NOTE

Evaluation of digital and film hemispherical photography and spherical densiometry for measuring forest light environments

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Abstract: This study presents the results of a comparison of digital and film hemispherical photography as means of characterizing forest light environments and canopy openness. We also compared hemispherical photography to spherical densiometry. Our results showed that differences in digital image quality due to the loss of resolution that occurred when images were processed for computer analysis did not affect estimates of unweighted openness. Weighted openness and total site factor estimates were significantly higher in digital images compared with film photos. The differences between the two techniques might be a result of underexposure of the film images or differences in lens optical quality and field of view. We found densiometer measurements significantly increased in consistency with user practice and were correlated with total site factor and weighted-openness estimates derived from hemispherical photography. Digital photography was effective and more convenient and inexpensive than film cameras, but until the differences we observed are better explained, we recommend caution when comparisons are made between the two techniques. We also concluded that spherical densiometers effectively characterize forest light environments.

Résumé : Cet article présente les résultats d'une comparaison entre la photographie hémisphérique digitale et sur film comme moyen pour caractériser l'environnement radiatif de la forêt et l'ouverture de la canopée. Nous avons également comparé la photographie hémisphérique et la densitométrie sphérique. Nos résultats montrent que les différences dans la qualité des images digitales dues à la perte de résolution qui survient lors de la manipulation des images pour l'analyse par ordinateur n'ont pas affecté les estimations de l'ouverture non pondérée. Les estimations de l'ouverture pondérée et du facteur global de station étaient significativement plus élevées avec les images digitales qu'avec les films photographiques. Les différences entre les deux techniques pourraient être le résultat d'une sous-exposition des images sur film ou de différences dans la qualité optique des lentilles et dans le champ de vision. Nous avons constaté que la consistance des mesures prises avec le densitomètre augmentait significativement avec l'expérience de l'utilisateur et qu'elles étaient corrélées avec les estimés du facteur global de station et de l'ouverture pondérée obtenus à partir des photographies hémisphériques. La photographie digitale était efficace, plus pratique et moins coûteuse que les caméras fonctionnant avec un film. Mais jusqu'à ce que les différences que nous avons observées puissent être mieux expliquées, nous recommandons la prudence lorsqu'il s'agit d'effectuer des comparaisons entre les deux techniques. Nous concluons aussi que le densitomètre sphérique permet de caractériser efficacement l'environnement radiatif de la forêt.

[Traduit par la Rédaction]

Introduction

Forest light environments greatly affect stand regeneration, structure, and productivity. A variety of methods have been developed to measure incoming radiation at different spatial and temporal scales (see Engelbrecht and Herz 2000; Comeau et al. 1998). Light sensors coupled to dataloggers give the most accurate measure of photosynthetic photon flux density (PPFD) at a specific place and time, but their expense and high maintenance demands limit their application to spatially or temporally intensive studies. Furthermore, Rich et al. (1993) found that PPFD measurements in the understory are highly variable temporally because of changes in solar angle and weather; therefore, short-term

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PPFD measurements are likely to be inadequate for characterizing long-term light environments. Various alternatives for estimating long-term light environments have been developed, including spherical densiometry (Lemmon 1956) and analysis of hemispherical photographs taken with film cameras and fish-eye lenses (Rich 1989). Here we report a comparison of spherical densiometry, film hemispherical photography, and a new method, hemispherical photography using a digital camera. We were particularly interested in the digital method, because it eliminates the need for film processing and image scanning but still provides a permanent record of the measurements taken.

Hemispherical photography is useful for measuring changes over time in forest light environments (Rich et al. 1993; Engelbrecht and Herz 2000). A variety of image analysis programs have been developed to calculate weighted openness and, by accounting for solar angles, to estimate diffuse and direct light coming through openings in the canopy (ter Steege 1996; Rich 1989; Chazdon and Field 1987). Estimation of PPFD from photographs can be comparable with long-term quantum sensor measurements (Rich et al. 1993; Comeau et al. 1998).

The spherical densiometer (Lemmon 1956) is an inexpensive and conceptually simple instrument for estimating canopy cover. It consists of a convex or concave mirror etched with a grid of 24 squares, within each of which the observer scores canopy cover at four equally spaced points. Although Lemmon (1956) found no differences between observers, Vales and Bunnell (1988) found systematic variation among untrained observers. However, Lemmon (1956) suggested that experience was required to judge percent cover accurately. Both Bunnell and Vales (1990) and Cook et al. (1995) reported that instruments that measure wide sky angles, like the densiometer, underestimate canopy cover compared with methods that measure narrow angles such as the moosehorn (Garrison 1949).

Few studies have compared densiometer measurements to estimates of light by hemispherical photography (Engelbrecht and Herz 2000) and, to our knowledge, none have compared digital and film hemispherical photography. In evaluating these methods we had several objectives: (*i*) to develop procedures for systematically taking and analyzing digital hemispherical photographs; (*ii*) to compare results from digital and film hemispherical photography, and (*iii*) to assess how densiometer measurements compare with those from hemispherical photography.

Study area and methods

We carried out this study at the La Selva Biological Station in the Atlantic lowlands of Costa Rica (10°26′N, 84°00′W). The La Selva forest is classified as tropical wet forest in the Holdridge Life Zone System (Hartshorn 1978). The forest in the study area had a mean canopy height of approximately 23 m (Clark et al. 1996) with emergent trees to ca. 60 m, a tree density (≥10 cm diameter) of ca. 450 stems/ha, and a basal area of 26 m^2/ha (Clark and Clark 2000).

We established two sample areas, one with 20 points and one with 30 points; the point locations were chosen haphazardly to represent a broad range of understory light environments in old growth. We first used the 20-point area to compare different image qualities in digital photography and to evaluate consistency in densiometer measurements. We then used the 30-point area to compare light measurements among the densiometer, digital camera, and film camera. Digital photos were taken 2 weeks prior to the film photos because of equipment availability. All photos were taken under solidly overcast skies between 08:00 and 16:00.

Digital photography

We used a Nikon Coolpix 950® with a FC-E8 fish-eye lens converter. We taped a small 3-V halogen flashlight bulb to the side of the lens and oriented it toward north. The light was just visible in the field of view and appeared as a small dot in the image. The camera was mounted at a height of 1 m above the ground and was leveled with a bubble level. We used an automatic setting for aperture width and shutter speed. We took photographs on only uniformly cloudy days because of the difficulties in judging vegetation edges in photographs taken on sunny days or under skies with patchy clouds.

We tested four image qualities of photographs taken at largest possible image size, 1600 × 1200 pixels. On the Nikon Coolpix 950, basic, normal, and fine image qualities use JPEG compression to reduce the amount of memory required to store the photos and have a high, medium, and low compression ratio, respectively. High-quality images are stored in uncompressed TIFF format. The images are approximately 250 kB, 500 kB, 1 MB, and 6 MB, respectively. Thus, an 8-MB memory card can hold 32 basic images, 16 normal images, 8 fine images, or 1 high-quality image.

Film photography

We used a Nikon MF-16 camera and a Nikkor 8-mm fish-eye lens with TriX ASA 400 film, a red filter to increase sharpness of leaf edges, and the focus set to infinity. The field setup was identical to that of the digital camera. We used a shutter speed at 1/125 s whenever possible; under low light conditions, we used speeds of 1/60 or 1/30 s and the timed shutter release. We adjusted the aperture using the through-the-lens light meter.

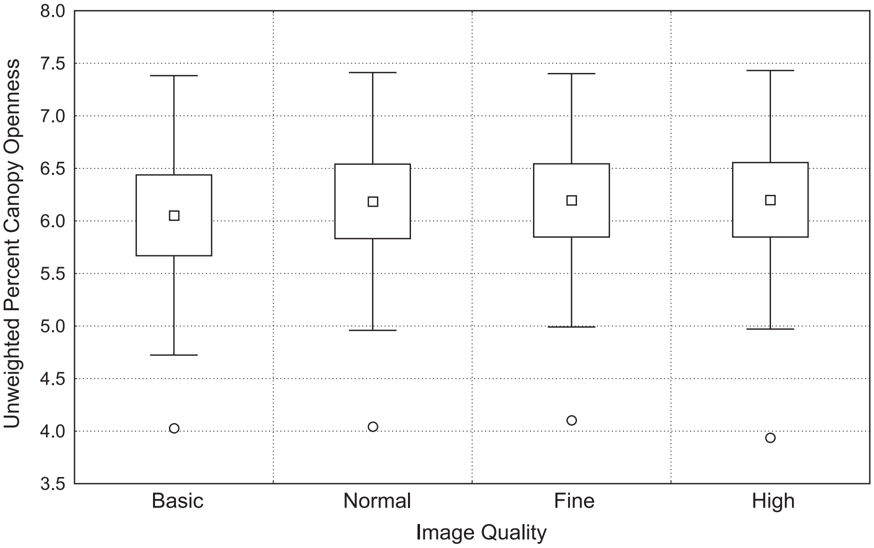
Image analysis

Photographs were printed at 7.6 × 12.7 cm and scanned with a Hewlett Packard ScanJet ADF scanner and saved in JPEG format The photographs were positioned in the same spot on the scanner bed using a paper template. The dimensions of all the scanned images were 14.8 × 9.6 cm. Digital images did not require additional processing. We analyzed images using Image Tool software (University of Texas Health Science Center, San Antonio). All images were first converted to gray scale (256 levels) and then to binary (black and white pixels) using an interactive manual threshold: the user decided which grays should be converted to black and which should be converted to white. Because the user had to adjust the threshold to compensate for different sky conditions, the user's judgment could affect subsequent analyses and introduce errors.

We tested two methods of determining the appropriate threshold. In one approach, we adjusted the threshold with the gray-scale image displayed at a zoom of 2:1, focusing on the details of a small area with fine leaves, usually towards the zenith; in another series of analyses we set the threshold while keeping the entire image in view. We then compared all the binary images to the original images to visually assess accuracy. Once in binary form, we used Image Tool to count the total number of black and white pixels. To assess threshold precision, we reconverted the images to binary using the same technique but in a different order to avoid bias.

For the zoom technique, we established an arbitrary unweighted openness acceptance criterion of 0.3% (i.e., the unweighted openness of the two binary images had to be within 0.3% of each other). If unweighted openness calculations in two binary images differed by more than 0.3%, we reconverted them until they met the criterion. We also converted the same gray-scale image to binary twice while viewing the entire image and averaged the two threshold values. Afterwards, we reconverted the original gray-

Fig. 1. Box–whisker plots of unweighted openness for the four image qualities tested. The boxes show ±1 SE, and the whiskers show ±1 SD. The small open circles are values that are more than 1.5 SD from the mean.



scale image to binary at the average threshold value and used this binary image for all further analyses.

Fish-eye images are circular with a rectangular black background. To determine the number of pixels in the circular area of the lens, we took both digital and film photographs of a white background (“empty images”) and converted them to binary images in Image Tool. The number of white pixels represented the digital area of the lens. We calculated unweighted openness as the number of white pixels in each binary image divided by the number of pixels in the area of the lens.

Digital and film photographs were also analyzed with WINPHOT 5.00 (ter Steege 1996) for weighted openness. Since WINPHOT has limitations on image type and size, we changed all binary images to PCX format and reduced the size of the digital and scanned film camera images to a width of 1024 pixels. All images were aligned based on either the film or digital “empty” images showing the area of the lens. North was marked on all images as a white spot left by the flashlight bulb. Unlike Image Tool, which simply counts the number of black and white pixels, WINPHOT recognizes that the two-dimensional projection represents a hemisphere and weights the pixels according to the area that they represent in the sky.

Diffuse, direct, and total site factors are the fractions of diffuse, direct, and total radiation that reach a specific point on the forest floor through the canopy. WINPHOT calculates the fraction of diffuse and direct radiation reaching a point using estimates of above-canopy irradiance, solar angle, and stand structure. The total site factor (TSF) is a function of the relative contributions of direct and diffuse light, which are influenced by cloudiness and other atmospheric conditions as follows:

$$[1]\qquad \mathrm{TSF} = \frac{\text{below-canopy diffuse PPFD}}{\text{above-canopy diffuse PPFD}}(X) + \frac{\text{below-canopy direct PPFD}}{\text{above-canopy direct PPFD}}(Y)$$

where X is the proportion of diffuse global PPFD and Y is the proportion of direct global PPFD $(1 - X)$. We used $X = 0.45$ and $Y = 0.55$ following the results of Rich et al. (1993) at this site. We calculated TSF for 365 days/year at ground level, weighted openness, and weighted openness for a 57.8° segment of the hemispherical image representing the view angle of the densiometer (see below).

Densiometer

We used a Model A convex spherical densiometer (Forest Densiometers, 24113 North Kenmore Street, Arlington, VA 22207, U.S.A.), which consists of a convex mirror divided into a cross-shaped grid of 24 squares (Lemmon 1956). The senior author took all measurements. The densiometer was held level at waist height, just far enough from the body so that the observer’s face was out of view. The observer counted how many of four points equally spaced within each grid square were in the open (nonvegetation), and then summed these quantities. Measurements were taken in four cardinal directions at each point, averaged and divided by 96 to obtain a measurement of canopy cover. Measurement precision was evaluated by taking measurements along the 20-point transect four times over 4 days. To compare the densiometer to photography, the same observer took measurements along the 30-point transect twice over 2 days. Regression of the two sets of measurements confirmed that the user was consistent; therefore, one set of measurements was used for all analyses.

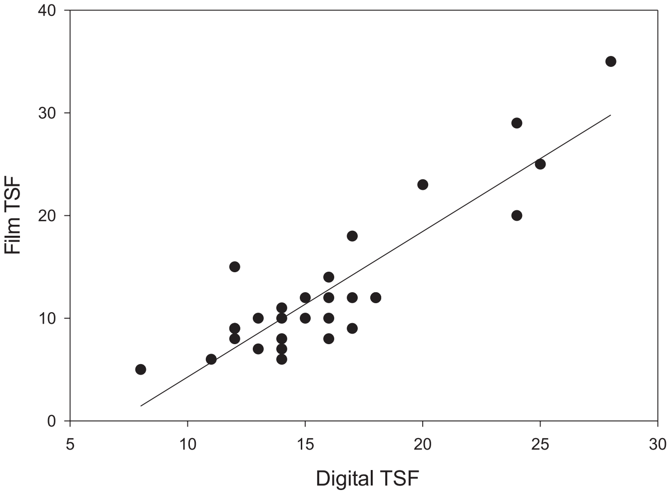
We determined the view angle of the densiometer by placing an object on a tower at a height of either 5 or 10 m and moving the densiometer to the point where the object came into view. We calculated the angle from the height of the object and the horizontal distance of the densiometer from the tower. We repeated the procedure for a point behind the observer. The angle was not symmetrical over the observer’s head, but because canopy cover in this angle was measured facing all four directions, the average of the four measurements represented the view angle centered over the densiometer. We used this angle to compare densiometer measurements to calculations of weighted openness for the same view angle in the hemispherical photographs.

Results

Digital photo image quality

To test image quality of the digital camera, we compared the calculations of unweighted openness for photographs taken at each quality level. The values of unweighted openness appeared normally distributed with homogeneous variances (Fig. 1). We tested for differences among the means with a repeated-measure ANOVA. We found no statistical differences between the mean image qualities ($F_{[3,48]} = 0.709$, $p = 0.55$). Variation in converting the gray-scale images to

Fig. 2. Relation between digital and film hemispherical photography for total site factor (TSF; see Methods). The fitted line was $y = 1.42x - 9.91$, $R^2 = 0.79$, $p < 0.0001$.



binary outweighed any difference caused by resolution of the images. Thus, basic quality images are adequate and, because of their small size, facilitate data collection and storage. We used the basic quality images for all our further analyses.

Comparison of digital and film hemispherical photography

In our initial analysis, we twice converted both film and digital images to binary at a high zoom. From these binary images we used WINPHOT 5.00 to calculate weighted openness and TSF. These data showed that measurements of weighted openness and TSF between digital and film photography were poorly correlated (weighted openness: $y = 0.2447x + 4.9764$, $R^2 = 0.2273$, $p = 0.0077$; TSF: $y = 0.23x + 12.316$, $R^2 = 0.1598$, $p = 0.0286$). The low correlation between different methods of photography could be explained by inaccurate conversions of the original images to binary. Although the zoom allows the user to find the exact edges of leaves in the zoomed image, focusing on a fragment of the image can cause inaccuracy in delineating the edges of objects in other parts of the image that have different shades of gray. The binary images were visually assessed for accuracy, but the eye was unable to detect this difference. Furthermore, when repeating the conversion to reach the acceptance criteria, it is difficult to be unbiased in choosing the gray-scale threshold. Differences in digital image capture and optical quality could also have caused the variance. Digital and film weighted-openness calculations using the data from images converted with the whole image in view were better correlated than in the initial analysis ($y = 1.25x - 3.61$, $R^2 = 0.40$, $p = 0.0003$). Digital images produced significantly higher estimates of weighted openness (paired t test: digital mean = 7.50, film mean = 5.90, $t = 5.1$, df = 28, $p < 0.0001$). Digital and film TSF values were highly correlated (Fig. 2; $R^2 = 0.79$). We examined the mean weighted openness per degree zenith angle for 10 of the plots (Fig. 3). The techniques began to diverge around 10° and converged at 53°; digital images had consistently higher values than film where they differed. Our site is close to the equator; therefore, the better correlation among TSF estimates was explained by the convergence in weighted-openness calculations close to the zenith (Fig. 3). Differences in TSF estimates between the techniques would probably be greater at higher latitudes because of the divergence in weighted openness seen at intermediate zenith angles.

Estimates of TSF for the digital photographs were significantly higher than those for film photographs (paired t test: digital mean = 16.03, film mean = 12.83, $t = 4.5$, df = 28, $p = 0.0001$). Although inaccurate conversions may account for some of these differences, by visual comparison we judged that the binary images were similar to the originals for both digital and film images. Digital photography appeared to record smaller canopy holes than film photography. This was obvious when we compared the original film and digital images and again when we compared the binary conversions of the digital and film photographs.

Although the digital and film photographs were taken 2 weeks apart, it is improbable that the holes were filled in by vegetation in the intervening period. It is more likely that additional leaves, branches, and trees would have fallen, resulting in higher calculations of weighted openness and TSF for the film photographs, the reverse of what we observed. Thus, it seems that the film photographs did not record as much light coming through small holes in the canopy. It is possible that more small holes could be captured on film by shooting at a variety of exposures at each site.

It was apparent in some digital images that some leaves with glare were converted to white pixels in the binary image. This might account for the higher calculations of weighted openness and TSF but cannot alone account for the difference in estimated TSF between digital and film images. The film images appeared much darker than the digital images. This may have been the result of camera settings or lens characteristics and may have been responsible for the disparity in TSF and weighted openness values among the methods.

Evaluation of consistency in densiometer measurements

The spherical densiometer requires estimating the fraction of each square (in fourths) that is filled by small specks of light. Consistency between readings over a point improved significantly with practice (Table 1). The close correlation of the third and fourth readings showed that the observer's measurements became more precise with practice. The increase in values of the y intercepts over time suggests that initially the user overestimated canopy cover.

Comparison of hemispherical photography with the densiometer

We determined the view angle of the densiometer to be 48.4 ± 2.1° (mean ± SD; $n = 4$) in front of the observer, and 9.4 ± 0.7° ($n = 4$) behind the observer. This angle may be slightly different for different observers. Knowing this angle allowed us to compare densiometer measurements of weighted openness to photographic measurements of the equivalent sky area, a 57.8° segment centered above the observer. Measurements of weighted openness obtained using the densiometer were highly correlated to digital and film calculations of weighted openness for the 57.8° angle. The relationship

Fig. 3. Plot of mean weighted openness per degree zenith angle in 1 degree increments for digital and film techniques. Zero degrees is the zenith. The means were taken from a random selection of 10 sample points, error bars are SEs.

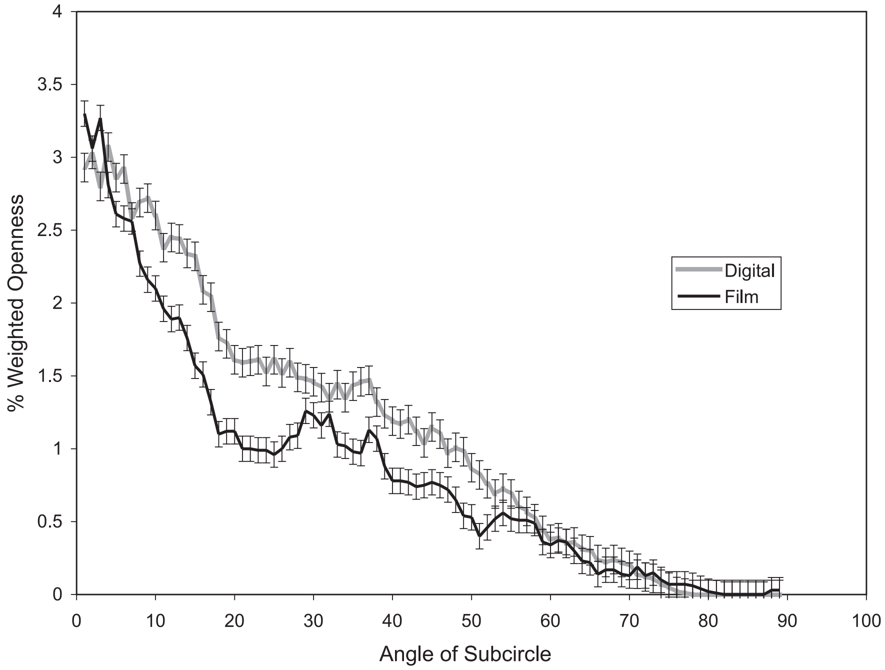


Table 1. Relation of successive densiometer measurements taken at 20 points selected to span a range of understory light environments.

Trial comparison (x vs. y)	Slope of regression	Intercept	r^2
1 vs. 2	1.08	–2.35	0.87
2 vs. 3	0.98	–1.85	0.96
3 vs. 4	0.97	2.46	0.96

Note: Estimates were taken on 4 days. The desired outcome was perfect consistency between trials, i.e., the regression of one set of values on another would have a slope of 1.00 and a y intercept of 0.

was best fit with a cubic function (digital: $R^2 = 0.84$, $p < 0.0001$; film: $R^2 = 0.89$, $p < 0.0001$). Because TSF heavily weights the sky directly overhead at lower latitudes, it is highly correlated to WINPHOT calculations of weighted openness for the small angle representing 57.8° (digital: $R^2 = 0.87$, $p < 0.0001$, film: $R^2 = 0.95$, $p < 0.0001$). Therefore, densiometer measurements were also correlated to calculations of TSF from digital and film images (Fig. 4). Although the densiometer only measures open and closed canopy, it can be used for ranking sites by TSF.

Conclusions

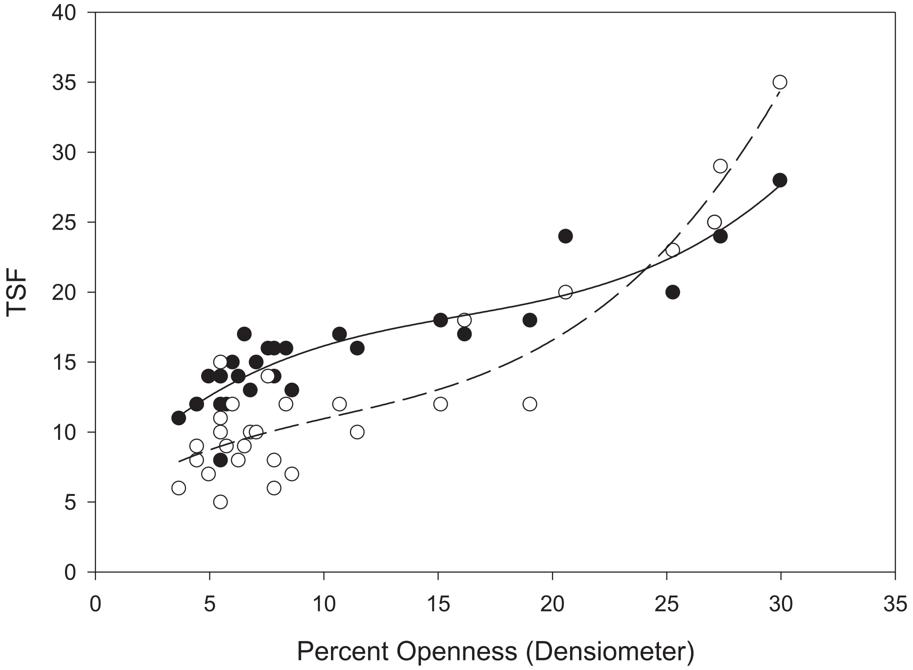
These results suggest that digital cameras are an effective and useful tool for taking hemispherical canopy photographs. Costs are similar or less than film photography, no film scanning is necessary, and poor-quality images can be immediately retaken in the field. We found that the lowest quality image on the Nikon Coolpix 950® was adequate, which greatly increases the utility of the technique in the field.

With reasonable care, the digital camera can be as durable as a film camera. The field conditions during our study were wet and humid, and the camera never malfunctioned during 2 months of field use. Camera batteries are drained rapidly; we usually used eight AA rechargeable batteries per day, so provisions must be made for an adequate battery supply in remote locations. We used an accessory 48-MB memory card, which stores 256 basic quality images. The cost of this card is negligible compared with the long-term costs of film purchase and developing costs.

To determine the most accurate binary image, we recommend converting it to binary with the entire image in view so that the observer can assure that all holes in the canopy are adequately represented by the binary image. To account for a decrease in precision with this method (caused by errors in threshold judgment), we recommend averaging two chosen thresholds and then analyzing the images that are converted to binary at the average threshold.

Comparison of film and digital images revealed a significant difference in both weighted openness and TSF. These differences were probably not caused by differences in image resolution between film and digital photography. Although our best-quality digital images were much lower in resolution than film images, these differences were insignificant compared with the error introduced by binary conversion. With current scanning and canopy image processing software limitations, differences in resolution probably are not a significant source of error. Light reflecting off leaves might have caused a slight overestimation of light in digital images, which perhaps could have been avoided by camera features that reduce glare or by taking photographs under more specific sky conditions. The film photographs appeared darker than the digital photographs, which may have been due to a combination of lens aperture setting, film type, the red filter, and sky conditions. More likely, the differences we

Fig. 4. Correlation between densiometer measurements of weighted openness to TSF calculated from digital (solid circles) and film (open circles) hemispherical photographs. The fitted line for the film data (broken line) was calculated using the cubic polynomial $y = 4.7074 + 1.0885x - 0.068x^2 + 0.0022x^3$ and explained 88% of the variance. The digital data line fit (solid line) was estimated by the function $y = 5.8167 + 1.7661x - 0.0926x^2 + 0.0019x^3$, $R^2 = 0.85$, $p < 0.0001$.



saw were the result of differences between the light sensitivity of the digital camera and the film we used. The digital photos all looked much brighter. This would explain the divergence between the methods at intermediate zenith angles where most of the smaller holes appear. Since the photographs could not be taken on the same day, differences in sky conditions and camera placement may have introduced error. This error would likely have been random and, therefore, less likely to cause the observed systematic differences between techniques. Another potential source of error we did not investigate were differences in distortion and field of view of the two different lenses. The manufacturer reports that the field of view of the digital fish-eye lens is 183° and could be larger (G.W. Frazer, personal communication), whereas the Nikkor lens has a field of view of 180°. Since the calculations are TSF weighted according to sky area, differences in distortion or a field of view might cause the differences in TSF we saw among the two techniques. A thorough comparison of photographic techniques with different film and camera settings would be valuable for ecologists and foresters using either film or digital canopy photography, and would help resolve some of these possibilities. We cannot say which technique better represented the true canopy cover and TSF of our study site. Nevertheless, digital hemispherical photography is a relatively inexpensive and more convenient method for characterizing long-term light environments through space and time. Care must be taken when comparing absolute values of TSF both within and between the two techniques until truly standard methods are developed. Film cameras are currently more flexible; there are a wide variety of filters, film types, and optically superior lenses available, and the archival photos are superior in resolution. Digital photography saves time and money by eliminating film processing and scanning. The tradeoff for this convenience is lower archival image quality and less control over exposure settings. As technology improves it is likely that digital methods will become more versatile.

Our data show that consistency in densiometer measurements improves with practice, thus emphasizing the importance of training users to a consistent standard. The same approach could be used with multiple users. By regressing the measurements of one trained user to those of a different user, adjustments can be made for systematic differences among observers.

Comparison of densiometer measurements to calculations of TSF from hemispherical photography shows that the densiometer can reliably rank sites by TSF. Although it does not measure the entire sky angle, densiometer measurements are highly correlated to camera measurements of weighted openness in its 57.8° view angle, and this angle is weighted heavily in measurements of TSF. In addition, very little radiation enters beyond zenith angles greater than 58° (Fig. 3). Hemispherical photography is a more versatile technique than the spherical densiometer and provides a lasting record of the environment measured. However, the equipment is more expensive, analysis time is not trivial, and waiting for appropriate conditions for taking pictures is a significant limitation. The spherical densiometer is a quick, inexpensive, and potentially reasonably precise method for ranking long-term light environments in an ecologically meaningful way.

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