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Determining digital hemispherical photograph exposure for leaf area index estimation

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Abstract

A correct exposure is of crucial importance for accurate retrieval of canopy parameters using hemispherical photograph techniques. Digital hemispherical photographs were collected under different sky brightness conditions using a Nikon CoolPix 4500 camera with an FC-E8 fish-eye lens for canopies of different species and openness. Different exposure schemes were employed to investigate the effects of photographic exposure on the estimations of the effective leaf area index (L_e) and gap fraction. The contrast between the sky and foliage under each exposure scheme was calculated to determine the correct exposure under different weather conditions. The results demonstrated that digital hemispherical photographs taken with automatic exposure are not reliable, causing L_e underestimations by 16–71% for medium and high density canopies (L_e = 3.2–4.8) and corresponding gap fraction overestimations by 18–72%. While for open canopies with $L_e < 1.26$, L_e was overestimated by 11–29%, and the corresponding gap fraction was underestimated by 4–28%. Studies showed that increasing one stop of exposure results in 3–28% differences in L_e for canopies with different openness. Based on the analysis, we determined the optimum exposure and developed a protocol for acquiring digital hemispherical photographs. The protocol requires first measuring reference exposure for the open sky using a built-in camera light meter, and then take photographs inside the canopy using the same camera with two stops of more exposure than the reference exposure in order to make the sky appear white and consequently also maximize the contrast between the sky and foliage. This protocol is applicable for different sky brightness and for different canopy openness. In dense canopies, this procedure requires much less exposure than automatic exposure, but in very open canopies, this procedure requires more exposure than automatic exposure. Using the exposure determined with this procedure rather than the automatic exposure, the comparison of L_e values from the LAI-2000 and digital photographs is greatly improved, with R^2 increasing from 0.77 to 0.95, and RMSE decreasing from 1.29 to 0.38.

Keywords: Digital hemispherical photographs; Exposure; Leaf area index; Gap fraction

1. Introduction

Leaf area index (LAI) is defined as half the total green leaf area per unit ground surface area (Chen and Black, 1992). It is a critical canopy structural parameter required in ecological and process-based canopy photosynthesis models (Amiro et al., 2000; Chen et al., 1999; Kimball et al., 1997; Liu et al., 1997, 2002; Running and Hunt, 1993). The LAI of a canopy determines light, thermal and moisture conditions within the canopy, and thus influences its carbon, water, and energy balances (Fassnacht et al., 1994). Direct and indirect methods are often used for determining LAI (Fassnacht et al., 1994; Gower

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et al., 1999; Jonckheere et al., 2004; Mussche et al., 2001; Rich et al., 1993; Weiss et al., 2004). Indirect methods, which use optical instruments such as tracing radiation and architecture of canopies (TRAC), LAI-2000 (Plant Canopy Analyzer, LI-COR, Lincoln, NE), are widely adopted for LAI acquisition due to their fast and non-destructive nature. A combination of these two instruments is suggested for accurate LAI measurements (Chen et al., 1997).

Hemispherical or fish-eye photography is another common means for measuring LAI as well as studying canopy architecture and solar radiation in forests (Easter and Spies, 1994; Englund et al., 2000; Frazer et al., 2001; Wagner, 2001). Hemispherical photographs capture the light obstruction/penetration patterns in the canopy, from which the canopy architecture and foliage area can be quantified (Chen et al., 1991; Fournier et al., 1996; Nilson, 1999; Ross, 1981). Hemispherical photographs have the advantage of spatial discrimination, and are particularly useful for acquiring foliage angular distributions, and gap fractions at different zenith and azimuthal angles. Gap fraction is generally calculated from the photographs to quantify canopy openness and architectures. The plant area index (including both green and non-green canopy materials) and the leaf inclination angle distribution of a canopy can be simultaneously calculated by measuring gap fractions at several zenith angles (Chen et al., 1991). By dividing each annulus into small segments, the 3D canopy structure and its angular variations can be quantified (van Gardingen et al., 1999).

A good correlation has been found between film and digital systems in open canopies under overcast sky conditions for estimating canopy structure, light transmission, and LAI (Englund et al., 2000; Frazer et al., 2001). With the development of affordable digital technologies, digital cameras have been widely used to replace conventional film cameras for hemispherical photograph acquisition. Digital hemispherical photographs are less expensive and can be acquired with greater ease and convenience. Digital photographs can be kept as permanent records of the measurements while eliminating errors in film development and image scanning (Chen et al., 1991; Mussche et al., 2001). It has been found that conventional film hemispherical photography produces inaccurate estimations of canopy openness and light transmission when the stands are dense with many small gaps (canopy openness is less than 10%) (Frazer et al., 2001; Machado and Reich, 1999; Roxburgh and Kelly, 1995). High-resolution digital photographs can distinguish leaf area from sky area more accurately than photographic films and avoid the aggregation of pixels in images with lower resolutions (Blennow, 1995). The availability of computer software for image processing allows efficient use of digital hemispherical photographs. Digital photographs can also be used to derive vegetation clumping index, which characterizes the spatial distribution of foliage, and thus the actual LAI, by adopting the gap size distribution theory used in the TRAC instrument (Leblanc et al., 2005). Both the LAI-2000 and hemispherical photographs make use of diffuse light. Compared with the LAI-2000, hemispherical photographs can provide more detailed information about the canopies. A digital hemispherical camera can potentially substitute for the LAI-2000 instrument to provide accurate LAI measurements, if operated appropriately.

Although hemispherical photography is believed to be an efficient way for long-term arid ecosystem monitoring and LAI measurements, the accuracy and reliability of digital hemispherical photographs for LAI and canopy structure estimations need to be assessed systematically. Compared with destructive harvest results, LAI obtained from hemispherical photographs was found to be underestimated by up to 50% (Brenner et al., 1995; Sommer and Lang, 1994). Even with the segmented method, which divides each annulus into a number of small segments, the underestimation cannot be completely eliminated (van Gardingen et al., 1999).

Camera exposure settings influence the estimation of light transmission and LAI and are demonstrated as a major cause of measurement errors (Chen et al., 1991; Englund et al., 2000; Macfarlane et al., 2000; Wagner, 1998). Photography exposure influences the grey value of unobscured pixels, which are used as a reference for discriminating completely and partly obscured pixels (Wagner, 1998, 2001). It can also result in a discrepancy in the canopy openness derived from digital and film techniques (Englund et al., 2000). It is found that the estimated effective leaf area index (L_e) from film-based camera decreases with the increase of photographic exposure (Chen et al., 1991; Macfarlane et al., 2000). Olsson et al. (1982) suggested the use of a spot light meter, instead of the film camera's built-in exposure meter, for obtaining the right exposure regardless of canopy openness. Chen et al. (1991) proposed the use of the unobstructed zenith area of overcast sky as a standard reference and 1–2 stops more exposure relative to the brightness of the sky for measuring LAI inside the canopy. An overexposure of three stops relative to the sky reference was advised as the best exposure setting for measuring the light transmission through achieving the sky uniformity (Clearwater et al., 1999; Wagner, 1998). So far, a standard exposure setting for digital hemispherical photography has not been verified for LAI measurements, and no systematic study has been reported for this purpose. It is found that for film-based hemispherical photographs, even one stop exposure can influence the LAI estimation by 13% (Macfarlane et al., 2000). Compared with the logarithmic response of film cameras to light, digital cameras have the advantage of a linear response, which effectively lighten the midtone pixels (Covington Innovations, 2004). Digital hemispherical systems are found to be more sensitive to sky conditions and produce much higher estimations for canopy openness and lower effective LAI estimations than film systems (Englund et al., 2000; Frazer et al., 2001). It is suggested that the digital system may be more sensitive than film system to exposure, particularly at low light levels (Hale and Edwards, 2002). To accurately estimate forest LAI and canopy structural parameters using digital cameras, researchers called for a standardized protocol for exposure setting for acquiring hemispherical photographs (Jonckheere et al., 2004).

The objectives of this paper are (1) to summarize the theoretical basis of photograph exposure for optimum measurements of canopy architectural parameters; (2) to investigate whether the maximum contrast between sky and foliage in the photograph would be the criterion for setting the optimum exposure using field data from forest stands of various types and densities; and (3) to propose a protocol for determining digital photograph exposure for LAI and gap fraction estimations based on this investigation.

2. Exposure theory of digital cameras

The photochemical reaction taking place during exposure obeys the reciprocity law (Bunsen and Roscoe, 1862), i.e. the exposure E may be expressed as:

$$E = I \times T \tag{1}$$

where I is the illuminance in lux (metric quantity), which is the intensity of the light acting upon the sensitized photographic material, and T is the time that this illumination acts on the photographic material. The reciprocal law states that the illumination time and the irradiance level are reciprocal for induction of a photochemical effect, i.e. an exposure at a high irradiance for a short time is photochemically equivalent to an exposure at a low intensity for a long time. Exposure in a camera is determined by two settings: the shutter speed and the lens aperture. The length of time that the photosensitive material is exposed (shutter speed) is inversely proportional to the amount of light hitting the surface (lens aperture). When taking photographs, the shutter speed and aperture can be traded to yield the same exposure. Decreasing the shutter speed by one stop has the same effect on exposure as increasing the lens aperture by one stop.

This reciprocity is a reliable rule for most typical shutter speeds. However, at very slow or, more conversely, very fast shutter speeds, photosensitive materials do not respond linearly as predicted and the law of reciprocity does not hold. Digital cameras are designed to mimic film response to light, but the response pattern can be significantly different from films. Digital cameras acquire photographs using a charge coupled device (CCD) matrix, which is a light-sensitive integrated circuit placed at the focal plane of an optical imaging system. Digital cameras respond to light linearly from a lower threshold to an upper threshold exposure. After the upper threshold, the digital response is saturated (Fig. 1). In comparison, film's response to exposure shows gradual variations at both low and high exposures (Norman, 2003). The linear response range of digital cameras shown in Fig. 1 is larger than that of films, but this may be camera dependent. The difference in the light response pattern between films and digital media suggests that we need to re-evaluate exposure theories developed for films for use in digital cameras.

It has been discovered that the average scene reflects 18% of the light that falls on it (Unwin, 1980). All the light meters, film and now digital cameras are designed to have an automatic mode. The camera's built-in light meter reads the reflected light from objects and adjusts the combination of shutter speed and aperture to get an

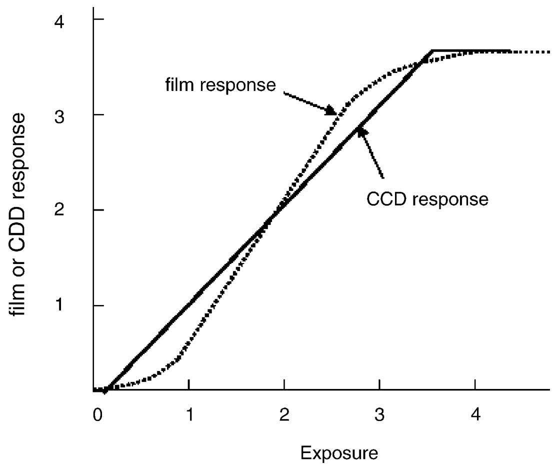

Fig. 1. Schematic diagram for characteristic curves of the response of digital and film media to exposure (both axes are on logarithmic scales).

18% gray tone on the photograph. The automatic exposure mode guarantees exposure settings that reproduce objects at a medium gray level of 18% brightness. But when taking digital hemispherical photographs inside a canopy, the large contrast between the bright sky and dark canopy components creates a significant potential of incorrect exposure using automatic settings. The spatial heterogeneity of the scene can cause underexposure or overexposure. Underexposure can result in a loss of details in the dark subjects, while overexposure can result in a loss of detail in bright objects. As the automatic exposure varies with the average sky brightness and canopy openness, a significant error in the determination of LAI may be introduced when the sky luminance is not uniform with respect to the zenith angle.

The illuminance measured with a photometer can be converted to camera exposure based on the formula proposed by Unwin (1980), which assumes the scene as an 18% gray body. Based on this formula, Chen et al. (1991) suggested that the optimum exposure inside a vegetation canopy would be 1–2 stops larger than the reference exposure found outside the stand in order to make the sky appear white. Theoretically, 2.5 stops of overexposure are required to make an unobscured overcast sky appear completely white, i.e. increasing the reflectivity from 18 to 100% (one stop to increase to 36%, two stops to increase to 72%, and three stops to increase to 144%) (Macfarlane et al., 2000). Chen et al. (1991) postulated that 1–2 stops rather than 2–3 stops of overexposure compared with sky reference are needed possibly because of multiple scattering in the canopy which enhances the brightness of foliage in the photograph. However, this suggested exposure setting has not been systematically tested for either film or digital cameras. For digital cameras, one criterion for the optimum exposure inside the canopy is to make use of the full digital range to capture the scene components, i.e. the foliage appears black (digital number (DN) = 0) and the sky background appears white (DN = 255). In practice, the optimum exposure for hemispherical photographs in a forest canopy should make the sky appear as white as possible and in the meantime the canopy components as dark as possible. Thus for the optimum exposure, the relative contrast between the sky pixels and foliage pixels should theoretically approach the maximum.

Photographs require more exposure in dense than in open stands, therefore analysis on the influences of the digital camera exposure on LAI and gap fraction estimations is necessary for determining an optimal exposure for different stand structures and sky conditions. A reliable way to determine the optimum exposure is to measure hemispherical sky brightness and then adjust the camera settings accordingly. This sky reference reading should be made in a large opening outside the forest stand, which provides an unobstructed sky view up to the 75° zenith angle in all azimuthal directions. With experience in angular variations of sky radiance, this reference reading can also be made in small openings (Clearwater et al., 1999; Wagner, 1998, 2001). When the camera's aperture size is fixed to ensure a consistent field of view, a decrease of the camera's shutter speed by 2–3 stops will provide the desired exposure. The following experiments were conducted to explore the effects of exposure and test whether this simple rule of decreasing the shutter speed by two or three stops relative to a sky reference reading can be the most appropriate exposure for leaf area index estimation. In this operation, it is critical that the same camera is used for both sky reference reading and photograph acquisition inside a stand as the camera automatic exposure reading may differ by a few to several stops (Chen et al., 1991).

3. Experiments and methods

3.1. Study site description

Experiments were conducted in one deciduous and three coniferous stands of different canopy openness.

One sugar maple stand (*Acer Saccharum*) was selected in Haliburton Forest, Ontario (45°14′15.5″N, 78°32′18.0″W). The average diameter at breast height (DBH) for the dominant, co-dominant and suppressed trees were, respectively, 51.9, 35.0, and 20.4 cm. Three 50 m-long transects separated by 10 m were set up in the east–west direction. Each transect was marked every 10 m using forestry flags for location identification.

One mature Douglas-Fir stand was near the Campbell River on Vancouver Island, which is one of the tower flux stations of Fluxnet Canada Research Network (49°54′18.0″N, 125°21′57.6″W). A 400 m transect was set up in the southwest-northeast direction. The transect was divided into two portions using the flux tower as the midway marker and forestry flags were also used every 10 m along the transect.

Two black spruce (*Picea Mariana*, abbreviation SB) stands in Sudbury: SB1 at 47°09′45.3″N, 81°44′44.3″W and SB2 at 47°12′9.4″ to 81°54′30.3″W, were investigated. These two stands have different canopy closure and growth conditions. The SB1 stand is relatively young and has a vigorous understory including Labrador tea, blueberry, and bog rosemary.

The dominant understory in SB2 includes moss and Labrador tea under a mature canopy. Ten trees at each site were selected to measure the tree height and DBH. The average tree heights of the SB1 and SB2 were 4.53 ± 1.507 and 14.04 ± 2.012 m, and the DBH were 4.98 ± 2.157 and 16.71 ± 3.358 cm, respectively. For each stand, two 50 m parallel transects separated by 20 m were set up in the east-west direction, marked every 10 m by forestry flags.

3.2. Experimental methods

Above forestry flags in the four stands, a series of photographs using different exposure settings were taken to evaluate the effect of exposure and sky brightness on the accuracy of forest structure estimation. All hemispherical photographs were taken with the high-resolution (4 Mega pixels) Nikon CoolPix 4500 digital camera, which has a large range of shutter speed. Compared with previous models such as CoolPix 950, the Nikon CoolPix 4500 has less chromatic aberration (e.g. Digital Photography Review, 2003; Frazer et al., 2001). A Nikon FC-E8 fish-eye lens with a field of view of 183° was attached to the camera. The camera was mounted on a tripod to facilitate a horizontal camera setting.

As the interference of direct sunlight can cause errors of up to 50% (Welles and Norman, 1991), all the photographs were taken under uniform sky conditions (overcast weather) or near sunset or sunrise. The following cameras settings were chosen before the measurements (for Nikon CoolPix 4500, and may vary for other cameras): (1) manual mode; (2) Fish-eye 1 lens (fixed with centrally weighted exposure for automatic exposure); (3) in the manual mode, aperture fixed at F5.3; (4) high image quality (2272×1704 pixels), and (5) JPEG format (no difference in digital values was found between JPEG and TIFF format, Frazer et al., 2001).

Our experiments were conducted under different sky brightness conditions to analyze variations of the image contrast with exposure. Photographs were taken starting from the sky reference exposure up to the automatic exposure. For example, if the sky reference exposure time were determined to be 1/1000 s (F5.3), a series of photographs would be taken with the aperture fixed at F5.3 and the shutter speed decreasing systematically from 1/1000, 1/500, 1/250, and 1/125 to 1/60 s, until the shutter speed indicator corresponded to the automatic exposure. Hemispherical photographs were taken near sunset on 27 May 2004 for the sugar maple stands along one transect. The sky exposure before and after the measurements was respectively 1/500 s (F5.3) at 18:40 p.m. and 1/250 s (F5.3) at 19:55 p.m. On 25 August 2004, along the 400 m transect in the Douglas-Fir stand, series of photographs were collected under overcast conditions at every 50 m markers. The sky exposure before and after the measurements was 1/2000 s (F5.3) at 15:20 p.m. and 1/1000 s (F5.3) at 16:45 p.m. local time. Hemispherical photographs were collected on overcast days from 7th to 12th August 2004 at the SB1 and SB2 stand. The sky conditions were ideally stable at 1/1000 s (F5.3) before and after the measurements for both stands.

The LAI-2000 instrument was used to measure L_e at approximately the same time as hemispherical photographs. A 90° view restrictor was used to block the influence of the operator and bright sky near sunset behind the operator. LAI-2000 measurements were taken at nearly the same position and the same height of the fish-eye lens so that L_e results from two measurements can be compared.

3.3. Digital image processing

Hemispherical photographs in the JPEG format have three 8-bit image channels (red, green, and blue), producing a DN range from 0 to 255. In the blue band of the electromagnetic spectrum, foliage elements have the lowest reflectivity and transmittance, making the foliage in the blue band darker than in the red or green band. To minimize the interference of multiple scattering in the canopy and chromatic aberration, only the blue band of photographs was used in our analysis. For the Nikon CoolPix 4500, the diameter of the 180° circular projected hemispherical photographs was estimated to be 1590 pixels. To calculate the within pixel gap fraction, the digital hemispherical photography (DHP) software was used to process images (Leblanc, 2003; Leblanc et al., 2005) instead of the time-saving automatic thresholding method (Nobis and Hunziker, 2005). In the DHP software, techniques for film-based hemispherical photographs proposed by Wagner (1998, 2001) were adopted and applied for digital photographs. The software analyzes fixed zenithal annulus segments and divides the images into up to ten rings. Two thresholds are used for each annulus to distinguish leaf from sky. By setting two threshold gray values, a blue channel image is classified as completely transparent, completely obscured, and partially obscured pixels, to represent sky, foliage, and mixed sky and foliage pixels, respectively. The thresholds are set where the histogram digital number values start to deviate from the straight line in the logarithmic plot (Fig. 2). When no linear part can be

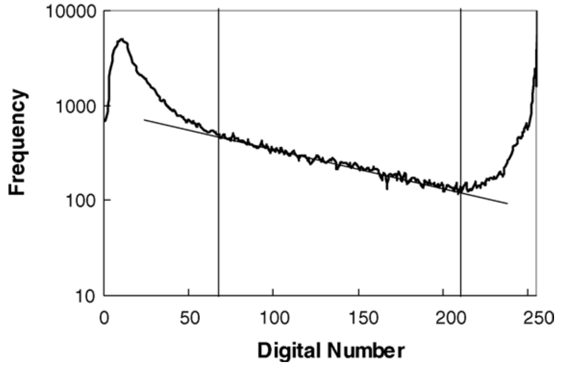

Fig. 2. Digital number histogram of a nine-degree annulus from a single digital hemispherical photograph. The *y*-axis is in a logarithm scale to demonstrate the mixed pixel part of the histogram found between the two thresholds ($DN_{min} = 71$, $DN_{max} = 212$). DN_{min} and DN_{max} are respectively determined where the linear part of the histogram in a logarithm starts and ends.

found on the histogram, the visual inspection of the image under the colour mode can be compared to the original 8-bit blue channel to find the correct thresholds. For mixed pixels between the two thresholds, the program uses the linearity of the camera CCD array to calculate the within pixel gap fraction using a linear unmixing procedure (Leblanc et al., 2005).

Image misclassification is known to be a source of error for LAI estimation (Jonckheere et al., 2004; Rich et al., 1993). To minimize this error, images were processed according to the methods proposed by Leblanc et al. (2005). All images were analyzed in the same way by one person to ensure the consistency of classification. Each image was divided into 10 rings (each ring has a 9° zenith angle range) and each ring was analyzed separately for determining the two thresholds to minimize the influence of sky luminance heterogeneity, vignetting properties of lenses and multiple scattering in the canopy (Wagner, 2001). The exposure setting affects the division of pixels among the sky, foliage, and mixed classes. It is found that the foliage in the 45–60° zenith angle is least affected by multiple scattering (Leblanc and Chen, 2001). Accordingly, the thresholds for rings within the zenith angle range from 45 to 63° were investigated first to find the range of thresholds and then to provide references for thresholds of other rings.

Series of photographs were processed and the DN of two thresholds for each ring were exported to calculate the gap fraction of each ring and the whole image, the mean DN values of sky, foliage and mixed pixels of each ring and the whole image. The contrast between sky and foliage pixels of each ring and whole image were further calculated to analyze the effects of exposure and to explore the optimal exposure.

4. Results and analysis

4.1. The effects of exposure on LAI and gap fraction estimations

Digital hemispherical photographs taken with different exposures are visually different. Fig. 3 demonstrates the photographs with the fixed aperture F5.3 and varying shutter speeds 1/60, 1/125, 1/250, 1/500, 1/1000, and 1/2000 s taken in the Douglas-Fir stand on Vancouver Island. It is visually apparent that with the increase in exposure, the image brightness increases. The decrease in exposure (increasing shutter speed) diminishes the image sharpness. The edges of leaves and tree branches blur due to the light scattering and diffraction. This makes it difficult to distinguish bright leaves from relatively small and underexposed gaps, and can lead to estimation biases for leaf area index and gap fraction.

Photographic exposure influences the magnitude of the canopy gap fraction. Fig. 4 shows variations of gap fraction with exposure for the four forest stands. The sky reference exposure is denoted as 0, and the relative increases of exposure from the sky reference are denoted as 1–7 stops of relative exposure. It can be seen that as the exposure increases, the gap fraction increases almost linearly. Take the series of photographs from the Douglas-Fir stand in Fig. 3 as an example, when the shutter speed decreases from 1/2000 to 1/60 s, the gap fraction increases from 2.9 to 10.4%.

Conversely, the effective leaf area index L_e decreases with the increase in exposure. Increases of gap fraction with exposure cause increases in estimated global radiation penetration and loss of leaf area. Fig. 5 shows variations of L_e inverted from digital hemispherical photographs with exposure. When the shutter speed decreases from 1/2000 to 1/60 s, L_e of the Douglas-Fir stand in Fig. 3 decreases correspondingly from 5.16 to 2.40.

The effects of exposure on gap fraction and L_e agree with previous findings from film-based cameras (Chen et al., 1991; Macfarlane et al., 2000). For canopies with large gap fractions, the influences of exposure on the gap fraction and L_e are small (see Figs. 4c and 5c). However, for closed canopies, such as the sugar maple stand in Haliburton Forest (Figs. 4a and 5a) and Douglas-Fir stand on Vancouver Island (Figs. 4b and 5b), the estimated gap fraction and L_e vary dramatically with exposure. For example, at the No. 2 flag in the Douglas-Fir stand, when the relative exposure increases from 1/1000 to 1/500, 1/250, 1/125, and 1/60 s, the gap fraction increases by 19, 48, 108, and 185%, while the

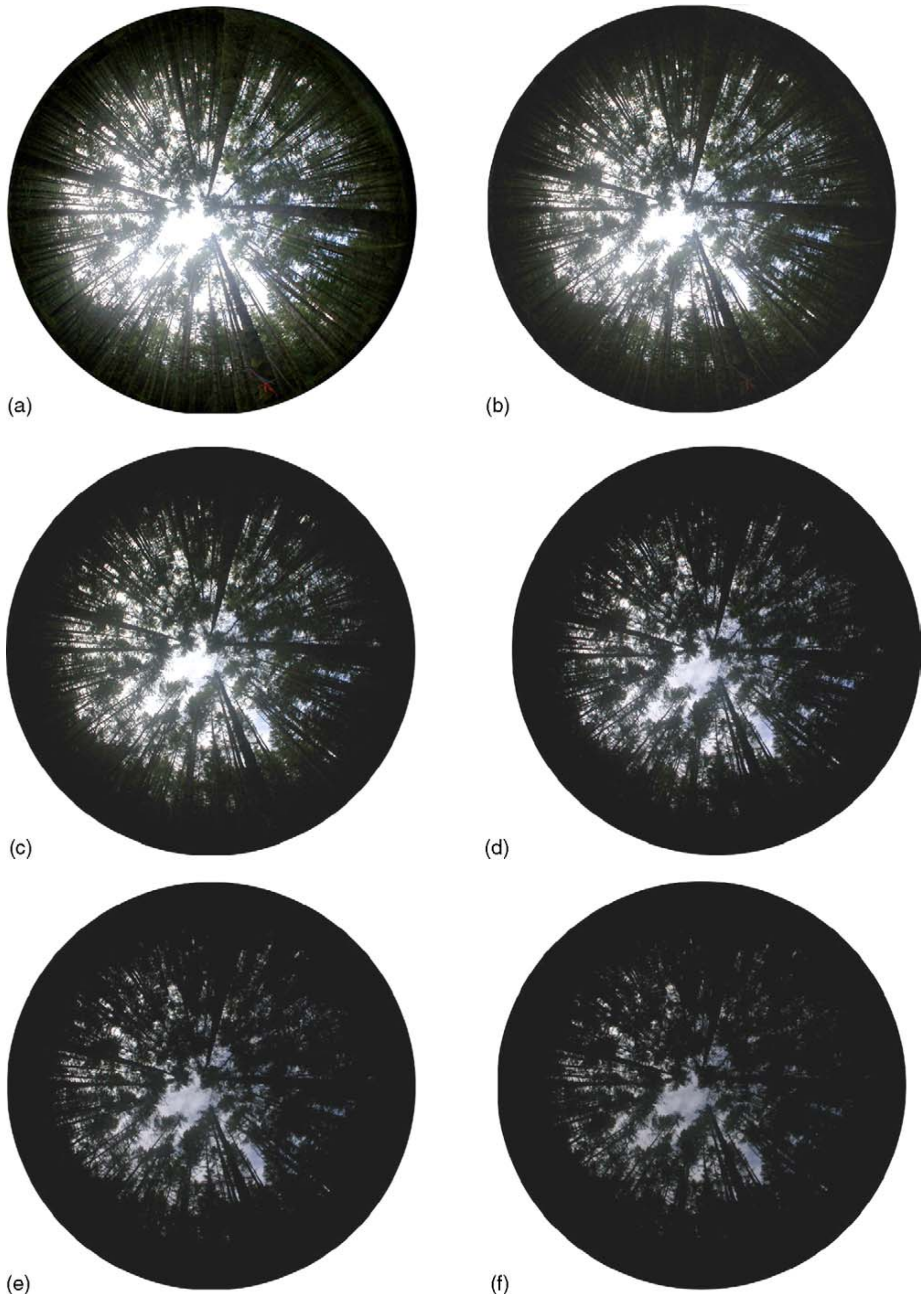

Fig. 3. The influence of photographic exposure. The aperture was fixed at F5.3, and photographs were taken with different shutter speeds. The gap fraction decreases visually from the photograph with the 1/60 s shutter speed to the photograph with the 1/2000 s shutter speed. (a) Hemispherical photograph taken with 1/60 s shutter speed; (b) hemispherical photograph taken with 1/125 s shutter speed; (c) hemispherical photograph taken with 1/250 s shutter speed; (d) hemispherical photograph taken with 1/500 s shutter speed; (e) hemispherical photograph taken with 1/1000 s shutter speed; (f) hemispherical photograph taken with 1/2000 s shutter speed.

L_e decreases by 12, 24, 39, and 50%, respectively. All the photographs from these four sites showed that increasing one stop of exposure results in 14–26% differences in L_e for the Douglas-Fir site, and 7–22% for the sugar maple site. The difference in L_e varies from 3 to 28% for the SB1 site, and 10–20% for the SB2 site. Therefore, determining an appropriate photographic exposure is critical to accurately estimate the leaf area

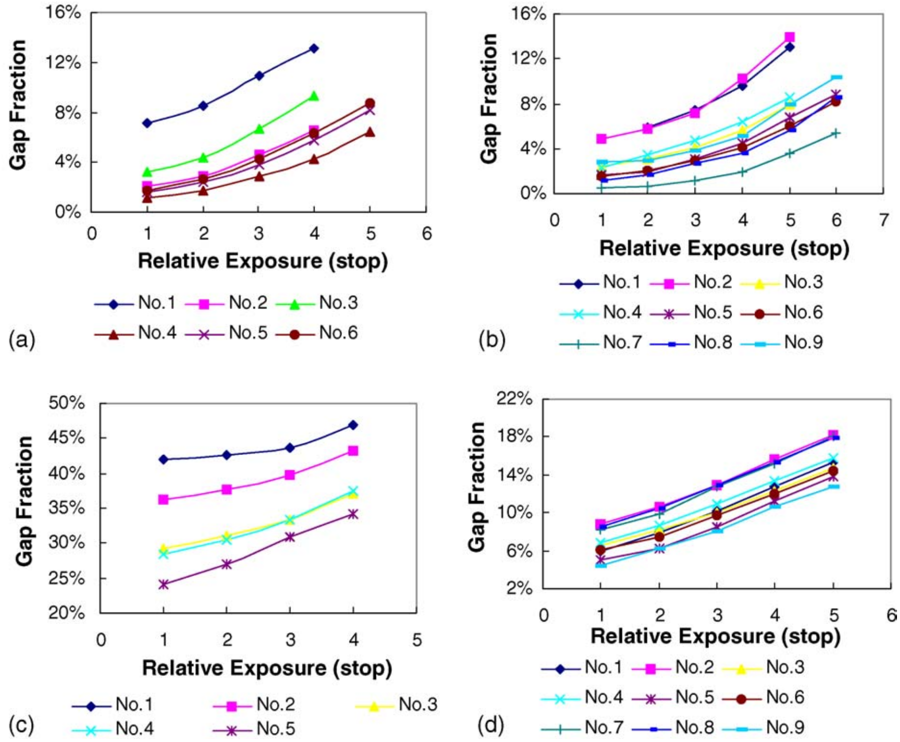

Fig. 4. Variations of gap fraction with photographic exposure. Hemispherical photographs were taken adjacent to forest flags (denoted as No.) with different exposure schemes at (a) a sugar maple stand in Haliburton Forest; (b) a Douglas-Fir stand on Vancouver Island; (c) a black spruce stand (SB1) in Sudbury; (d) a black spruce stand (SB2) in Sudbury. The relative exposure 0 represents the sky reference, and 1–7 represent 1–7 stops of more exposure relative to the sky reference.

index and gap fraction from digital hemispherical photographs.

4.2. The ideal exposure setting

One criterion for determining the optimum exposure would be to maximize the difference between the mean DN of sky pixels and that of foliage pixels, i.e. the contrast between these two classes of pixels is the greatest. The leaf area index and gap fraction calculated from the automatic exposure and other exposure schemes were compared to investigate the optimum exposure for accurate leaf area index estimation. Fig. 6 demonstrates the variations of the mean DN of sky pixels, foliage pixels, mixed pixels and the DN range between sky and foliage pixels with exposure. With the increase in exposure, the mean DN of sky, foliage and mixed pixels increases. The contrast between foliage and sky pixels also increases. The error of misclassification can be reduced with the increase in image contrast. Although there is an evidence that non-linear mixing occurs, particularly for component DN values with high contrasts, the error will clearly increase with a diminishing dynamic range (Borel and Gerstl, 1994). The variation of the DN range between foliage and sky pixels with exposure follows an approximate parabolic shape. With a further increase in exposure, the sky pixels reach the maximum brightness and saturate, while the brightness of foliage and mixed pixels continues to increase. The DN difference between these two categories of pixels reaches the maximum and then decreases with further increases in exposure.

With the gradual change in exposure, the intermediate gray levels, i.e. mixed pixels with the sky and foliage components, are of particular concern. The fraction of pixels that are mixed increases greatly (Fig. 7). The sub-pixel proportions of foliage and sky in these pixels are determined through a linear unmixing procedure, given the thresholds representing the 'pure' sky and foliage (Leblanc et al., 2005).

The DN differences between foliage and sky pixels of all photographs were calculated to explore the optimum exposure. Fig. 8a shows the variation of the DN range with exposure for the sugar maple site in Haliburton Forest. Considering the sky reference change (1/500 s at the beginning and 1/250 s at the end of the measurements), the sky references for the first series of three photographs were taken as 1/500 s

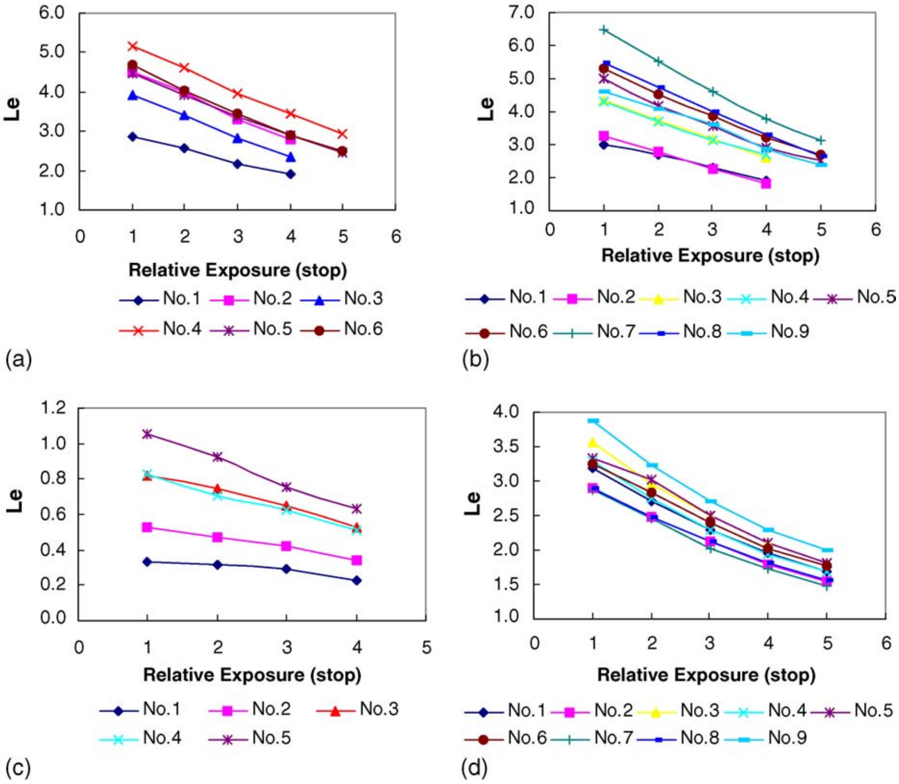

Fig. 5. Variations of effective leaf area index (L_e) with the relative exposure. Hemispherical photographs were taken adjacent to forest flags with different exposure schemes at: (a) a sugar maple stand in Haliburton Forest; (b) a Douglas-Fir stand on Vancouver Island; (c) a black spruce stand (SB1) in Sudbury; (d) a black spruce stand (SB2) in Sudbury. The relative exposure 0 represents the sky reference, and 1–7 represent 1–7 stops of more exposure relative to the sky reference.

and the last series of three as 1/250 s. Among several series of six photographs, the series at locations Nos. 1, 4, 5, and 6 reach the largest image contrast at a two-stop overexposure relative to the sky reference. Series at other two locations, Nos. 3 and 4 have the maximum contrast at three stops of overexposure.

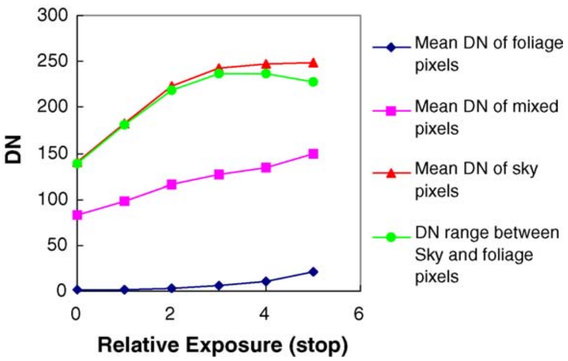

Fig. 6. Variations of mean DN for sky pixels, foliage pixels, mixed pixels, and range between sky and foliage pixels with the relative exposure. The relative exposure 0 represents the sky reference, and 1–5 represent 1–5 stops of more exposure relative to the sky reference.

Fig. 8b shows the results from the Douglas-Fir stand on Vancouver Island. All images from nine locations reach the maximum contrast at 1/250 s, which is three stops overexposure relative to the sky reference. Photographs from two locations, Nos. 8 and 9, reach

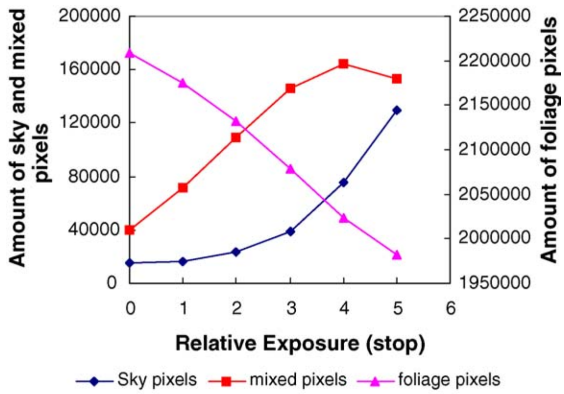

Fig. 7. Variations of the amount of sky pixels, foliage pixels, mixed pixels with relative exposure. The relative exposure 0 represents the sky reference, and 1–5 represent 1–5 stops of more exposure relative to the sky reference.

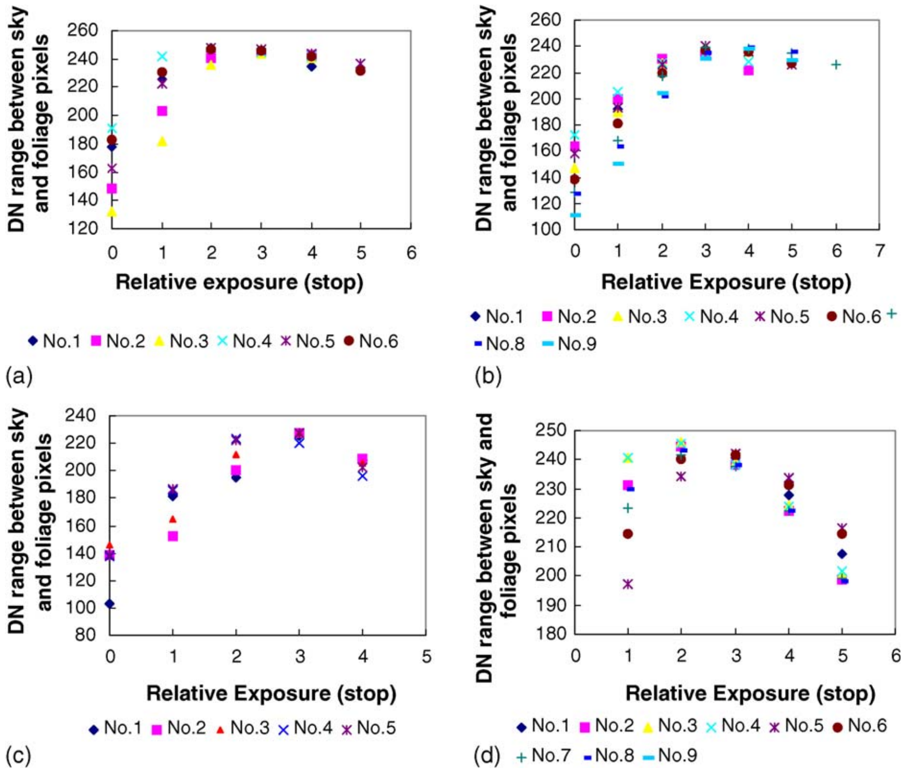

Fig. 8. Variations of image contrast with exposure for: (a) a sugar maple stand in Haliburton Forest; (b) a Douglas-Fir stand on Vancouver Island; (c) a black spruce stand (SB1) in Sudbury; (d) a black spruce stand (SB2) in Sudbury. The relative exposure 0 represents the sky reference, and 1–7 represent 1–7 stops of more exposure relative to the sky reference.

the maximum contrast at 1/125 s. The sky exposure was measured as 1/1000 s right after taking these two series of the photographs. Considering the changes of the sky brightness and the timing of reference measurements, the sky reference for these two series of photographs should be 1/1000 s instead of 1/2000 s taken at the beginning of measurements. So for these two locations, three stops of more exposure result in the largest image contrast as well.

For the SB1 stand, three stops of overexposure (1/125 s) relative to sky reference provides the largest image contrast for four locations, Nos. 1, 2, 3, and 5, and two stops of overexposure (1/250 s) for one location No. 4 (See Fig. 8c).

Nine series of photographs were taken for the SB2 stand. The largest image contrast was found at 1/250 s (two stops of overexposure relative to the sky reference) for eight of nine series of photographs, and three stops of overexposure for one series of photographs (Fig. 8d).

It can be concluded that an increase of exposure by 2–3 stops from the sky reference exposure produces the largest sky-foliage contrast. The results agree with the finding from film-based hemispherical photographs (Chen et al., 1991). Although the exposure inside canopies depends on the relative contributions of the sky and canopy to the total hemispherical solid angles, the extent of relative overexposure inside the canopy is independent of canopy openness because the auto-exposure of camera light meter fixes the open reference sky as an 18% mid-grey body. To make the sky appear white, two–three stops of overexposure relative to the open sky reference exposure can theoretically satisfy this requirement. The experiments in sparse and close canopies confirm that this exposure scheme can produce the largest image contrast for canopies of different openness.

4.3. The effect of automatic exposure

The photographs taken with automatic exposure and the exposure giving the largest image contrast are visually different in terms of image brightness and sharpness. The difference can be easily seen from the photographs taken in the deciduous stand. Fig. 9 shows the photographs taken with the automatic exposure and two stops of overexposure with reference to the open

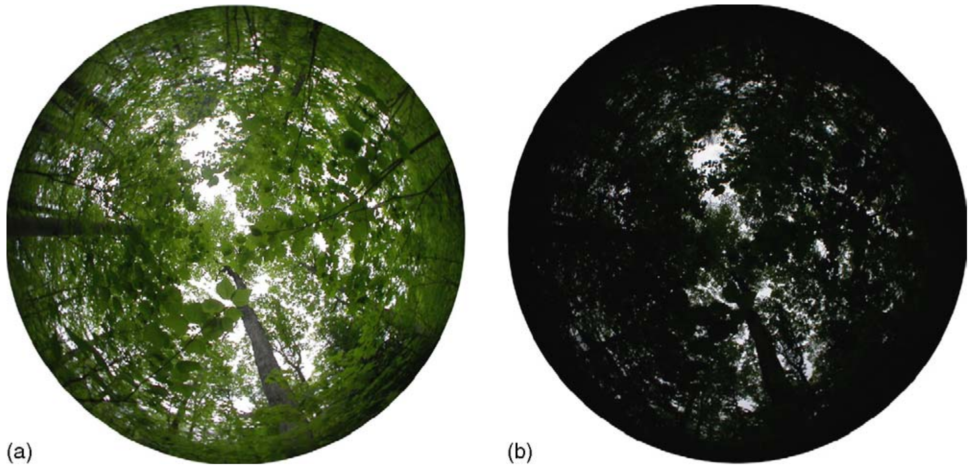

Fig. 9. Comparison for the photograph taken with automatic exposure and the photograph taken with the exposure that produces the largest image contrast (a): digital hemispherical photograph taken with the automatic exposure, showing the composite canopy and sky scene as a 18% grey body (b): digital hemispherical photograph taken with the exposure that producing the largest contrast, making the foliage appear dark but in the mean time allowing the sky to appear white.

sky in the Haliburton Forest stand. Photographs taken with the automatic exposure are much brighter than the counterpart taken with the exposure producing the largest sky-foliage contrast. Visually, the foliage taken with the automatic exposure appears green, while it appears black in the counterpart with the largest contrast. Canopy gaps in photographs acquired with automatic exposure are visually larger than those in the counterpart, thus resulting in an overestimation of gap fraction and an underestimation of L_e.

Table 1 provides a summary of L_e and gap fraction estimated from photographs with the automatic exposure and with the exposure producing the largest sky-foliage contrast for these four sites. For medium to closed canopies, the photographs with automatic exposure underestimate the L_e by 11–71% compared with the photographs with the largest contrast. It shows that for the SB2 stand, the automatic exposure is one stop larger than the exposure producing the largest image contrast. For the sugar maple stand in Haliburton Forest and the Douglas-Fir stand, the automatic exposure is larger than the largest contrast exposure by 1–2 stops. The difference can be as large as three stops for portions of canopies that have large L_e values and thus small gap fractions. For example, the automatic exposure at the No. 7 of the Douglas-Fir site is three stops larger than the exposure that produces the largest contrast. The mean L_e values derived from photographs with the automatic exposure and largest contrast are 2.69 and 4.61, and the gap fractions are 1.98 and 7.29%, respectively. For this location, the L_e is underestimated by 71% if the automatic exposure setting is used.

The results from the sugar maple, Douglas-Fir, and SB2 stands demonstrate that digital hemispherical photographs taken with automatic exposure can result in underestimations of L_e in medium to dense canopies. But the estimations from open canopies had an opposite trend. In sparse canopies, the contribution of sky pixels is much larger than that of foliage pixels. So under the same sky brightness conditions, the whole scene of sparse canopies is much brighter than that of closed canopies. The camera automatically images sparse canopies with less exposure, i.e. the automatic exposure would be less than two stops of overexposure relative to the sky reference. Thus the foliage is under-exposed compared with closed canopies, which leads to losses of many small canopy gaps and consequently an overestimation of L_e. For the SB1 stand, the automatic exposure underexposes the photographs by 1–2 stops, resulting in L_e overestimations by 14–42% and gap fraction underestimations by 4–22%. Therefore, the automatic exposure can be particularly problematic in either very open or very closed canopies.

4.4. Comparison of L_e from different instruments

To test whether two or three stops of overexposure relative to the sky reference is the optimum exposure for leaf area index estimation, L_e derived from digital hemispherical photographs described previously was evaluated in comparison with the corresponding L_e values measured at same locations by the LAI-2000 instrument. The LAI-2000 measures the blue light (400–490 nm) attenuation through the canopy at five

Table 1
Comparisons between the automatic exposure and the exposure producing the largest sky-foliage contrast

Stand	Location (No.)	Exposure(s)		L_e Result from		Gap fraction	
		Automatic	Largest contrast	Automatic exposure	Exposure with largest contrast	Automatic exposure (%)	Exposure with largest contrast (%)
Sugar Maple stand in Haliburton Forest	1	1/60	1/125	2.181	2.552	10.92	8.54
	2	1/30	1/60	2.801	3.298	6.58	4.59
	3	1/30	1/60	2.347	2.807	9.35	6.72
	4	1/15	1/60	2.925	3.964	6.50	2.88
	5	1/8	1/60	2.671	4.263	8.17	2.37
	6	1/8	1/60	2.493	4.031	8.80	2.70
Douglas-Fir stand on Vancouver Island	1	1/125	1/250	1.907	2.288	13.09	9.66
	2	1/125	1/250	1.828	2.267	13.93	10.19
	3	1/125	1/250	2.624	3.154	7.97	5.67
	4	1/125	1/250	2.691	3.130	8.52	6.37
	5	1/60	1/250	2.507	3.563	8.87	4.49
	6	1/60	1/250	2.711	3.876	8.21	4.13
	7	1/30	1/250	2.698	4.613	7.29	1.98
	8	1/60	1/125	2.635	3.285	8.54	5.58
	9	1/60	1/125	2.400	2.860	10.39	7.99
Black Spruce (SB1) stand in Sudbury	1	1/500	1/125	0.329	0.293	41.96	43.68
	2	1/500	1/125	0.524	0.419	36.25	39.80
	3	1/500	1/125	0.820	0.650	29.15	33.32
	4	1/1000	1/250	0.911	0.705	26.54	30.49
	5	1/500	1/125	1.055	0.752	24.10	30.99
Black Spruce (SB2) stand in Sudbury	1	1/125	1/250	2.295	2.714	10.16	7.87
	2	1/125	1/250	2.118	2.470	12.97	10.68
	3	1/125	1/250	2.497	2.948	10.06	8.25
	4	1/125	1/250	2.285	2.740	10.99	8.72
	5	1/125	1/250	2.503	2.825	8.54	6.21
	6	1/125	1/250	2.387	2.835	9.74	7.43
	7	1/125	1/250	2.031	2.460	12.71	9.87
	8	1/125	1/250	2.127	2.486	12.84	10.45
	9	1/125	1/250	2.711	3.224	8.05	6.27

concentric rings: 0–13°, 16–28°, 32–43°, 47–58°, and 61–74° (Li-Cor, 1992). The ratio of the below to above canopy readings for each ring is measured to obtain the gap fraction of each ring and the effective leaf area index.

According to the LAI-2000 instrument, L_e was 4.84 for the sugar maple stand on May 27, 2004, and 3.93, 1.26, and 3.20 for the Douglas-Fir, SB1 and SB2 stands, respectively. For the purpose of comparison, hemispherical photographs at the zenith angles from 0 to 75° of were used to calculate L_e, which matches the angle range of the LAI-2000. The root mean square error (RMSE) is calculated to estimate the deviation between two measurements:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{y}_i - y_i)^2} \tag{2}$$

where $\hat{y}_i$ and y_i are the L_e values estimated from the LAI-2000 and hemispherical photographs, respectively, and n is the number of locations where the measurements were taken.

Fig. 10a demonstrates that the L_e values estimated from photographs with automatic exposure correlates with those from the LAI-2000 ($R^2 = 0.77$). But compared with the LAI-2000, the hemispherical photographs with automatic exposure underestimate L_e, especially for closed canopies. L_e estimated from hemispherical photographs deviates that from the LAI-2000. The RMSE between two measurements is 1.26. Comparisons for other canopies also confirmed that digital hemispherical photographs underestimate L_e (van Gardingen et al., 1999). Fig. 10b shows the comparison of L_e values from LAI-2000 and hemispherical photographs with the largest contrast. With the increase in image contrast, the correlation and the

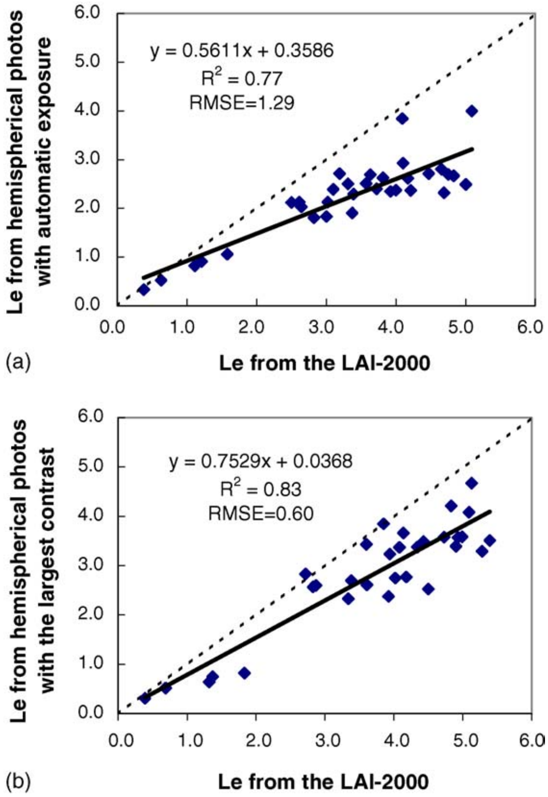

Fig. 10. Relationship between Le derived from the LAI-2000 and from digital hemispherical photographs (the dotted line is 1:1 line): (a) L_e from the LAI-2000 and digital hemispherical photographs with the automatic exposure; (b) L_e from the LAI-2000 and digital hemispherical photographs with the largest contrast.

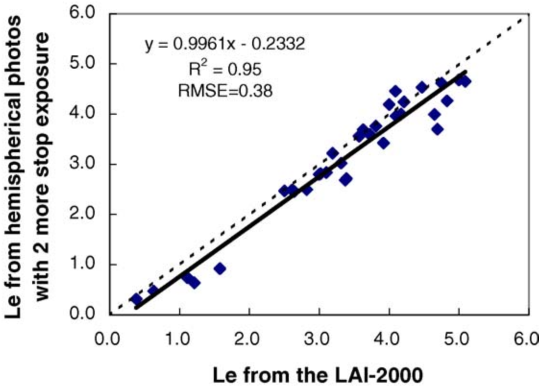

Fig. 11. Relationship between L_e derived from the LAI-2000 and from digital hemispherical photographs with two stops of more exposure relative to the sky automatic exposure (the dotted line is 1:1 line).

accuracy of L_e estimations from hemispherical photographs are both improved ($R^2 = 0.83$, RMSE = 0.60). Compared with LAI-2000 measurements, photographs with automatic exposure underestimate L_e by 48.7% on average, while photographs with largest image contrasts underestimate L_e by 23.1% on average.

We analyzed all 10 rings of hemispherical photographs to investigate whether two or three stops of overexposure can create the largest image contrast for all zenith angles. Contrasts between sky and foliage pixels for every 9° annulus rings were calculated and compared separately. In near-vertical directions, canopies generally have large gap fractions and thus the light intensity is high. It is found that at three stops of overexposure, ring 1 or 2 tends to be saturated though the whole image reaches the largest contrast. Generally, when the whole image reaches the maximum contrast, sections at small zenith angles are overexposed by one stop, resulting in underestimations of the foliage area in near-vertical directions. The overexposure in the near-vertical direction may be due to the multiple scattering inside the canopy. Chen et al. (1991) demonstrated that film-based photographs are overexposed at small zenith angles and underexposed at large zenith angles where gaps are small and the probability of viewing top foliage is low. As in our analysis, only zenith angles below 75° were included for comparisons, the underexposure in near horizontal directions has been eliminated. Therefore, to avoid overexposure in near-vertical directions, all the photographs at the two stops of overexposure were compared with those from the LAI-2000. Compared with the photographs with the largest contrast, the photographs with two stops of overexposure compensate the overexposure in near-vertical directions and thus produce larger L_e values (Fig. 11). The correlation and accuracy of L_e estimations are greatly improved ($R^2 = 0.95$, and RMSE = 0.38). It is found that at two stops of overexposure, the image contrast is actually very close to the maximum contrast. Therefore, two stops of overexposure relative to the sky reference is the optimum exposure of digital photographs for accurate estimation of LAI. A zenith angle range from 0 to 75° is recommended to avoid the underexposure in near horizontal directions.

5. Discussion and suggested measurement protocol

Overexposure by two stops relative to the sky reference is determined to be the optimum exposure for digital photographs for LAI measurements based on the comparison with the LAI-2000 measurements. Though the LAI-2000 tends to underestimate LAI (Battaglia et al., 1998; Chen, 1996a; Kalácska et al., 2005), this is mostly due to foliage clumping (Chen, 1996b). Multiple scattering of blue light within the canopy could have similar effects on the gap fraction determination using both LAI-2000 and fish-eye photography, but would not influence considerably their intercomparison. The reason for using two stops rather than theoretical 2.5–3 stops (Chen et al., 1991; Wagner, 2001) is clearly the need to minimize the effect of strong scattering of light by foliage near the vertical direction. From the above analysis, it should be noted that finding the optimum exposure to obtain the correct leaf area index is actually a balancing act between the overexposure near vertical directions and underexposure near horizontal directions. This may be an inherent limitation of hemispherical photography technique for canopy structural measurements. Because of the non-uniform effect of exposure across the zenith angle range, the inversion of leaf angle distribution using gap fractions at various zenith angles can still be distorted even when the optimum exposure is found (Chen et al., 1991). Until this exposure angular effect is resolved, the hemispherical photographic technique should only remain as a proxy measurement technique. Furthermore, variations of the sky conditions during measurements need to be taken into consideration. Stable sky conditions are ideal for taking hemispherical photographs. Near sunrise or sunset, the sky brightness could vary and the correct exposure inside the canopy needs to be changed accordingly. When the plot is large or the sky condition is not stable, recording the sky reference before and after the measurements is necessary for determining the correct exposure. Two photographs are recommended for each location, with two stops and one stop or three stops of more exposure depending on the change of sky brightness. Determining the optimum exposure based on the sky brightness, although it is physically meaningful, can sometimes be difficult to implement in the field because it is often not possible to find a very large open field in a forested area. With some experience, the sky brightness can be measured from inside the stand using a tele-lens through a large canopy gap. Using spot meter with a narrow angle of view is practical to measure the sky luminance in this case (Clearwater et al., 1999; Wagner, 2001). Although sky brightness can sometimes be variable in different directions, it will take a 50% difference in sky brightness to change the exposure by one stop. Therefore, taking the measurements in one or two gaps is normally sufficient, although all reference measurements are made in large open areas for the purposes of this study. Based on results of this research, we propose the following protocol in using digital cameras for plant canopy structural measurements:

1. to determine the sky exposure. The ideal determination would be using the same camera with the same fish-eye lens in a very large opening with no obstructions above 15° of the elevation angle in all directions. In case this is not possible, similar measurements can be made in large canopy gaps using a tele-lens, but in this case precautions should be taken for directional variability of sky brightness. The preferred aperture is F5.3 or similar.
2. to determine the in-stand exposure by increasing the shutter speed by two stops with the aperture unchanged at F5.3. For example, if the sky reference is F5.3 and S1000 (i.e. speed of 1/1000 s), the correct exposure inside the stand is F5.3 and S250. This exposure setting is not influenced by the density of the stand.
3. to distinguish sky and foliage in the digital photograph by finding two thresholds, one for pure sky and one for pure foliage, with brightness in between as mixed sky and foliage. A software which is capable of unmixing the mixed pixels should be used (Leblanc et al., 2005).

6. Conclusion

Correct exposure is the key to taking digital hemispherical photographs for accurate estimation of L_e, clumping index and the actual LAI. Photographic exposure affects LAI and gap fraction retrievals even if no saturation occurs. Automatic exposure for collection of digital photographs is unreliable for the LAI estimation. Photographs taken with the automatic exposure underestimate L_e in medium to dense canopies and overestimate L_e in very open canopies. This paper proposed a protocol for acquiring digital hemispherical photographs under various sky brightness conditions and in canopies with different closures. Two stops of overexposure relative to the sky reference is proven theoretically and experimentally to be the optimum exposure for taking digital hemispherical photographs for the purposes of obtaining the mean canopy gap fraction and the effective LAI. Taking LAI-2000 measurements as a standard for comparison, the proposed optimum exposure greatly improves the accuracy of L_e estimates relative to those with automatic exposure.

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