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**Estimating light environment in forests with a new
thresholding method for hemispherical photography**

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Abstract: Light environment estimates derived from hemispherical photography are known to be affected by variations in sky illumination. During photo acquisition, rapid changes in sky illumination can occur and any changes in sky illumination will result in changes in detected canopy gap size and frequency. Any resulting problems in image consistency will become more serious with increased time lags between setting the reference exposure and hemispherical photograph acquisition. We showed that if camera exposure setting was kept constant during photo acquisition, the estimated diffuse transmittance would be greatly influenced by sky illumination change. We developed a new pixel thresholding method which calculated the optimal threshold value for the separation of sky and plant pixels as a function of the above-canopy photosynthetic photon flux density (PPFD). We tested the performance of our method for estimating transmittance against two established methods that assume exposure to be held constant to 2 stops higher than the reference exposure. Our method compensates for changes in sky illumination, producing a smaller pixel threshold when sky illumination decreases and a larger pixel threshold value when photographs are taken under increased sky illumination. The new method achieved accurate and reproducible results, even in situations where under- or overexposure was caused by changes in sky illumination during photo acquisition.

Key words: **Sky illumination, Gap fraction, Light availability, Indirect site factor, Exposure.**

1. Introduction

Light is often a resource limiting the performance of plants and regulating species interactions in structurally complex communities such as forests (Denslow 1987). Data on light availability is essential for studies of forest dynamics (Stark et al. 2012) and as a result, is of great importance for forest management (Grayson et al. 2012). However, obtaining accurate and reliable measurements is challenging, due to spatial and temporal variations in light availability (Fix 2013). Hemispherical photography is a common tool for characterising the light environment of forest understory (Čater et al. 2013). In addition, hemispherical photography is widely used to estimate canopy properties such as leaf area index (LAI), leaf angle distribution (Jonckheere et al. 2004). Hemispherical photography is also a photographic method that has been widely used in calibrating remote sensing data (Hancock et al. 2014).

Two major sources of errors in estimating canopy parameters or forest light environment through photographic methods are involved in exposure and setting a suitable pixel threshold value (Chen et al. 1991). The pixel threshold value is used by image processing software to separate sky pixels from vegetation pixels. In order to avoid errors caused by the subjective visual assessment of users, many automatic thresholding methods have been proposed (e.g., Nobis and Hunzicker 2005). However, these methods can produce reliable estimates only if photos are properly exposed (Macfarlane 2011). The major problem with exposure is the positive correlation between exposure and the estimated canopy gap fraction. As exposure increases, gap fraction estimates also increase, resulting in a decrease in the estimated leaf area index (LAI). The standardized camera exposure setting requires measurement of a reference exposure under open sky

with a fixed aperture and unfixed exposure time (under the ‘aperture priority’ mode). Two stops of exposure time are then added for acquiring photos in the forest (Zhang et al. 2005). The standardized exposure is thus essentially determined by the sky illumination (PPFD in open land) as determined by the built-in camera light meter. In reality, however, sky illumination is known to change rapidly both in full sunshine and in overcast conditions. The resulting uncertainty in standardized exposure greatly hinders the quality of measurements using hemispherical photography, because over-exposed photos lose the detail of vegetation (Beckshäfer et al. 2013) while under-exposure reduce the uniformity of the sky brightness (Wagner 1998), thus making it difficult to distinguish dark cloud from vegetation. However, the effect of the change in sky illumination during photo acquisition and the importance of exposure in hemispherical photography are not fully appreciated.

In this study, we first showed how the change in sky illumination during photo acquisition affected photo exposure and thus affected transmittance estimation when the exposure setting was kept constant. We then developed a new thresholding method by proposing a relationship between the optimum threshold value and the above-canopy PPFD (measured in open land). Finally, we evaluated the performance of the new thresholding method in handling differently exposed photos by comparing photo derived ISF (indirect site factor=diffuse transmittance) with the directly measured diffuse transmittance. We showed our new method outperformed the two established thresholding methods in estimating diffuse transmittance, especially in handling those over- or under-exposed photos.

2. Materials and Methods

2.1. The threshold equation

The reciprocity law (Bunsen and Roscoe 1862) states that the intensity of the light and duration of the exposure result in identical exposure, i.e., the total exposure (E) could be expressed as

$$E = I \cdot T, \quad (1)$$

where I is illumination in lux which is the light density received by the light sensitive material, and T is the time that this illumination acts on the light sensitive material.

Decreasing the received light density by a half has the same effect on exposure as decreasing the exposure time to a half.

An average scene in nature reflects 18% of the light that falls on a built-in light meter of common cameras (Unwin 1980) so that cameras are made to have standard built-in light meter that receives light and adjusts exposure to obtain a photo with 18% brightness. When the camera aperture setting is fixed and exposure time is unfixed (i.e., the ‘aperture priority’ mode), the camera’s built-in light meter reads the light density it receives and adjusts the shutter speed (i.e., exposure time) to get an 18% gray tone on the photograph. When measuring reference exposures towards the open sky, the exposure time is adjusted according to the sky illumination to guarantee it produces objects at a medium grey level of 18% brightness. As a result, we have

$$\frac{1}{T} = k \cdot S, \quad (2)$$

where T is the reference exposure time in second, S is the above-canopy PPFD in $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, and k is a constant when the aperture value is fixed for the same camera and lens.

The k in equation (2) describes the relationship between metered exposure in the open site and the sky illumination. This linear relationship between $1/T$ and S is theoretically derived from the reciprocity law (1) and the 18% gray tone principle. However, any change in camera, lens or aperture value requires recalculating the value of k , because different cameras may have different gamma functions, i.e., the relationship between light density and the film density of the negative. The lens used and the aperture value selected influence the light density received by the photosensitive material and therefore influences the value of k .

Song et al. (2013) developed a plastic canopy model system by which they knew exactly the true value of the gap fractions and they tested which threshold value could produce the true gap fraction when processing photos acquired using different camera exposure settings. They then provided an empirical relationship between the optimum threshold value and the relative reference exposure for normal 8-bit images (digital number varies from 0 to 255):

$$Y = \frac{260.542}{1 + \exp(-X + 1.422) / 1.160}, \quad (3)$$

where Y is the optimum threshold value, and X is the increased number of f-stops for exposure time relative to the reference exposure. An increase in X by 1 means an increase in exposure time by 1 f-stop, i.e., increasing the exposure time 1 fold. Thus, we have:

$$\frac{T_m}{T} = 2^X, \quad (4)$$

where T_m is the exposure time we used in the field, T is the reference exposure time measured in open land, and X is the increased number by f-stops of exposure time

compared to the reference exposure time. Substituting equation (2) and (4) into equation (3), we have:

$$Y = \frac{260.542}{1 + \exp(-\ln(T_m \cdot k \cdot S - 2) + 1.422) / 1.160} \quad (5)$$

Parameter k in equation (5) is the constant in equation (2), which can be calculated by dividing the reciprocal of reference exposure time ($1/T$) by above-canopy PPFD (S) (Figure 1). When we use fixed exposure time (T_m) in the field under manual mode, the only unknown value on the right hand side of equation (5) is S , the above-canopy PPFD. Hence the optimum threshold value Y can be calculated purely as a function of the above-canopy PPFD.

Sky radiance heterogeneity and the effect of lens vignetting (central part of the photosensitive material gets more light) make the low zenith angle area brighter than the high zenith angle area (Wagner 2001; Lang et al. 2010). Wagner (2001) suggested calculating threshold for different rings depending on their zenith angles. However, a global threshold value for the whole photo used in this study has already obtained good estimation of diffuse transmittance. As a result, there is no need to take lens vignetting into consideration. The zenith angle range used for analysis in this study was 0-90°.

2.2. Study sites

Our study was conducted in a subtropical evergreen broad-leaved forest at Heishiding Nature Reserve (23°27'N, 111°5'E; 150-927 m in altitude), located in southern China. This region has a subtropical moist monsoon climate and is dominated by species of Fagaceae and Lauraceae families. Annual precipitation is about 1700 mm and mean daily temperature is 19.6°C. Nineteen sites were selected within this nature reserve and each site was marked with a PVC pipe to facilitate re-location. In order to cover a large range

of light availability, we selected sites with different canopy conditions (from dense canopy to near gap) and different photography height (Table 1). Our sites don't include extreme sparse canopy locations ($ISF > 0.3$) because we found that photos taken in these locations were not sensitive to exposure and thresholding (see the Appendix for the detailed explanation on why we focused on dense and medium canopy locations).

2.3 Photograph acquisition in the forest

We used a single Nikon Coolpix 4500 camera with a calibrated FC-E8 fisheye converter for all photography. We did reference exposure only once using center weighted light metering mode and read a reference exposure (F5.3, 1/500 second), after increasing 2 stops to it (1 stop = 1 fold), we used F5.3, 1/125s manual exposure for all photo acquisition (ISO = 100 for all photos taken in this study). The camera was installed on a self leveling system to ensure lens orientation was consistent and directly upward. All photos were taken under uniformly overcast sky.

In order to take photos under differing sky illumination we took 19 sets of photographs between the 7th and 15th of April, 2014. On each occasion we took photographs in the same order, moving sequentially from location 1 to location 19 and each round of photographs took around 30 minutes to complete. In total we took 361 (19×19) photographs. All these photos were taken with F5.3 aperture value and 1/125 second exposure time.

2.4 Above-canopy PPFD measurement

In this study sky illumination was measured as PPFD in open land and it was measured using a calibrated LI-190 quantum sensor (LICOR LI-190, Lincoln, Nebraska, USA), which recorded PPFD at 5 sec intervals on a data-logger (CR1000, Campbell

Scientific, Utah, USA) at two locations, located around 2 km apart. One sensor was mounted on the top of a tower which is 70 meters in height and 2 km away from the photographic sampling sites, the other was mounted on top of a building which is 15 meters in height and 300 meters away from the sample sites. Hemispherical photos are only recommended to be acquired under overcast sky conditions, close to sunrise or sunset. And PPFD measurements for the two locations showed great accordance ($y = 0.97x$, $R^2 = 0.99$) under these sky conditions. Therefore, only the PPFD data collected from the tower was used in our analysis. Acquisition time of photos was matched with the acquisition time of PPFD to find which photo was acquired under which above-canopy PPFD.

2.5 Relationship between above-canopy PPFD and reference exposure time

In this step, we measured reference exposure time (T) and above-canopy PPFD (S) to calculate the value of k in equation (2). Although one measurement of T and S is enough for the calculation of k , we want to show the proportional relationship between $1/T$ and S (i.e., experimentally validate that k is a constant). For that purpose, hemispherical photos were repeatedly acquired without moving the camera from the rooftop of the building deployed with the light sensor. In this study, we applied a north orientation system which was combined with our remote control system and it contains 90 small red lights uniformly distributed around the camera lens. This system first detects the magnetic north direction and then the light dot in the north will turn on automatically so that it leaves a small red dot in the photo to indicate north direction. This north orientation system has an effect on photo exposure which was equivalent to decreasing the aperture size. Therefore, photography with that system has a smaller k value than those acquired manually.

However, it is necessary to use the remote controller in some locations when the camera was not in reach of the operator. We acquired a total of 156 images; 40 of them were taken using the remote controller while the remaining 116 were taken manually. All these images were acquired only for calculating k and they were taken with center weighted metering and aperture priority mode (aperture value fixed to F5.3, ISO=100). Under this mode, the exposure time of the photo was determined automatically by the camera and we recorded them as T_i ($i=1$ to 40 for photos acquired with remote controller, and $i=41$ to 156 for photos acquired manually). Sky illumination (above-canopy PPFD) when a certain photo was acquired was recorded automatically in the data-logger and matched the photo by comparing their acquisition time. We did a simple linear regression between S_i and $1/T_i$ (Figure 1). The k in equation (1) could be calculated as $k=1/(T_i \bullet S_i)$ and it is also equal to the slope in Figure 1 for each case.

2.6 Image processing

Algorithms for ISF estimation are well established (e.g., Chan et al. 1986). In this study, hemispherical photo derived ISFs were calculated based on the WinSCANOPY software (Regent Instruments, version 2005a) using three thresholding methods (two traditional methods and our new method). Before we applied the two traditional thresholding methods, the blue channel of the RGB images was selected to get a large contrast between sky and vegetation pixels (Brusa and Bunker 2014). However, before we applied the new thresholding method, we followed Song et al. (2013) and didn't select any special color channel in the thresholding. Thresholding methods used were, respectively:

- (i) A histogram-based thresholding method used by WinSCANOPY (version 2005a) which automatically selects the pixel threshold value after the first peak in the pixel histogram. The detailed algorithm of this thresholding method is commercial-in-confidence of WinSCANOPY and not subject to scrutiny. According to the description in the user's manual, we believe it is a histogram-based algorithm similar to Ridler and Calvard (1978).
- (ii) The edge detection automatic thresholding method of Nobis and Hunzicker (2005) was applied using the image processing software SideLook 1.1 (Nobis 2005).
- (iii) Our new method, where the pixel threshold value was calculated using equation (5). The exposure time (T_m) we used was 1/125s, above-canopy PPFD (S) was recorded automatically on top of the tower, and the parameter k was calculated as the slope in Figure 1 ($k = 3.978$ for manual shutter, and $k = 2.200$ for photos acquired with our north orientation system which reduced the aperture size).

2.7 Directly measured diffuse transmittance

Instantaneous diffuse transmittance is stable if it is measured on overcast days (Messier and Puttonen 1995; Parent and Messier 1996). Directly measured ISF is computed as PPFD forest/PPFD open. PPFD of the sample sites were measured using a LI-190 light sensor and a hand held light meter (LICOR LI-250A, Lincoln, Nebraska, USA), and the above-canopy PPFD (i.e., PPFD open) was automatically recorded by the data-logger. In each PPFD measurement, average PPFD of one minute was used as an instantaneous PPFD. We have measured transmittance in each location three times on three different days. We therefore obtained three transmittance values for each location and we used the averaged value as the observed transmittance value in this study.

Directly measured transmittance showed a high degree of accordance among the three measures, for instance, the results of the 19 locations in the first two measures has a near 1:1 relationship ($y = 1.06x$, $R^2 = 0.95$). As a result, there is no need to increase the repeat times of direct measurement of transmittance. Direct measurement of transmittance with quantum sensors and acquisition of hemispherical photographs were conducted separately on different days.

Root mean squared errors (RMSE) between the directly measured diffuse transmittance and the ISF estimated from photos were used to evaluate the performance of different thresholding methods.

2.8 Comparison between estimated ISF with sky illumination

For each round of photos (composing of 19 photographs), the relationship between the estimated ISFs and the directly measured transmittance was fitted using a simple regression line, constrained to pass through the origin. Regression slopes could be used to indicate over-estimated (slope >1) or under-estimated (slope <1) ISF values. We then investigated the relationship between these regression slopes and the average above-canopy PPFD during that round of photo acquisition. Above-canopy PPFD for each round of photographs was computed as the average of the above-canopy PPFD measurements recorded over the period during which the 19 photos were taken. All data analyses were conducted using the R statistical language (<https://www.r-project.org/>).

2.9 Summarize on how to apply our method

Our method is simple and easy to perform. The implementation only involves three steps:

(1) Mount a light sensor in open land and connect it with a data logger. Turn the camera to the aperture priority mode and it is suggested to use a large aperture value (e.g., F5.3 for Nikon 4500). Choose center weighted light metering mode and take a photo towards the open sky. The exposure time of that photo and the above-canopy PPFD of that moment are recorded as T_r and S_r .

(2) Increase the exposure time by 2 stops to use in the forest and fix the exposure time, aperture and ISO values. This is similar to the standardized exposure method. The exposure time used is recorded as T_u .

(3) Threshold for each photo is calculated as

$$Y = \frac{260.542}{1 + \exp(-\ln(T_u \cdot k \cdot S - 2) + 1.422) / 1.160)}, \text{ where } T_u \text{ is the exposure time used, } k$$

is a constant value calculated as $k=1/(T_r \times S_r)$, and S is the above-canopy PPFD when this photo is taken. T_r and S_r are measured as in step (1).

3. Results

As expected, the reference exposure time was completely determined by the sky illumination (Figure 1). For Nikon coolpix 4500, F5.3, and ISO=100 used in our work, the k equals 3.978. When applying the north orientation system, k equals 2.200.

Photos acquired with constant manual exposure but under reduced sky illumination produced darker images compared with those acquired under high sky illumination (Figure 2A, B). Dark photos generated smaller gap-fraction after transformed to 1-bit images (pure black and white) than bright photos (Figure 2C, D), but dark and bright

photos produced similar 1-bit images if using our new thresholding method (Figure 2E, F).

Traditional thresholding methods are reliable in estimating transmittance if photos are correctly exposed (e.g., Figure 3A), otherwise they did not perform well (e.g., Figure 3B-D). A superiority of our method is that we don't need to change camera exposure in the field as conventional methods required and can obtain reliable estimates for transmittance in all circumstances (Figure 3E-H).

When above-canopy PPFD varied very little (equal to $200\text{--}400\ \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), which means photos were correctly exposed as the traditional methods required, all 3 thresholding methods would perform well (Figure 4). When above-canopy PPFD varied a lot, the slopes of the regression lines between estimated ISFs and observed ISFs were strongly related to the above-canopy PPFD for the two traditional thresholding methods, but they were clearly of different forms (Figure 4). The slopes derived from the pixel histogram method are nonlinear, following a positive logarithmic function with the above-canopy PPFD ($y = 0.3149\ln(x) + 0.814$; $R^2 = 0.95$; Figure 4a), while the slopes for the edge detection method form a strong linear function with the above-canopy PPFD ($y = 0.00079x + 0.756$; $R^2 = 0.87$; Figure 4b). For our new method (Equation 4; Figure 4c), there is a positive but rather weak relationship ($y = 0.00017x + 0.953$; $R^2 = 0.20$), indicating that change in sky illumination is of limited influence on ISF estimation when using our method. However, we would like to stress that these comparisons (Figure 4) don't mean that the two traditional methods are unreliable. Because the exposure was not re-adjusted in the field, the comparison favored the new method which could handle over- and under-exposed photos.

4. Discussion

Hemispherical photography is the most widely used non-destructive observation technique for estimating light conditions in forest and thus canopy structural parameters critical for modeling process-based canopy photosynthesis. The technique is favored because it can characterize radiation regimes in detail (Čater et al. 2013). However, the application of this technique to dense forests is a challenge, because the dense canopies have many small gaps which lead to an increased ratio of mixed pixels. As a result, photos acquired under dense canopies are more sensitive to exposure and selection of pixel thresholds.

In this study we took both the two main error sources of hemispherical photography (i.e., exposure and pixel threshold selection) into consideration and used them to counterbalance each other by selecting threshold value according to photo exposure. In previous studies which used above canopy reference exposure (e.g., Zhang et al. 2005; Song et al. 2013), researchers had to shorten the time interval between setting the reference exposure and acquiring photos in order to reduce the influence of the change in sky illumination. It is somewhat impractical to re-adjust exposure according to the change of sky illumination in forests. Our method overcomes this problem and does not require users to hurry from reference locations to sample sites, because accurate results can be obtained even when sky illumination varies considerably during photograph acquisition. There is also no need to repeatedly judge the correct exposure setting during field work, because photos can be well processed even when a certain degree of over or under exposure occurs. Our method is especially useful for large plots and dense forests

for two reasons. First, it's hard to find a very large open field in deep forest and re-adjust the correct exposure setting in the field. Second, photos acquired in dense forest have many more mixed pixels than those acquired from locations with less vegetation coverage (Macfarlane 2011) and thus are more prone to having errors. For instance, by applying this new technique, we could continuously work in our large dynamics plot for more than 2 hours during sunset and a whole day during overcast days with no need to worry about sky illumination change.

Light regime and canopy parameters derived from hemispherical photographs are calculated based on the gap fraction of hemispherical photographs and it's well known that estimated ISF is proportional to gap fraction and LAI is proportional to the negative of log transformed gap fraction (Gonsamo et al. 2010). As a result, exposure and sky illumination affect estimation of all parameters which are associated with gap fraction. For instance, it is found that for film-based hemispherical photographs, even one stop exposure can influence the leaf area index estimation by 13% (Macfarlane et al. 2000). Zhang et al. (2005) showed that increasing one stop of exposure resulted in 3–28% differences in effective leaf area index for canopies with different openness. The effect of sky illumination on hemispherical photography is no less a trivial problem than that of exposure setting (illumination change one fold=exposure setting change one stop). Some methods have been proposed to reduce the effect of camera exposure on gap fraction estimates. For instance, Cescatti (2007) provided a method using two cameras (below canopy and a reference) and making a linear conversion of the raw data reading from the digital camera sensors. Lang et al. (2010) modified this method and used only one camera by modeling a pure sky according to the gap pixels in the photo. Although sky radiance

has been considered, these works do not use threshold values to separate pixels but use the raw data to compute leaf area index and transmittance. Our study solves this problem in a very different way and we showed that reliable 1-bit images (pure black and white) could be obtained with optimum threshold values calculated from sky illumination. It is expected that our method would lead to more accurate estimation of other gap-fraction-dependent forest parameters such as LAI but empirical tests are needed to appreciate the gain in accuracy of the new method.

There is a limitation with our new method which requires collecting the above-canopy PPFD data. This will need extra requirement for a light sensor and a data-logger. Lang et al. (2010) suggested that the sky radiance could be estimated from the sky pixels in the photo, but the heterogeneous distribution of sky brightness caused by cloud may increase the difficulty in image processing. Although collecting the PPFD data increases the fieldwork to some degree, the gain is that we obtain accurate results that no other methods could achieve. Furthermore, users now do not need to worry about the change in sky illumination and rush between the reference locations and sample sites.

In conclusion, in this study we propose a method using a threshold determined from above-canopy PPFD significantly to improve the repeatability and accuracy of hemispherical photography, especially when there is a long time interval between doing the reference exposure and taking photos in forests. This method solves a long-standing problem in hemispherical photography that exposure difference caused by sky illumination change affects gap fraction and associated parameter estimation.

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465 Table 1. Description of the 19 sampled locations

Location number	Photography and light measurement height (m)	Location description
1	1.8	Completely closed canopy
2-5	1.8	No apparent gaps
6-7	1.8	Small gaps
8-9	1.8	Middle size gaps
10-11	2.3	Middle size gaps
12-13	2.8	Middle size gaps
14-15	3.3	Middle size gaps
16-17	3.8	Middle size gaps
18-19	4.3	Middle size gaps

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467

Figure legends

Fig. 1 Exposure time measured in open land with aperture priority mode (aperture fixed to F5.3) compared with above-canopy PPFD.

Fig. 2 The effect of sky illumination change on photo exposure when the camera exposure setting was unchanged. The photos of bright sky and dark sky were taken (A) when above-canopy PPFD was $430 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and (B) $73 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, respectively. (C) Binary image of the bright photo and (D) binary image of the dark photo processed with thresholding method of WinSCANOPY (version 2005a). (E) Binary image of the bright photo and (F) binary image of the dark photo processed with the new thresholding method. Directly measured ISF multiplied by 100% (diffuse transmittance rate) of this location is 11.9%, and the estimated ISF from photos (multiplied by 100%) were (C) 17.0%, (D) 7.5%, (E) 13.8% and (F) 14.6%, respectively.

Fig. 3 Results of SideLook (version 1.1) thresholding method (A-D) and the new method (E-H) for estimating diffuse transmittance, compared with the directly measured transmittance using light sensors. All photos were acquired with constant camera exposure setting and were captured (A, E) just after finishing the reference exposure measurement, (B, F) sky illumination increased, (C, G) sky illumination decreased, (D, H) or sky illumination decreased 2 times more than (C, G). The dashed line indicates the 1:1 relationship.

Fig. 4 Slopes of regression lines between estimated ISFs and observed ISFs compared with above-canopy PPFD when photos were acquired. Exposure was kept constant to 2 stops higher than the reference exposure measured at the beginning of the field work. Threshold selections are respectively based on: (1) pixel histogram (WinSCANOPY 2005a), (2) edge detection (SideLook 1.1), and (3) sky radiance.

493 Fig. 1

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1 The Appendix

2 **Explaining why we only focused on dense and medium canopy locations where diffuse**
3 **transmittance is less than 0.3; Open canopy locations are not sensitive to exposure.**

4 In order to test whether photos acquired in locations of different canopy openness was
5 sensitive to camera exposure, we compared diffuse transmittance estimated from
6 hemispherical photos and directly measured diffuse transmittance from light sensors.

7 Photos were acquired in 30 locations with automatic exposure setting and we obtained 30
8 photos. These photos were then processed using WinSCANOPY software with its default
9 threshold value, and we obtained estimated indirect site factor (ISF) for each location. We
10 also directly measured transmittance for each location as $\text{transmittance} = \text{light in forest} / \text{light in open}$. Light in forest was measured as the instantaneous photosynthetic photon flux density
11 (PPFD) in the sample location, and light in open was measured in open land and recorded
12 automatically in a data-logger. Estimated ISFs were then compared with directly measured
13 transmittance.
14

15 We found that even automatic exposure setting produced reliable estimates of
16 transmittance compared with direct measured transmittance for large open canopies (Figure
17 A1, $\text{ISF} > 0.3$), but it greatly overestimated transmittance under dense canopies (Figure A1,
18 $\text{ISF} < 0.15$). The camera receives a lot of light in open canopies and reads a relatively low
19 exposure setting (Beckshäfer 2013), therefore the overexposure effect becomes negligible
20 with the increase in canopy openness. Besides, homogeneous regions of sky and vegetation
21 pixels are easily identified for open-canopy photos, making it easy to separate the pixels
22 between sky and vegetation (Macfarlane 2011). However, extra care must be taken to choose

23 exposure and thresholds for photos of dense and medium canopies (Figure A1, ISF<0.3),
24 because photos of closed canopies could be seriously overexposed if automatic exposure is
25 used.

26 If we included these open canopy locations into analysis, even automatic exposed photos
27 could produce an overall good estimate of transmittance (Figure A1-a) but that would conceal
28 the serious problem of transmittance overestimation associated with dense canopies (Figure
29 A1-b). Because of this problem, hereafter we only focused on the 19 locations where the ISF
30 was less than 0.3. For open canopy locations where the ISF was larger than 0.3, we found that
31 automatic exposure and all the three thresholding methods produced reliable results.

32

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Figure A1. Estimated diffuse transmittance (ISF) from automatic exposed photos of (a) 30 locations (ISF: 0~0.7) and (b) a subset of these 30 locations (ISF: 0~0.3) compared with the directly measured diffuse transmittance (i.e., the observed ISF). The right panel (b) is just the enlargement of a subset of the left panel indicated by the blue rectangular with ISF less than 0.3 (19 locations). Dash line indicates the 1:1 line.