The Way Light Falls on the Landscape: Modeling Insolation

by Stuart B. Weiss

Where are the best flowers going to be this year, and when will they bloom? Both wildflower enthusiasts and butterflies would like to know! Ecologists like myself also want to predict the wheres and whens of the spring bloom. Not only do we enjoy the flowers, but we are interested in their phenology—the timing of flowering and senescence—and how differences in the phenology of plants affect the herbivores that eat them.

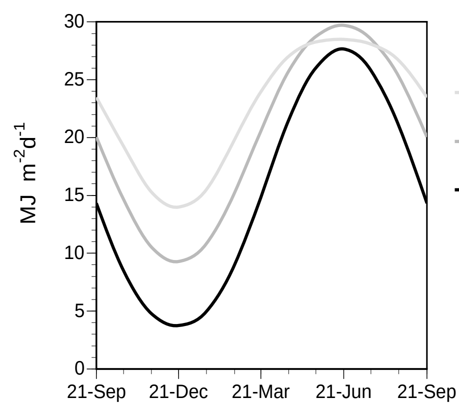
Studies at the Jasper Ridge Biological Preserve have shown that insolation—the amount of solar energy striking a given area—plays an essential role in determining where particular plants grow and the timing of their life cycles. Since insolation drives important ecological processes, its variability has a profound effect on a broad scale across landscapes, as well as on a local scale, for example, on opposite slopes of a hill.

The variability of insolation through time is mainly a function of two factors, the seasonal cycle (see graph this page) and cloud cover. First, the seasonal cycle of the sun's path across the sky leads to lower levels of insolation in winter, when the sun appears lower in the sky and strikes higher latitudes at more indirect angles, than in summer, when solar elevations are high. The effects are seen over an annual scale, with variation in air temperatures basically tracking change in solar elevation. In contrast to this yearly cycle, changes in cloud cover lead to short-term variation in insolation. Under clear skies, the solar beam is highly directional and strong, while under cloud cover, sunlight is attenuated and diffused.

Spatial variability of insolation—that is, the way it varies geographically—is affected primarily by topography. The varying illumination levels across the rounded hills of California are responsible for much of the beauty of our landscape. Not to take away from the aesthetics, these illumination levels can be exactly calculated by geometric algorithms. Insolation on a surface is a function of the intensity of the solar beam and the angle of incidence between the beam and the surface. As the angle of incidence increases, the beam is spread across a greater surface area according to Lambert's Cosine Law of Illumination.

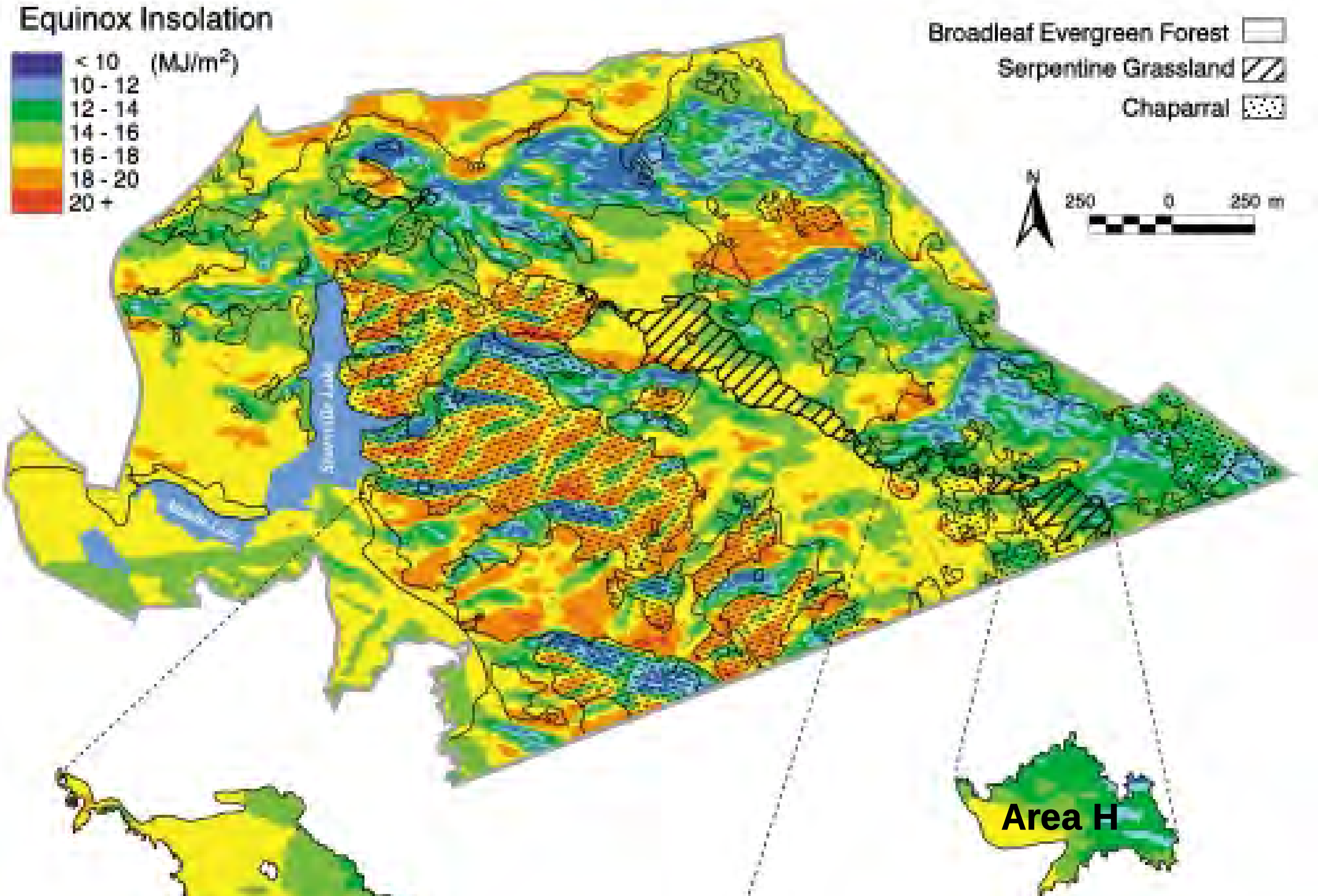
In collaboration with Dr. Paul Rich, University of Kansas, Lawrence, my colleagues and I have developed a geometric model of insolation called SOLARFLUX that runs on the Geographic Information System (GIS) at Stanford's Center for Conservation Biology (CCB). The input is a Digital Elevation Model (DEM), a representation of the landscape in which elevations are specified on a regular grid. With SOLARFLUX, we can calculate the position of the sun at every hour throughout the day, and determine which portions of the landscape are exposed to direct sunlight. In addition, we can obtain clear-sky

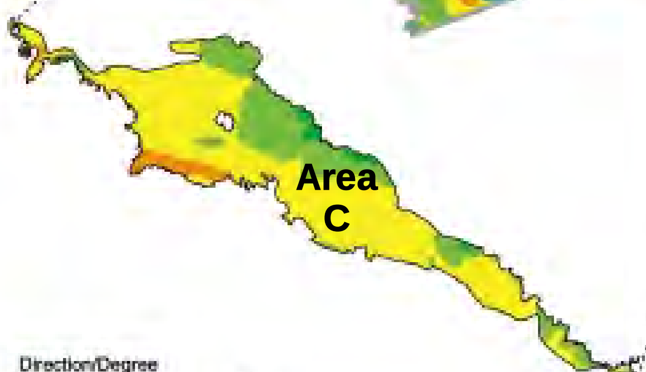
➢ page 21



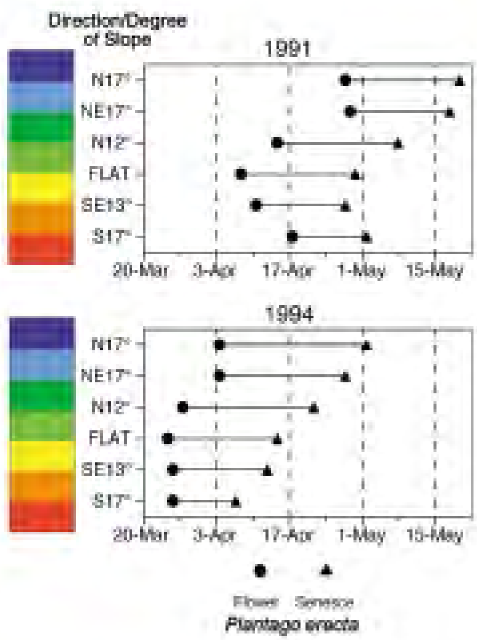
The yearly course of insolation on tilted surfaces under clear skies can be directly calculated using geometric algorithms. The vertical axis is megajoules per square meter per day. (The approximate equivalent of 1 MJ/m^2 is a 300-watt light bulb shining for an hour over one square meter.)

These three curves (a north-facing slope with a tilt of 20°, a flat area, and a south-facing slope with a tilt of 20°) show the major features of yearly insolation curves. The minimum is at the winter solstice, and insolation rapidly rises during the late winter and early spring. The maximum insolation occurs on the summer solstice, and then decreases throughout the summer and fall until the next winter solstice. The difference between north- and south-facing slopes is substantial throughout the year, with the north-facing slope receiving less insolation.





The enlarged views of the serpentine grassland areas show that Area C, which is relatively flat, has a large area of moderate insolation (yellow), while Area H has significant areas of north-facing slopes with lower insolation (blue and green).



Above: The insolation map of the Jasper Ridge Biological Preserve shows the amount of solar radiation that is received across the landscape on a clear day at the spring equinox (March 21). The relationship between aspect (the direction the slope faces) and insolation is clear, with south-facing slopes in red and orange, and north-facing slopes in green and blue. The chaparral and mixed-evergreen forests are well separated along the insolation gradient.

Left: *Plantago erecta* shows substantial variation in flowering and senescence from year to year and from slope to slope. In 1991, for example, flowering and senescence were nearly two weeks later than in 1994. The spread of flowering times between the north- and south-facing slopes of Area H was about 10 days, while the spread of senescence times was nearly three weeks. Most plants in the serpentine grassland exhibit similar patterns across slopes and between years.

MODELING INSOLATION, *continued from page 10*

insolation, according to Lambert's Law, at any grid point for any day of the year.

Insolation for the spring equinox provides a good index for insolation over the entire year. Spring equinox SOLARFLUX results are shown on the map on page 11. While the steepest north-facing slopes (dark blue on the map) receive less than 10 MJ/m^2 (megajoules of energy per square meter, the standard measure for insolation) on March 21, steep south-facing slopes (red on the map) receive more than twice that amount, over 20 MJ/m^2. Flat areas (light green on the map) receive intermediate insolation, approximately 15 MJ/m^2.

The striking correlation of this variation in spatial insolation with the distribution of plant communities can be seen clearly on the map—areas with the lowest insolation support mixed evergreen forest and small patches of redwoods, while areas receiving the highest insolation are covered with chaparral. Intermediate areas are grassland and open woodland.

At a finer scale, spatial variation in insolation creates visible differences in plant composition. For example, within the Area H serpentine grassland (see enlarged view on page 11), the variation in insolation is readily apparent, with the north-facing slope (green and blue) receiving low insolation, and a small portion of the south-facing slope (yellow) receiving high insolation. Plant surveys performed by Dr. Richard Hobbs of CSIRO, Australia, and me have shown substantial differences in plant species composition across this hill. Several plant species, for example, *Minuartia douglasii* (Douglas' sandwort) and *Gilia achilleifolia* (California gilia), are restricted to the warmer slope, while others, such as the *Ranunculus californicus* (California buttercup), *Phlox gracilis* (slender phlox) and *Claytonia perfoliata* (miner's lettuce), are found only on the cooler slopes.

Insolation differences between the north- and south-facing slopes are responsible for substantial temperature gradients within the grassland. Consider noon on January 12, 1992 (a crystal clear day): While the air temperature was approximately 13°C, the surface temperature on the south-facing 17° slope in Area H was 25°C, and the surface temperature on the nearby north-facing 17°slope was only 8°C. Temperatures on the south slope can become quite hot, exceeding 40°C even in April, well before the height of summer.

Since the rates at which plants develop are temperature dependent, differences in insolation lead to substantial differences in the seasonal timing of flowering and senescence. This, in turn, can have monumental effects on organisms that feed on flowering plants. *Plantago erecta* (California plantain) has been of particular interest because its phenology has major impacts on the population dynamics of the Bay checkerspot butterfly *(Euphydryas editha bayensis)*, an organism studied for over three decades at the Preserve. (See "A Flicker of Life Before Extinction" on page 5 of this issue and "Research Update: Bay Checkerspot Butterfly in Area H" in the Spring 1994 issue of *Jasper Ridge Views.*)

The magnitude of the insolation effect can be seen by comparing the flowering times for *P. erecta* on warmer and cooler slopes of Area H. (See graph on page 11.) During both 1991 and 1994, the time of flowering between north- and south-facing slopes varied by 10 days, and the date of senescence by an even greater number. To the casual observer, this spatial variation was most apparent in April, when the warm slopes appeared dry and brown, while the cooler slopes still supported lush green plants.

In contrast, Area C, which is located on the ridgetop, has much more uniform topography than area H, and lacks the cool extremes (blue areas). The spread of flowering and senescence across Area C, therefore, is much narrower than that in Area H. Because there are no cool slopes in Area C, the habitat lacks late-senescing *P. erecta*, food for Bay checkerspot larvae during drought years. This probably contributed to the earlier extinction of Bay checkerspots in Area C.

Although the time spread between the dates flowering began on Area H warm and cool slopes was approximately the same for both 1991 and 1994, the actual month and day that flowering commenced varied from year to year, as did the month and day for senescence. These differences can be explained by weather: The year 1991 had a cool spring with heavy March rains, while 1994 experienced a warm dry March. Statistical fits have shown that the flowering phenology of *P. erecta* and other serpentine grassland plants can be predicted by a simple combination of accumulated air temperature and accumulated slope-specific insolation.

The work in the serpentine grassland has demonstrated the utility of insolation models for predicting phenology, especially when coupled with data from the Preserve weather stations. Eventually, the combination of GIS, the SOLARFLUX model, and field studies may be extended to the remainder of the Preserve, elucidating the relationship between the way light falls on the landscape and many ecological variables, such as temperature, flowering and senescence, and water balance.❖

Dr. Stuart B. Weiss worked on the Bay checkerspot butterfly (and other species) for 10 years as a staff researcher at the Center for Conservation Biology (CCB). He completed his doctorate with Dr. Paul Ehrlich in 1996, and a postdoctoral fellowship at CCB in 1999. Weiss currently works on a wide variety of projects as a freelance ecologist.