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MODELING INSOLATION ON COMPLEX SURFACES

Spatially based insolation models, which calculate incident solar radiation on complex surfaces, are useful in many fields of study. We have developed the insolation model SOLARFLUX to calculate insolation based on surface orientation (slope and aspect), solar angle (azimuth and zenith), and topographic shading. SOLARFLUX is implemented in the ARC/INFO and GRID geographical information system (GIS) as an Arc Macro Language (AML) program. A convenient user interface allows specification of program parameters including latitude, time interval for simulation, topographic surface, atmospheric conditions (transmittivity), and output format. The topographic surface is specified as an array of elevation values (GRID). Output from the current version of SOLARFLUX is of five basic types: 1) total direct radiation, 2) duration of direct sunlight, 3) total diffuse radiation, 4) skyview factor (proportion of unobscured sky), and 5) fisheye projections of sky obstructions for specified surface locations. The importance of shadow patterns can be evaluated by performing simulations with and without topographic shading. For example, simulations of incident solar radiation for the Big Creek Reserve, California demonstrated that topographic shading was more important than surface orientation. Because calculations of insolation on complex surfaces are scale independent, SOLARFLUX can be applied to a wide range of theoretical and applied problems at both landscape and local scales. SOLARFLUX serves as a prototype for a more comprehensive program that provides calculations and simulations of solar radiation, a tool urgently needed by scientists, engineers, designers, and planners.

INTRODUCTION -- THE NEED FOR SPATIALLY BASED INSOLATION MODELS

Because of the pervasive effects of solar radiation on the ecosystem, assessment of solar radiation flux is of interest to a diverse scientific community whose investigations involve earth system processes. The behavior of solar radiation is relatively well understood (Geiger 1966, Lee and Baumgartner 1966, Lunde 1980); however, because of the intensive calculation requirements, previously it has not been practical to integrate theoretical insolation calculations over complex geometric surfaces and incorporate predicted insolation within spatially based data sets. Modeling solar radiation flux on complex surfaces is only now becoming practical because of advances in computer technology, both software and hardware.

Spatially based insolation models offer powerful analytical capabilities of value to numerous disciplines. In ecology, solar radiation models can be applied at individual, community, ecosystem, and landscape levels. For example, local light conditions influence growth of individual plants (Percy 1983); heterogeneity of microclimate influences distribution of different species in a community (Weiss et al. 1988); solar radiation limits ecosystem productivity and influences energy and water balances (Lit et al. 1992); and quantifying solar radiation flux is essential for evaluating climate fluctuations at the landscape level (Pacala and Hurtt 1993, Schimel 1993). In remote sensing, coupling insolation models with vegetation canopy reflectance models (God 1988) and landscape topographic patterns (Dubayah et al. 1989) can enhance the interpretation of reflectance measurements. Insolation models can also be used in architecture, landscape design, and urban planning to simulate various design and management options. For example, different building sites can be evaluated on simulated landscapes. Similarly, changes in landscape features (e.g. addition or removal of trees or structures) can be evaluated. Because simulation of incident radiation on complex surfaces is scale independent, except at very local scales where penumbral effects become important (Smith et al. 1989), spatially based insolation models have broad applications in both theoretical and applied problems at many scales.

SOLARFLUX - A PROTOTYPE INSOLATION MODEL

SOLARFLUX is a GIS-based program which predicts insolation based on surface orientation, solar angle, topographic shading, and atmospheric conditions. SOLARFLUX was implemented in Arc Macro Language (AML) using the ARC/INFO and GRID GIS platforms (Hetrick et al. 1993). The menu system allows the user to define all program parameters including global location of the surface (latitude and longitude) and time interval for calculation. Surface topography is defined by an array (GRID) of elevation data. Solar radiation flux, the energy intercepted per unit area, is comprised of direct, diffuse, and reflected insolation components (Monteith and Unsworth 1990). Direct radiation is generally the largest component of total radiation, ranging from about 85% direct and 15% diffuse radiation under clear sky conditions to no direct and near 100% diffuse under overcast conditions. Reflected radiation, by contrast, in which direct and diffuse components are reflected to a location from surrounding topographic features, generally accounts for a small proportion of total incident radiation (Gates 1980). Calculations for each surface location are integrated for a specified time interval by summing insolation components over a series of discrete time increments. A graphical display shows a hemispherical projection of the solar track for each incremental time of simulation.

The current version of SOLARFLUX calculates total direct radiation, duration of direct sunlight, total diffuse radiation, skyview factor (proportion of unobscured sky), and fisheye projections of sky obstructions for specified surface locations:

Total direct radiation, the intercepted direct beam solar energy, is calculated for each position on the surface using standard calculating formulae to determine solar angle (zenith and

azimuth) and atmospheric attenuation (Monteith and Unsworth 1990, Gates 1980, List 1971). The solar azimuth calculation presented in most standard references is only valid for azimuths less than 90 degrees (Rich 1989, Mitchell and Whitmore 1993), so a modified calculating formula for azimuth is applied:

$$\alpha = 2 \tan^{-1} ((\cos \delta \sin h) / (\cos \Phi, \sin \delta - \sin \Phi \cos \delta \cos h - \sin \theta))$$

where α is the solar azimuth angle, δ is the solar declination, Φ is the latitude, h is the hour angle, and θ is the solar zenith angle. Other calculations are based on formulae exactly as specified in standard references. Atmospheric attenuation is based on a transmittivity value t , the proportion of radiation that passes unimpeded through the atmosphere in a vertical direction, and the length of atmosphere traversed in non-vertical directions. Higher zenith angles lead to lower incident direct radiation due to atmospheric attenuation. Elevation effects are accounted for on surfaces with high relief by calculating changes in transmittivity as a function of elevation. The effect of surface orientation is accounted for using a cosine correction based on the angle of incidence. i.e. the angle between the solar angle and the axis normal to the surface. For each time interval, shadow patterns are determined using the HILLSHADE function which assigns values of zero to locations shaded by topographic features (i.e., no direct radiation received during that time interval). Optional output with the HILLSHADE function disabled makes it possible to evaluate the importance of shading.

Duration of direct sunlight, the total time during which a surface position receives direct beam radiation, is calculated by tallying when surface locations are not shaded.

Sky view factor, the proportion of sky directions not obscured by topographic features, is calculated by examining upward viewsheds for each location on the topographic surface. This is accomplished by ray tracing in a series of directions from a focal position and determining the maximum elevation angle of obscured horizon in each direction. The number of directions involved in ray tracing can be specified by the user. A curve is fit to the points in a hemispherical projection and the proportion of unobscured directions is calculated, i.e., the area on a hemisphere that is not obscured normalized to the total area of the hemisphere.

Total diffuse radiation, the intercepted solar energy that is scattered by the atmosphere, is currently calculated based on an isotropic model, i.e., all sky directions contribute equally to diffuse radiation. This is accomplished by multiplying the sky view factor by a coefficient that converts to units of diffuse radiation flux.

Hemispherical projections of sky obstructions are calculated by storing the elevation angles calculated when determining sky view factors. These angles can be used to simulate hemispherical (fisheye) views upward from a particular surface location and used as input to programs for analysis of hemispherical imagery, for example the analysis program CANOPY (Rich 1989, 1990). CANOPY can calculate a variety of insolation indices, including direct and diffuse site factors (the proportion of direct and diffuse radiation reaching a location, relative to an unobstructed sky) and the duration and timing of direct radiation.

CALCULATING DIFFUSE AND REFLECTED INSOLATION COMPONENTS

Calculations of diffuse radiation as implemented are simplified by assuming the atmosphere is isotropic. Anisotropic distributions can be calculated using programs such as CANOPY. The ability to simulate anisotropic distributions can readily be implemented in SOLARFLUX by dividing the upward viewshed into angular regions, with each region assigned an appropriate weighting.

Models of reflected radiation are inherently complex. Similar to the viewshed approach used for diffuse radiation, direct and diffuse reflected radiation can be estimated based on downward and upward viewsheds and reflectance properties of the surface in the viewsheds. Such reflectance simulation can vary in detail. The most detailed approach can include anisotropic properties (e.g., bidirectional reflectance), but calculations become extremely intensive. For most purposes a simpler model is sufficient, and for many purposes reflected insolation can be neglected.

EVALUATING THE EFFECTS OF TOPOGRAPHIC SHADING

Topographic shading affects the direct insolation component. The importance of topographic shading increases with surface complexity. For especially complex surfaces topographic shading may be more important than surface orientation in limiting solar radiation interception. As an example of the importance of topographic shading at a landscape scale, we simulated insolation, with and without topographic shading, for the Big Creek Reserve, a unit University of California Natural Reserve System. Big Creek, situated in the rugged Santa Lucia Mountains of the central California coast, includes elevations ranging from sea level to 1200 m (4000 ft) with an average slope of 30 degrees (Figure 1) (Norris 1985, Saving et al. 1993). Because of its topographic diversity, Big Creek comprises a broad range of microclimates, which in turn lead to a diversity of plant communities, from mesic redwood forest to xeric coastal scrub (Bickford and Rich 1979). Slope, aspect, and elevation are known by ecologists to have a significant influence on microclimate, however, the importance of topographic shading is less appreciated and previously was difficult to quantify.

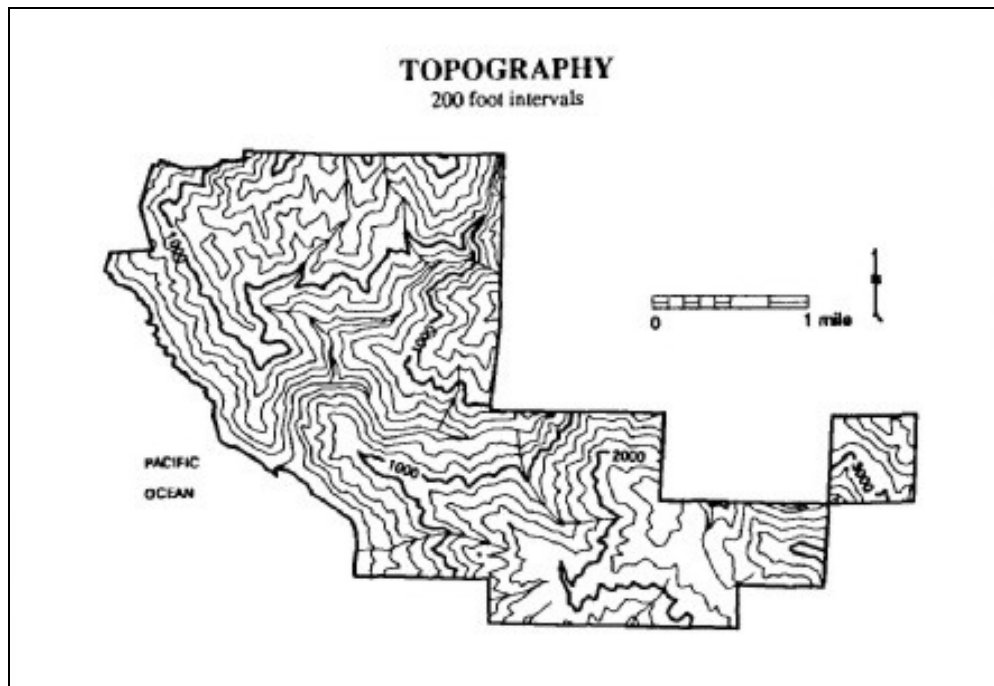


Figure 1. Topography of Big Creek Reserve (derived from the USGS Lopez Point 7.5 quadrangle).

Direct insolation was simulated for the winter solstice, equinox, and summer solstice, with topographic shading (Figures 2a, 3a, and 4a) and without topographic shading (Figures 2b, 3b, and 4b). Importance of topographic shading was evaluated using a shading index, calculated as the proportional decrease in direct insolation due to shading (Figures 2c, 3c, and 4c). Regions where daily insolation was zero for both simulations (with and without topographic shading included) were assigned a shading index of zero, i.e. shading did not affect incident solar radiation. Note that regions where no shading occurs also have a shading index of zero. Canyon bottoms had the highest shading index on the summer solstice; whereas northern slopes had the highest shading index on the winter solstice. The lowest shading index occurred on south facing slopes near the tops of ridges. Topographic shading, in general, is most important at high zenith angles (low elevation angles) and is dependent upon the particular arrangement of features in the Big Creek topography.

TRADE-OFFS - CALCULATION TIME, GRID SIZE, & CALCULATION INTERVAL

Insolation models are inherently calculation intensive; therefore it is important to consider trade-offs in terms of calculation time and accuracy. In particular, simulations involving large grids or long time intervals will tend to be slower than smaller grids or shorter intervals. For example, simulations for Big Creek Reserve (a grid of 100 by 600 cells) ranged from 4 computing hours for winter solstice using 30 minute incremental intervals to 6 hours for summer solstice. Inclusion of more detailed viewshed analysis in diffuse or reflected calculations will also significantly increase calculation time. Although computing power of workstations is increasing, more detailed analyses still require supercomputers. It is always important for one to scale insolation simulations appropriately for the problem being addressed.. This depends on the size of the grid (granularity), the calculation interval, and the increments within the calculation interval. Performance is inherently slowed when developed in interpreted languages such as AML. For this reason, it is currently impractical to use SOLARFLUX to simulate insolation for very large grids or long time intervals. Compilation of SOLARFLUX could significantly enhance performance.

A COMPREHENSIVE INSOLATION PROGRAM

Scientists and engineers have been analyzing the influence of solar radiation on the environment by consulting tables and formulae in standard references, and many have developed computer simulations to meet specific needs (e.g. Brown 1992, Dubayah *et al.* 1990, Hetrick *et al.* 1993). It is surprising that software developers have not recognized such needs and produced a commercial insolation program. A comprehensive insolation program would include the functionality of a program like SOLARFLUX, as well as capabilities of other analysis programs such as CANOPY (Rich 1989, 1990). Integration with CANOPY could allow examination of the influence of complex patterns of sky obstruction (e.g., effects of plant canopies) on near- ground solar radiation flux at both local (Lin *et al.* 1992, Rich and Weiss 1991) and landscape levels (Gab 1992).

This comprehensive insolation program could be a module of a GIS package, or designed as a stand-alone product; however, independent of the development platform, CAD and GIS databases should be accessible. Other calculations should include insolation calculations for complex surfaces (both GIS surfaces and CAD surfaces which can define surfaces with overhangs), and fisheye calculations for solar radiation assessment at individual locations. Graphics display should include a downward view of the surface (map), fisheye upward/downward from a surface location (fisheye), three-dimensional surface view from any angular perspective (surface perspective), and a sun/earth view (astronomical). The program should be able to produce two- and three-dimensional graphs, tables, and maps, all in standard data export formats.

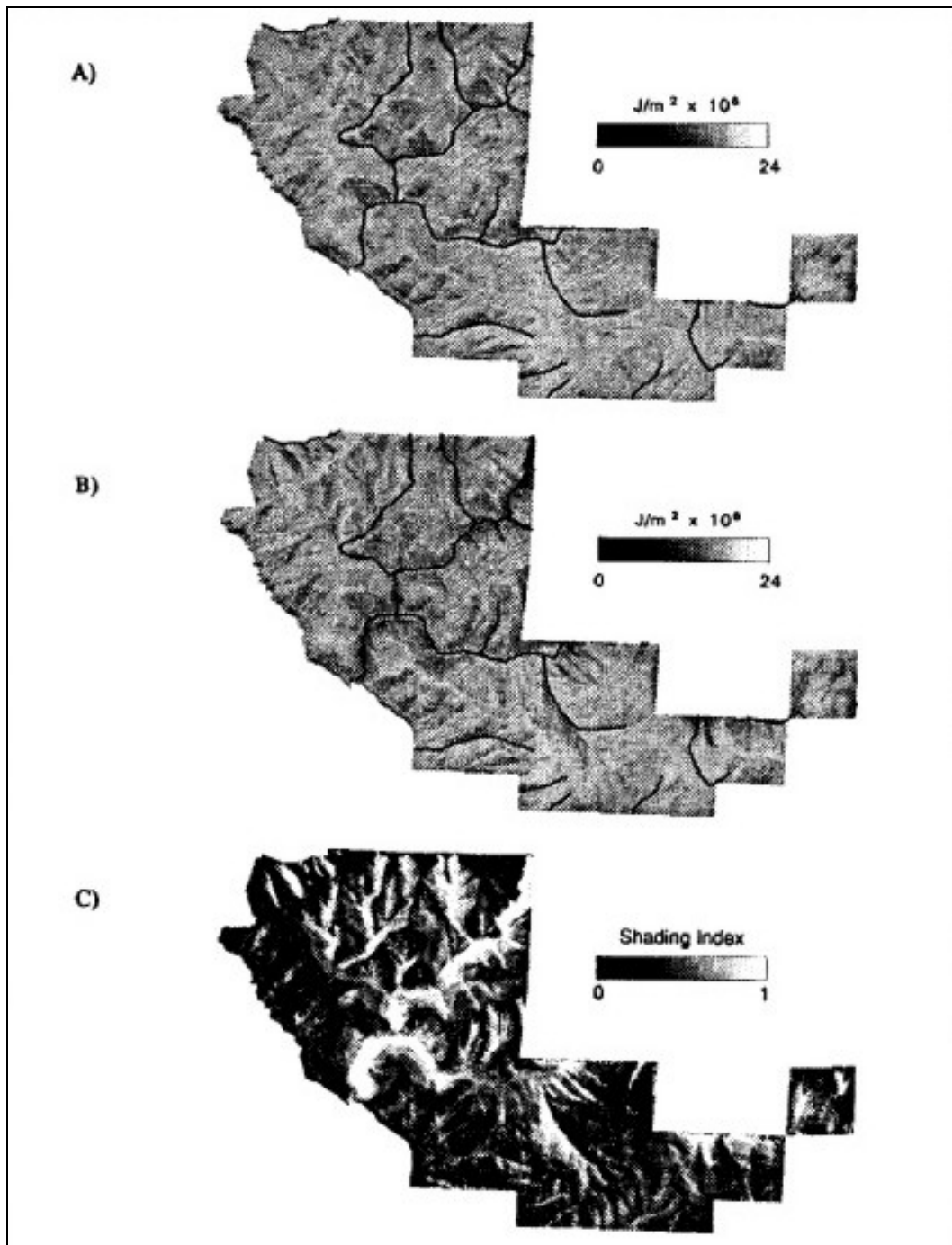


Figure 2. Daily insolation on the summer solstice A) with topographic shading, B) without topographic shading, and C) shading index (proportional decrease in direct insolation due to topographic shading).

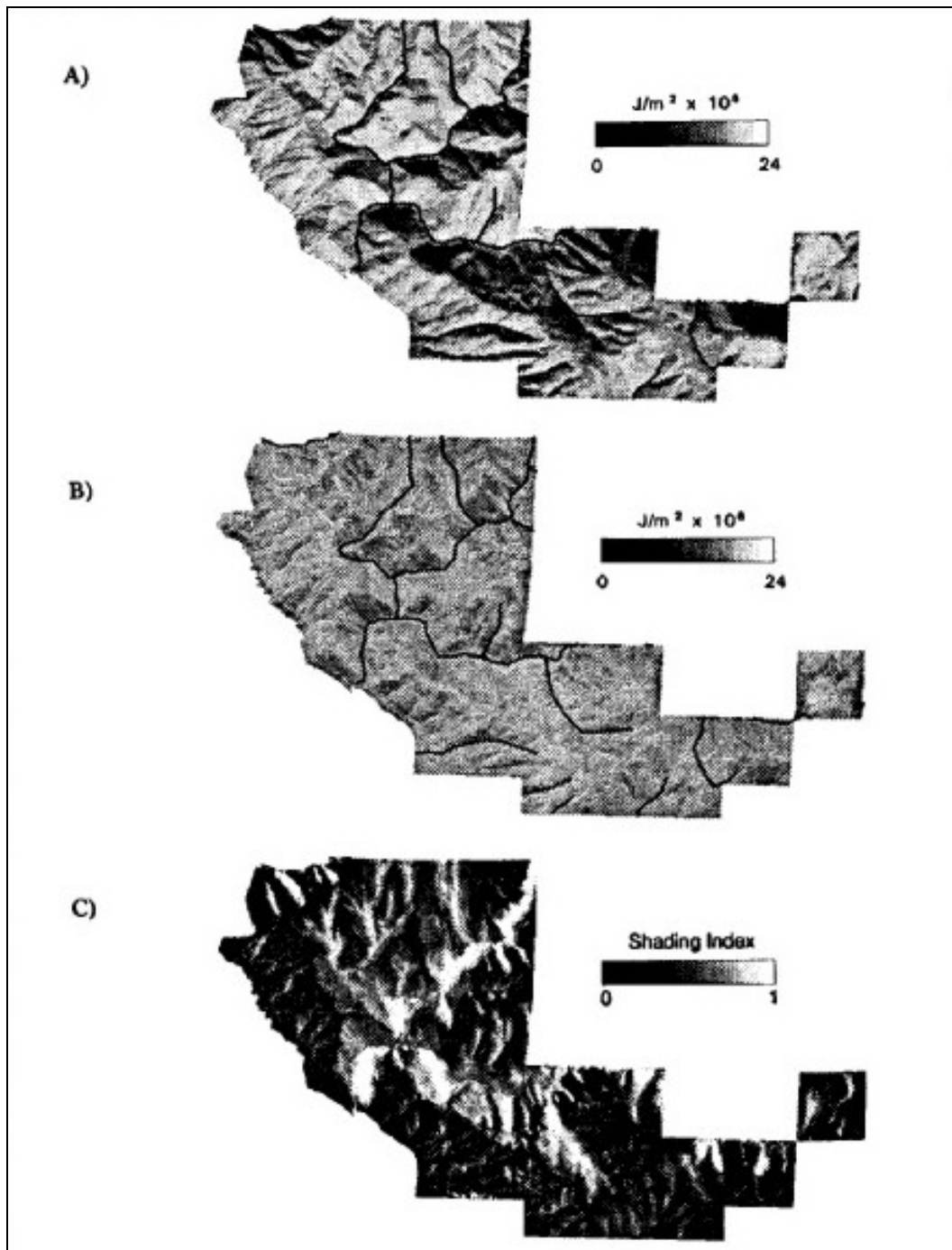


Figure 3. Daily insolation on the equinox A) with topographic shading, B) without topographic shading, and C) shading index (proportional decrease in direct insolation due to topographic shading).

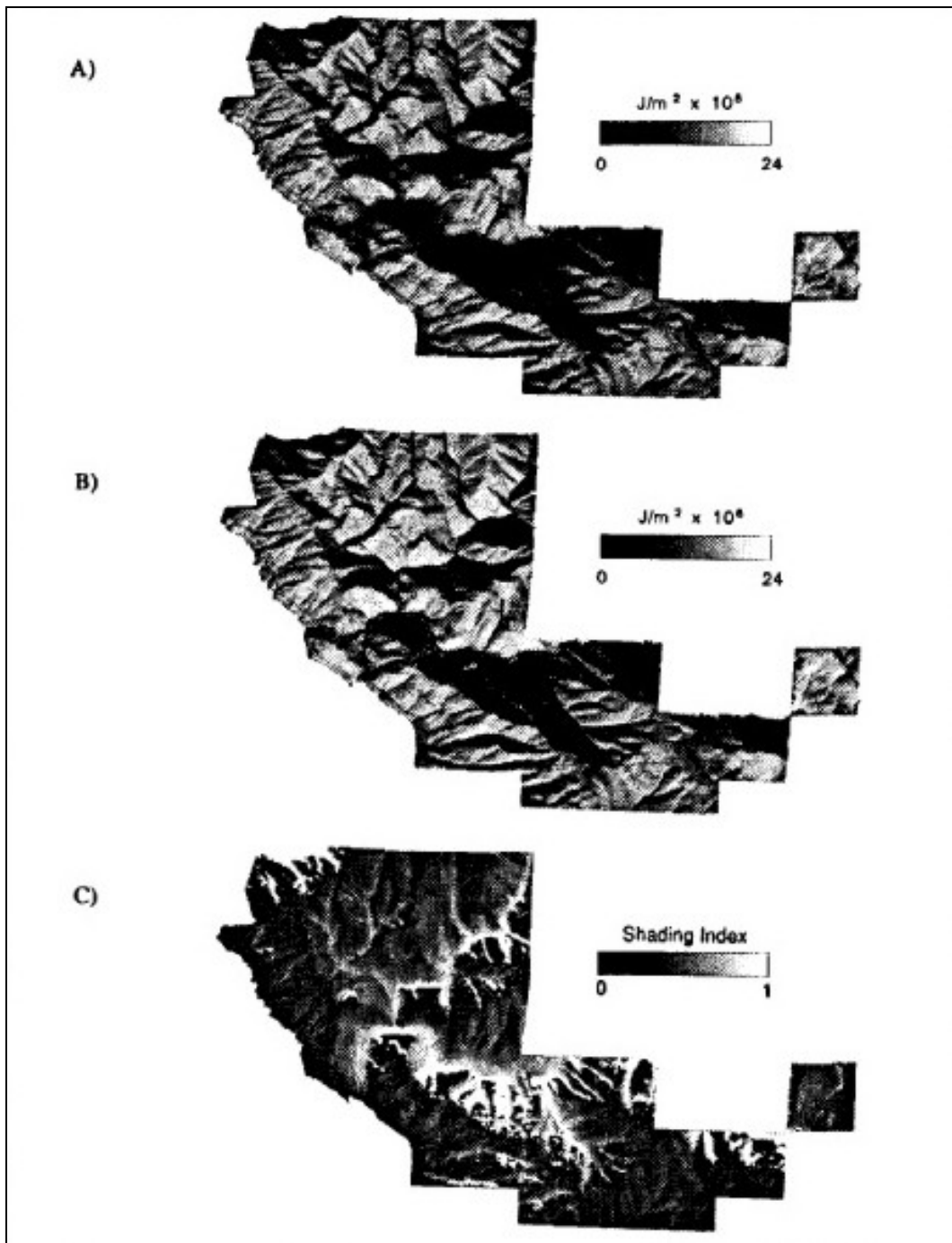


Figure 4. Daily insolation on the winter solstice A) with topographic shading. B) without topographic shading, and C) shading index (proportional decrease in direct radiation due to topographic shading).

A well developed insolation program with a user friendly interface, would be a valuable tool and marketable at a variety of levels: 1) GIS module (high end), 2) CAD module (medium), 3) PC/Mac/SUN stand alone (low end, high volume), 4) education stand alone (low end, high volume). The following list summarizes major needs that could be addressed by a comprehensive insolation program:

What are major capabilities of a comprehensive insolation program?

- Standard Conversions, Tables, Calculations
 - julian day, calendar day, and solar declination
 - local time, solar time, and hour angle
 - solar angle (as a function of julian day, time of day, and latitude)
 - lines of sunrise and sunset
 - transmittivity and atmosphere traversed (as a function of solar angle)
 - diffuse radiation flux (as function of transmittivity, sky direction, surface orientation)
 - direct radiation flux (as function of solar angle, transmittivity, surface orientation)
 - solar radiation flux partitioned by wavelength

- Simulations for Complex Surfaces
 - shadow patterns, hours of direct sunlight
 - solar radiation flux (direct, diffuse, reflected)
 - shading indices

- Simulations of Complex Sky Obstruction
 - analysis of hemispherical photography
 - generation of hemispherical viewsheds

- Graphical Display
 - downward view (planar projection)
 - upward view (hemispherical projection)
 - additional views and projections (surface perspective, astronomical...)

- Input and Output
 - integration with GIS, CAD, Image Processing, Photo CD
 - output of data files, tables, graphs, additional graphics

CONCLUSION

SOLARFLUX is a GIS-based model for calculating insolation for complex surfaces based on surface orientation, solar angle, shadowing due to topographic features, and atmospheric attenuation. This GIS approach offers scale independent simulations and facilitates coupling insolation analysis with other earth system models. Simulating insolation for Big Creek Reserve, with and without consideration of shadow patterns, allowed assessment of the importance of topographic shading. Computer technology has advanced to a level that modeling insolation for complex surfaces is feasible. A commercially developed comprehensive insolation software package is needed by scientists, engineers, designers, and educators: 1) to provide access to standard tables and formulae, 2) to provide graphical display in both two- and three- dimensional perspectives, and 3) to model insolation on complex surfaces.

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