insolation from October through February, but insolation declines to a minimum at the summer solstice. North-facing 30° slopes experience an opposing insolation regime -- minimum at the winter solstice and maximum at the summer solstice. Importantly, south-facing slopes receive more insolation than north-facing slopes around the winter solstice, and north-facing slopes receive more insolation than south-facing slopes around the summer solstice.

Seasonal differences in cloud cover may either accentuate or diminish these slope-to-slope differences. Slope to slope differentiation under clear skies is greatest during the December - March dry season. Diffuse radiation under cloudy conditions is evenly distributed across all aspects, so slope-to-slope differences under cloudy conditions depend only on slope and horizon shading. Because of the high frequency of clouds during the rainy season from May through November, and the almost constant availability of moisture, the reversal of insolation regimes on north- and south-facing slopes may not be strongly expressed at this time of the year.

Fig. 3 Clear Sky Insolation, 10°N Latitude



**Topoclimatic Model of Habitat and Biodiversity.** The landscape at Las Alturas supports a mosaic of topoclimates (topographically-induced local climates) that should strongly structure the distribution of species in that area. Quantifying the topoclimatic mosaic through elevational and solar exposure calculations form the basis for a set of testable hypotheses regarding the distribution of organisms across the study area. We conjecture that, for example, representative species of low elevation life zones will reach their highest elevational extent on south-facing slopes. Overall physiognomy of the vegetation, especially degree of deciduousness, should also closely follow these topoclimatic gradients. By defining our gradients in terms of elevation, slope, and aspect, we can readily use GIS to delineate climate zones at a finer-scale than is possible with the Holdridge system. A similar analysis in Queensland, Australia, assessed the representativeness of protected areas on a GIS using elevation, climate, and solar exposure (Mackey et al. 1987) -- that study amounted to a “climatic” gap analysis.

#### **Relation to Field Inventory**

Effective field inventory of biodiversity is much more than species collection. Logistical considerations include scale, intensity, precision, and scope. Sampling across environmental gradients and over time are both required, and sampling intensity should be designed to detect rare species (Debinski 1991, 1992, Debinski and Brussard 1992). Distribution and abundance data are being collected for selected taxa (including birds, butterflies, and trees) across elevational and disturbance gradients at Las Alturas. Initial data on butterflies show relations between topography and species diversity (Sparrow 1991). Species diversity decreases with elevation, but a number of species are restricted to higher elevations, and others occupy distinct elevational belts, a pattern that is common throughout both temperate and tropical regions (Debinski 1991, De Vries 1987). During the dry season, butterflies are most diverse on south- and east-facing slopes, where morning insolation is highest. Because we can set these explicit topographic criteria, it should be possible to project the data from our transects to a broader region. For example, we may attempt to identify dry season butterfly “hotspots” by searching for south- and east-facing slopes within particular elevational belts. The reversal of insolation regimes on north and south slopes at the summer solstice (Fig. 3) may also cause seasonal shifts in these hotspots. Such local hotspots may be thought of as analogous to regional and global hotspots of biodiversity (Myers 1988).

With the completion of the physiographic inventory, we will use the GIS data base to design sampling schemes that equitably sample across the diverse topo-climatic gradients. A rudimentary trail system is in place, and the placement of additional trails will be planned using the GIS. Each trail segment will be characterized by topography, climate, disturbance, and species composition in monitored taxa. Collections along the trail system, therefore, will provide the first spatial distributions along environmental gradients. In addition, new trail segments may be designed "on screen" and routes optimized by computer techniques. Because all collections at Las Alturas will be map-referenced, species distributions can be correlated with physical parameters. Such correlations become testable hypotheses on the distribution and abundance of species elsewhere in the region.

### ***Remote sensing***

Remote sensing (RS), used in conjunction with GIS, promises to facilitate development and validation of models concerning habitat and biodiversity (Quaurochi and Pelletier 1991, Dunn et al. 1991). RS can supply basic map data for construction of DEMs, classification of land use, and assessment of the extent of deforestation. Quantifying the changes in patch sizes and length of edges in a landscape can allow prediction of landscape thresholds of habitat fragmentation, below which population viability falls dramatically and species loss becomes likely (Turner and Gardner 1991, Gardner 1987). One of the great challenges before us is integrating the use of RS and GIS to predict shifts in habitat quality and associated species composition that might occur under different scenarios of human modification of the landscape, including those resulting from global climate change.

### **CONCLUSION**

Identification and protection of diverse and intact physiographic gradients provides a practical and scientifically sound means to protect biodiversity (Noss 1990). Unlike many organisms that change distributions in time and space, physiography is quite stable. The strength of using GIS along with a strong physiographic approach lies in the ability to directly relate underlying physical determinants of habitat to the distribution and abundance of species. Because population viability often depends upon critical microhabitat components, physiographic analyses can also be used in species-level planning (Weiss and Murphy 1990, Murphy et al. 1990). The landscape is the level at which major conservation decisions are made, and GIS provides the means to represent complex landscape-level analyses directly to planners. Thus, a GIS-based physiographic approach can both direct biological sampling and provide for data management, analysis, and presentation needs.

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