APPENDIX 3: Hemispherical photography

A3.1 Methods

It is acknowledged that hemispherical photography involves a multi-step process which can accrue significant errors as well as bias at each step (Rich, 1990). However effort was made to reduce or account for some of these errors throughout the procedure (Table A3.1). Furthermore correction for error was made to some extent by local calibration of photograph estimates against continuous measurements (Comeau, 2000).

Photographs were taken only under uniformly overcast sky conditions or in the early evening to achieve even sky illumination (Rich, 1990) over both growing seasons. Photographic images were recorded using an 8 mm fish eyes lens (Nikkor, 8 mm, f 2.8, Nikon Corporation, Tokyo 100, Japan) attached to a mechanical camera body (FM2 Nikon Corporation, Tokyo, Japan) with a digital databack (MF16 data-back, Nikon Corporation, Tokyo, Japan) used to record reference information on the film. The camera and lens were mounted on a rigid telescopic tripod (Benbo Trekker) just above seedling level and in the centre of each plot. A bubble reading attached to the lens cap was used to level the camera and a compass was used to orientate the top of the film towards magnetic north. North and South were marked using yellow light emitting diodes attached to a collar around the lens. A right angled view finder was used to view the overstorey before photography.

The exposure was calculated using a photographic spot light meter with a 1° field of view (Spot Meter F, Minolta Camera Co., Osaka, Japan) set on an ISO reading of 25. This overexposes the images by 2 stops to obtain a white sky (rather than grey) to maximise the contrast between sky and foliage. Light refraction errors from overexposing the film were acknowledged but it was decided that maximising the contrast initially at image acquisition stage, would help reduce further errors accrued when setting the threshold at the image analysis stage.

Consistent exposures were obtained by sighting the spot meter through small canopy gaps and taking the reading for the sky only. On the camera, the focus was set to infinity and aperture and speed set to correspond to the spot meter readings before photos were taken. Photos were bracketed at one exposure stop above and below the spot meter value. Out of the three photographs taken per plot, the processed image that most clearly distinguished sky from canopy was chosen for analysis. Images were recorded using an ISO-100 monochrome T-grain film (T-max 100, Kodak 5052 TMX, Kodak Ltd, Hemel Hempstead, Herts). This particular film was chosen as it has been proven to provide a high standard of resolving power

Table A3.1 Levels at which errors can be introduced in hemispherical canopy photography (revised from Rich, 1990). Notes outline where an effort was made to reduce error or account for it.

Levels	Notes
HUMAN ERROR	
IMAGE ACQUISITION	
Camera positioning	Rigid telescopic tripod used with camera set straight using a leveling balance.
Sky lighting evenness	Day to day variation in estimated PPFD% was measured to estimate variance due to weather conditions.
Foliage lighting evenness (reflections)	Photos were taken in the evening or on uniform overcast days.
Optical distortion	Corrected at the image analysis stage (overlay of annuli)
Exposure	A spot meter was used to improve accuracy in setting the aperture.
Film	Tmax 100 Kodak film used: has a high standard of resolving power and image sharpness.
Film processing / acutance	Tmax processing fluid used with new full bottle for each set of films. Processors limited to 2 experts.
IMAGE DIGITATION	
Registration/alignment	Current technology probably reduces these very
Focus	small errors substantially
Aperture adjustment	
Optical distortion	
Video & digitizer noise	
Resolution limitations	
IMAGE ANALYSIS	
Threshold setting	Contrast maximised at image acquisition stage aided the distinction between foliage and canopy openings when setting the threshold. Furthermore the threshold was set for the same image on different days to assess potential variation.
Assumed direct sunlight distribution	Fractions of daily direct and diffuse transmittance
Assumed diffuse skylight distribution	were calculated from the Aviemore MET weather station. Aviemore is further east than Glen Affric and thus subjected to sunnier conditions but no radiation data was available on site or in a western location in Scotland.
Assumed surface of interception	
Calculation assumptions	

compared with other film types (P.R. van Gardingen, personal communication). Furthermore T grain technology is known to increase resolving power and sharpness of the image.

Negatives were captured using a 35 mm slide scanner (ScanMaker 35T, Microtek Lab. Inc. CA 90278-1226) at a resolution of 1024 * 1024 pixels. Images were processed using macros written for a commercial image analysis package (Optimas 5.2, Optimas, Washington) to give estimates of diffuse and daily direct transmission factors (otherwise known as indirect and direct site factors) (courtesy of Paul van

Gardingen). The threshold was set using a standardised thresholding procedure that maximised the contrast between the foliage and the sky. During this procedure, scanned images were compared against originals using a hand lens and light box to improve precision. When thresholds for the same images were set on different days, it was discovered there was very little difference in settings.

The diffuse transmission factor (T_d) represents the proportion of diffuse photosynthetic photon flux densities (PPFD) incident on a horizontal surface above the canopy that is transmitted to the point of the photograph. The projected image of the hemisphere was divided into 20 concentric annuli representing equal areas of sky and the proportion of pixels classified as sky within each annulus extracted. All pixels were checked when estimating the proportion classified as sky. The diffuse transmission factor was then calculated as:

$$T_d = \frac{\sum_{i=1}^{20} p_i w_i}{\sum_{i=1}^{20} w_i}$$ Equation A3.1

where p_i is the proportion of sky in annulus i and w_i is a weighting for annulus i which includes the cosine correction for a horizontal surface and the Standard Overcast Sky assumption[1] (Anderson, 1964 in Clearwater *et al*., 1999).

The direct transmission factor represents the proportion of total daily direct PPFD incident on a horizontal surface that is transmitted to the point of the photograph beneath the canopy (Clearwater *et al*., 1999). Equations for solar geometry (Iqbal, 1983) (involving the azimuth and elevation of the sun), were used to construct solar track diagrams across each image for a specific latitude and requested number of Julian days. Latitude 57° 16.9 N was used corresponding to the co-ordinates of Glen Affric. An estimate of total PPFD over the growing season from April to September was required so 6 Julian days were requested, each representing a day in each growing season month. The actual Julian day representing each month was calculated as a central date related to the equinox (i.e.: Julian day 94 (April 4th), 125 (May 5th), 156 (June 5th), 187 (July 6th), 218 (August 6th), 249 (September 6th). The proportion of open pixels were sampled at 5 minute time steps along each solar track and Equation A3.2 was used to estimate the direct transmission factor.

[1] The Standard Overcast Sky assumption assumes a distribution that depends on zenith angle, with more diffuse radiation flux from sky directions towards the zenith (Rich, 1990). The cosine "law of illumination" states that the amount of unidirectional flux reaching a plane surface is proportional to the cosine of the angle of incidence (Walsh, 1961). When light comes in at an oblique angle, there is a reduction in response to light, otherwise know as the cosine error, which can be corrected for.

$$T_b = \frac{\sum_{i=1}^{n} p_i v_i}{\sum_{i=1}^{n} v_i}$$ Equation A3.2

where p_i is the proportion of open pixels at time step *i* and v_i is a weighting factor for time step i which includes corrections for a horizontal surface and the optical pathlength through the atmosphere (Clearwater *et al*., 1999).

A3.1.1 PPFD calculations

The calculation of total daily PPFD from hemispherical photographs requires an estimate of the mean daily diffuse transmittance and mean daily direct transmittance, both expressed as a proportion of global radiation. Raw daily diffuse and direct transmittance data were obtained from the Aviemore meteorological weather station (UK Land Surface Stations Database, British Atmospheric Data Centre (BADC) as it was the nearest station to Glen Affric that records this information. Direct and diffuse fractions were calculated for each month from April to September for 1999 (2001 & 2002 data unavailable). The mean seasonal diffuse and direct fraction was 0.61 and 0.39 respectively.

Hemispherical analysis output provides estimates of indirect and diffuse transmission factors, which are not corrected, for the actual daily diffuse and direct fraction. The following calculations were performed to correct for the fraction and to calculate total daily PPFD under the canopy for each specific Julian day.

i) Diffuse PPFD = Global radiation x 0.61 x Indirect Site Factor
ii) Direct PPFD = Global radiation x 0.39 x Direct Site Factor

Equation A3.3

To calculate the total PPFD for the whole growing season, each monthly value was multiplied by the number of days in each month and monthly values summed.

Calibration of hemispherical estimates of total daily PPFD involved setting up a calibration curve with observed values from quantum sensors on the y axis and estimated values from hemispherical photographs on the x axis. Each value represented a mean of total daily PPFD recorded over 3-4 days in each plot with hemispherical estimates calculated for the corresponding Julian days. Data collected on abnormally sunny days (+ 23 mol m^{-2} d^{-1} in the open stand) were removed from the calculations due to the atypical direct: diffuse ratio.

A3.2 Results

A strong linear relationship was found when estimated values from hemispherical photographs were regressed against observed values ($y = 0.479 + 0.74x$, $R^2 = 0.94$, $P < 0.001$). Despite a very good fit, the slope indicates that the estimates from hemispherical photography underestimated direct measures of PPFD. The calibration curve used to adjust estimated values is illustrated in Figure A3.1 with calibrated and uncalibrated PPFD values recorded in Table A3.2.

The variation in PPFD estimates obtained from images taken at the same time on different evenings in the same position under pole stand (Block 6) is shown in Table A3.3. Estimated transmittance was found to vary by 1.6% across five evenings which provides some idea about how evening to evening variation in continuous cloud cover affects image analysis.

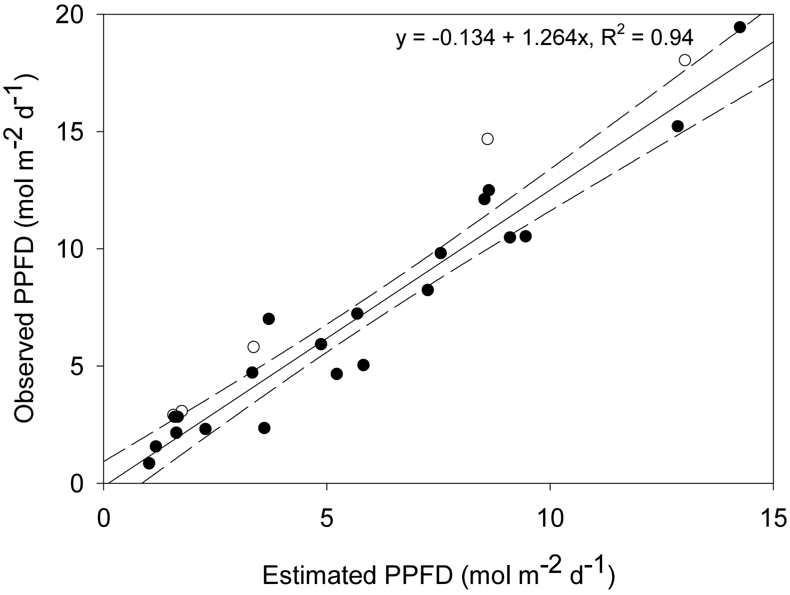

Figure A3.1 Calibration plot regressing observed PPFD values from quantum sensors against estimated PPFD values from hemispherical photographs[2]. Each observed value is a mean of total daily PPFD recorded over 3-4 logging days for each treatment plot. The corresponding estimated PPFD values are means of total daily PPFD calculated for the same Julian days. Values reflect measurements in all three stand treatments in 7 blocks. 95% confidence intervals have been attached with the fitted regression line. Open symbols represent values logged on abnormally sunny days and have not been included in the analysis.

[2] It was assumed that the days in which PPFD was logged in the field were representative of typical direct /diffuse fraction days. Error in x (estimated PPFD) is realised. However Quinn & Keough (2002) state that when the main aim of the regression analysis is prediction, then the usual ordinary least squares regression model can be used when x and y are random as long as the probability distributions of y_i at each x_i are normal and independent. As the relationship between blocks is small compared to large differences within blocks, blocks are assumed to be independent.

Table A3.2 Calibrated total PPFD (mol m^{-2}) for the growing season (April - September) and uncalibrated total PPFD and PPFD%. Means have been pooled across blocks (n = 7, ± standard deviation).

	Calibrated	Uncalibrated	
Block	PPFD	PPFD	PPFD%
		Open	
1	3089	2465	89.8
2	2342	1873	67.8
3	2459	1965	70.7
4	2335	1867	67.5
5	2635	2105	75.3
6	1717	1379	49.1
7	2577	2058	73.9
Mean	2451 (± 412)	2081 (± 503)	70.6 (± 12.1)
		Pole	
1	405	340	12.8
2	371	313	11.0
3	411	345	12.4
4	558	461	15.9
5	280	241	9.1
6	681	559	19.9
7	797	650	22.8
Mean	500 (± 185)	424 (± 136)	14.9 (± 5.0)
		Old-growth	
1	1948	1561	57.7
2	1003	813	30.2
3	1907	1528	54.3
4	2026	1623	59.5
5	1013	821	28.2
6	1128	912	33.2
7	1511	1215	44.9
Mean	1505 (± 459)	1254 (± 325)	44.0 (± 13.5)

Table A3.3 Total PPFD (April-Sept) and PPFD% (uncalibrated) of each hemispherical photo taken under Block 6 pole stage on different evenings between 7 and 8 pm. Means for the 5 PPFD readings are included (n = 5, ± standard deviation)

Photo replication	Total PPFD	PPFD%
1	312	11.5
2	280	10.3
3	267	9.8
4	198	7.2
5	303	9.1
Mean	272 (± 45.1)	9.6 (± 1.6)

A3.3 Discussion

The time and length in which continuous direct measurements of PPFD were made in the field can explain the under-estimation of PPFD by hemispherical photography. It was assumed that PPFD was logged on days with cloud conditions representative of the direct diffuse fraction used to estimate PPFD from hemipherical photographs. Logging was carried out in July and August, so it is possible that readings were taken on less cloudy days than the seasonal average. Calibrated values for open stand treatments were found to be greater than hemispherical global radiation readings giving rise to nonsensical transmission percentages. These results can also be explained by the lack of continuous logged data and not having a good estimate of the daily diffuse direct fraction in Glen Affric for appropriate days / months in 2001/2002. Unfortunately continuous logging over a 6 month period (April-September) with a shadow-band in 21 sites was not logistically possible. Despite these limitations, the strong relationship between estimated and observed PPFD does provide an acceptable degree of confidence in PPFD estimates where under-estimation can be explained by methodology.