Research Report

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Selecting and testing an instrument for surveying stream shade

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Abstract

We evaluated the suitability of several different instruments for surveying stream shade, selected one as most suitable for our purposes, and tested its accuracy. Five different operators used the instrument to estimate shade as angular canopy density (ACD), canopy density above 60°, and canopy density above 80° in two plots—one in a mixed-age coniferous stand and one in a mixed-age deciduous stand. We compared operator estimates (ocular method) with measurements from fisheye photographs (computer-fisheye method). In a random coefficients regression model, the effect of "plot" on regression slopes and intercepts was not significant at $\alpha = 0.05$. The regression line for ACD by the ocular method versus the computer-fisheye method had a slope of 0.87 and an intercept of 0.02. The slope was significantly different from 1 at $\alpha = 0.05$, indicating a tendency for human operators to underestimate ACD. Estimates of mean ACD on the two plots by individual operators were 2–11 percentage points lower, respectively, than mean ACD calculated from fisheye photos and the effect of operator was highly significant ($p < 0.0001$). Operators who received 45 minutes of training performed better than did an operator who received 15 minutes of training. Results suggest that operator variability is a large potential source of error in ocular estimates and that an investment of at least 1 hour of formal training may be worthwhile. The errors associated with any ocular-type canopy density measuring instrument should be documented before it is used to make statistical inferences.

KEYWORDS: *angular canopy density, crown closure, field methods, instrument calibration, measurement error, spherical ACD meter, stream shade.*

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Introduction

British Columbia's Forest Planning and Practices Regulation requires that forest licensees retain sufficient shade for temperature protection on certain types of streams, but it does not provide any objective criteria to help them comply with this rule. Although compliance can be ensured by leaving all vegetation in the appropriate riparian areas, a more rational method would consist of quantitative limits on the reduction of shade. The purpose of this paper is to review ground-based canopy parameters and instruments for measuring them, to select an instrument for stream shade surveys, and to test its accuracy.

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Among the many different methods used to quantify forest canopy properties, ground-based optical methods are among the most common. They can provide estimates of well-defined parameters and are widely applied in wildlife habitat, forest regeneration, and ecological studies. They can be relatively fast and simple, and can yield high resolution and accuracy; some of them use photography, which is versatile, intuitive, and self-documenting; however, no single method combines all of these advantages. The simplest is ocular estimation without the aid of an instrument. This method is logistically ideal but quantitatively questionable due to poor control over parameters and errors (Vales and Bunnell 1988; Vora 1988; Gatch *et al.* 2001). One of the most complex methods is canopy photography, which may deliver the highest precision, accuracy, and flexibility, but requires costly field equipment and time for data analysis.

Canopy Density Parameters

Jennings *et al.* (1999) discussed the potential for confusion with canopy parameter terminology. They suggested that *canopy cover* is the proportion of ground that is covered by vertical projections of tree crowns—a definition that is consistent with Vora (1988) and Cook *et al.* (1995), and with its usage in ecology and remote sensing (e.g., Gill *et al.* 1999). However, other suggested definitions are neither generally followed nor self-explanatory (e.g., *canopy density* and *canopy closure* to mean the proportion of the entire hemisphere that is obscured by vegetation) (Jennings *et al.* 1999). Importantly, Bunnell and Vales (1990) suggested that when attempting to explain forest processes as a function of canopy, researchers should use angles of view appropriate to the factor being studied. In this paper, we define canopy parameters in terms of physical processes and (or) the properties of measuring instruments. We use *canopy density* to mean the proportion of sky obscured by vegetation within a defined part of the sky. This is equivalent to Bunnell and Vales' (1990) suggested usage of *mean crown completeness*.

Various tools have been developed to try to bridge the gap between unaided ocular estimation of canopy density and more complicated methods. These include:

- the *spherical densiometer*, which is designed for canopy density above an angle of about 35° (Lemmon 1956, 1957);
- the *moosehorn* and similar instruments, which are for canopy density within several degrees of the zenith (Bonnor 1967; Vales and Bunnell 1988; Ganey and Block 1994; Cook *et al.* 1995); and
- the *Solar Pathfinder*™, which is for canopy density along the sun's path from sunrise to sunset (Platts *et al.* 1987).

These tools rely on the vision and judgement of the user to distinguish canopy from sky, but they differ from unaided ocular estimation in that they limit the field of view to a specific part of the sky and provide a means of directional orientation.

Selecting a Shade Parameter

Brazier and Brown (1973), Wooldridge and Stern (1979), and Beschta *et al.* (1987) suggest that for regulating summertime stream temperature, shade is most important between 10 AM and 2 PM. They proposed *angular canopy density* (ACD) to indicate the percentage of time that shade is available during this 4-hour period. Because the path of the sun across the sky is a known function of date and latitude, the region of the sky in which ACD should be measured can be determined in local polar co-ordinates for any day of the year by reference to a solar ephemeris (e.g., *http://ssd.jpl.nasa.gov/horizons.html*). *Effective shade* has been defined more recently (Allen and Dent 2001) as the percentage by which shade sources reduce radiant energy over a full day. We interpret "radiant energy" to mean direct solar radiation under clear skies because this is when the absence of shade has the greatest effect on stream temperature. Effective shade is an attractive parameter because it has percent energy units rather than simply percent canopy units. We are investigating the relationship between ACD and stream energy budgets; meanwhile, the literature suggests that both ACD and effective shade are suitable parameters. At the time we started our work (1999), ACD was the most logical shade parameter in the stream temperature literature so we selected it for the purpose of this paper.

Since the path of the sun across the sky varies through the season, we expand on the definition of ACD by specifying the season of interest. Here we use ACD during August, which fully specifies the area of sky where canopy density should be measured at a given latitude (Figure 1).

Selecting an Instrument

Having selected ACD as the shade parameter, the next step was to select an instrument to measure it. ACD can be measured on fisheye photos, but we wanted a compact instrument that could conveniently sample ACD over the width and length of streams having deep water, steep gradients, or dense riparian vegetation. A camera on a tripod is not well suited to these

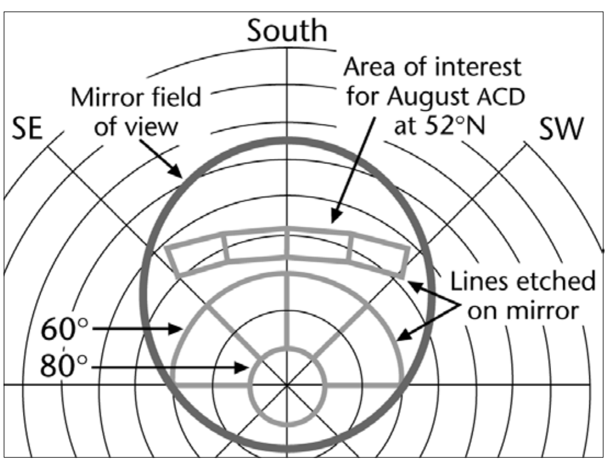

FIGURE 1. Locations of areas of interest on the spherical ACD meter projected onto polar co-ordinates. The image is flipped vertically relative to a fisheye photo to correspond with views in the convex mirror.

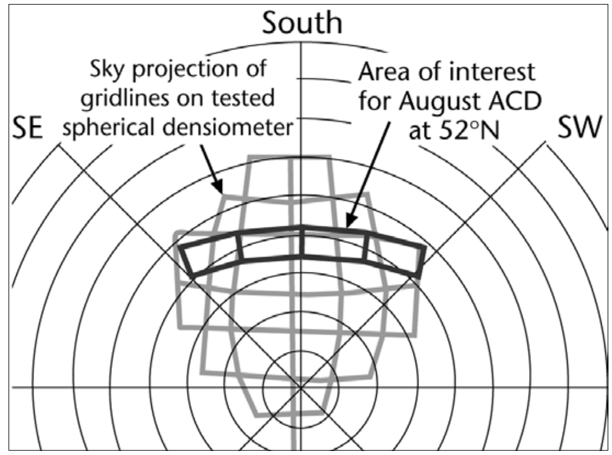

FIGURE 2. Locations of spherical densiometer gridlines and August ACD area of interest at 52°N in polar co-ordinates. The image is flipped vertically relative to a fisheye photo to correspond with views in the convex mirror.

conditions. The time required for fieldwork and image analysis is also an issue with photographic methods. We considered five instruments:

1. convex spherical densiometer
2. spherical ACD meter (described by Teti 2001)
3. Solar Pathfinder
4. user-made ACD device described by Brazier and Brown (1973) and Belt *et al.* (1992)
5. LAI-2000

Convex Spherical Densiometer

The traditional spherical densiometer is one of the most compact and widely used instruments of its type. Although its field of view differs considerably from the region of sky for measuring ACD, we considered adapting it to our purpose. We projected the field of view of a convex spherical densiometer onto altitude–azimuth co-ordinates (Figure 2) and found that when it was pointed south, one of its rows of grid squares approximately corresponds to the area for measuring August ACD at our latitude. Although its projected grid was asymmetric due to slight distortion in its mirror, this finding suggested that we might be able to estimate ACD by averaging canopy density in that part of its field of view.

Spherical ACD Meter

We tested the accuracy of ACD estimates made using the spherical densiometer in this way by comparing them with estimates of ACD measured on fisheye photographs. The field site was a forest canopy of moderate density and high fragmentation, a combination of conditions that makes ocular estimation difficult. At the same time, we tested two versions of the spherical ACD meter: one having a convex mirror with a diameter of 9 cm and one having a convex mirror with a diameter of 20 cm as described in Teti (2001). With the spherical densiometer, we estimated percent canopy density in each of the six grid squares to the nearest 25% (having judged this to be easier than the recommended dot counting method) and averaged the result to estimate ACD. We noted that the quality of the canopy image was better in the 9-cm convex mirror of the spherical ACD meter than in the spherical densiometer and that it was best in the 20-cm convex mirror (Figure 4 in Teti 2001). Figure 3 shows the increasing accuracy with which ACD could be estimated as optical resolution of the instruments increased. The 20-cm spherical ACD meter does not fit in the back of a field vest, however, unlike the one with the 9-cm mirror.

Solar Pathfinder

The Solar Pathfinder was designed to identify full-sky obstructions to sunlight for purposes such as assessing the suitability of sites for placing solar panels. A nearly identical instrument called the horizontoscope (Brang 1998) has been used in Europe for many years to document canopy gaps for research. Like the horizontoscope, the Solar Pathfinder uses interchangeable reference grids with sun paths for different dates and can be adapted to measure ACD. However, we found it difficult under some lighting conditions to distinguish sky from canopy in the unmirrored plastic dome of this instrument.

User-made ACD Device

The ACD measuring instrument described by Brazier and Brown (1973) and Belt *et al.* (1992) calls for a square mirror 30 cm on a side, which we found difficult to carry and use in dense vegetation and in very small streams. A reflection of the sun in a flat mirror is also dangerous to the user's eyes.

LAI-2000

Another instrument that measures the attenuation of light by canopies is the LAI-2000 (Welles and Norman 1991); however, it was not designed to measure shade and must be used under cloudy or shaded conditions. It is also necessary to use two instruments simultaneously, with one in an opening acting as a reference. Davies-Colley and Payne (1998) have used it successfully to estimate stream shade. However, we would not recommend it for extensive stream shade surveys because it does not measure canopy along the sun's path and due to the above-mentioned requirements.

Based on instrument characteristics, the purpose of our surveys, and preliminary results described previously, we determined that the spherical ACD meter with a 9-cm mirror was best suited for our stream shade surveys. We selected it over the more accurate version having a 20-cm mirror due to its greater portability and ease of use in small streams. Different criteria could result in a different instrument being selected. Table 1 summarizes our assessment of instruments for stream shade surveys.

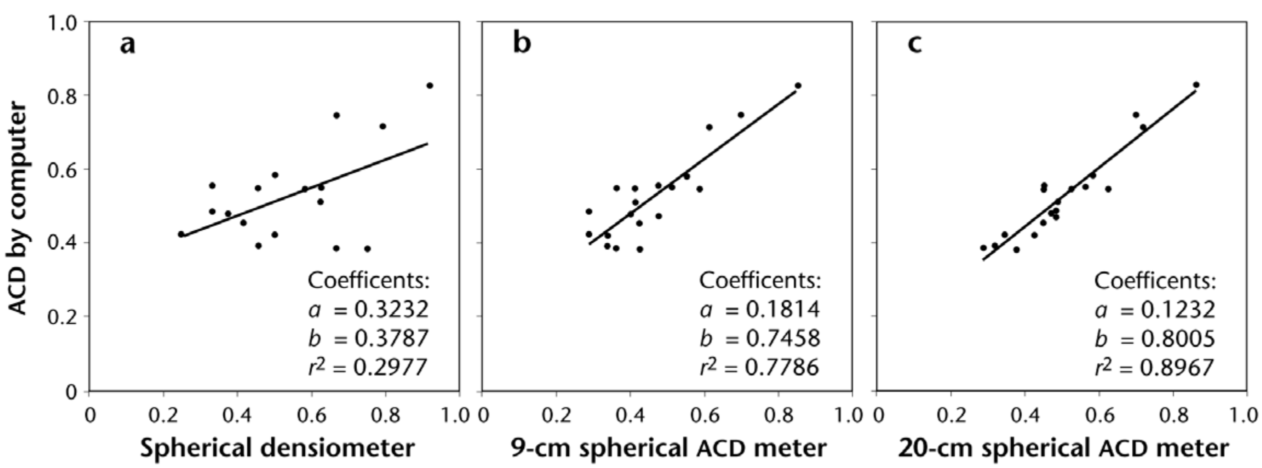

FIGURE 3. Scattergrams of point ACD measurements on canopy photos versus ocular estimates of ACD using (a) a convex spherical densiometer as described in the text, (b) the spherical ACD meter with 9-cm mirror, and (c) a spherical ACD meter with 20-cm mirror.

TABLE 1. Comparison of ground-based instruments for measuring stream shade

Instrument	Field of view	Advantages	Disadvantages	References
Convex spherical densiometer	Conical, about 110° wide centred on zenith, if original procedure is followed	Widely used as a general index of canopy. Most compact instrument.	Not designed to measure shade. If adapted to estimate ACD, optical quality limits accuracy.	Lemmon (1956, 1957)
Spherical ACD meter with 9-cm mirror	Sun's path from 10 AM to 2 PM	Can be used to estimate ACD and other parameters. Folds flat for easy transport. Provides high quality image.	Does not account for shade before 10 AM or after 2 PM.	Teti (2001)
Spherical ACD meter with 20-cm mirror	Same as above	Same as above, but provides an even higher-quality image.	Same as above, but larger size makes it more difficult to carry and use in very small streams.	Teti (2001)
Solar Pathfinder	Sun's path from sunrise to sunset	Can be used to estimate effective shade if used in combination with solar data.	Unmirrored plastic dome provides poor canopy image under some lighting conditions.	Platts *et al.* (1987)
Original ACD instrument	Sun's path from 10 AM to 2 PM	Can be used to estimate ACD. Provides clearest image.	Awkward to carry and use in small streams. Reflection can be dangerous to eyes.	Brazier and Brown (1973)
LAI-2000	Conical, about 150° wide centred on zenith. Can be modified.	Can provide objective measure of cosine -weighted canopy density in the field of view.	Not designed to measure shade. Cannot be used in direct sunlight. Pair of instruments is required.	Welles and Norman (1991); Davies-Colley and Payne (1998)
Moosehorn or any of several similar devices	Narrow angle around the zenith	Used to estimate canopy cover.	Not designed to measure shade.	Bonnor (1967); Cook *et al.* (1995); Vales and Bunnell (1988); Ganey and Block (1994)
Fisheye camera with suitable software	Entire celestial hemisphere	Can be used to calculate any canopy density parameter. Provides permanent record. More accurate than ocular methods.	Highest capital cost. Most difficult to use in the field. Skill and time required to analyze images.	Anderson (1964); Rich (1990); Englund *et al.* (2000); Frazer *et al.* (2001)

Previous Tests of Canopy Density Instruments

Each ocular-type canopy density measuring instrument has a variety of properties such as a field of view, a grid pattern corresponding with regions in the sky, and optical quality that allows a certain angular resolution of canopy features. Random and systematic errors can result from mechanical flaws, limited resolution, incorrect orientation, and ocular estimation errors. Therefore, overall accuracy is a function of human-determined factors, site factors, field methods, and properties of the instrument.

Few published tests of canopy density instruments have compared estimates of the same parameters using an ocular instrument and a photographic method. Some studies have compared measurements using ocular-based instruments with different fields of view. This tends to confound our understanding of sources of error. Bonnor (1967) compared average canopy density measured with a moosehorn (10° field of view centred on the zenith) with that measured using a "vertical dot" instrument and found "good agreement." Using data in his Table 3, we regressed average canopy density by moosehorn against that measured with his vertical dot instrument and found an r^2 equal to 0.96 and a slope of 1.03. This close agreement is logical because the fields of view of the two instruments were similar.

In contrast, Ganey and Block (1994) compared the concave spherical densiometer with a vertical sighting tube and Cook *et al.* (1995) compared concave and convex spherical densiometers with a moosehorn. Both studies found that spherical densiometers consistently overestimated mean cover measured along vertical projections. This result is to be expected due to the differing angles of view of the instruments and the properties of forest canopies noted by Bunnell and Vales (1990). Ganey and Block (1994) and Cook *et al.* (1995) did not document spherical densiometer accuracy *per se*, but a source of error that can result from using the densiometer to estimate a different parameter than that for which it was designed.

Bunnell and Vales (1990) compared the accuracy of 13 techniques for estimating average canopy density directly overhead and found that the spherical densiometer consistently overestimated it; they did not, however, document the accuracy of the spherical densiometer in measuring what it was designed for. Englund *et al.* (2000) correlated canopy density by spherical densiometer with total site factor (TSF) calculated from fisheye photographs. Their calculated TSF was an estimate of overall attenuation of diffuse and direct solar radiation based on a hemispherical radiation model (similar to effective shade). They found an r^2 equal to 0.89, which does not represent the accuracy of the spherical densiometer for estimating the parameter for which it was designed. Lieffers *et al.* (1999) cited similar results for photosynthetically active radiation (PAR) during the growing season.

Researchers at Humboldt State University (Anonymous 2000) compared spherical densiometer measurements with measurements of canopy density on fisheye photos along two streams and found a large difference between means in one of two samples (55% canopy density by spherical densiometer vs. 85% from fisheye photos). They noted that the angle of view is one of the biggest differences among methods and that an appropriate and consistent angle of view should be used.

We infer from the experiences of previous researchers that it is advantageous to:

- clearly define the canopy parameter of interest based on physical principles,
- select a suitable instrument to measure that parameter, and
- estimate errors in measuring the selected parameter with the selected instrument under representative field conditions.

Having selected angular canopy density as our parameter and the spherical ACD meter with a 9-cm mirror as our instrument, we performed an experiment to better document its accuracy.

Methods

Field Methods

Plots for surveying canopy density were laid out along five lines with eight points each in a mixed-age coniferous stand, and four lines with 7–14 points each in a mixed-age deciduous stand. Stands with fragmented canopies were selected to challenge the skills of the operators. Points in the coniferous stand were marked with permanent bamboo stakes attached to steel rebar and those in the deciduous stand were marked with paint spots on the ground. For this experiment, we made ocular estimates of canopy density at a height corresponding with the height of the fisheye camera on a tripod. When doing actual shade surveys with the spherical ACD meter, however, we measure at the surface of a stream to capture all shade sources.

For fisheye photography, we used a Nikon Coolpix 990 digital camera with Fisheye adapter FC-E8 mounted on a Manfrotto tripod with grip-action ball head having a built-in bubble level. We set up the camera at a height of about 1.1 m over marked points on the ground. Exposures were made with centre-weighted metering using a correction of +0.7 EV, the sharpness option off, and highest resolution (2048 × 1536 pixels). Images were saved in normal quality JPEG format, which produced files averaging 15% of the size of uncompressed files. Inspection of images indicated that compression had virtually no effect on our ability to distinguish canopy from sky, but that colour blurring due to chromatic aberration beyond angles of more than 45° from the zenith could be a limiting factor. This finding is consistent with Frazer *et al.* (2001), who used similar equipment. However, we were interested only in canopy at higher angles in the sky so, in contrast with their findings, we had acceptable sharpness and discrimination between canopy and sky in the blue colour channel. We were unable to restrict our photography to overcast days so when the camera lens was in the sun, we shaded it with a 15 × 15 cm paddle on the end of a 2-m pole and retouched the images before analysis.

We estimated canopy density with a spherical ACD Meter having a 9-cm mirror on which polygons had been etched to define:

- August ACD in 1-hour increments of sun travel,
- the area above a vertical angle of 80°, and
- the area from 60° to 80° in one-half of the sky in azimuth increments of 45° (Figure 1).

Each operator received about 15 minutes of training outdoors on how to use the instrument. This included showing them sample images with computer-calculated canopy densities that come with the instrument. Operators 1–4 had at least 30 minutes of additional practice with an experienced user during which they could compare canopy density estimates. Operator 5 surveyed the coniferous plot after only 15 minutes of training and did not have an opportunity to practice with an experienced user at the field site.

At each observation point, the observer positioned the instrument so that the mirror was over a marked location at a height of 1.1 m ± 0.10 m, held it level pointing true south, and estimated canopy density in each of the nine areas etched on the mirror. The observer then turned around, repositioned the mirror over the ground point, and estimated canopy density in the four areas representing 60–80° of altitude for the north half of the sky. This was repeated by each of five operators at points in the coniferous plot and four operators in the deciduous plot. During each survey there was only one designated instrument user; after a survey started there was no swapping of roles between instrument-user and note-taker.

Canopy photos were taken in July 2001 at the coniferous plot and September 2002 at the deciduous plot. Ocular estimates were made by operator 5 at the coniferous plot in September 2001 and at both plots by operators 1–4 in September 2002. We took replicate fisheye photos at a subset of points in the coniferous plot in August 2003 to test the reproducibility of measurements by the computer-fisheye method.

Image Analysis Methods

Various commercial and public domain software packages are available to assist in the extraction of shade information from canopy photos. As none of these were designed to calculate ACD, we developed our own procedure, which required a minimum of commercial software.

We calibrated the geometry of our fisheye lens optics by photographing the walls and ceiling of a room in which we had marked the vertices of polygons representing altitude–azimuth co-ordinates and sun positions. This allowed us to map polygons of interest in the sky onto x,y locations in the image plane, thus eliminating uncertainties about the projection geometry of the fisheye lens as discussed by Herbert (1987) and Frazer *et al.* (2001). We defined 65 polygons in equal increments of altitude and azimuth, and 48 polygons representing sun positions from 8 AM to 4 PM solar time between 1 July and 15 October (Figure 4). Subsets of these corresponded with the parts of the sky in which canopy density was estimated in the field with the spherical ACD meter (Figure 4).

We measured canopy density on fisheye photos using a combination of procedures in Adobe Photoshop® LE, or Photoshop Elements and Scion Image (public domain software available at: *www.scioncorp.com*). Procedures in Photoshop were as follows.

- Subsample the image by 50% in both x and y.
- Mark location of the zenith, which was at a consistent location in the digital image when the tripod mount was levelled.
- Mark the direction of true north, indicated by a hand-held target visible on each photo.

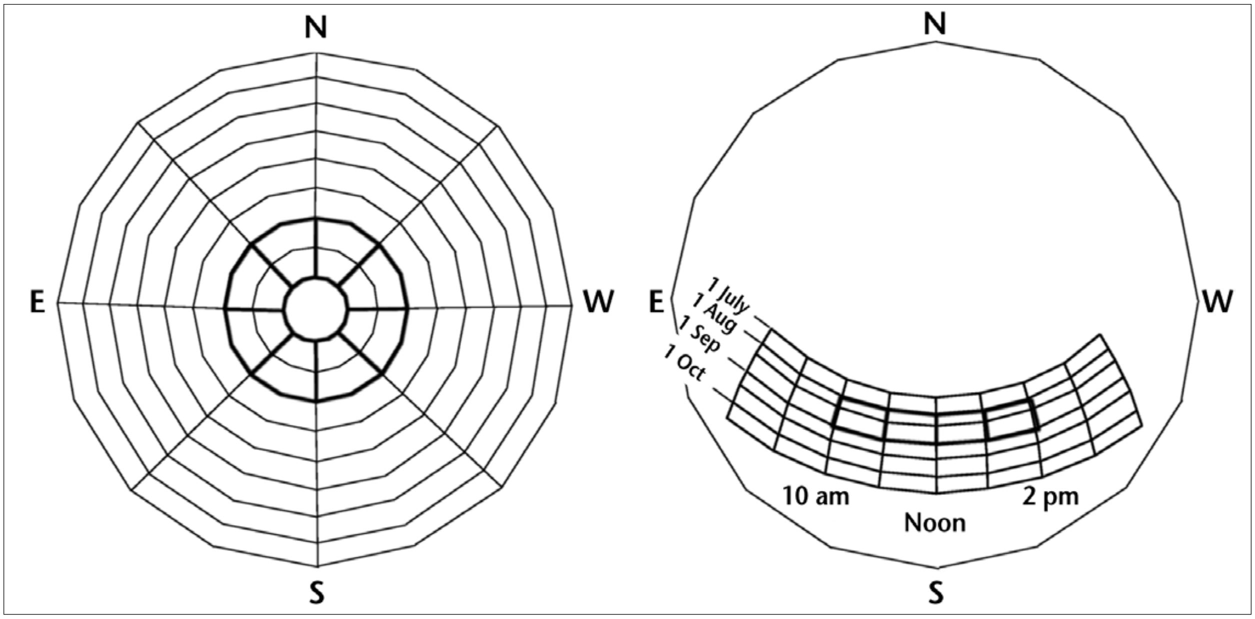

FIGURE 4. Polygons in which canopy density was calculated from fisheye photographs: those bounded by altitudes and azimuths (left) and those bounded by sun paths (right). Heavier lines indicate polygons in which ocular estimates of canopy density were compared with those measured on fisheye photos. Directions correspond with those seen with a vertically oriented fisheye lens.

- Register image to the reference image calibrated as described previously.
- Retouch image. This consisted of painting non-canopy features such as the paddle used to shade the lens and darkening tree trunks when they were illuminated by low-angle sunlight.

Scion Image allows the red, green, and blue channels of a colour image to be analyzed separately. We usually found good discrimination between sky and canopy in the blue channel using an operator-selected threshold. Then, in a programming language built into Scion Image, we executed a macro that measured average brightness in each predefined polygon. With canopy represented as black (zero) and sky represented as white (255), canopy density of each polygon was calculated as average brightness divided by 255.

Figure 5 shows the ACD portion of a fisheye photo before and after subsampling, and after processing. It illustrates that lens optics is such that subsampling this portion of the field of view from a width of about 1000 pixels to 500 pixels causes little incremental loss of quality. ACD was calculated to be 78% on this image.

While ACD was the main parameter of interest, the spherical ACD meter also allows the user to estimate canopy density within 10–30° of the zenith as previously described. Canopy density within a zenith angle of 10° is useful because it corresponds closely with canopy cover as discussed in the Introduction. Canopy density within 30° of the zenith has been shown to be correlated with snow accumulation in a forest containing small gaps (Teti 2003). We therefore tested the accuracy with which operators could estimate canopy density in addition to ACD in these projected areas of sky.

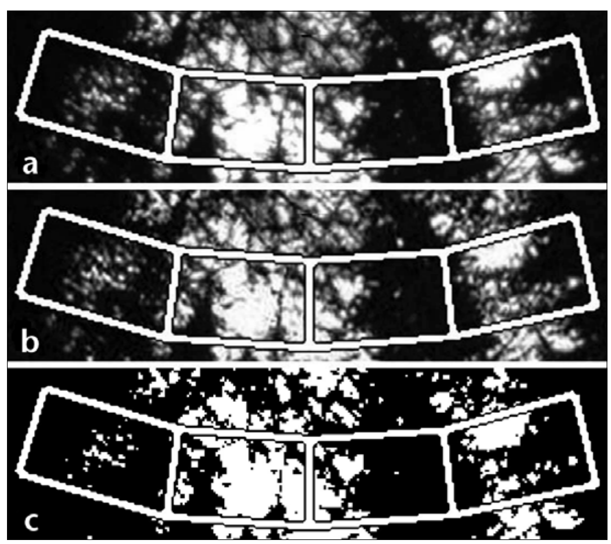

FIGURE 5. Enlarged segment of a fisheye image showing ACD area: (a) at original resolution, (b) after subsampling, and (c) after pixel classification.

Results and Analysis

Figure 6 shows scattergrams of canopy densities by the ocular versus the computer-fisheye method. Data were analyzed with a random coefficients regression model using "PROC MIXED" in SAS (SAS Institute Inc. 1999). The model was:

$$y_{ijkl} = (\alpha_i + A_{ij}) + (\beta_i + B_{ij})\, x_{ikl} + L_{k(i)} + P_{l(ik)} + E_{ijkl}$$

where:

y_{ijkl} = ocular estimate for plot i, observer j, line k, point l

x_{ikl} = fisheye estimate for plot i, line k, point l

α_i = intercept for plot i (fixed effect)

β_i = slope for plot i (fixed effect)

A_{ij} = random effect of observer j on intercept for plot i

B_{ij} = random effect of observer j on slope for plot i

$L_{k(i)}$ = random effect of line k, plot i

$P_{l(ik)}$ = random effect of point l in line k, plot i

E_{ijkl} = residual random effect

The model assumes an overall linear relationship between ocular and computer estimates for all operators, described by intercept α_i and slope β_i, where one or both may depend on *plot*. The relationship for an individual operator represents a random deviation (described by A_{ij} and B_{ij}) from the overall line. Table 2 shows the results for Model 1, which assumes $\alpha_1 \neq \alpha_2$ and $\beta_1 \neq \beta_2$. Tests of $\alpha_1 - \alpha_2 = 0$ and $\beta_1 - \beta_2 = 0$ indicate that the slopes and intercepts were not significantly different for ocular estimates of any of the three canopy parameters on the two plots ($p > 0.5$ in all cases). While the effect of *plot* was not significant, we cannot generalize about the consistency of the relationship between coniferous and deciduous stands because we had only one sample from each. However, this does allow us to describe our results in a model without subscript i for *plot*, as follows:

$$y_{jkl} = (\alpha + A_j) + (\beta + B_j)\, x_{kl} + L_k + P_{l(k)} + E_{jkl}$$

Table 2 shows the results for Model 2. Average slopes for estimates of the three canopy parameters ranged from 0.87 to 0.91 and were significantly different from Model 1 at $\alpha = 0.05$. Intercepts ranged from –0.01 to 0.025 and were not significantly different from zero (p = 0.22–0.43). Regression slopes indicated that operators had a tendency to underestimate all three canopy parameters by similar ratios. The potential effect of *lines* within plots was considered because points were more closely grouped within lines than between lines; however, *lines* were not significant for any of the parameters as indicated by the P values calculated for $L_{k(i)}$, so the model simplifies to:

$$y_{jl} = (\alpha + A_j) + (\beta + B_j)\, x_l + P_l + E_{jl}$$

Operator variability in Model 2 is represented by the variance of A_j and B_j. Significant differences were observed between operators in the regressions for canopy density above 60° and canopy density above 80°, but not for ACD at $\alpha = 0.05$. The inverses of the regressions in Model 2 (Table 3) are the formulae for estimating a computer-fisheye canopy density from an ocular estimate (by an operator randomly chosen from the population we sampled). For ACD this is:

$$x_l = 1.145 y_l - 0.02$$

In many applications, it is mean canopy density that is of interest rather than individual point estimates. Table 4 compares ocular estimates of mean canopy densities with those determined by the computer-fisheye method. Ocular estimates of mean ACDs were on average 6% lower than measurements by the computer-fisheye method. Similar results were obtained for canopy densities above 60° and canopy densities above 80°. Operator variability in the estimates of all three means was highly significant ($p < 0.0001$). The operator who received 15 minutes of training (operator 5 in Table 4) underestimated mean ACD by 11.4 percentage points at the coniferous site while the operators who received 45 minutes or more of training underestimated it by 1.9–9.0 percentage points.

The reproducibility of measurements by the computer-fisheye method was investigated by analyzing fisheye photos at 16 points in the coniferous plot 2 years after the first set of photos was taken. Different people analyzed photos taken in 2001 and 2003. Scattergrams and regression results of canopy densities in 2003 versus canopy densities in 2001 are shown in Figure 7. All r^2 values were greater than 0.95 and slopes ranged from 0.997 to 1.04.

Discussion

Ocular estimates of average ACDs on our two plots using the spherical ACD meter were 6% lower than those by the computer-fisheye method; however, we would not expect this to always be the case even for the same group of operators because it would depend on the frequency distribution of ACD in the unknown population.

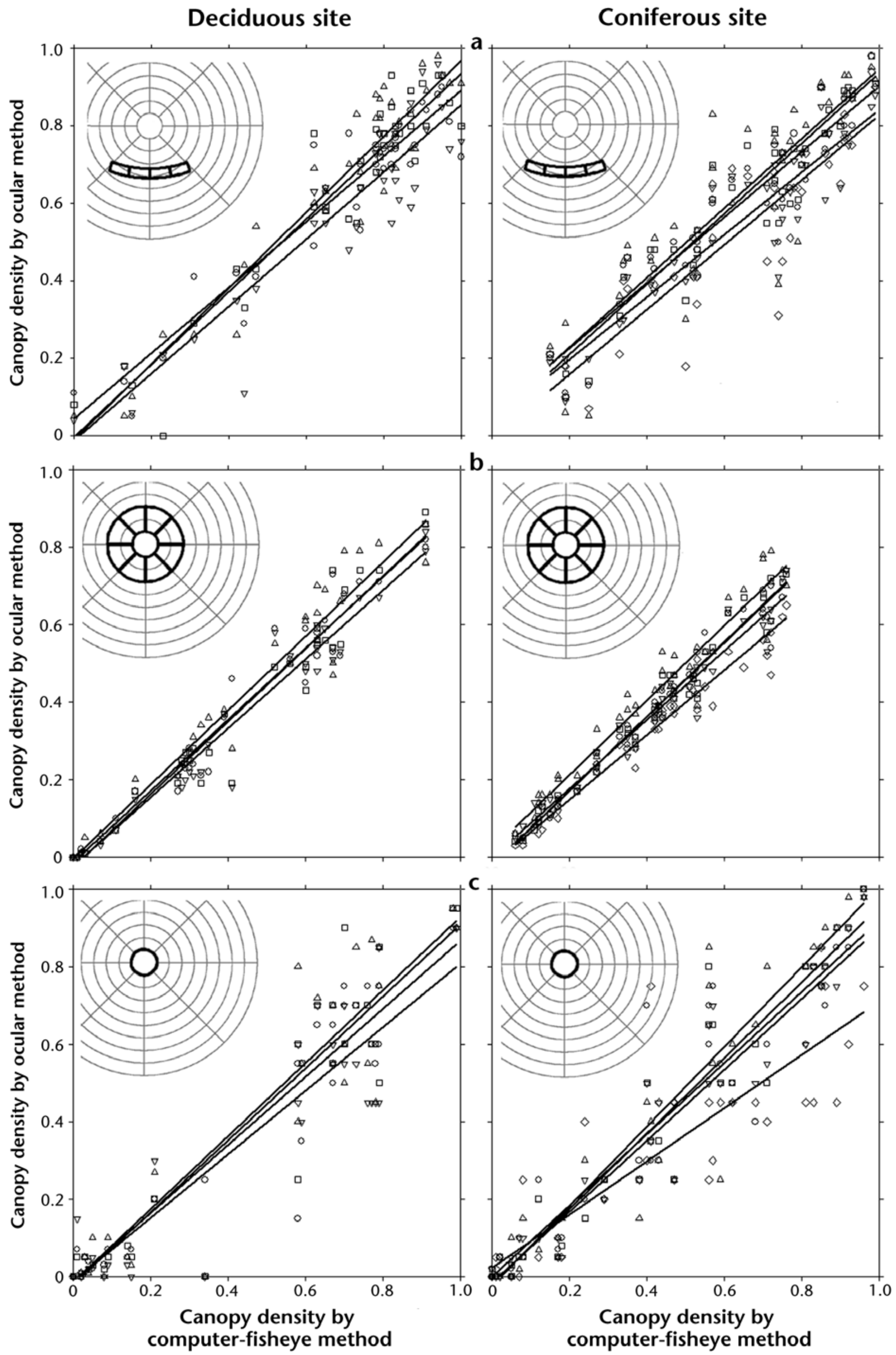

FIGURE 6. Ocular estimates of three canopy density parameters versus measurements by the computer-fisheye method: (a) ACD (each point represents the average of four estimates); (b) canopy above 60° (each point represents the average of nine estimates); and (c) canopy above 80° (each point represents one estimate).

TABLE 2. Model 1: Unequal intercepts and slopes for coniferous and deciduous plots ($\alpha_1 \neq \alpha_2$, $\beta_1 \neq \beta_2$)

	Angular canopy density					Canopy density above 60°					Canopy density above 80°				
Fixed effect	Estimate	SE	df	t	$P > \|t\|$	Estimate	SE	df	t	$P > \|t\|$	Estimate	SE	df	t	$P > \|t\|$
α_1 (coniferous)	0.033	0.034	51.6	0.98	0.330	–0.009	0.013	37.4	–0.67	0.504	–0.007	0.016	69.3	–0.42	0.678
α_2 (deciduous)	0.008	0.036	54.4	0.23	0.820	–0.017	0.012	17.0	–1.43	0.172	–0.014	0.017	79.0	–0.82	0.413
β_1 (coniferous)	0.858	0.052	63.9	16.61	< .0001	0.923	0.032	29.8	28.71	< .0001	0.905	0.047	26.5	19.45	< .0001
β_2 (deciduous)	0.903	0.052	59.5	17.22	< .0001	0.927	0.030	15.3	30.73	< .0001	0.892	0.050	23.0	17.97	< .0001
$\alpha_1 - \alpha_2$	0.025	0.049	53.1	0.51	0.615	0.008	0.017	26.1	0.45	0.656	0.007	0.023	74.3	0.32	0.754
$\beta_1 - \beta_2$	–0.046	0.074	61.8	–0.62	0.536	–0.004	0.044	22.1	–0.09	0.928	0.013	0.068	24.5	0.19	0.850

	Angular canopy density			Canopy density above 60°			Canopy density above 80°		
Random effect	ML[a] estimate	–2 ln λ[b]	P > –2 ln λ[c]	ML[a] estimate	–2 ln λ[b]	P > –2 ln λ[c]	ML[a] estimate	–2 ln λ[b]	P > –2 ln λ[c]
$A_{ij}\,(\sigma_A{}^2)$	0.000	0.27	0.979	0.000	1.78	0.698	0.000	< .0001	1.000
$B_{ij}\,(\sigma_B{}^2)$	0.002	5.68	0.176	0.002	11.64	0.014	0.005	33.53	< .0001
$L_{k(i)}\,(\sigma_L{}^2)$	0.000	0.06	0.998	0.000	0.01	1.000	0.000	< .0001	1.000
$P_{l(ik)}\,(\sigma_P{}^2)$	0.004	121.14	< .0001	0.001	52.59	< .0001	0.004	48.64	< .0001
$E_{ijkl}\,(\sigma^2)$	0.004			0.001			0.007		

[a] Maximum likelihood estimate.
[b] –2 ln λ is the likelihood ratio statistic.
[c] Probability that variance equals zero.

TABLE 3. Model 2: Equal intercepts and slopes for coniferous and deciduous plots ($\alpha_1 = \alpha_2$, $\beta_1 = \beta_2$)

	Angular canopy density					Canopy density above 60°					Canopy density above 80°				
Fixed effect	Estimate	SE	df	t	$P > \|t\|$	Estimate	SE	df	t	$P > \|t\|$	Estimate	SE	df	t	$P > \|t\|$
α	0.020	0.025	36.5	0.80	0.430	–0.012	0.010	15.0	–1.27	0.222	–.009	0.012	73.8	–0.79	0.433
β	0.873	0.039	29.8	22.17	< .0001	0.913	0.029	8.2	31.97	< .0001	0.880	0.046	8.3	19.31	< .0001
$\beta - 1$	–0.127	0.039	29.8	3.23	0.003	–0.087	0.029	8.2	3.05	0.016	–0.120	0.046	8.3	2.63	0.030

	Angular canopy density			Canopy density above 60°			Canopy density above 80°		
Random effect	ML[a] estimate	–2 ln λ[b]	P > –2 ln λ[c]	ML[a] estimate	–2 ln λ[b]	P > –2 ln λ[c]	ML[a] estimate	–2 ln λ[b]	P > –2 ln λ[c]
$A_j\,(\sigma_A{}^2)$	0.000	0.52	0.944	0.000	2.24	0.608	0.000	0.00	1.000
$B_j\,(\sigma_B{}^2)$	0.002	6.31	0.137	0.003	13.17	0.007	0.007	34.83	< .0001
$L_{k(i)}\,(\sigma_L{}^2)$	0.000	0.08	0.996	0.000	0.31	0.974	0.000	0.00	1.000
$P_{l(ik)}\,(\sigma_P{}^2)$	0.004	123.07	< .0001	0.001	54.40	< .0001	0.004	53.13	< .0001
$E_{ijkl}\,(\sigma^2)$	0.004			0.001			0.006		

[a] Maximum likelihood estimate.
[b] –2 ln λ is the likelihood ratio statistic.
[c] Probability that variance equals zero.

TABLE 4. Estimates of mean canopy densities

	ACD		Canopy density above 60°		Canopy density above 80°	
	Coniferous	Deciduous	Coniferous	Deciduous	Coniferous	Deciduous
Computer fisheye	0.645	0.690	0.417	0.403	0.349	0.357
Operator 1	0.601	0.625	0.380	0.358	0.322	0.303
Operator 2	0.612	0.641	0.381	0.354	0.321	0.313
Operator 3	0.626	0.663	0.422	0.383	0.336	0.323
Operator 4	0.555	0.583	0.372	0.336	0.305	0.282
Operator 5	0.531	missing	0.330	missing	0.263	missing
Average of operators	0.585	0.628	0.377	0.358	0.309	0.305
Operator average minus computer average	–0.060	–0.062	–0.040	–0.046	–0.040	–0.052

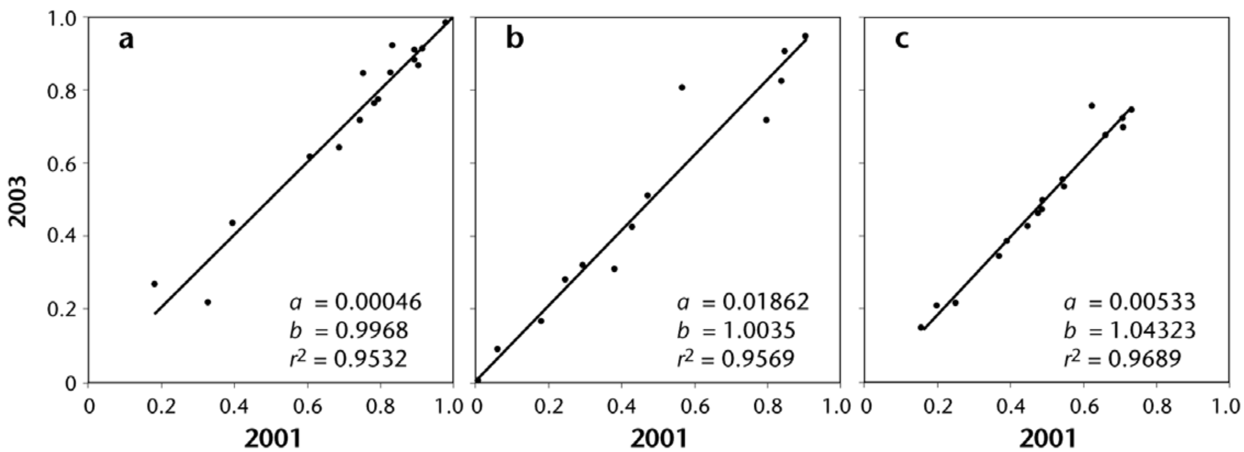

FIGURE 7. Replicate measurements of three canopy density parameters by the computer-fisheye method in the coniferous plot in 2001 and 2003: (a) ACD; (b) canopy above 80°; and (c) canopy above 60° (each point represents one estimate).

However, if our relationship for individual estimates of ACD is representative of those at an unknown site, we would estimate mean ACD as the sample mean of individual corrected ACD estimates using the inverse regression relation; that is,

$$\frac{\sum_{l=1}^{n} \hat{x}_l}{n}$$

where: $\hat{x}_l = 1.145y_l - 0.02$.

The absence of a significant difference in regression relations between our mixed-age coniferous plot and our mixed-age deciduous plot provides some justification for cautiously applying this relationship to other plots. However, we need to obtain more samples of mean ACDs using more operators in a wider range of stands and compare them with mean ACDs by the computer-fisheye method. Although we did not find a significant difference in ACD regressions between operators at $\alpha = 0.05$ ($p = 0.137$), operator variability probably exists because ocular estimates require judgement and because we found significant differences between operators for estimates of the other two canopy density parameters (above 60°, $p = 0.007$ and above 80°, $p < 0.0001$).

The regression model assumes that canopy densities by the computer-fisheye method are measured without error. While this method is accurate, it is not error-free. Frazer *et al.* (2001) reported that digital photos were difficult to threshold and gave different results under different sky conditions. They found a significant amount of scatter in canopy openness measurements from digitized film photos and those from digital camera images. On the other hand, Hale and Edwards (2002) reported no significant differences in estimates of canopy parameters by film and digital camera methods. Englund *et al.* (2000) found that digital camera images produced consistently lower canopy densities than a film camera although they noted that this could have been due to differences in camera settings. They also suggested that the process of determining a threshold for distinguishing sky from canopy at the computer was a much greater source of variation than differences due to the type of camera used.

We, too, found the process of categorizing pixels based on a threshold (i.e., *binarization*) to be a critical step in image analysis. Binarization becomes more problematic as image brightness becomes more variable across the field of view. The person analyzing photos at the computer, however, does have some control over ensuring that binarization does not introduce bias. This step is somewhat subjective, but we believe that the human ability to recognize canopy over a wide range of lighting conditions justifies it, particularly since original, intermediate, and final binarized images can be saved for quality control.

Clearly no binarization errors are made when canopy is absent or when it is continuous. This applies to ocular estimation as well as photography. We found that canopy density was most difficult to estimate at medium canopy densities and when canopy was highly fragmented. This is consistent with Bonnor (1967), who found errors were highest at 50% canopy density and decreased as they approached zero and 100%. Errors in photographic methods also tend to increase as canopy becomes more fragmented. When the dimension of individual canopy elements is small in relation to the angular resolution of the imaging system, resolution becomes a factor in misclassification of pixels. For example, a single pixel on our photos represented an angle of about 0.23° in the region where we measured ACD. Trees were up to 25 m tall so this angle corresponded with a linear dimension of up to 12 cm in the canopy. Many canopy features were smaller than that and misclassification at edges could therefore have occurred. The misclassification of pixels containing mostly canopy might have been balanced by the misclassification of other pixels containing mostly sky. However, this assumption may not have been satisfied if foliage was highly non-random. This may be a source of error in all photographic methods because canopy is non-random and the smallest canopy features can never be resolved.

Our criterion for determining a threshold for each image was to attempt to balance overestimates of canopy density in areas with high canopy density with underestimates in areas with low canopy densities. We only considered the image area above a vertical angle of about 45° because this area included all of the sky regions in which we were interested. This reduced the errors that could have occurred if we had been analyzing canopy in the full sky where a wider range of background brightness would have been present. Binarization errors are increased by uneven background illumination and many researchers have therefore recommended that canopy photography be done under uniformly overcast skies. This was not possible at our sites, which we photographed on days that ranged from mostly cloudy to a fairly uniform overcast.

Other potential sources of error in our photographic method were imperfect camera positioning over a point and imperfect orientation of the camera with respect to north and the zenith. We think that random errors associated with sky conditions, operator practices in the field, and operator practices during image analysis were greater than those due to systematic errors with our digital camera system. We documented the combined effect of random errors by re-photographing and re-analyzing canopy densities at 16 points in the coniferous site 2 years after the original photography. During sampling, cloud conditions were almost uniformly overcast in 2001 and scattered in 2003. The difference in illumination between the two sets of photos was fairly representative of the range of conditions we had in this study. The photography and image analysis done in 2001 and 2003 would have introduced errors that we suggest represent an upper limit of random errors in this method.

Errors in the measurement of the independent variable can violate the assumptions of ordinary least squares regression. However, if the error in the independent variable is much smaller than that in the dependent variable, then ordinary least squares is appropriate (Kennedy 1998). Our results indicate that this condition was met for the three canopy parameters we measured. The measurement errors associated with the computer-fisheye method would have actually been less than those indicated in Figure 7 because some of

Angular canopy density is a well-defined and logical shade parameter, but more work is needed to determine how accurately it describes the attenuation of solar energy.

the variability would have been due to actual changes in the canopy during the 2 years between replicate measurements. We cannot be as certain about systematic errors in the computer-fisheye method because we did not have an independent method with which to compare them. A high quality film camera may be more accurate than the digital camera we used (e.g., Frazer *et al.* 2001), but all photographic methods are subject to similar types of errors and must ultimately rely on the visual quality control by the user. Visual verification of photographic canopy measurements is subjective but convincing and we think that our computer-fisheye method was accurate enough to use as a standard for testing ocular methods.

The operator who received the least training produced the least accurate estimates of ACD. We cannot draw conclusions from this because we did not adequately control training intensity. However, we hypothesize that operator accuracy would improve significantly with 1 or more hours of formal training. This could consist of an operator repeatedly making an ocular estimate of canopy density on an image and then being given the correct value.

In this paper, we have emphasized errors that are inherent in instruments, but we have not addressed all sources of error. For example, Davies-Colley and Payne (1998) found higher shade at water level than at bank height on small streams and we have observed greater ACD at water level than at a height at which a fisheye camera can be conveniently set up. In such cases, an instrument like the spherical ACD meter, which can be used within a few centimetres of water level, has an additional advantage over a fisheye camera.

Conclusion

Angular canopy density is a well-defined and logical shade parameter, but more work is needed to determine how accurately it describes the attenuation of solar energy. Meanwhile, we endorse it as an indicator of shade on small streams.

With minimal training, it is possible for a human operator to estimate mean ACD, and mean canopy density within 10–30° of the zenith with the spherical ACD meter to within about 10% of computer-fisheye measurements; however, operator variability can be significant and more work is needed to optimize training methods. Our results indicate that at least 1 hour of formal training is advisable. As stream shade is used more frequently to help manage riparian areas, more attention should be given to the accuracy of any instrument that relies on ocular estimates. We also need to better understand the incremental effect of shade and other factors on daily maximum temperatures under different circumstances so that we can specify the accuracy required for shade surveys.

The choice of a canopy measuring instrument should depend on the parameter desired, accuracy requirements, cost of fieldwork, and cost of data analysis. For surveying shade on small forest streams, it is advantageous to have a compact instrument that can measure shade under low overhanging vegetation. Suitable instruments such as the Solar Pathfinder and spherical ACD meter have become available only relatively recently. Instruments not designed to measure canopy along the path of the sun, such as the spherical densiometer and moosehorn, should not be used to make inferences about shade. The first consideration in choosing an instrument should be whether it was designed to measure a parameter that corresponds with the physical process being studied.

We are using the spherical ACD meter to survey stream shade in British Columbia to help managers better understand how shade varies naturally and under different riparian management scenarios. The results reported here will add credibility to our findings.

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Test Your Knowledge . . .

Selecting and testing an instrument for surveying stream shade

How well can you recall some of the main messages in the preceding research report? Test your knowledge by answering the following questions. Answers are at the bottom of the page.

1. As stream shade becomes more frequently used to help manage riparian areas, more attention should be given to the accuracy of any instrument that relies on ocular estimates. With minimal training, it is possible for a human operator to estimate mean angular canopy density (ACD), and mean canopy density within 10–30° of the zenith with the Spherical ACD Meter, to within about ___ % of computer-fisheye measurements:
   A) 5%
   B) 10%
   C) 20%
   D) 90%
   E) none of the above

2. In this study, five operators using the Spherical ACD Meter were found to have underestimated mean ACD by an average of 6%. The standard procedure for making an unbiased estimate of average ACD should therefore be for any operator to multiply the mean of ocular ACD estimates by 1.06.
   A) True
   B) False

3. The accuracy of the canopy density measurements made by the computer-fisheye method was difficult to know precisely because:
   A) there was no alternative objective method available for comparison
   B) it varied by an unknown amount with changing sky conditions
   C) it was partly a function of the judgement of the computer operators
   D) all of the above

4. Instruments not designed to measure canopy along the path of the sun should not be used to make inferences about shade. The first consideration in choosing an instrument should be whether it was designed to measure a parameter that corresponds with the physical process being studied. Which of the following instruments are designed to measure canopy along the path of the sun?
   A) Solar Pathfinder
   B) Spherical ACD Meter
   C) Spherical Densiometer
   D) Moosehorn
   E) all of the above
   F) A and B
   G) B and C
   H) A and C

ANSWERS

1. B 2. B 3. D 4. F