Increasing the precision of canopy closure estimates from hemispherical photography: Blue channel analysis and under-exposure

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Increasing the precision of canopy closure estimates from hemispherical photography: Blue channel analysis and under-exposure

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ABSTRACT

Accurate measurement of canopy structure is fundamental to the fields of ecological modeling and restoration. A large number of methods exist for estimating the structure of forest canopies, with widely varying costs and effectiveness. Hemispherical photography has been in use for several decades, and the rise of lower-cost consumer grade digital SLR cameras has expanded the availability of this technique. We examine two improvements to the hemispherical photography technique for estimating canopy closure: computer-based blue channel analysis and under-exposing images. Photographs taken in the field (without a filter) showed much lower variation in the blue channel than in red or green channel of the same images. We found a higher variance in canopy closure measurements due to over-exposure of images, while images with automatic light metering and under-exposed images remained consistent. We conclude that under- or normal exposure combined with blue channel analysis together minimize variability and maximize the precision of canopy closure estimates. Results from hemispherical photography were comparable to the widely used LAI-2200, supporting hemispherical photography as a viable, low-cost alternative.

1. Introduction

Forest canopy cover is a key feature of forests worldwide, positively affecting both the functioning of the forest canopy itself and also strongly impacting environmental conditions in the forest understory. Accurate assessment of forest canopies and their effect on the understory environment are necessary for numerous ecological and agricultural efforts, from estimates of net primary productivity (NPP) to conservation and restoration of understory species. Analysis of forest canopies has proven useful in accelerating hurricane recovery and invasive species control (Uriarte et al., 2005; Malik et al., 2010), and for monitoring water and carbon cycles (Leblanc and Chen, 2001). Canopy characteristics are important to these fields because light availability is frequently the limiting resource in understories (Finzi and Canham, 2000). Canopy characteristics also strongly predict NPP and other import forest ecosystem functions (Bartemucci et al., 2006; Comita et al., 2009; Dube et al., 2001; Finzi and Canham, 2000; Gravel et al., 2010; Jelaska et al., 2006; Knowles et al., 1999; Kobe, 1996; Kobe et al., 1995; Pacala et al., 1996; Sudderth et al., 2012; Uriarte et al., 2005). Canopy openness is a strong predictor of seedling survival in early stages of ecosystem recovery (Comita et al., 2009). Other work has also shown that light availability is an important factor in models that predict sapling mortality (Kobe et al., 1995), canopy growth (Beaudet and Messier, 2002; Sonnentag et al., 2012), and regeneration (Comita et al., 2009; Romell et al., 2009), indicating a long term role in forest dynamics. Canopy structure provides much needed insight into forest ecosystem function, highlighting the importance of accurate quantification of forest canopy characteristics.

Because forest canopies impact forest communities and ecosystems in numerous ways, several metrics have been developed to describe canopy characteristics. Leaf Area Index (LAI) provides information about the physical structure of a canopy, and thus is well suited to applications where canopy functions such as NPP need to be estimated or modeled. In contrast, when the objective is to evaluate environmental conditions at a particular point or set of points in the understory, direct measurement of light availability at particular points in the understory may be more

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Table 1
Common canopy variables and their definitions.

Variable	Physical measurement
Canopy closure	Proportion of sky blocked by canopy at all angles from a single point
Canopy coverage	Proportion of sky blocked by canopy at vertical angle from multiple points
Diffuse non-interceptance	Amount of light, both direct and indirect, received from the sky
Gap fraction	Proportion of open space in a canopy
Leaf area index	Amount of foliage that a vertical line through the canopy will intersect
Light metering	Amount of photonic energy from the sun

appropriate. Metrics of understory light availability include canopy closure, canopy coverage, diffuse non-interceptance (DIFN), and gap fraction (Table 1). Multiple methodologies exist for quantifying understory light availability (Table 2), including the LI-COR LAI-2200 (Li-Cor Inc., Lincoln, NE, USA), spherical densiometers, photosensitive diazo paper, LIDAR devices, and hemispherical photography (Bao et al., 2008; Ferment et al., 2001; Lang et al., 2010). In the present paper we are focused on improvements to hemispherical photography techniques that quantify canopy closure, defined as the proportion of sky which is blocked by the canopy when viewed at all angles from a single point in the understory (Jelaska et al., 2006; Jennings et al., 1999). Canopy closure has been shown to be a better estimator of solar radiation levels than canopy coverage (Table 1), particularly in north facing sites (Jelaska et al., 2006).

The central premise of hemispherical photography is that the specialized lens captures an image that spans a 180° arc, and when pointed vertically can capture all possible angles of incoming light, making it well suited for estimating canopy closure. These images are then digitally processed to differentiate sky from canopy. Hemispherical photographs have been used alongside other techniques and found to provide comparable measurements in many studies (Bao et al., 2008; Bellow and Nair, 2003; Chianucci and Cutini, 2013; Ferment et al., 2001; Guevara-Escobar et al., 2005; Hopkinson and Chasmer, 2007; Leblanc and Fournier, 2005; Pueschel et al., 2012; Sasaki et al., 2008; Seidel et al., 2012; Takashima et al., 2006). While hemispherical photography has been used for decades with film cameras (e.g., Chen et al., 1991), use has risen in recent years due to the ready availability of high quality digital cameras on the consumer market. Analysis of hemispherical photographs on computers is greatly facilitated by the digital format, as film images must be scanned before analysis, resulting in the potential degradation of image data, which can directly impact the results of sky to canopy separation techniques (Jelaska et al., 2006). As optics, digital cameras, and computational methodologies continue to improve, techniques for canopy analysis can be refined and improved.

Our investigation here refines hemispherical photographic techniques by maximizing the precision of canopy closure estimates.

2. Hypotheses

2.1. Hypothesis 1: post-processing analysis of the blue channel of a hemispherical photograph reduces the variance of canopy closure estimates

Canopy closure is the proportion of sky that is blocked by the canopy at a given point in the understory. Thus, accurate and precise discrimination of sky and canopy is critical to effective quantification of canopy closure. In hemispherical photography, the incoming rays are captured in individual pixels, which are subsequently categorized as either sky or canopy based on light intensity, and the ratio of these counts is used to derive a canopy closure value. The foundation of these methods rests on a sorting algorithm that isolates light and dark regions of the sky by setting a threshold based on a histogram of light intensity across all pixels. The higher the contrast between these parts of the image, the more confident we can be in the resulting measurements. The best images then would be ones that generate an image histogram with a strongly bimodal distribution. A properly exposed, high contrast image will yield similar results regardless of the algorithm used in setting a threshold.

This separation can be enhanced by evaluating color channels of an image, and taking advantage of the difference between the colors of plant pigmentation and the sky. The sky has a high transmittance of blue for the majority of the day, while most plants have pigments that strongly absorb both blue and red light (Lariguet and Dunand, 2005). This means that evaluation of the blue channel of images should have a high degree of contrast. Practical applications of this can already be seen, as the use of color filters in the field is quite common (Ferment et al., 2001; Jonckheere et al., 2005; Leblanc and Chen, 2001; Zhang et al., 2005). The majority of cameras available today are digital, allowing direct access to color channel information, precluding the need for a color filter in the field. Our investigation was to see if these benefits could extended to post-processing techniques of images taken without a filter. We predict that canopy closure estimates from post-processed blue channel images will have reduced variance and thus increased precision of canopy closure estimates.

2.2. Hypothesis 2: under-exposure of hemispherical photographs reduces the variance of canopy closure estimates

We also evaluated the impact of image exposure levels on the reliability of image thresholding. Although this aspect of hemispherical photography has been well studied, the literature remains divided on what the optimum exposure technique should be. Zhang

Table 2
Techniques for assessing tree canopy variables, associated costs, and restrictions.

Method	Measurement type	Cost	Weather restrictions	Other notes
LIDAR	LAI, Gap Fraction, Gap Size Distribution, FIPAR, Crown Closure, distance	$100,000	Any light condition, avoid rain	“active” system, doesn't require light to penetrate canopy
LAI-2000	LAI, DIFN, Gap Fraction, Crown Closure	$9000	Avoid direct sunlight (corrections can be made)	Has a built-in 490 nm filter
Hemispherical photos	Gap Fraction, Gap Size Distribution, can compute LAI, directional closure (sun tracks), Crown Closure	$1000	Uniform sky works best, avoid rain	
Spherical densiometer	Sky openness, extremely rough estimates	$100		Unreliable, based on human counting
Diazo paper	General light exposure (amount of radiation received)	Varies		Price depends on area covered
TRAC	Gap Fraction, Gap Size Distribution	$3000	Requires strong sunlight	Direct light measurement, requires transect, time intensive

et al. (2005) recommend calibrating camera sensors against open sky, then increasing the image exposure by 2 stops for use under the canopy. Macfarlane et al. also recommend calibrating exposure levels outside of the canopy (2000). Such a recommendation, however, ignores the state of the canopy to be measured; given the wide variety of canopy conditions any predetermined exposure adjustments will not always be correct. Chen et al. (1991) recommend underexposing images by as much as 5 stops, although this work was performed in a conifer stand and may not be applicable to broad leaf forests. Other researchers have used exposure at one stop below automatic (Hopkinson and Chasmer, 2007) as well as using the automatic exposure settings (Finzi and Canham, 2000; Macfarlane et al., 2007). Some authors recommend calibration using an external light meter (Chianucci and Cutini, 2013; Ferment et al., 2001; Macfarlane et al., 2000) while others use the camera's internal light meter (Finzi and Canham, 2000; Macfarlane et al., 2007). The wide divergence of recommendations make it worth reexamining guidelines for optimum exposure.

Preliminary observations showed that over-exposure does result in more washed out sky pixels, making those pixels much easier to separate through computer analysis. Unfortunately, this also lightened the canopy pixels, introducing more color information in those regions and making them more difficult to isolate. Under-exposure of an image will create a similar effect in the opposite direction, allowing for easier canopy identification while increasing the risk of categorizing dark regions of the sky as leaf matter. We predict that Images 1 exposure stop below the camera's automatic light metering will have lower variance of canopy closure estimates compared to the default exposure and over-exposure. We also predict that the lowest variance will be achieved by combining underexposure with blue channel analysis as described above.

3. Materials and methods

3.1. Field photography

Digital images used in this study were photographed on the Rutgers-Newark campus from the end of April through June of 2010. Four sites were selected in the Norman Samuels Plaza with no direct foot traffic and varying degrees of forest canopy overhead. All sites were under a light to moderate density broad leaf canopy, with trees 13–20 m tall. All photographs were taken at a northern compass direction, with the camera vertically aligned. Three photographs were taken daily in the morning, at each site, across a two-month period to characterize the same canopy under a variety of lighting conditions and exposures.

Images were taken using a Nikon D40 digital single-lens reflex (DSLR) camera (Nikon, Tokyo, Japan), fitted with a Sigma 4.5 mm F2.8 EX DC HSM Circular Fisheye lens (Sigma, Ronkonkoma, NY, USA). Images were recorded in 3008×2000 pixel raster image format, the highest resolution setting possible on the camera. Maximum possible resolution was used because analysis methods are performed on a pixel-by-pixel basis, and image resolution is a major factor in the quality of predictions from hemispherical photographs (Jelaska et al., 2006). Our analysis may be used on images of any size, but higher resolution is recommended. High quality jpeg compression was used, as previous work has shown no loss of quality when using jpeg format (with less than 1:4 compression) compared to uncompressed images (Frazer et al., 2001).

To minimize motion blur, all images were taken under the shutter priority setting with a maximum exposure time of 1/30th of a second. Faster shutter speeds were used as necessary, when ambient light levels were higher. Aperture size ranged from F14 to F22. Exposure levels were calibrated under matrix metering using the camera's "through the lens" (TTL) internal light sensor. Our automatic exposure treatment was determined based on the manufacturer's "optimal exposure" recommendation (for brightness and contrast). The ISO setting, which controls how sensitive the camera sensor is to light, was set to 800. Higher ISO values increase the risk of images with stray pixels or "noise." Since our analysis was performed at a pixel by pixel level, image artifacts from high ISO would be reflected in the results. Exposure levels were one of our experimental treatments, so image exposures were bracketed manually by adjusting shutter speed plus or minus one exposure stop.

To confirm that the accuracy of our hemispherical photography estimates were not affected by color channel treatments, we compared these estimates against estimates acquired from a LI-COR LAI-2200. We captured photographs and LAI readings back to back on 12 days during a 2 week period in May of 2013, using a new location on the Rutgers-Newark campus. Camera settings used were the same as described above, although no bracketing was done for the photographs for this part of the study. We converted the LAI-2200 diffuse non-interceptance (DIFN) values into their corresponding canopy closure values (Canopy closure = 1 − DIFN) for comparison.

3.2. Image processing

Image processing, calculation and analysis of canopy closure, and figure generation were all performed with *Mathematica 9.0* (Wolfram Research Inc., 2012). Images were first cropped with a circular mask to remove the lens margin and chromatic aberration from the image margin. Thresholding, as described above, separates pixels of an image into two groups based on their intensity. By using high contrast images these two groups will correspond to the sky and canopy pixels. Thresholding of images was performed using a cluster analysis approach (*Mathematica*'s binarize function), as previous work demonstrated this cluster analysis to be the most robust approach (Jonckheere et al., 2005; Macfarlane et al., 2007). The accuracy of thresholding results was visually confirmed. Once coded, all images were processed with the same script. Color channels were analyzed individually to test for their effects. Scripted analyses allowed for rapid and automated image analysis.

3.3. Statistical analysis

Raw canopy closure values were first converted into proportional differences through a logit transformation (Sokal, R.R. and F.J. Rohlf (1995). *Biometry*. New York, Freeman & Company). Canopy growth over the course of our observation period caused a natural increase in canopy closure. To correct for this we detrended the observations through the standard first difference approach (Hamilton, 1994). First differencing allowed us to focus on precision, giving us a sense of how consistent the measurement technique was and quantifying its variance. The differencing approach enabled us to pool data between the same treatments from different sites, giving us a much larger sample size for variance analysis.

While the canopy closure value itself is ecologically significant, the variance in canopy closure values determines the reliability of any particular instrument or method. Variance was compared using the Conover Variance Equivalence test (Conover and Iman, 1978; Conover et al., 1981) in *Mathematica 9.0* (Wolfram Research Inc., 2012).

Mean canopy closure from hemispherical photography and LAI-2200 was compared with one-way ANOVA in *Mathematica 9.0* (Wolfram Research Inc., 2012).

4. Results

Blue image channels displayed the tightest clustering around the mean value, while red and green images had long tails (Fig. 1).

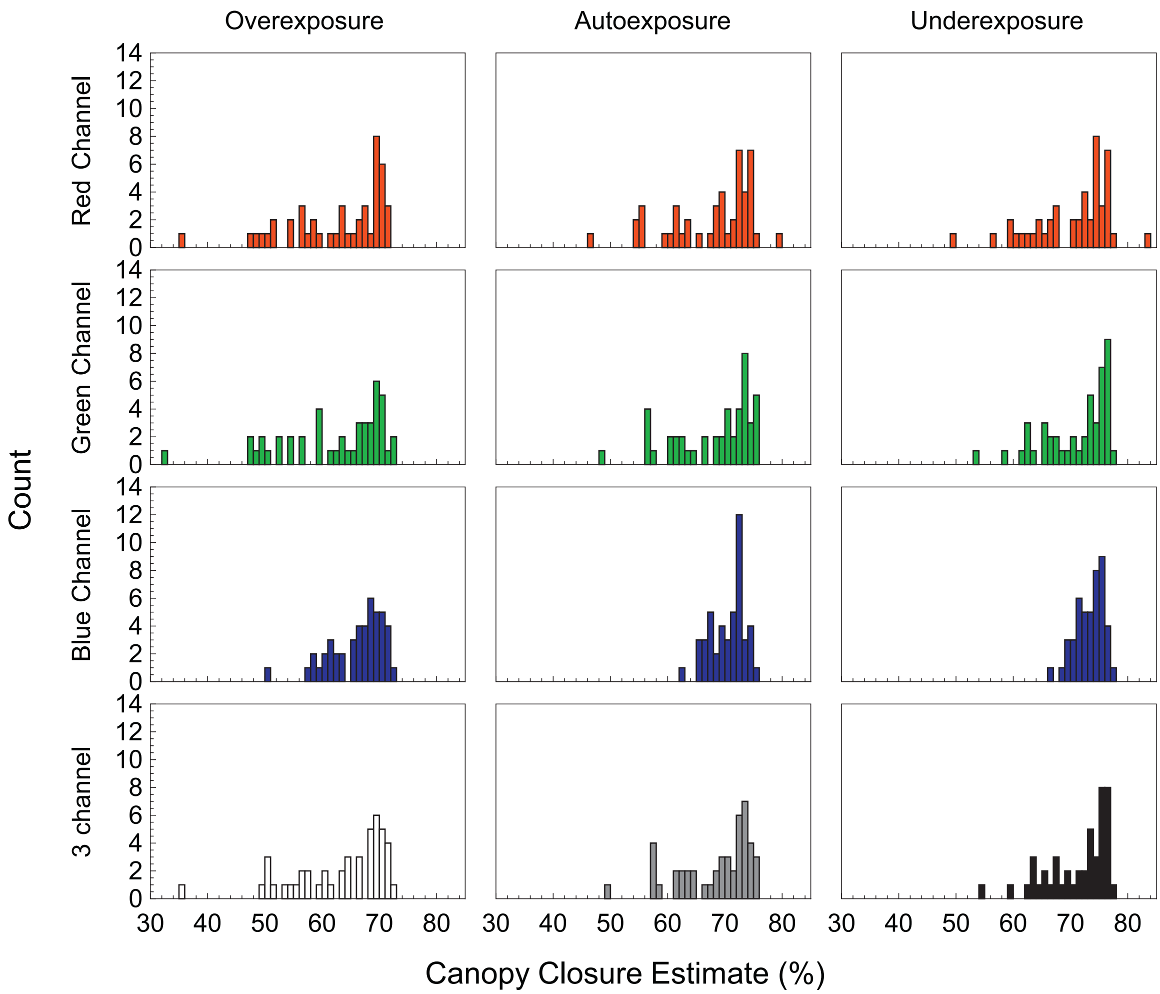

Fig. 1. Histograms of canopy closure estimates at site 1, with all combinations of exposure level and color channel shown. The variability of the estimates is lowest in the blue channel. Overexposed images show an increase in variability across all color channels, indicating a sensitivity to excessive light.

Over-exposed images also increased the variability of the distribution, as can be seen in the wider distribution of the over-exposed blue channel graph. The overall shift in mean canopy closure estimates between exposure levels is the result of light levels causing pixels to be categorized incorrectly. We account for the effects of exposure on these estimates in the LAI-meter comparison bellow. Initial comparison of the treatments supports our hypotheses. Blue channel images have the narrowest distribution, as do the two lower exposure levels. In depth analysis of variances follows.

Post processing methods based on color channel separation resulted in statistically significant differences in canopy closure estimates between treatments. Fig. 2 illustrates the variance in canopy closure estimates estimated from each individual color channel and exposure treatment. Pooled across all 4 sites, the blue channel automatic exposure images exhibited significantly less variability than red ($p < 0.0001$) or green ($p < 0.0001$) channel images (Fig. 2). Lower variance values indicate a higher degree of measurement precision, indicating that canopy closure estimates made from post-processed blue channel images were the least affected by small changes in day to day conditions.

Both automatic exposure and under-exposed images (−1 stop) demonstrated substantially less variance than over-exposed images (+1 stop) across all channels (Fig. 2). Red channel images had significantly lower variance for both automatic and under-exposed images when compared against over-exposed, $p = 0.014$ and 0.0043, respectively. Green channel showed a similar difference ($p < 0.0001$ and $p = 0.0003$). Blue channels show a difference between under and over-exposed images ($p = 0.0003$) but only showed near significance between automatic and over-exposed images ($p = 0.056$). We believe that the lack of significance is due to an overall reduction of variance across all data, this explanation is supported by a lack of significance between under and automatic exposure blue channel images ($p = 0.052$).

Comparisons of blue channel hemispherical photographs and LAI-2200 showed no significant difference in mean estimates of canopy closure (one way ANOVA, $p = 0.73$), indicating that the techniques provide comparable results (Fig. 3). Similar results were found when comparing 3-channel images against the LAI-2200 (one way ANOVA, $p = 0.51$). Variance equivalence test also showed no significant difference against the LAI-2200 (blue channel, $p = 0.16$; 3-channel, $p = 0.18$), although blue channel hemispherical photographs had the lowest variance overall (Fig. 3). These results indicate that our modified hemispherical photography technique produces measurements that are comparable to the more expensive LAI-2200 method.

5. Discussion

Our results show that when using hemispherical photography to evaluate canopy closure, modifying exposure levels of the images can have far reaching effects on the level of precision of resulting estimates. Images that were over-exposed provided much more

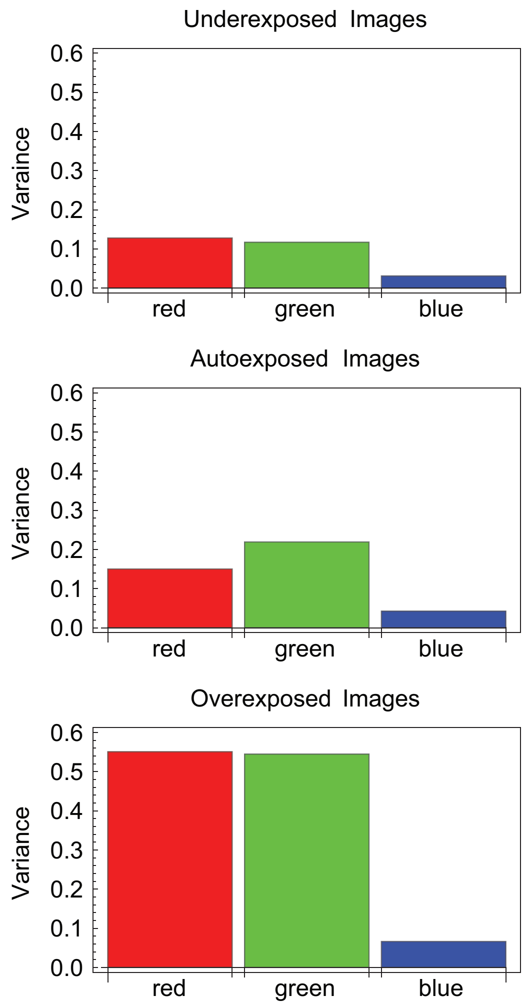

Fig. 2. Variance of canopy closure measurements across all 4 sites and 46 days ($n = 184$) using color separation on all exposure levels. Overexposed images have much higher variance than either automatic or underexposed images. Within a given exposure level, the blue channel is consistently lower in variance than red or green channels.

erratic estimates of canopy closure, likely due to diffraction and reflection effects being erroneously classified as open sky. These over-exposed images showed wide variation in estimates, resulting in less precision and confidence in canopy closure estimates. The automatic exposure images and the under-exposed images showed similar levels of variation, and both performed much better than the over-exposed images. Although under-exposed images did maintain an equivalent level of precision throughout the experiment, they also had lower canopy closure estimates. Our work illustrates that there is a high risk for error in hemispherical photographs from excessive exposure, and that is better to err on the side of under-exposing an image. While determining exposure by using the camera's internal light metering remains the best standard, this information could be useful under adverse field conditions, such as sites with fluctuating light levels due to high wind activity.

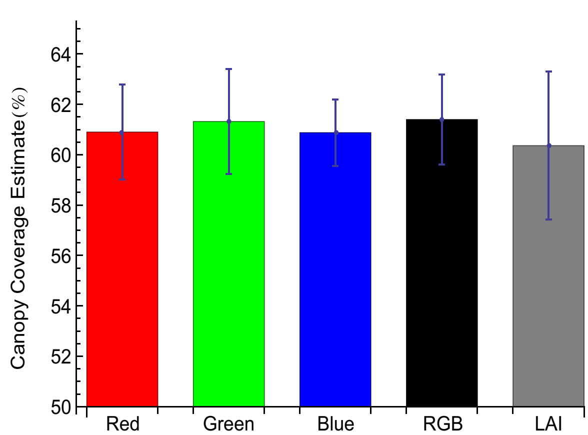

Fig. 3. Mean canopy closure estimates comparing hemispherical photography and LAI-2200 methods at a single site. Canopy closure estimates by LAI-2200 and hemispherical photography were not significantly different, indicating a parity of techniques.

The results of color channel separation in post-processing mirrored the already established method of using colored filters in the field. Blue provided the optimum separation of sky and canopy due to the high levels of blue light transmittance in the atmosphere combined with the low levels of blue reflectance in foliage. Also as expected, green channel images resulted in the most confusion between sky and canopy, due to lower visual contrast between sky and plant materials. While this information was already well known to apply to physical color filters placed on lenses, our study expanded the possible application of this concept. Our work demonstrates that we can obtain a more consistent and reliable estimate of canopy closure that is less affected by external conditions, even if a colored filter was unavailable during field photography. Because modern DSLR cameras record image data in separate color channels, the need for a filter is eliminated. Another benefit of this technique is that it requires no additional field methods and can be easily automated, allowing for increased precision of measurements with no increase in workload.

A comparison of hemispherical photography against the LI-COR LAI-2200 showed no significant difference in mean canopy estimates, as well as no significant difference in variance of those measurements. The LAI-2200 can provide useful information about canopy structure, biomass, and other community level concerns, while hemispherical photography provides focused information on environmental conditions at a particular point in space. If canopy closure provides sufficient information then using hemispherical photography is acceptable, as it has been shown to give comparable results in terms of accuracy and precision (Fig. 3; Guevara-Escobar et al., 2005).

Our results demonstrate that canopy closure estimates from hemispherical photography can be improved by avoiding over-exposure of images, and by analyzing only the blue channel. Canopy closure estimates are sensitive to high light levels, indicating that lower exposure can increase repeatability of field measurements. By using only the blue channel for analysis, as can be done directly from the raw image and without the use of filters, precision can be improved. These two techniques combined produce an estimate of canopy closure with minimal variance.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agrformet.2014.05.001.

References

Bao, Y.F., Cao, C.X., Zhang, H., Chen, E.X., He, Q.S., Huang, H.B., Li, Z.Y., Li, X.W., Gong, P., 2008. Synchronous estimation of DTM and fractional vegetation cover in forested area from airborne LIDAR height and intensity data. Sci. China Ser. E: Technol. Sci. 51 (supp. 2), 176–187.

Bartemucci, P., Messier, C., Canham, C.D., 2006. Overstory influences on light attenuation patterns and understory plant community diversity and composition in southern boreal forests of Quebec. Can. J. For. Res. 36 (9), 2065–2079.

Beaudet, M., Messier, C., 2002. Variation in canopy openness and light transmission following selection cutting in northern hardwood stands: an assessment based on hemispherical photographs. Agric. For. Meteorol. 110 (3), 217–228.
Bellow, J.G., Nair, P.K.R., 2003. Comparing common methods for assessing understory light availability in shaded-perennial agroforestry systems. Agric. For. Meteorol. 114 (3–4), 197–211.
Chen, J.M., Black, T.A., Adams, R.S., 1991. Evaluation of hemispherical photography for determining plant-area index and geometry of a forest stand. Agric. For. Meteorol. 56 (1–2), 129–143.
Chianucci, F., Cutini, A., 2013. Estimation of canopy properties in deciduous forests with digital hemispherical and cover photography. Agric. For. Meteorol. 168, 130–139.
Comita, L.S., Uriarte, M., Thompson, J., Jonckheere, I., Canham, C.D., Zimmerman, J.K., 2009. Abiotic and biotic drivers of seedling survival in a hurricane-impacted tropical forest. J. Ecol. 97 (6), 1346–1359.
Conover, W.J., Iman, R.L., 1978. Some exact tables for the squared ranks test. Commun. Stat. Simul. Comput. 7, 491–513.
Conover, W.J., Johnson, M.E., Johnson, M.M., 1981. A comparative study of tests for homogeneity of variances, with applications to the outer continental shelf bidding data. Technometrics 23, 351–361.
Dube, P., Fortin, M.J., Canham, C.D., Marceau, D.J., 2001. Quantifying gap dynamics at the patch mosaic level using a spatially-explicit model of a northern hardwood forest ecosystem. Ecol. Modell. 142 (1–2), 39–60.
Ferment, A., Picard, N., Gourlet-Fleury, S., Baraloto, C., 2001. A comparison of five indirect methods for characterizing the light environment in a tropical forest. Ann. For. Sci. 58 (8), 877–891.
Finzi, A.C., Canham, C.D., 2000. Sapling growth in response to light and nitrogen availability in a southern New England forest. For. Ecol. Manage. 131 (1–3), 153–165.
Frazer, G.W., Fournier, R.A., Trofymow, J.A., Hall, R.J., 2001. A comparison of digital and film fisheye photography for analysis of forest canopy structure and gap light transmission. Agric. For. Meteorol. 109 (4), 249–263.
Gravel, D., Canham, C.D., Beaudet, M., Messier, C., 2010. Shade tolerance, canopy gaps and mechanisms of coexistence of forest trees. Oikos 119, 475–486.
Guevara-Escobar, A., Tellez, J., Gonzalez-Sosa, E., 2005. Use of digital photography for analysis of canopy closure. Agrofor. Syst. 65 (3), 175–185.
Hamilton, J.D., 1994. Time Series Analysis. Princeton University Press, Princeton, NJ.
Hopkinson, C., Chasmer, L.E.,2007. Modelling canopy gap fraction from lidar intensity. In: ISPRS Workshop on Laser Scanning 2007 and SilviLaser 2007. IAPRS, Espoo, Finland, p. 5.
Jelaska, S.D., Antonic, O., Bozic, M., Krizan, J., Kusan, V., 2006. Responses of forest herbs to available understory light measured with hemispherical photographs in silver fir-beech forest in Croatia. Ecol. Modell. 194 (1–3), 209–218.
Jennings, S.B., Brown, N.D., Sheil, D., 1999. Assessing forest canopies and understory illumination: canopy closure, canopy cover and other measures. Forestry 72, 15.
Jonckheere, I., Nackaerts, K., Muys, B., Coppin, P., 2005. Assessment of automatic gap fraction estimation of forests from digital hemispherical photography. Agric. For. Meteorol. 132 (1–2), 96–114.
Knowles, R.L., Horvath, G.C., Carter, M.A., Hawke, M.F., 1999. Developing a canopy closure model to predict overstorey understorey relationships in *Pinus radiata* silvopastoral systems. Agrofor. Syst. 43 (1–3), 109–119.
Kobe, R.K., 1996. Intraspecific variation in sapling mortality and growth predicts geographic variation in forest composition. Ecol. Monogr. 66 (2), 181–201.
Kobe, R.K., Pacala, S.W., Silander, J.A., Canham, C.D., 1995. Juvenile tree survivorship as a component of shade tolerance. Ecol. Appl. 5 (2), 517–532.
Lang, M., Kuusk, A., Mottus, M., Rautiainen, M., Nilson, T., 2010. Canopy gap fraction estimation from digital hemispherical images using sky radiance models and a linear conversion method. Agric. For. Meteorol. 150 (1), 20–29.
Lariguet, P., Dunand, C., 2005. Plant photoreceptors: phylogenetic overview. J. Mol. Evol. 61 (4), 559–569.
Leblanc, S.G., Chen, J.M., 2001. A practical scheme for correcting multiple scattering effects on optical LAI measurements. Agric. For. Meteorol. 110 (2), 125–139.
Leblanc, S.G., Fournier, R.A., 2005. In: C.C.f.R. Sensing (Ed.), Towards a better understanding of in-situ canopy measurements used in the derivation and validation of remote sensing leaf area index products. Natural Resources Canada, p. 4.
Macfarlane, C., Coote, M., White, D.A., Adams, M.A., 2000. Photographic exposure affects indirect estimation of leaf area in plantations of *Eucalyptus globulus* Labill. Agric. For. Meterol. 100, 155–168.
Macfarlane, C., Hoffman, M., Eamus, D., Kerp, N., Higginson, S., McMurtie, R., Adams, M., 2007. Estimation of leaf area index in eucalypt forest using digital photography. Agric. For. Meterol. 143, 176–188.
Malik, M.S., Norsworthy, J.K., Riley, M.B., Bridges, W., 2010. Temperature and light requirements for wild radish (*Raphanus raphanistrum*) germination over a 12-month period following maturation. Weed Sci. 58 (2), 136–140.
Pacala, S.W., Canham, C.D., Saponara, J., Silander, J.A., Kobe, R.K., Ribbens, E., 1996. Forest models defined by field measurements: estimation, error analysis and dynamics. Ecol. Monogr. 66 (1), 1–43.
Pueschel, P., Buddenbaum, H., Hill, J., 2012. An efficient approach to standardizing the processing of hemispherical images for the estimation of forest structural attributes. Agric. For. Meteorol. 160, 1–13.
Romell, E., Hallsby, G., Karlsson, A., 2009. Forest floor light conditions in a secondary tropical rain forest: after artificial gap creation in northern Borneo. Agric. For. Meteorol. 149 (6–7), 929–937.
Sasaki, T., Imanishi, J., Ioki, K., Morimoto, Y., Kitada, K., 2008. Estimation of leaf area index and canopy openness in broadleaved forest using an airborne laser scanner in comparison with high-resolution near-infrared digital photography. Landsc. Ecol. Eng. 4 (1), 47–55.
Seidel, D., Fleck, S., Leuschner, C., 2012. Analyzing forest canopies with ground-based laser scanning: a comparison with hemispherical photography. Agric. For. Meteorol. 154, 1–8.
Sonnentag, O., et al., 2012. Digital repeat photography for phenological research in forest ecosystems. Agric. For. Meteorol. 152, 159–177.
Sudderth, E.A., St. Clair, S.B., Placella, S.A., Swarbreck, S.M., Castanha, C., Herman, D.J., Fischer, M.L., Kleber, M., Sudderth, E.B., Torn, M.S., Firestone, M.K., Andersen, G.L., Ackerly, D.D., 2012. Annual grassland resource pools and fluxes: sensitivity to precipitation and dry periods on two contrasting soils. Ecosphere 3 (8), 24.
Takashima, A., Kume, A., Yoshida, S., 2006. Methods for estimating understory light conditions using crown projection maps and topographic data. Ecol. Res. 21 (4), 560–569.
Uriarte, M., Canham, C.D., Thompson, J., Zimmerman, J.K., Brokaw, N., 2005. Seedling recruitment in a hurricane-driven tropical forest: light limitation, density-dependence and the spatial distribution of parent trees. J. Ecol. 93 (2), 291–304.
Zhang, Y.Q., Chen, J.M., Miller, J.R., 2005. Determining digital hemispherical photograph exposure for leaf area index estimation. Agric. For. Meteorol. 133 (1–4), 166–181.