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Characterizing Plant Canopies with Hemispherical Photographs

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I. INTRODUCTION

A. The Nature of Hemispherical Canopy Photography

Hemispherical (fisheye) canopy photography is a technique for characterizing plant canopies using photographs taken through an extreme wide-angle lens (Anderson, 1964). Typically, the viewing angle approaches or equals 180°. Hemispherical photographs can be taken either looking upward from within a canopy or looking downward from above a canopy. The resulting photographs serve as permanent records of the geometry of canopy openings. The geometric distribution of openings can be measured precisely and used to estimate potential solar radiation penetration through openings and to determine aspects of canopy architecture such as ground cover, leaf area index (LAI), and leaf angle distribution. Hemispherical photographs can be analyzed by hand using sampling grids; however, hand analysis is extremely tedious and generally impractical for large numbers of photographs. Digital image analysis techniques have recently been developed that allow for efficient analysis of large numbers of photographs (Chazdon and Field, 1987b: Rich, 1988, 1989; Becker *et al.,* 1989).

Hemispherical photography can theoretically be used to study any plant canopy, including forests, shrublands, and crops. The primary limitations are the size of the camera setup and the ability to position the setup within or above the plant canopy. Photographs can be taken along transects or in horizontal or vertical grid patterns to sample spatial heterogeneity within canopies. Such sampling designs can be used to map light penetration and stand structure characteristics as a function of horizontal and vertical position (Figure 1), Dynamics and temporal variation can be monitored by repeated sampling from the same camera positions. Hemispherical photographs can be used to characterize formation and closure of canopy gaps through time and to monitor seasonal changes in foliage densities. Canopy structure and light environment can be sampled above individual plants for studies of demography and ecophysiology. Thus applications of the technique range from ecosystem level characterization of canopy architecture to assessment of local microenvironments.

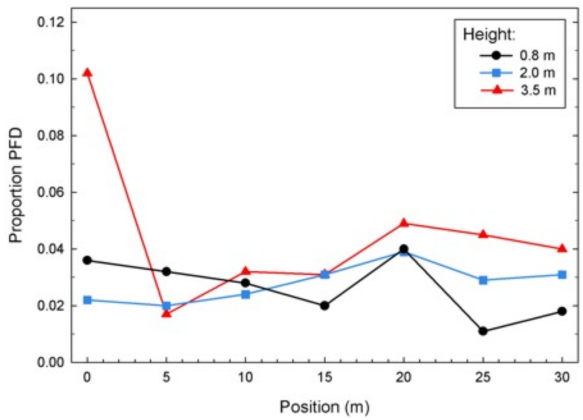

Figure 1. A light map in primary tropical wet forest at La Selva Biological Station, Costa Rica. The light map was constructed using photon flux density (PFD) estimated from hemispherical canopy photographs taken along a 30 m transect, with photographs taken every 5 m at heights of 0.8, 2.0 and 3.5 m above the forest floor. A moderate size treefall gap was situated above position 0. For the 3.5 m height, PFD under the gap was greater than 10% (relative to levels outside the canopy); whereas PFD at the edge of the gap was lower than PFDs at the 0.8 and 2.0 m heights. This resulted because of very dense foliage growing in from the sides of the gap. For the 0.8 and 2.0 m photograph heights, PFD varied from 1-4% and the gap was not apparent because of dense undergrowth.

B. Background

The hemispherical (fisheye) lens was originally designed by Hill (1924) to provide a view of the entire sky for studies of cloud formation. Foresters and forest ecologists conceived of using photographic techniques to study the light environment under forest canopies. Evans and Coombe (1959) estimated sunlight penetration through forest canopy openings by overlaying diagrams of the sun track on hemispherical photographs. Anderson (1964, 1971) provided a thorough theoretical treatment for calculating the penetration of sunlight (direct) and skylight (indirect or diffuse) components of solar radiation through canopy openings as determined using hemispherical photographs. In recent years, many researchers have successfully used hemispherical canopy photography to study solar radiation penetration and canopy architecture (see reviews in Chazdon and Field, 1987b; Rich, 1988, 1989; Becker *et al.*, 1989). For example, hemispherical photographs have been used to predict plant growth rates (Pearcy, 1983), photosynthetic capacity (Chazdon and Field, 1987a), and leaf area index (Neumann *et al.*, 1989). Detailed treatments of field and analytical methodology have been provided by Pearcy (1989) and Rich (1989).

II. PRINCIPLES

A. Hemispherical Projections

A hemispherical lens produces an image that is essentially a projection of a hemisphere of directions on a plane. The exact nature of the projection depends upon the lens being used. When used viewing upward, a hemispherical lens provides a complete view of the entire sky. In such a view, a circular image is produced, with the zenith in the center and the horizon at the edges. Relative to north, east is counterclockwise and west is clockwise because the view direction is upward. Each sky direction can be represented by a unique zenith angle θ (the angle between the zenith and the sky direction) and a unique azimuth angle α (the angle measured counterclockwise between north and the compass direction of the sky direction). Many hemispherical lenses use an equiangular (polar) projection in which zenith angle is proportional to distance along a radial line (Figure 2). When taken from within a plant canopy looking upward, a hemispherical photograph records the angular coordinates of all canopy openings, as seen from the position from which the photograph is taken (Figure 3).

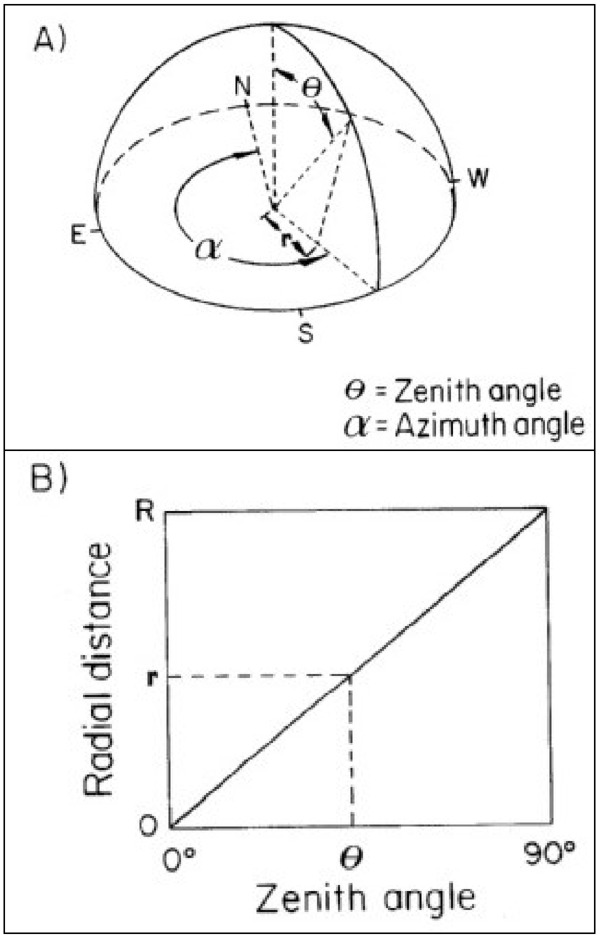

Figure 2. The projection as seen with a hemispherical lens looking upward. A) A hemispherical lens projects a hemisphere of directions on a plane. Each sky direction can be represented by unique angular coordinates, a zenith angle θ and an azimuth angle α. B) One common projection is an equiangular projection in which distance along a radius is proportional to zenith angle.

Similarly, when taken from above a plant canopy looking downward, a hemispherical photograph provides a view of all directions on the ground, with the nadir view in the image center and the horizon on the edges (Norman and Campbell, 1989). As long as the projection produced by a particular hemispherical lens is understood, it is possible to calculate angular coordinates in the resulting photographs. Herbert (1987) provides a discussion of hemispherical projections and lens distortion corrections. A calibration function for a particular hemispherical lens can easily be calculated based upon projected area measurements of a circular target viewed at a series of known angles with respect to the lens optical axis (Herbert, 1987).

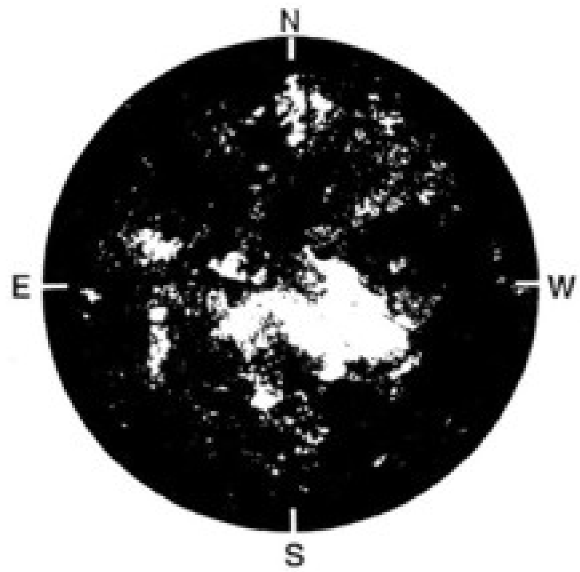

Figure 3. Example of a view through a hemispherical lens looking upward from beneath a plant canopy. This is a view of a treefall gap in the tropical rain forest of La Selva Biological Field Station, Costa Rica.

B. Hemispherical Photographs as Archival Records

In essence, hemispherical photographs are a type of close-range remote imagery that contain fundamental information about canopy architecture. Hemispherical photographs provide a permanent record of the geometry of canopy openings. They can be inspected to provide insight into heterogeneity within a given canopy and to compare canopies at different sites. They can be analyzed by hand or by automated digital image analysis to precisely measure the geometry of canopy openings. In turn, solar radiation penetration and canopy architecture can be inferred from the patterning of canopy openings. Analogous to the way voucher specimens are collected for vegetation or floristic studies, hemispherical photographs can be collected for studies of plant canopies. In general, hemispherical photographs are best stored as negatives or transparencies. Photographic media have distinct advantages of low cost and high resolution. As permanent records, hemispherical photographs can be studied using existing analytical methodology and saved for future study as methods are further developed and refined.

C. Estimation of Solar Radiation Penetration

Hemispherical photographs taken looking upward can be used to estimate solar radiation penetration to a given position in a plant canopy. The photographs must be taken such that the film plane is level and the orientation relative to north is known. Radiation flux density is calculated as the sum of direct sunlight and diffuse skylight that passes unimpeded through canopy openings. Calculation of solar radiation penetration from hemispherical photographs is based on the assumption that canopy openings allow unimpeded passage of solar radiation and foliage absolutely blocks penetration. This simple model neglects scattered radiation, radiation reflected from or transmitted through leaves. Using theoretical or empirical relations that describe the way direct sunlight and diffuse skylight fluxes vary as a function of sky direction and with knowledge of the distribution of canopy openings, it is possible to make reasonable estimates of solar radiation penetration to given positions under a plant canopy. Calculations of direct sunlight and diffuse skylight are generally expressed as direct and indirect site factors. Direct site factor is the proportion of direct sunlight and indirect site factor is the proportion of diffuse skylight under the canopy relative to that outside the canopy.

Direct sunlight penetration through canopy openings is calculated by determining the intersection of the sun path with canopy openings. The apparent sky direction of the sun can be calculated with great accuracy, as it varies with latitude, time of day, and time of year (List, 1971; see also Pearcy, 1989; Rich, 1989). Direct sunlight coming from a given sky direction can be approximated by correcting for attenuation as a function of the pathlength that must be traversed through the atmosphere (Gates, 1980). Variations due to cloudiness and other site-specific atmospheric conditions are not easily predicted and are best measured empirically. In the absence of empirical data, it is most common to calculate potential direct sunlight penetration with only a correction for atmospheric attenuation.

Diffuse skylight penetration through canopy openings is calculated by assuming a distribution of skylight as a function of sky direction. Two diffuse skylight distributions are in common usage, the Uniform Overcast Sky (UOC) and the Standard Overcast Sky (SOC) (see Pearcy, 1989; Rich, 1989). The UOC assumes that diffuse radiation flux is the same from all sky directions. The SOC assumes a distribution that depends on zenith angle, with more diffuse radiation flux from sky directions toward the zenith. It is widely recognized that these distributions do not adequately describe diffuse skylight distributions, but no better alternatives are currently available. Though somewhat arbitrary, the UOC and SOC do allow standardization of calculations between researchers. More research is required to provide diffuse skylight distributions for both clear and overcast days, and to determine site-specific diffuse skylight distributions that integrate contributions from clear and overcast days.

Ideally, long-term monitoring of direct sunlight and diffuse skylight can provide empirical calibrations for a particular site. However, reasonable results can be obtained using theoretical sunlight and skylight distributions. When practical, it is desirable to establish long-term, site-specific records of solar flux. Monitoring is accomplished using a pair of light sensors (pyranometers for total radiation or quantum sensors for photosynthetically active radiation) attached to a data logger, one to monitor global radiation flux and the other to monitor radiation flux from skylight. The light sensors should be positioned in the open; one sensor should be unobstructed and used to monitor global radiation flux, and the other sensor should be fitted with a shadowband, to block radiation along the sun path, and used to monitor diffuse radiation flux from skylight (Becker, 1987). Radiation flux from direct sunlight can be calculated as the difference between global and diffuse radiation flux.

The relative contribution of direct sunlight and diffuse skylight to global radiation flux can either be determined empirically or estimated from atmospheric clearness (Decker, 1987). A typical atmospheric clearness of 0.65 implies that 70-90% of global radiation flux comes from direct sunlight. Radiation flux estimates from photographs taken beneath plant canopies can be expressed in absolute units, such as mole/m^2/s, or as a proportion of radiation flux in the open. When possible both absolute and relative units should be presented. Absolute units define the biophysical limitations for a site; whereas, relative units indicate the attenuation caused by the canopy itself.

Analyses of radiation flux can be applied for any range of solar radiation wavelength, and to either photon or energy flux, because the basis for analysis is the geometry of canopy openings, not direct measurements of radiation flux. For example, photosynthetically active radiation (400-700 nm) photon flux density (mole/m^2/s) is useful for studying radiation available for photosynthesis; whereas, energy flux (W/m^2) from total solar radiation is most useful for calculating energy balances. Empirical or theoretical models used to describe the sky distributions of direct sunlight and diffuse skylight must be tailored to the range of relevant radiation wavelengths; though for many purposes these distributions are not expected to be very different.

A cosine correction can be included in calculations of light interception by a flat surface within a canopy. Such a cosine correction should be calculated relative to the normal of the plane of interception. For a horizontal surface, the normal is in the zenith direction. Horizontal surface cosine corrections are useful when making comparisons between hemispherical radiation flux estimates and measurements from cosine corrected light sensors. However, for purposes where it is desirable to measure solar radiation from all directions, no cosine correction should be included. An example of such a case would be calculation of the potential light interception by a plant that has leaves at many orientations. In some cases it may be most meaningful to weight incoming radiation by the leaf angle distribution for a particular plant or level within a canopy.

Radiation flux can be predicted from hemispherical photographs for periods ranging from minutes, to months, to an entire year. Determination of exact timing of direct sunlight penetration (sunflecks) within a day is theoretically possible, within the resolution of digitization. Such measurements require very precise registration of photographic images for determination of sky directions (Chazdon and Field, 1987b). Seasonal variation in light penetration for evergreen canopies can readily be calculated from a single photograph, based on the assumption that canopy openings do not change significantly through the year. Integrated totals for an entire year can similarly be calculated from a single photograph, based on the same assumption. In cases where canopies undergo seasonal or directional changes during the course of a year, a set of photographs can be taken at time intervals and analyzed individually for given periods of the year. For calculations, sky distributions of direct sunlight and diffuse skylight should be formulated with respect to the time period being examined.

D. Measurement of Canopy Architecture

Hemispherical photographs can be analyzed to infer various aspects of canopy architecture, including cover, foliage distribution, LAI, and leaf angle distribution. Hemispherical photography is an excellent alternative for obtaining gap fraction data that can be used as input for inversion models to calculate structural features of a canopy (Norman and Campbell, 1989). A full discussion of inversion techniques and alternative means for measuring gap fractions is presented by Welles (1990) in this volume. Gap fraction inversion techniques can produce excellent estimates of LAI and leaf orientation for full-cover canopies as well as heterogeneous canopies. Gap fraction data can be calculated from hemispherical photographs taken looking either upward from within a canopy or downward from above a canopy (Norman and Campbell, 1989). Hemispherical photography offers distinct advantages over other techniques, because it directly examines the distribution of gap fractions at high resolution, because photographs can be rapidly acquired in the field, and because the photographs provide a permanent archival record of gap fractions.

Results from hemispherical photographs can also be used to estimate radiation levels within a canopy for any wavelength by using inverted values of LAI and mean leaf inclination angle in a radiative transfer model, for example the model of Idso and de Wit (1970). The radiative transfer model would be used to estimate the scattered radiation, while the estimate non-intercepted direct sunlight and diffuse skylight radiation would come directly from the hemispherical photograph. Although the inversion algorithm may assume random foliage distribution, radiation models generally make the same assumption, so errors from this assumption are minimized. The quantity most likely to be in error from the inversion is the LAI and inclination angle, and these quantities usually compare well with direct measurements. Furthermore, scattered radiation is not very sensitive to randomness assumptions (Ross, 1981).

III. METHODS

A. Field Acquisition of Photographs

Field acquisition involves taking hemispherical photographs within or above plant canopies. The goal is to obtain high contrast photographs from a known position and orientation. Typically, set-up and acquisition of each photograph requires less than five minutes, so many samples can be rapidly obtained. The camera fitted with a hemispherical lens should be supported so that the film plane is horizontal and the camera is oriented relative to north. A good practice is to align magnetic north with the top of the camera and to correct for magnetic declination during analysis. The camera set-up can be supported on a tripod or monopod when taking photographs pointed upward, or on a cantilevered boom when taking photographs pointed downward. Various researchers have constructed self-leveling mounts that can be supported on a tripod or monopod (for example, Rich, 1989). Meticulous care should be taken to level and orient the camera set-up, especially when it is desirable to register sun paths with the photographs. Some researchers have found it useful to use small lights mounted at the edges of the field of view to mark the image boundaries (for example, Chazdon and Field, 1987b; Becker *et al.* 1989). The position of a number printed by a camera databack can be useful both to uniquely label each photograph and to serve as internal reference that can be used for determining image boundaries. Lights mounted on poles in a known direction within the field of view can provide an internal cross-check of image orientation.

Generally, high speed black-and-white film should be used when looking upward from beneath canopies (see Rich, 1989) and black-and-white infrared film should be used when looking down on canopies. Satisfactory results can also be obtained with color transparency film when looking upward. Some researchers have preferred high contrast, fine grain copy film (see Cohen and Fuchs, 1987). To enhance contrast between foliage and sky when working with visible light, a red filter can be used on overcast days and a blue filter on sunny days. A filter that blocks visible wavelengths can be used for infrared photographs. Many hemispherical lenses have built in filter wheels. For lenses with out filter wheels or filters not included in filter wheels, filters can be mounted internally on the camera side of the lens. Hemispherical photographs taken looking upward are best taken on overcast days or early or late in the day to achieve even sky illumination. Exposures can be determined using internal camera light meters or a series of spot readings with a hand-held light meter. Test photographs should be taken to determine proper exposure. A shutter speed of 1/125 second or greater will generally freeze foliage movement caused by wind. Often it is advisable to take photographs at more than one exposure for each sample position, for example, "bracketing" the exposure (taken at, one F-stop above, and one F-stop below the metered reading). If the lens has a focus adjustment, the focus ring should be set at infinity and taped in place to avoid slippage. Film should be developed promptly, the quality of photographs verified, and any poor quality photographs retaken. Negatives or transparencies can be stored in archival-quality storage sleeves or plastic holders. Table 1 provides a listing of equipment and supplies for image acquisition in the field. The listing includes information about various major manufacturers of hemispherical lenses, including Canon, Minolta, Nikon and Olympus. Inexpensive fisheye adapter lenses that screw on in front of standard photographic lenses have also been used successfully (see Chazdon and Field, 1987b).

Table 1. Equipment and supplies for acquisition of hemispherical canopy photographs. Approximate list prices are given in U.S. dollars.

CAMERA BODY

Canon T90 ($920; Canon Incorporated; 1 Canon Plaza; Lake Success, NY 11042; tel. (516)488-1400).

Minolta X700 ($370; Minolta Incorporated; 101 Williams Drive; Ramsey, NJ 07446; tel. (201)825-4000).

Nikon FM2 ($525; Nikon Incorporated; 623 Stewart Avenue; Garden City, NY 11530; tel. (516)222-0200).

Olympus OM4T ($1,100; Olympus Corporation; Crossways Park; Woodbury, NY 11797; tel. (516)364-3000).

HEMISPHERICAL LENS

Canon 7.5mm f/5.6 ($1,010; Canon Incorporated; 1 Canon Plaza; Lake Success, NY 11042; tel. (516)488-1400).

Minolta 7.5mm f/4 ($1,280; Minolta Incorporated; 101 Williams Drive; Ramsey, NJ 07446; tel. (201)825-4000).

Nikkor 8mm f/2.8 ($1,870 Nikon Incorporated; 623 Stewart Avenue; Garden City, NY 11530; tel. (516)222-0200).

Zuiko 8mm f/2.8 ($2,090; Olympus Corporation; Crossways Park; Woodbury, NY 11797; tel.x (516)364-3000).

Screw-on fisheye adapter lens (for example, Soligor, Spiratone, or Telesor; check photographic suppliers for price and availability).

MONOPOD OR TRIPOD
COMPASS
BUBBLE LEVEL
CUSTOM SELF-LEVELING MOUNT
FILM

black-and-white visible (Kodak Tri-X, Kodak P-Max, Ilford HP-3)

black-and-white infrared (Kodak High Speed Infrared)

color transparency (Kodak Ektachrome, Kodak Kodachrome)

DARKROOM SUPPLIES AND EQUIPMENT

developing tank, dark bag

developer, stop bath, fixer

(note: color transparency film is generally best developed commercially)

negative/transparency storage cases

B. Image Analysis

Manual analysis of hemispherical photographs requires either the overlay of clear sampling grids upon prints or the projection of photographs on an opaque sampling grid. Separate sampling grids are used for direct sunlight and diffuse skylight. Details for manual sampling techniques are presented in Anderson (1964). Manual analysis is tedious and time-consuming. For this reason, various attempts have been made to automate the process. Analysis systems have been developed that use mechanical digitization devices to move a light sensor to sample different positions within a projected photograph (Bonhomme and Chartier, 1972; Chan *et al.*, 1986) and that use diode-array scanners (Olsson *et al.*, 1982). Chazdon and Field (1987b) developed a digital image analysis system called SOLARCALC that is based on the Apple Macintosh personal computer and that uses a digital scanner for input from photographic prints. Most recently, two systems, CANOPY (Rich 1988, 1989) and SYLVA (Becker *et al.*, 1989), have been developed that are based on IBM-compatible microcomputers and that use video for direct input from negatives. CANOPY and SYLVA have various advantages over SOLARCALC, including more rapid and convenient video digitization and better integrated analysis and hardware control capabilities; however, SOLARCALC requires less expensive equipment. CANOPY has many advantages over SYLVA, including use of a higher quality digitization and display adapter, direct display of negatives as positives, an explicit interactive means for choosing thresholds to distinguish canopy openings from foliage, and greater flexibility for incorporating site-specific information. Rich *et al.*, (1989) provide a detailed discussion of the principles and methodology for microcomputer image analysis.

The functioning of CANOPY serves to illustrate the steps involved in analysis of hemispherical photographs. The fundamental steps of analysis involve input of the negatives, determination of a threshold that distinguishes openings from foliage, automated calculation, anti automated output of results (Rich, 1989). Precise registration of the negatives is critical to allow calculation of sky directions. First negatives are placed in a backlit film holder. Backlighting of negatives reduces problems of uneven lighting, which result when using reflected light to digitize prints. Images are input with a solid-state black-and-white video camera fitted with a macro lens. The images are digitized at 512(h) x 480(v) pixel resolution using a framegrabber digitizer/display adapter that simultaneously digitizes and displays at the rate of 30 images per second. With the use of hardware lookup tables, the digitized negatives are displayed as positives in real time on an image display screen. The display screen includes a grid that facilitates adjustment of the size, translation, and rotation of the image. Once the image is properly positioned, a threshold is determined that distinguishes openings from foliage. This is determined by comparing a threshold image, in which all pixels are displayed as either black (foliage) or white (openings), with a continuous tone black-and-white image and interactively changing the threshold up or down until the edges of openings in the threshold image match the edges observed in the continuous tone image. Automatic calculations and data output are then initiated. The process can then be repeated for the next photograph. From 10 to 15 photographs can be analyzed per hour, including setup, threshold selection, calculation and data output.

Calculations by CANOPY involve, first, examining each pixel within the image to determine whether it is counted as foliage or opening, and then, determining the contributions of direct sunlight and diffuse skylight from the corresponding sky direction if it is an opening. To enhance performance, many of the calculations are made ahead of time and stored in look-up tables. Direct site factor, indirect site factor, and gap fraction data (openings as a function of zenith and azimuth angles) are displayed on the screen or optionally output to data files. The system is fully configurable for a given site. It can incorporate either empirical or theoretical distributions of direct sunlight and diffuse skylight. Sunlight and skylight distributions are calculated in a way that can accommodate different hemispherical projections and corrections for lens distortion. A cosine correction can also be included, as can corrections for other interception surfaces (for example, a correction that parallels leaf angle distribution).

Currently there are no commercially available systems for analysis of hemispherical canopy photographs. Table 2 provides a listing of equipment for assembly of an image analysis system based on an IBM-compatible personal computer. This system is designed for use with the program CANOPY (Rich, 1988, 1989). As an add-on to an existing personal computer, such a system would cost less than $8,000 US. It should be noted that the personal computer could be made available for other purposes when not analyzing photographs, and the image analysis system can also be used for many other applications (see Rich *et al.,* 1989). The program SYLVA runs on almost identical hardware, so the costs are comparable (Becker *et al.,* 1988). The only difference is that SYLVA currently uses a Chorus Data Systems PC-EYE PC-1l00 6-bit digitizer (approximate cost $700) and a Tecmar GRAPHICS MASTER display adapter (approximate cost $700) and two black-and-white display monitors in place of the single color monitor (approximate cost $600 per monitor). SOLARCALC uses a THUNDERSCANNER (approximate cost $250), based on an Apple Macintosh personal computer (approximate cost $2,500-$6,000), and requires no additional hardware. Alternatively, SOLARCALC can use any other scanner that allows image input to a Macintosh personal computer.

Table 2. Image analysis system hardware for use with the program CANOPY. Approximate list prices are given in U.S. dollars (adapted with permission from Rich, 1988).

MICROCOMPUTER
IBM-compatible with 640K RAM, hard disk, and mathematics coprocessor; printer and mouse optional ($2,000-$6,000).

VIDEO DIGITIZER/DISPLAY ADAPTER
video framegrabber with hardware lookup tables (Imaging Technology PCVISIONp1us with external synchronization cable, $2,100; Imaging Technology Incorporated; 600 West Cummings Park; Woburn, MA 01801; tel. (800)532-3500 or (617)938-8444.)

VIDEO DISPLAY MONITOR
standard RGB video with underscan and external synchronization (Sony PVM-13420, $1,100; Sony Corporation of America; Headquarters; 1600 Queen Anne Road; Teaneck, NJ 07666; tel. (201)833-5200.)

VIDEO CAMERA AND MACRO LENS
solid-state video camera with F to C mount adapter and quality macro lens (Cohu 4815-2100, $1,800; Cohu Incorporated; 575 Kearny Villa Road; P.O. Box 85623; San Diego, CA 92123; tel. (619)277-6700; Nikkor 55 mm micro $390; F to C amount adapter $60; Nikon Incorporated; 623 Stewart Avenue; Garden City, NY 11530; tel. (516)222-0200.)

FILM HOLDER
precision film positioner with X, Y and rotation adjustment (Marron Carrell positioner compound with 35mm negative carrier, $800; Marron Carrel; 2640 West 10th Place; Tempe, AZ 85281; tel. (602)966-2189, custom stand, $200.)

LAMP
even backlighting source (Aristo V-56 with 7452 standard color lamp, $250; Aristo Grid Lamp Products Incorporated; 35 Lumber Road; Roslyn, NY 11576; tel. (516)484-6141)

COPY STAND AND TABLE ($200-500)

CABLES AND CONNECTORS ($50)

IV. PERSPECTIVE

A. Strengths

The primary strength of hemispherical canopy photography is that it is a direct means for measuring the geometry of canopy openings. Each photograph serves as a permanent record of canopy architecture as viewed from a particular canopy position. Relatively simple models allow the extraction of meaningful estimates of light penetration and canopy architecture. Photographs can be taken rapidly in the field, so large samples can be collected. Only a moderate investment is necessary for image acquisition; the cost for a camera, hemispherical lens, and film. Field time for sample collection is minimal; however, significant analysis time can be required, especially for manual analysis. Manual analysis is possible without major investment in equipment; however, manual analysis is impractical for large numbers of photographs. Recently developed digital image analysis systems allow rapid analysis of large numbers of photographs, but with significant cost for analysis equipment.

It is instructive to consider the differences between the techniques of hemispherical photography and light sensor measurements for determination of radiation flux (see Table 3). The techniques are fundamentally different in that hemispherical photography involves measurement of geometry and indirect calculation of radiation flux; whereas, light sensor measurements involve direct measurement of radiation flux. Light sensor measurements are highly variable in time and space and therefore best integrated over time, for example, by long-term monitoring with a light sensor attached to a data logger. For this reason, light sensor techniques are limited in the number of field locations that can be sampled, both because of the expense and effort involved; whereas large sample sizes can be rapidly obtained with hemispherical photographs. Both techniques can require considerable efforts for data analysis, though hemispherical photography is more labor intensive. Field equipment tends to be more expensive for light sensor measurements; whereas analysis equipment can be more expensive for hemispherical photography. The techniques should not be viewed as exclusive of each other, but rather as complementary. Light sensor measurements can be used to obtain basic site-specific radiation flux data for calibration of hemispherical photographs.

Table 3. Comparison of hemispherical photography and light sensor techniques.

	HEMI-SPHERICAL PHOTOGRAPHY	LIGHT SENSOR
Measurements	indirect	direct
Field Data Acquisition Time	low - moderate	high
Sample Size Possible	large	small
Sensitivity/ Reproducibility	high?	high
Cost of Field Equipment	$300-1,500	$1,000-$2,000
Cost of Analysis Equipment (including microcomputer)	$3,000-$15,000	$2,000-$5,000
Analysis Effort	moderate - high	moderate - high

B. Limitations and Problems

Hemispherical photography involves many steps. Errors can occur during image acquisition, digitization, and analysis. Table 4 lists steps at which errors can be introduced. Stringent protocols must be adopted to minimize compounding of errors. The means for distinguishing foliage from canopy openings presents a considerable challenge. A simple threshold technique involves binary classification of pixel intensity values relative to a specified threshold value. For example, in positive digital images of hemispherical photographs, pixel values above the threshold are classified as openings and values below the threshold are classified as foliage. Similarly, in negative images pixel values above the threshold are classified as foliage and values below the threshold are classified as openings. Problems arise because of uneven exposure, uneven reflectance within foliage and background, penumbral effects, and edge sampling effects. Penumbral effects cause intermediate reflectance at edges. Edge sampling effects occur because edge pixels include both foliage and opening, and therefore appear as an intermediate gray value. When working with photographs taken looking upward, a simple threshold can mistakenly classify reflections on leaves as openings and dark sky regions as foliage. Also, large openings tend to be over-represented and small openings under-represented. Even backlighting of the sky and reduced reflections can be achieved by taking photographs on overcast days; although this severely limits field time. Alternatively, photographs can generally be taken early or late in the day to prevent overexposed regions around the sun; however, problems still arise because the antisolar dark spot of the clear sky is near the zenith. Similarly, photographs taken looking downward have problems of shadows and contrast between foliage and background. Infrared photography greatly enhances this contrast. Judicious editing of images can be helpful, for instance to remove reflections from leaves. Further work is needed to explore alternative means for classifying images, including use of convolutions and Fourier transform techniques. Editing and image enhancement techniques are readily available, but can greatly increase image processing time and introduce additional types of errors.

Table 4. Levels at which errors can be introduced in hemispherical canopy photography (reprinted by permission from Rich, 1988).

IMAGE ACQUISITION
- Camera positioning
- —horizontal/vertical position
- —film plane horizontality
- —azimuth rotation
- Exposure
- Sky lighting evenness
- Foliage lighting evenness (reflections)
- Optical distortion

IMAGE DIGITIZATION
- Registration/alignment
- —size
- —x,y translation
- —rotation
- Focus
- Aperture adjustment
- Optical distortion
- Video noise
- Digitizer noise
- Resolution limitations

IMAGE ANALYSIS
- Distinguishing foliage from canopy openings
- Assumed direct sunlight distribution
- Assumed diffuse skylight distribution
- Assumed surface of interception
- Image editing/enhancement
- Calculation assumptions

Even with the problems of image classification, excellent estimates of the distribution of canopy openings can be obtained. Further errors can arise from calculation assumptions for light penetration or inversion models. The light penetration model depends on accurate formulation of sky distributions of direct sunlight and diffuse skylight. Inversion models make assumptions about the randomness of the distribution of canopy elements. More work is required to assess the sensitivity and resilience of these models.

C. Enhancements and Future Prospects

Techniques for hemispherical photography eventually need to be standardized, so results from different sites can be readily compared. Already, general practice and consensus has standardized the general approach for image acquisition and analysis. Lacking is a rigorous assessment of the degree to which results are comparable when obtained using different lenses, different exposure protocols and different analysis systems. The significance of errors at each stage of the process must be further evaluated; and the sensitivity and reproducibility of results need to be fully tested. Detailed studies of radiation flux are required that compare and calibrate estimates from hemispherical photographs with long-term studies using light sensors. Detailed studies of canopy architecture are required that compare and calibrate estimates from hemispherical photographs with other indirect and direct means for study of canopy structure. If demand proves to be sufficient, eventually it may be desirable to establish regional facilities dedicated to hemispherical photograph analysis, thus reducing analysis costs and insuring analysis quality.

Beyond refinement of existing systems, it is desirable to develop an integrated hemispherical canopy analysis system in which steps of image acquisition, digitization, analysis, and data output are combined in a single field instrument. Such a hemispherical field instrument could provide nearly instantaneous estimates of light penetration and measures of canopy architecture. The basic components of such an instrument would include a hemispherical lens, a high-resolution solid- state video camera, a framegrabber digitizer/display adapter, an LCD image display monitor and a portable microcomputer. Further enhancements of the technique could involve miniaturization, use of fiber optics and design of telescoping mounts. Such enhancements could extend the utility of the technique for study of both within short canopies and at higher positions within tall canopies. Eventually, active close-range remote sensing techniques using scanning lasers could allow greater confidence in locating canopy openings.

V. SUMMARY

1. Hemispherical (fisheye) canopy photography involves determination of the distribution of canopy openings using photographs taken through an extreme wide-angle lens, either looking upward from within a canopy or looking downward from above a canopy. Hemispherical photographs can be used to estimate light penetration into canopies and to assess canopy architecture. Hemispherical photography is an excellent means for obtaining gap fraction data to use as input for inversion models.

2. Recently developed digital image analysis techniques provide a means for rapid analysis of large numbers of photographs. A digital image analysis system can be assembled as a moderate priced add-on to an existing personal computer system. In particular, video image analysis systems allow input directly from negatives, interactive image registration, interactive threshold determination to distinguish foliage from canopy openings, rapid calculation, and automated data output.

3. The primary strength of hemispherical photography is that it provides a means for direct measurement of canopy geometry. Large sample sizes can rapidly be collected in a non-destructive manner. The photographs provide a permanent archival record of canopy architecture.

4. The technique has several notable limitations. It is a multi-step process that can accrue significant errors at each step, including errors in camera positioning and orientation, exposure, registration during digitization, and selection of a threshold. Use of a threshold to distinguish foliage from openings contributes subjectivity, over-represents large openings, and under-represents small openings, especially for poorly exposed images. For evenness of lighting conditions, the technique is best used on overcast days, limiting the time when field work may be practical. Also, calculation assumptions, of radiation flux distributions or leaf distributions for inversion, can lead to errors.

5. There is a need-to establish standard protocols for image acquisition and analysis, so results between sites can be compared. Further work is needed to assess the sensitivity and utility of the technique. To minimize compounding of errors and increase flexibility, it is desirable to develop a hemispherical field instrument that integrates image acquisition, digitization, and analysis capabilities. It is also desirable to enhance the technique for study both within short canopies and higher positions within tall canopies.

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