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SHORT COMMUNICATION

USES AND LIMITATIONS OF HEMISPHERICAL PHOTOGRAPHY FOR ESTIMATING FOREST LIGHT ENVIRONMENTS

Summary: We compare hemispherical (fisheye) photography and direct measurement using dataloggers for quantifying light intensity (photon flux density) in a New Zealand forest remnant. The hemispherical method was generally accurate, and faster than using dataloggers, but deviated from measured light intensity at low light levels (<20% of full sunlight). For deeply shaded sites, diazo-paper chemical light meters may be more suitable.

Keywords: light intensity; hemispherical canopy photographs; fisheye photographs.

Introduction

Hemispherical canopy (fisheye) photography is a technique used to measure subcanopy light conditions. Hill (1924) built the first hemispherical lens to study clouds and cloud cover. The first researchers to apply hemispherical photography to a biological purpose were Evans and Coombe (1959), using the technique to study woodland light environments. Much of the theoretical foundation of hemispherical photography was developed by Anderson (1964a, 1964b, 1966, 1970, 1971), largely using manual analysis of the photographs. Since then a number of studies have used computerised analysis of hemispherical photographs, including Bonhomme and Chartier (1972), Chan *et al.* (1986), Chazdon and Field (1987), Becker *et al.* (1989), Rich (1989), Barrie *et al.* (1990), Rich *et al.* (1993), and Easter and Spies (1994). A number of studies have been undertaken in New Zealand using hemispherical photography and allied light environment measurement techniques, including Roxburgh (1991), McDonald (1989), Turton (1982), and Enright *et al.* (1993).

Photographs can be analysed manually or, as in the case of this work, computer analysed to determine the geometry and position of canopy openings, the path of the sun at various times, and subsequently to indirectly estimate various light parameters beneath plant canopies. Therefore, hemispherical photography can be used to assess local light environments beneath plant canopies, and to infer properties of those canopies.

As with many remote sensing techniques, there are a number of problems associated with hemispherical photography. For hemispherical photograph analysis systems to operate, a number of assumptions must be made. Probably the most significant of these is the assumption that all and any leaves completely block the passage of light. Hemispherical analysis systems currently do not have the ability to cope with light transmission and reflection from leaves, or layers of leaves; reflection and transmission may also be affected by leaf orientation relative to sun angle. In the digitised image, canopy areas are assigned to either black (completely blocked) or white (clear sky). This may introduce errors in darker areas where a significant proportion of the total light arrives via reflection or partial transmission through a complete canopy layer. Hemispherical systems also assume that the canopy above the photograph is a single layer. If these problems do not introduce unacceptable errors, hemispherical photography may be a useful technique for measuring percentage canopy openness, gap formation and closure, and other physical properties of plant canopies.

The aim of this experiment was to compare the accuracy of subcanopy light predictions made by Solarcalc version 5.41, designed by Chazdon and Field (1987), with direct measurements of the light environment in a field situation. This was to test the usefulness of this technique for rapid assessment of light environments. Chazdon and Field (1987) showed generally good agreement between measured and predicted Photon Flux Density (PFD) in a tropical forest, but the predicted PFD values were least reliable in shaded sites. Other authors have found generally good agreement between measured and predicted PPFD in forest sites (Rich *et al.*, 1993; Easter and Spies, 1994).

Methods

Photographs and field measurements for this work were taken at Ahuriri Summit Bush (NZMS 260 M36 795272), a 2.5 ha remnant of broadleaf/podocarp forest dominated by *Fuchsia excorticata* (J.R. et G. Forst.) Lynn. f., matai (*Prumnopitys taxifolia* (D.Don) Laubenf.), and kahikatea (*Dacrycarpus dacrydioides* (A. Rich.) Laubenf.). This area is situated on the southern rim of the extinct Lyttleton volcano, on the Port Hills near Christchurch. Photographs and direct measurements were taken at 14 field growth trial sites chosen to represent a range of light environments from full shade to small and large clearings (Roxburgh, 1991).

Direct instrumental measurements of light intensity (PFD) were assumed to most accurately measure the light environment (following Chazdon and Field, 1987, Rich *et al.*, 1993, and Easter and Spies, 1994). There are problems with direct measurements, including variation between sunny and cloudy days, and seasonal variations due to changes in the position of the suntrack and seasonal leaf fall. Easter and Spies (1994) showed that the calibration between measured and estimated PPFD was affected by seasonal variation in cloudiness. In this study the effect of cloudiness was minimised by running the instruments over four days, and then expressing the light intensity as a fraction of that received in the open nearby. Rich *et al.* (1993) showed that including light levels measured in the open improved the fit of their models comparing measured and predicted PPFD.

The direct field measurements were made using a number of LiCor (Lincoln, Nebraska, USA) LI-190 quantum light sensors attached to Campbell Scientific (Logan, Utah, USA) CR21X dataloggers. Light levels (PPFD, Photosynthetically-active Photon Flux Density) at each site were sampled every 60 seconds, with the mean recorded hourly for a four day period. Operation was continuous over the whole diurnal cycle. A second datalogger recorded the PPFD in an open site in a large clearing on the edge of the Bush, and the subcanopy readings were converted to percent of full sunlight. All data were log transformed before analysis to improve normality.

Hemispherical photographs were taken using a Nikon (Tokyo, Japan) F 35 mm camera and Nikkor 8 mm f2.8 fisheye lens. The resulting image gives an almost 180 degree view in all directions, with the zenith at the centre and the horizon at the edges of the photograph. A heavy tripod held the camera 750 mm from the ground with the lens axis vertical. A small light-emitting diode (LED) indicator on the true north lens edge provided a reference mark for alignment of the digitised images. We used ASA 125 black and white negative film, exposed at 1/125 second with exposures bracketed to one stop either side of the value (typically f8) indicated by a light meter. The best photographs resulted when there was no direct sunshine: under evenly overcast skies, or in early morning and late evening on cloudless days. This is especially important in relatively closed canopies, where bright reflections can be mistaken in analysis for areas of open sky. All photographs were printed onto gloss paper. Consistency of print density is very important for repeatable results, although some corrections can be made by altering the grey-scale cutoff during analysis of the digitised image.

A number of computer programs and associated systems exist to analyse hemispherical photographs. We used Solarcalc 5.41, on an Apple Macintosh computer, with input of images via an Applescan digitising scanner at 150 dots per inch. The grey-scale, which sets the cut off point between black and white, was reassessed for each print by visually comparing the digitised image with the photograph. However, given consistent print quality, the grey-scale setting should need little adjustment. From the scanned images, Solarcalc computed estimated PPFD, estimated % canopy openness, and number and estimated total minutes of direct PPFD per day (i.e., sunflecks). Estimated PPFD was converted into a percent of full sunshine by dividing by the estimated PPFD for a photo taken adjacent to the full-sunlight sensor on the same slope just outside the forest.

Results

There were highly significant relationships between measured (datalogger) photosynthetic photon flux density (PPFD), and estimated (hemispherical) PPFD, estimated percent canopy openness, and estimated minutes of direct PPFD per day (Table 1). Canopy openness and minutes of direct PPFD per day were not recorded instrumentally, but Table 1 shows that the Solarcalc estimates of these are

Table 1: *Comparison of measured total photosynthetically active photon flux density (PPFD) recorded by dataloggers over 4 days, and estimated light variables derived by Solarcalc from hemispherical canopy photographs at the same 14 spots in Ahuriri Summit Bush.*

Estimated variable	R^2	P	Slope	Intercept
Estimated PPFD	0.963	<0.001	1.244	-2.90
% Canopy openness	0.954	<0.001	2.62	-5.99
Minutes of direct PPFD	0.947	<0.001	21.17	-53.6
Number of sunflecks	0.172	NS		
% of PPFD as sunflecks	0.184	NS		

highly correlated with measured PPFD, so measured PPFD could be used to predict canopy openness and minutes direct PPFD if necessary. Solarcalc also provides estimates of sunfleck number and importance, from the number of canopy openings on the suntracks, but these were not significantly correlated with measured total PPFD.

Figure 1a shows the shape of the relationship between predicted and measured PPFD, expressed as a fraction of full sunlight over the sampling intervals. There was close agreement between measured and predicted PPFD ($R^2 = 0.963$), although the slope was significantly greater than 1.0 (1.24 with a 95% confidence interval of 0.15) and the y-intercept was significantly less than zero (-2.90 $\pm$ 2.31). Therefore Solarcalc slightly over-estimated the light received under the relatively open canopy sites and under-estimated that received in shaded sites. Although the absolute deviations from measured PPFD were always less than 6.5 percentage points and usually less than 2.0, the relative deviations were large only in the most shaded sites (Fig. 1b). Deviations exceeded 50% below 5% of full sunlight and may have been large between 20% and 5% of full sun where we had few data.

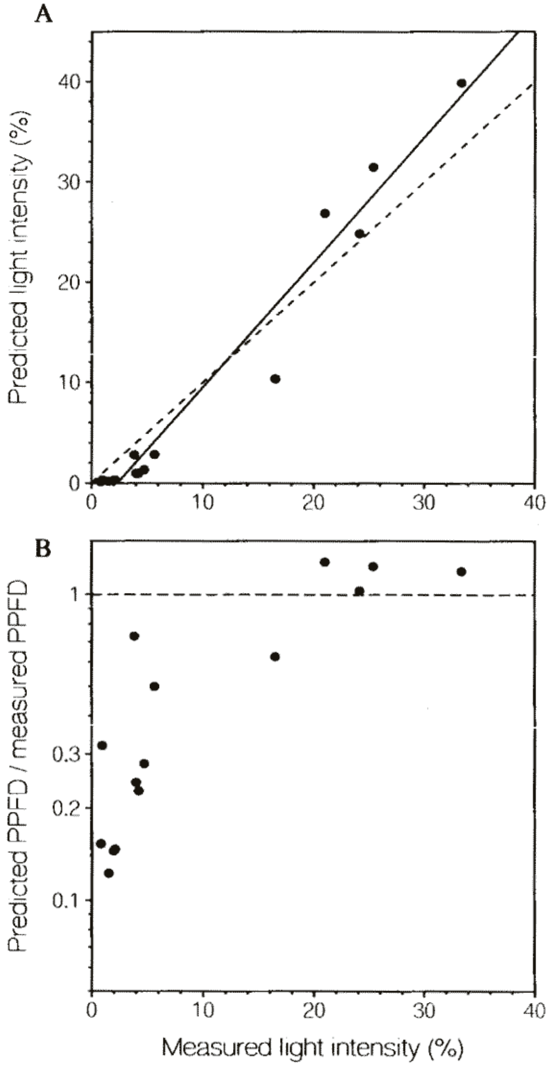

Figure 1: *Comparison of measured photosynthetically active photon flux density (PPFD) at 14 sites in Ahuriri Summit Bush, with estimated PPFD derived from Solarcalc analysis of hemispherical photographs. (A) Measured PPFD versus estimated PPFD (% of full sunlight). The regression is significant* ($y = -2.90 + 1.24x$, $R^2 = 0.963$, $P < 0.001$). *(B) Ratio of (predicted PPFD / measured PPFD) versus measured PPFD. Predicted PPFD deviates most from measured PPFD at lower light intensites.*

Discussion

Difficulties arise in the interpretation of light absorption, reflection and transmission by leaves. By digitising each part of the image to either black or white, hemispherical photograph analysis systems are unable to distinguish between a single-leaf-layer canopy which may transmit 40% of incident light, and a dense multi-layer canopy which transmits practically no light at all. It appears that the differences we found between measured and estimated PPFD were mainly because below a certain level (approx 3% measured PPFD) Solarcalc registers almost no light at all. This may be because at these low levels there is at least one leaf blocking almost every area of sky, but the measured PPFD does record some light transmitted and/or reflected through the canopy.

Our results contrast with those of Chazdon and Field (1987) who found that Solarcalc overestimated PPFD, especially at low light intensities. They ascribe their results to the assumption in Solarcalc that the sky is always clear, whereas measured PPFD will be reduced by cloud. Their data were presented in direct units of photon flux. In this study, by converting the data to percent of full sunlight measured nearby, the clear-sky assumption is reduced as a source of error (Rich *et al.,* 1993).

While our results are based on only one site and must be interpreted with caution, it seems that Solarcalc may be less suitable for use in very shady environments. This agrees with the caveats of Chazdon and Field (1987), but for different reasons.

In particular, hemispherical photography may have to be carefully calibrated if the aim is to study the light compensation point of shade tolerant species. However, Rich *et al*. (1993), after correcting for open light values, found good agreement between predicted and measured PPFD over the range 1 - 10% of full sun, so the results may depend on details of the particular site such as forest structure or cloudiness.

Conclusions

Hemispherical photography appears to give predictions of total PPFD which are similar to direct measurements across a wide range of moderate to high light intensities. Computerised hemispherical photograph analysis also gives estimates of a number of other parameters, such as percent canopy openness, minutes of direct PPFD and PFD per day, and length and duration of sunflecks. Some of those other parameters may be difficult to estimate by other techniques.

Data on light and canopy conditions can be gathered relatively quickly using hemispherical photography and Solarcalc analysis, compared to gathering data using light sensors and dataloggers. All of the photographs for this work were taken in one day, with processing and printing of the photographs, and analysis using Solarcalc taking a further two days (once the software and scanner were set up correctly). Data gathered using light sensors and dataloggers required one light sensor and datalogger set up at each of the 15 sites for four days (60 datalogger days), with another sensor and datalogger set up in the open site. Therefore, indirectly measuring light and canopy variables using Solarcalc is significantly faster than directly collecting the data using light sensors if numerous sites must be measured.

Hemispherical photograph analysis systems have a useful place in studying the light environment of plants, and inferring properties of plant canopies. They appear to accurately predict light conditions over a wide range of moderate to high light intensities, but are best suited to wide surveys where more shady areas (<20% of full sun) are not of crucial importance. For surveys involving only a few sites, use of instruments like data loggers may be simpler. Where many sites must be surveyed, and deep shade is important (such as in determining the light compensation point of shade-tolerant species), the calibration between measured and predicted PPFD should be checked. Alternatively, in shaded sites chemical light meters based on light-sensitive diazo paper provide a cheap alternative which may prove more suitable (Friend, 1961; Turton, 1982; Baars, 1995).

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