Waldökologie, Landschaftsforschung und Naturschutz	Heft 11 (2011)	S. 19–33	5 Fig., 11 Tab.	urn:nbn:de:0041-afsv-01117

Comparison of four different programs for the analysis of hemispherical photographs using parameters of canopy structure and solar radiation transmittance

Alvaro Promis, Stefanie Gärtner, David Butler-Manning, Cristabel Durán-Rangel, Albert Reif, Gustavo Cruz and Lionel Hernández

Abstract

There have been many studies involving the use of hemispherical photographs to indirectly estimate canopy structures and forest light environments. A variety of commercial and free software packages are available for the analysis of hemispherical photographs. The costs of investment might represent an advantage of the free programmes over the commercial, but as yet little has been documented about the differences in their outputs and in the technical applications from a user (ecologist and forester) perspective. The objective of the study was to compare the canopy structure variables (canopy openness and effective plant area index) and solar radiation transmission estimates (direct, diffuse and global solar radiation transmittances) from digital hemispherical photographs taken under two forest canopy conditions (gap and closed canopy) in three different broadleaf forest regions (Chile, Germany, Venezuela) and calculated using four different programmes. The hemispherical photographs were analysed using one commercial (HemiView) and three free programmes (Gap Light Analyzer, hemIMAGE and Winphot). The results obtained revealed that all of the programmes computed similar estimates of both canopy structures and below-canopy solar radiation. Only the results relating to the effective plant area index with an ellipsoidal leaf angle distribution made with HemiView and Winphot deviated significantly. Other user aspects are also discussed, such as costs, image formats, computer system requirements, etc.

Keywords: *hemispherical photography, solar radiation transmittances, canopy openness, plant area index, software packages*

Zusammenfassung

In vielen Studien werden Hemisphärenphotos genutzt um indirekt die Kronenstruktur und die Belichtungsverhältnisse zu schätzen. Verschiedene kommerzielle und kostenfreie Softwarepakete sind zu Analyse von Hemisphärenphotos verfügbar. Es gibt bisher keine umfassende Vergleichsstudie zu Ergebnissen oder technischer Handhabung aus Sicht der Nutzer dieser Programme (Ökologen und Forstwissenschaftler). Das Ziel dieser Studie war der Vergleich der Schätzungen von Kronenstrukturvariablen (Kronenöffnung und effektiver Pflanzenflächenindex) Solartransmission (direkte, diffuse und Global-Strahlung) aus digitalen Hemisphärenphotos berechnet mit vier verschiedenen Programmen (kostenpflichtig: HemiView und frei: Gap Light Analyzer, hemIMAGE and Winphot). Die verwendeten Photos stammen aus drei verschiedenen Laubwaldregionen (Chile, Deutschland und Venezuela) und repräsentieren jeweils Verhältnisse unter geschlossenem Kronendach und in Lücken.

Die ermittelten Schätzungen für die verschiedenen Strukturvariablen und Einstrahlungsverhältnisse zeigten eine sehr hohe Übereinstimmung. Einzig der effektive Pflanzenflächenindex basierend auf ellipsoider Blattwinkelverteilung unterschied sich signifikant zwischen den Programmen. Weitere für Nutzer interessante Aspekte wie Kosten, Bildformate, Systemvoraussetzungen und mehr wurden verglichen und diskutiert.

Stichwörter: Hemisphärenphotos, Solarstrahlung, Kronenöffnung, Pflanzenflächenindex, Lichtschätzungsssoftware

1 Introduction

The greatest importance of solar radiation for plant life lies in the plants' dependence upon photosynthesis for growth and development, and the dependence in turn of photosynthesis on light (Barnes et al. 1998). Several instruments have been developed to estimate either directly or indirectly the forest understorey light environment. Many comparisons of direct and indirect methods for the estimation of below-canopy irradiation have been conducted in order to determine the best way to estimate the light environment (Chazdon & Field 1987, Rich et al. 1993, Wagner 1996, Comeau et al. 1998, Engelbrecht & Herz 2001, Ferment et al. 2001, Bellow & Nair 2003). However, many ecologists and foresters prefer indirect means of light estimation due to the difficulties inherent in measuring light directly (Jennings et al. 1999), and because the amounts of light greatly changes in the microenvironments across the forests.

Since its introduction (Evans & Coombe 1959), hemispherical photography (Fig. 1) has become a widely applied means of calculating the forest light environments, but also to the estimation of canopy structure variables. A number of studies have demonstrated a high level of agreement between both estimates (Rich et al. 1993, Comeau et al. 1998, Gendron et al. 1998, Clearwater et al. 1999, Engelbrecht & Herz 2001). However, in deeply shaded environments, the applicability of hemispherical photographs for the calculation of understorey light environments still needs to be verified conclusively (Roxburgh & Kelly 1995, Machado & Reich 1999).

The theoretical basis for estimating the various components of solar radiation using hemispherical photography were developed by Anderson (1964, 1966). Then, a variety of semi-automated and computerised techniques have been developed (Chan et al. 1986, Chazdon & Field 1987, Becker et al. 1989, Barrie et al. 1990, Smith & Somers 1993, Walter & Torquebiau 2000). A range of software packages are currently available for the analysis of hemispherical photographs (Comeau 2000). These include both commercial and free versions, with the latter available for download from the internet.

The question that arises now is whether there are differences in the usability and the results provided by the different software solutions. Frazer et al. (1997) compared two canopy characteristics (percent open sky and effective leaf area

Abb. 1: Hemisphärische Fotografie einer Kronenlücke eines *Nothofagus betuloides*-Naturwaldes in Feuerland, Chile.

Fig. 1: *Hemispherical photograph showing a canopy gap. The photograph was taken in a* Nothofagus betuloides *forest in Tierra del Fuego, Chile (Photo: A. Promis).*

index) using two programmes (Hemiphot and PAMAP GIS) in eight chronosequences of coastal temperate rainforest in British Columbia, Canada. The authors documented high correlations between the percent open sky (R^2 = 0.98) and the effective leaf area index (R^2 = 0.96) results produced by the two programmes. Brunner (2002) wrote that the hemIMAGE software calculates results for transmitted light very similar to those computed by the GLI-C and Winphot software, but that the results differed significantly from those produced by the Solarcalc software. However, there is as yet no published study comparing the programmes commonly used for computing these variables from hemispherical photographs. In this paper we provide a comparison between four programs: (a) a commercial software package called HemiView, version 2.1 (http://www.delta-t.co.uk, Delta-T Devices, Cambridge, UK, Rich et al. 1999), and three free programmes: (b) Gap Light Analyzer version 2.0 (http://www.ecostudies.org/gla/, Frazer et al. 1999), (c) hemIMAGE version 15-09-2002 (http://statisk.umb.no/ina/ansatte/andrb.php, Brunner 2002) and (d) Winphot version 5.0 (http://www.bio.uu.nl/~herba/Guyana/winphot/wp_index.htm, Ter Steege 1996).

The objective of this study, therefore, was to compare the canopy structure variables and solar radiation transmission estimates calculated using the four different programmes. With this paper, we want to share our experience with the different programmes with other users in order to help them to decide which programme provides the information needed to answer their particular research questions.

2 Material and methods

2.1 Study areas

The hemispherical photographs used in the evaluation were obtained from three different broadleaf forest ecosystems. They were selected in order to have a variety of canopy structures and solar radiation characteristics, contrasting latitudes and forest ecosystems (Tab. 1).

2.2 Photographic source material

A total of 78 hemispherical photographs were used for the evaluation. These comprised 13 photos made in canopy gaps at each location and a further 13 under closed canopies. All of the images were made using a digital Nikon Coolpix 990® camera (Nikon Corporation, Tokyo, Japan) fitted with a Nikon FC-E8® fisheye converter (Nikon Corporation, Tokyo, Japan). The camera was mounted on a tripod at a height of approximately 1.3 m above the ground. In the Sierra de Lema cloud forest the photos were taken at a height of between 1.5–1.7 m above the ground. The camera and the lens were arranged horizontally with the aid of a spirit level, and pointed to the magnetic north. Automatic settings for aperture width and shutter speed were selected (Inoue et al. 2004). Details of the photograph formats are presented in Table 2. Comparisons of the different image qualities and image sizes obtained using

Tab. 1: Charakterisierung des Untersuchungsgebietes.

Tab. 1: *The study areas and their characteristics.*

Location	Altitude(m a.s.l.), Slope (º)	Forest type	Top height (m),stocking (trees ha-[1]), basal area (m^2 ha-[1])
Weberstedter Holz Hainich National Park (Germany) [1]) (51°01'N, 10°04'E)	430 0	Temperate mixed deciduous beech forest on limestone, dominated by *Fagus sylvatica*	34 519 36
Sierra de Lema Forest, Canaima National Park (Venezuela) [2]) (05°53'N, 61°26'W)	1,435 0	Tropical cloud forest, very humid submontane forest	40 700 53
Río Cóndor,Tierra del Fuego (Chile) [3]) (53°59'S, 69°58'W)	190 0–10	Cold temperate evergreen forest, dominated by *Nothofagus betuloides*	31 1,362 105

[1]) Butler-Manning (2008), [2]) Hernández & Castellanos (2006), [3]) Promis (2009).

Tab. 2: Einzelheiten der Formatansprüche an die digitalen hemisphärischen Fotos.

Tab. 2: *Details of the digital hemispherical photograph formats.*

Location	Colour	Image quality*)	Pixels*	Format	Capture date
Weberstedter Holz Hainich National Park (Germany)	black and white	BASIC	2048 × 1536	1:16 compression JPEG	September 2002
Sierra de Lema Forest, Canaima National Park (Venezuela)	colour	BASIC	2048 × 1536	1:16 compression JPEG	June and October 2006
Río Cóndor, Tierra del Fuego (Chile)	black and white	HI	2048 × 1536	uncompressed TIFF	January and February 2007

*) The Nikon Coolpix 990 allows for four image qualities, namely basic, normal, fine and hi. Three image sizes are also possible; the largest is 2048 x 1536 pixels, the medium 1024 x 768 pixels, and the lowest 640 x 480 pixels. Thus, an 8MB CompactFlash memory card can store approximately 0 hi-quality images (each image is larger than 9MB); between 5 and 48 fine-quality images, depending on the image size used; 10 to 91 normal-quality images, and 19 to 161 basic-quality images.

a digital Nikon Coolpix 990 camera have revealed no statistically discernable differences in the estimates of either gap fractions or canopy openness (Inoue et al. 2004). In so far as it was possible, the photographs were only taken when the sky overhead was almost uniformly cloudy, or else shortly after sunset. The reason for this was to avoid the occurrence of bright regions around the sun and light reflection of foliage and woody structures, which can render thresholding difficult.

2.3 Image processing

All of the images were first cropped to squares to clearly define the image boundaries and the image centre (refer to Brunner 2002). The reason for this is that the fisheye photograph is a projection on a plane of a hemisphere, with the zenith at the centre of the image and the horizons at the edges. This image renders it possible to ascertain the distribution of canopy openings, and to estimate the solar radiation that penetrates below the plant canopy (Rich 1990).

A threshold value was then set for the separation of canopy and sky elements, producing a binary black and white image (Anderson 1964). In this study, all of the digital images were converted to binary black and white pixels employing an automatic threshold setting method based on edge detection (Nobis & Hunziker 2005), using the SideLook 1.1.01 software (http://www.appleco.ch, Nobis 2005).

2.4 Image analyses

2.4.1 The software used and their settings

All images were analysed using HemiView, Gap Light Analyzer, hemIMAGE and Winphot. All photographs were saved in the BMP format for analysis using HemiView, Gap Light Analyzer and Winphot. The programme requirements of the hemIMAGE software necessitated that the hemispherical photographs had to be converted to the GIF format (Brunner 2002).

The lens used was the Nikon fisheye FC E8. The lens was originally designed to produce a simple polar or equiangular projection, but new calibrations to this lens type have since been made (Frazer et al. 2001). Three of the programmes compared provided the option to set different calibrations to correct for the lens distortion. The Coolpix 900 was selected for HemiView (Hale & Edwards 2002). A third-order polynomial derived by Frazer et al. (2001) was set in the hemIMAGE software (Nikon-Coolpix 950) and into Gap Light Analyzer. Lens options cannot be set in Winphot, which assumes a polar or equiangular projection (H. Ter Steege, personal communication).

A uniform overcast sky (UOC) model was selected to describe the light intensity of the diffuse sky (Monteith & Unsworth 1990). As no actual measurements of the diffuse and direct radiation above the study areas were available, a relative proportion of direct and diffuse radiation equal to 0.5 was assumed for the three latitudes (Canham et al. 1990), providing for a comparable and uniform data base. The results were calculated on the basis of the specific vegetation periods corresponding to each site, namely April to September in the Weberstedter Holz (Germany), all year round in the Sierra de Lema (Venezuela) and from October to March in the Río Cóndor (Chile). The option to set the entire year as the vegetation period for the Venezuelan forest did not present a problem with any of the programmes, nor did the setting of a specific vegetation period for the other two forests in either Gap Light Analyzer or hemIMAGE. With HemiView specific periods can be calculated from the outputs obtained (refer to Rich et al. 1999). Using Winphot a specific vegetation period comprising a maximum of only 12 days can be set. In this case 7 days during the respective vegetation periods were chosen for the Weberstedter Holz (1st April, 1st May, 1st June, 1st July, 1st August, 1st September and 30th September) and for the Río Cóndor (1st October, 1st November, 1st December, 1st January, 1st February, 1st March and 31st March). The option in Winphot to include diffuse canopy light, which corresponds to the scattered radiation transmitted or reflected from foliage, was not selected.

In HemiView and Gap Light Analyzer, the photographs were divided into 16 azimuth and 9 zenith regions (144 sky regions in total). Winphot and hemIMAGE, alternatively, employ 89 fixed concentric rings, each one corresponding to a circular sphere segment in the sky hemisphere (Ter Steege 1996). These divisions are used by the programmes to calculate canopy structures and solar radiation transmittances with greater accuracy.

2.4.2 Calculated canopy structure and forest solar radiation environments

The direct, diffuse and global solar radiation estimations produced by all four programmes were cosine-corrected. This is useful when comparing hemispherical radiation flux estimates and measurements from cosine-corrected light sensors (Rich 1990). HemiView and hemIMAGE also provide non-cosine-corrected transmitted solar radiation outputs, which may be desirable for the purposes of measuring solar radiation from all directions. This is an important feature of potential light interception by non-flat surfaces (Rich et al. 1999), for example, a plant which has leaves oriented in many directions (Rich 1990).

The canopy structural characteristics estimated were canopy openness (CO) and effective plant area index (Le). Canopy openness is a sine-weighted estimate (Frazer et al. 1999) that represents the proportion of the image not obstructed by canopy (Hale & Edwards 2002). Although HemiView, Gap Light Analyzer and Winphot estimate leaf area indexes, in this paper the term plant area index (Le) was used, because hemispherical photographs do not distinguish between opaque objects (stems) and photosynthetic tissues (Holst et al. 2004). Therefore Le was defined as the sum of all elements blocking canopy light (stems, twigs, leaves).

To obtain the Le, the programmes used methods based upon the determinations of gap fractions in the canopy and inversion procedures. Thus, Le can be derived by inverting Eq. (1) (Norman & Campbell 1989):

$$\ln(T_i) = -K_{ij}\, x\, L_i \quad (1)$$

where Ti is the gap fraction at zenith angle θi, Kij is the extinction coefficient for a beam at zenith angle θi and a leaf inclination angle (αj), and Li is the plant area index at zenith angle θi.

Using Eq. (1) Gap Light Analyzer and Winphot introduce other relationships which finally produce Eq. (2) for the calculation of Le (Welles & Norman 1991):

$$L_e = 2 \sum_{\theta_i=1}^{5} -\ln(T_i)\ \cos(\theta_i)\ W_i \quad (2)$$

where θi corresponds to five fixed viewing angles (7, 23, 38, 53 and 68), Ti is the gap fraction around each viewing angle in bands of 15 degrees, and Wi is a fixed value weighted to account for an area correction (0.034, 0.0104, 0.160, 0.218 and 0.484, for the five angles referred to above). This is similar to the technique employed by the LAI 2000 plant canopy analyser. For the purposes of this evaluation, and as Le was estimated over zenith angles of 0–75°, it is subsequently denoted Le–75 here.

Le was also estimated using an inversion algorithm for canopy transmission employing an ellipsoidal leaf angle distribution (Le-E), which is incorporated into HemiView and Winphot. The basis of this method is that the leaf angle distribution of a canopy can be represented by the distribution of the area on the surface of an ellipsoid of revolution (refer to Campbell 1986, Norman & Campbell 1989, Rich et al. 1999). For an elliptical leaf angle distribution, the extinction coefficient – as defined by Eq. (1) above (Campbell 1986, Norman & Campbell 1989) – is shown in Eq. (3):

$$K_i = K(\theta_i, x) = \frac{\left([x^2 + \tan(\theta_i)^2]^{\frac{1}{2}}\right)}{D} \quad (3)$$

where θi corresponds to the zenith angles, x corresponds to the ellipsoidal leaf angle distribution parameter (ELADP), which is a ratio of vertical to horizontal foliage area projections and describes the shape of the distribution. A spherical distribution occurs when x = 1, whereas the canopy tends to be vertical and horizontal if x < 1 or x > 1, respectively (Walter 1989–2006). D is an expression of a normalised ellipse area, which is given by Eq. (4) in Winphot (Ter Steege 1996) and by Eq. (5) in HemiView (Wood 2001):

$$D = x + 1.774\,(x + 1.182)^{-0.733} \quad (4)$$

$$D = x + 1.702\,(x + 1.12)^{-0.708} \quad (5)$$

In Winphot x and L in Eqs. (1, 3 and 4) are solved using a Pascal translation of the Basic programme (Norman & Campbell 1989), which has also been adopted in HemiView (Rich et al. 1999).

Furthermore, a mean leaf angle or mean tilt angle (A) can be calculated using Eq. (6) (Walter 1989–2006):

$$A(x) = 9.65\,(x + 3.0)^{-1.65} \quad (6)$$

where A (the mean leaf angle) is in radians and x corresponds to ELADP.

2.5 Statistical analyses

A linear regression analysis was performed to test the strength of the relationship between the outputs (solar radiation transmittances and canopy structures) calculated by the different programmes. The 78 hemispherical photographs used for this study were stratified into two groups, according to the canopy condition. The analysis was carried out separately for those images made under canopy gaps (n = 39) and those under closed canopies (n = 39). For the regression analysis the goodness-of-fit was calculated using the coefficient of determination (R^2) and the significance of the p-value (Sokal & Rohlf 2000). All of the statistical analyses were performed using SPSS 15.0 for Windows (SPSS Inc.).

3 Results

3.1 Comparison of canopy structure estimates

Only HemiView, Gap Light Analyzer and Winphot provided canopy structure outputs. The canopies of the three forests were generally very dense, with the estimates of canopy openness computed ranging between 11.1 and 22.6 % (Tab. 3).

The estimates of the effective plant area index integrated over the zenith angle 0–75° (Le-75) were similar in each case, showing a range of values with an average of between 3–4 $m^2\ m^{-2}$ (Table 3). However, the maximum values of Le-75 in the Weberstedter Holz (Germany) estimated by both of the programmes used were very different (6.8 $m^2\ m^{-2}$ with Gap Light Analyzer and 10.7 $m^2\ m^{-2}$ with Winphot). The tendency indicated by these values was also similar to the computed estimates of effective plant area index using an ellipsoidal distribution (Le-E) for all sites (Table 3). In the case of the Weberstedter Holz there were again differences between the

Tab. 3: Charakteristika des Kronendaches der drei Testgebiete unter Verwendung der Programme HemiView (HV), Gap Light Analyzer (GLA) und Winphot (Wp). Die berechneten Variablen sind Offenheit des Kronendaches (CO) und der effektive Pflanzenflächenindex, errechnet als integrierter Wert für den Zenithwinkel 0–75° (Le-75), kalkuliert als elliptische Verteilung (Le-E). Ein '-' bedeutet, dass das Programm diese Variablenberechnung nicht leistet. Zahlen in Klammern geben die Spannbreiten an.

Tab. 3: *Characteristics of the canopy structures estimated for the three study areas using the programmes HemiView (HV), Gap Light Analyzer (GLA) and Winphot (Wp). The variables included are the canopy openness (CO), and the effective plant area indexes integrated over the zenith angle 0–75° (Le-75) and calculated using an ellipsoidal distribution (Le-E). A '-' means that the programme does not compute outputs for the variable. Numbers in brackets are ranges.*

Programme	CO (%)	Le-75	Le-E
Weberstedter Holz, Hainich National Park, Germany (51° 01' N, 10° 04' E)			
HV	18.5 (15.5–21.2)	-	2.9 (2.3–4.1)
GLA	18.4 (15.4–21.1)	3.1 (2.5–6.8)	-
Wp	19.2 (15.9–22.0)	3.2 (2.4–10.7)	3.2 (2.3–11.9)
Sierra de Lema Forest, Canaima National Park, Venezuela (05° 53' N, 61° 26' W)			
HV	14.9 (11.2–21.4)	-	3.8 (2.8–5.7)
GLA	14.8 (11.1–21.3)	3.8 (3.1–4.9)	-
Wp	15.5 (11.4–22.6)	3.8 (3.1–4.9)	3.7 (3.0–4.8)
Río Cóndor, Tierra del Fuego, Chile (53° 59' S, 69° 58' W)			
HV	14.9 (11.6–20.2)	-	3.9 (2.6–6.4)
GLA	14.8 (11.6–20.1)	3.4 (2.4–4.3)	-
Wp	15.4 (12.0–21.3)	3.4 (2.4–4.1)	3.3 (2.3–4.0)

Tab. 4: Koeffizienten von linearen Regressionen zum Vergleich der Offenheit des Kronendaches für einen Lückenbereich sowie geschlossenes Kronendach, berechnet mit den Programmen HemiView (HV), Gap Light Analyzer (GLA) und Winphot (Wp). R^2 ist das Bestimmtheitsmaß. * bedeutet Signifikanz auf dem 5 % Niveau, und ** auf dem 1 % Niveau.

Tab. 4: *Linear regression coefficients for the comparison of the canopy openness values associated with the two types of canopy condition estimated using the programmes HemiView (HV), Gap Light Analyzer (GLA) and Winphot (Wp). The two canopy conditions are canopy gaps and closed canopies. R^2 is the coefficient of determination. * indicates significance at the 5 % level, and ** at the 1 % level.*

Condition	Variable	Intercept	Slope	R^2	p-value	n
Canopy gap	HV vs GLA	0.033	0.993**	0.998	0.000**	39
	HV vs Wp	0.151	1.035**	0.995	0.000**	39
	GLA vs Wp	0.149	1.041**	0.993	0.000**	39
Closed canopy	HV vs GLA (Fig. 2a)	-0.023	0.998**	1.00	0.000**	39
	HV vs Wp	-0.044	1.033**	0.997	0.000**	39
	GLA vs Wp	-0.018	1.035**	0.997	0.000**	39

maximum values computed (4.1 m^2 m^{-2} with HemiView and 11.9 m^2 m^{-2} with Winphot).

The estimates of canopy openness revealed a strong, and high, correlation between the different software outputs (Tab. 4 and Fig. 2a). This was the case for both the hemispherical photographs taken in canopy gaps and those from under closed canopies ($n = 39$; $R^2 > 0.993$; $p < 0.01$ for all).

The computed estimates of effective plant area index (Le-75) were also highly correlated between the two programmes that calculated this variable (Tab. 5), namely Gap Light Analyzer and Winphot. The strong relationship was found under closed canopy conditions ($n = 39$; $R^2 = 0.994$; $p < 0.01$). However, in canopy gaps one hemispherical photograph showed a strong deviation in the Le-75 estimate (Tab. 5 and Fig. 2b), which produced a decrease in the coefficient of determination ($n = 39$; $R^2 = 0.859$; $p < 0.01$).

The relationships between the estimates of Le-E computed using HemiView and Winphot were very weak (Tab. 5). The relationship found under the closed canopy conditions was characterised by large variation ($n = 39$; $R^2 = 0.053$; $p < 0.05$). In canopy gaps there was no correlation between the estimates provided by both programmes ($n = 39$; $R^2 = 0.000$; $p = 0.939$). In general, the estimates of Le-E provided by HemiView deviated from those calculated using Winphot, and vice versa, with great deviations between individual hemispherical photographs (Fig. 2c).

In addition, the mean leaf angle (MLA) estimated, which is used to estimate the Le-E, in both conditions, in canopy gaps

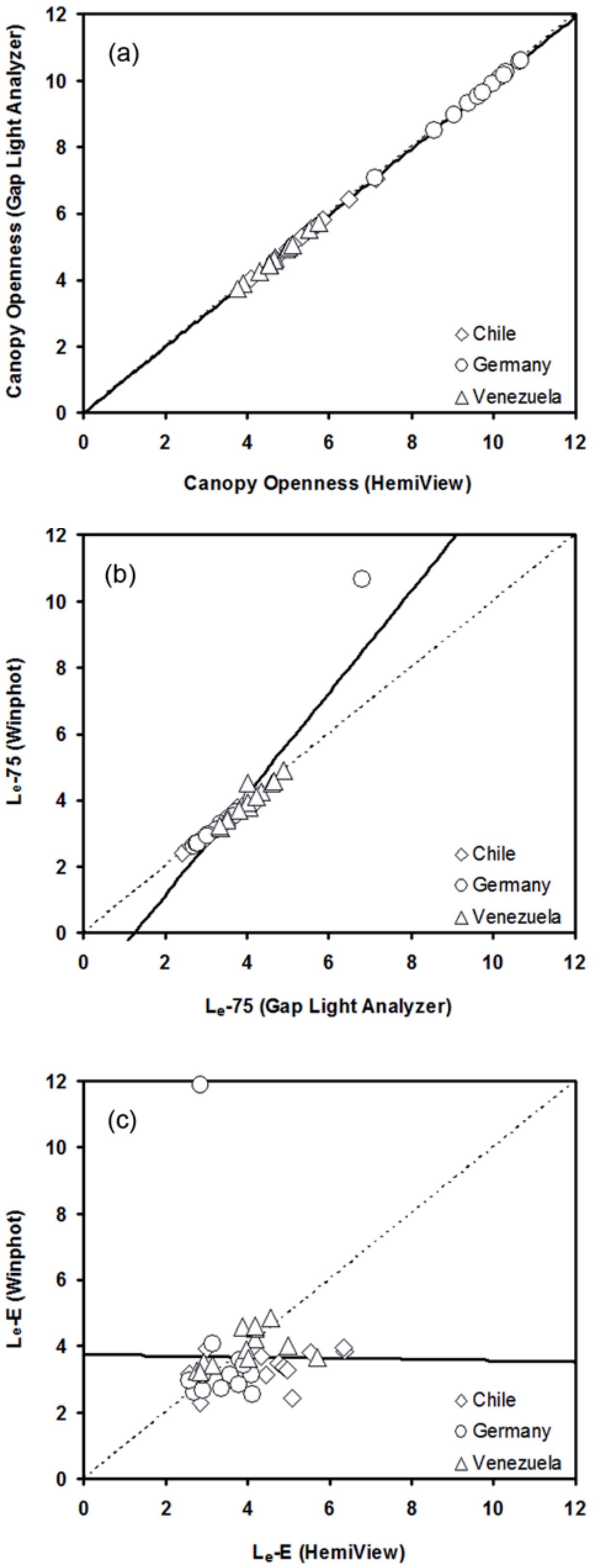

Abb. 2: Scatter plots der Beziehungen zwischen

(a) der Offenheit des Kronendaches unter geschlossenem Kronendach durch HemiView und Gap Light Analyzer,

(b) dem effektiven Pflanzenflächenindex, berechnet als integrierter Wert für den Zenithwinkel 0–75° (Le-75) in Kronendachlücken durch Gap Light Analyzer und Winphot, und

(c) der effektive Pflanzenflächenindex, berechnet als elliptische Verteilung (Le-E) in Kronendachlücken durch HemiView und Winphot.

Die durchgezogenen Linien entsprechen den Gleichungen in Tabelle 4 (Fig. 2a) und 5 (Figs. 2b und 2c). Die unterbrochenen Linien sind Referenzlinien des Verhältnisses zwischen den Variablen von 1:1.

Fig. 2: *Scatter plots of the relationships between*

(a) the canopy openness estimated under closed canopies using HemiView and Gap Light Analyzer,

(b) the effective plant area index integrated over the zenith angle 0–75° (Le-75) in canopy gaps estimated using Gap Light Analyzer and Winphot, and

(c) the effective plant area index calculated from an ellipsoidal leaf angle distribution (Le-E) in canopy gaps estimated using HemiView and Winphot.

The solid lines correspond to the equations in Tables 4 (Fig. 2a) and 5 (Figs. 2b and 2c). The broken lines represent a 1:1 reference.

and under closed canopy, showed variations. The weaker relationship was found for the canopy gaps (R^2 = 0.332), which indicates a high variability between the MLA estimated using HemiView and Winphot (Fig. 3).

3.2 Comparison of solar radiation transmittance estimates

All of the software packages evaluated in this study calculated cosine-corrected solar radiation transmittance. However, only two estimated the non-cosine-corrected solar radiation, namely HemiView and hemIMAGE.

3.2.1 Cosine-corrected solar radiation transmittance estimates

For all sites, the below-canopy cosine-corrected solar radiation values calculated from the hemispherical photographs were low to moderate (Tab. 6). The cosine-corrected direct, diffuse and global solar radiation transmittances ranged between 0.01–0.41, 0.06–0.25, and 0.04–0.36, respectively. The highest direct and global solar radiation transmittance values were always computed at the Sierra de Lema forest in Venezuela.

All of the estimates of the cosine-corrected direct, diffuse and global solar radiation transmittance under the two canopy variants incorporated in the study, namely gap and closed canopy, were significant and strongly correlated (n = 39; $R^2 > 0.886$; $p < 0.01$ for all). All four programmes calculated very similar estimates of the below-canopy solar radiation transmittance under both canopy conditions (Tables 7, 8 and 9 and Fig. 4).

3.2.2 Non-cosine-corrected solar radiation transmittance estimates

As with the previous results, the estimates of the non-cosine-corrected direct, diffuse and global solar radiation transmittances computed were between low to moderate (Table 7). The estimation of non-cosine-corrected direct, diffuse and global solar radiation transmittances ranged between 0.01–0.34, 0.04–0.13, and 0.03–0.23, respectively. Again, the brightest below-canopy environment was observed in the Sierra de Lema forest (Venezuela).

Tab. 5: Lineare Regressionskoeffizienten zum Vergleich des effektiven Pflanzenflächenindex für einen Lückenbereich sowie geschlossenes Kronendach, berechnet mit den Programmen HemiView (HV), Gap Light Analyzer (GLA) und Winphot (Wp), und errechnet als integrierter Wert für den Zenithwinkel 0–75° (Le-75), kalkuliert als elliptische Verteilung (Le-E). R^2 ist das Bestimmtheitsmaß. * bedeutet Signifikanz auf dem 5 % Niveau, und ** auf dem 1 % Niveau.

Tab. 5: *Linear regression coefficients for the comparison of both effective plant area indices associated with the two types of canopy condition estimated using the programmes HemiView (HV), Gap Light Analyzer (GLA) and Winphot (Wp). The variables are the effective plant area indices integrated over the zenith angle 0–75° (Le-75) and calculated using an ellipsoidal distribution (Le-E). The two canopy conditions are canopy gaps and closed canopies. R^2 is the coefficient of determination. * indicates significance at the 5 % level, and ** at the 1 % level.*

Condition	Variable	Intercept	Slope	R^2	p-value	n
Le-75						
Canopy gaps	HV vs GLA	0.033	0.993**	0.998	0.000**	39
Closed canopies	HV vs Wp	0.151	1.035**	0.995	0.000**	39
Le-E						
Canopy gaps	HV vs Wp (Fig. 2c)	3.758**	-0.018	0.000	0.939	39
Closed canopies	HV vs Wp	2.435**	0.273*	0.053	0.043*	39

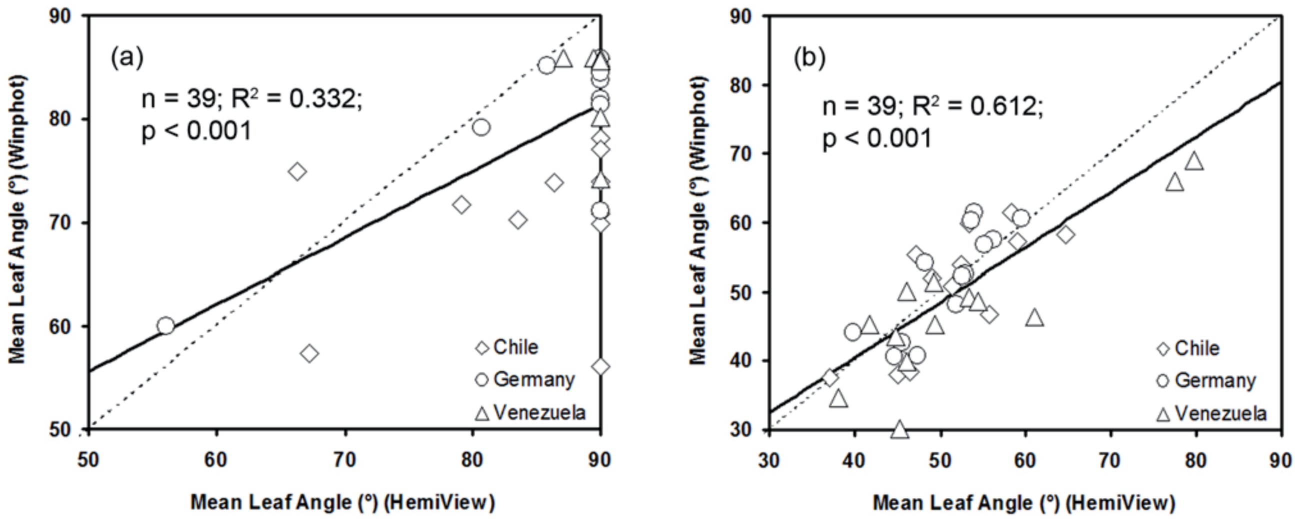

Abb. 3: Scatter plots einer linearen Regressionsanalyse des mittleren Blattwinkels (°) (MLA), berechnet durch HemiView und Winphot in a) Kronendachlücken und b) bei geschlossenem Kronendach. Die durchgezogenen Linien entsprechen den Gleichungen a) MLA (Winphot) = 23.357 + 0.645 MLA (HemiView), und b) MLA (Winphot) = 8.490 + 0.800 MLA (HemiView). Die unterbrochenen Linien sind Referenzlinien des Verhältnisses von 1:1 zwischen den beiden Berechnungsmethoden, also wenn HemiView und Winphot gleiche Werte erzielen würden.

Fig. 3: *Scatter plots of the linear regression analysis of the mean leaf angle (°) (MLA) estimated by HemiView and Winphot beneath a) canopy gaps and b) closed canopies. The solid lines correspond to the equations a) MLA (Winphot) = 23.357 + 0.645 MLA (HemiView), and b) MLA (Winphot) = 8.490 + 0.800 MLA (HemiView). The broken lines represent a 1:1 reference, where the mean leaf angle (°) estimated by HemiView would be equal to that estimated by Winphot*

Tab. 6: Charakteristika der transmittierten Einstrahlung (SRT) der drei Testgebiete, berechnet durch die Programme HemiView (HV), Gap Light Analyzer (GLA), hemIMAGE (hI) und Winphot (Wp). Die einbezogenen Variablen sind die direkte (DIR), diffuse (DIF) und gesamte (GLO) transmittierte Einstrahlung. Ein '-' bedeutet, dass das Programm diese Varablenberechnung nicht leistet. Zahlen in Klammern geben die Spannbreiten an.

Tab. 6: *Characteristics of the solar radiation transmittances of the three study areas estimated using the programmes HemiView (HV), Gap Light Analyzer (GLA), hemIMAGE (hI) and Winphot (Wp). The variables included are the direct (DIR), diffuse (DIF) and global (GLO) solar radiation transmittances. A '-' means that the programme does not compute outputs for the variable. Numbers in brackets are ranges.*

	Cosine-corrected SRT			**Non-cosine-corrected SRT**		
	DIR	DIF	GLO	DIR	DIF	GLO
Weberstedter Holz, Hainich National Park, Germany (51° 01' N, 10° 04' E)						
HV	0.12 (0.01–0.19)	0.16 (0.10–0.23)	0.15 (0.10–0.20)	0.11 (0.01–0.17)	0.10 (0.07–0.13)	0.10 (0.07–0.14)
GLA	0.12 (0.01–0.19)	0.16 (0.10–0.22)	0.14 (0.09–0.20)	-	-	-
hI	0.12 (0.02–0.19)	0.16 (0.10–0.23)	0.14 (0.09–0.20)	0.10 (0.01–0.16)	0.10 (0.07–0.13)	0.10 (0.05–0.15)
Wp	0.13 (0.02–0.22)	0.17 (0.11–0.24)	0.14 (0.07–0.21)	-	-	-
Sierra de Lema Forest, Canaima National Park, Venezuela (05° 53' N, 61° 26' W)						
HV	0.19 (0.03–0.39)	0.12 (0.06–0.23)	0.15 (0.04–0.31)	0.16 (0.02–0.34)	0.07 (0.04–0.13)	0.11 (0.03–0.22)
GLA	0.18 (0.03–0.37)	0.11 (0.06–0.23)	0.15 (0.04–0.30)	-	-	-
hI	0.18 (0.02–0.39)	0.11 (0.06–0.23)	0.15 (0.04–0.30)	0.16 (0.02–0.32)	0.07 (0.04–0.13)	0.11 (0.03–0.23)
Wp	0.20 (0.03–0.41)	0.12 (0.06–0.25)	0.17 (0.04–0.36)	-	-	-
Río Cóndor, Tierra del Fuego, Chile (53° 59' S, 69° 58' W)						
HV	0.08 (0.02–0.15)	0.11 (0.07–0.22)	0.10 (0.07–0.17)	0.07 (0.02–0.13)	0.07 (0.04–0.12)	0.07 (0.04–0.11)
GLA	0.08 (0.02–0.15)	0.11 (0.07–0.21)	0.09 (0.06–0.15)	-	-	-
hI	0.08 (0.02–0.15)	0.11 (0.07–0.21)	0.09 (0.06–0.15)	0.07 (0.02–0.13)	0.07 (0.04–0.12)	0.07 (0.04–0.10)
Wp	0.08 (0.02–0.14)	0.11 (0.07–0.24)	0.09 (0.05–0.14)	-	-	-

Tab. 7: Lineare Regressionskoeffizienten für den Vergleich der cosinus-korrigierten direkten transmittierten Einstrahlung für Kronendachlücken und geschlossenes Kronendach, berechnet durch die Programme HemiView (HV), Gap Light Analyzer (GLA), hemIMAGE (hI) und Winphot (Wp). R^2 ist das Bestimmtheitsmaß. * bedeutet Signifikanz auf dem 5 % Niveau, und ** auf dem 1 % Niveau.

Tab. 7: *Linear regression coefficients for the comparison of the cosine-corrected direct solar radiation transmittances associated with the two types of canopy condition estimated using the programmes HemiView (HV), Gap Light Analyzer (GLA), hemIMAGE (hI) and Winphot (Wp). The two canopy conditions are canopy gaps and closed canopies.* R^2 *is the coefficient of determination. * indicates significance at the 5 % level, and ** at the 1 % level.*

Condition	**Variable**	**Intercept**	**Slope**	R^2	**p-value**	**n**
Canopy gaps	HV vs GLA (Fig. 4a)	0.004**	0.930**	0.998	0.000**	39
	HV vs hI	0.001	0.973**	0.997	0.000**	39
	HV vs Wp	-0.003	1.067**	0.994	0.000**	39
	GLA vs hI	-0.003	1.044**	0.997	0.000**	39
	GLA vs Wp	-0.007*	1.145**	0.992	0.000**	39
	hI vs Wp	-0.003	1.096**	0.994	0.000**	39
Closed canopies	HV vs GLA	0.003	0.959**	0.987	0.000**	39
	HV vs hI	0.003	0.952**	0.938	0.000**	39
	HV vs Wp	-0.002	1.043	0.942	0.000**	39
	GLA vs hI	0.002	0.981**	0.928	0.000**	39
	GLA vs Wp	-0.002	1.068**	0.920	0.000**	39
	hI vs Wp	0.002	1.029**	0.886	0.000**	39

Tab. 8: Lineare Regressionskoeffizienten zum Vergleich der cosinus-korrigierten diffusen transmittierten Einstrahlung für Kronendachlücken und geschlossenes Kronendach, berechnet durch die Programme HemiView (HV), Gap Light Analyzer (GLA), hemIMAGE (hI) und Winphot (Wp). R^2 ist das Bestimmtheitsmaß. * bedeutet Signifikanz auf dem 5 % Niveau, und ** auf dem 1 % Niveau.

Tab. 8: *Linear regression coefficients for the comparison of the cosine-corrected diffuse solar radiation transmittances associated with the two types of canopy condition estimated using the programmes HemiView (HV), Gap Light Analyzer (GLA), hemIMAGE (hI) and Winphot (Wp). The two canopy conditions are canopy gaps and closed canopies. R^2 is the coefficient of determination. * indicates significance at the 5 % level, and ** at the 1 % level.*

Condition	Variable	Intercept	Slope	R^2	p-value	n
Canopy gaps	HV vs GLA	-0.001	0.993**	0.998	0.000**	39
	HV vs hI	0.000	0.997**	1.000	0.000**	39
	HV vs Wp	0.001	1.072**	0.994	0.000**	39
	GLA vs hI	0.001	1.002**	0.998	0.000**	39
	GLA vs Wp (Fig. 4b)	0.002	1.077	0.992	0.000**	39
	hI vs Wp	0.001	1.075	0.994	0.000**	39
Closed canopies	HV vs GLA	0.000	0.996**	0.999	0.000**	39
	HV vs hI	0.000	0.999**	1.000	0.000**	39
	HV vs Wp	-0.001	1.047**	0.997	0.000**	39
	GLA vs hI	0.000	1.003**	0.999	0.000**	39
	GLA vs Wp	0.000	1.050**	0.996	0.000**	39
	hI vs Wp	0.000	1.047**	0.997	0.000**	39

Tab. 9: Lineare Regressionskoeffizienten zum Vergleich der cosinus-korrigierten globalen transmittierten Einstrahlung für Kronendachlücken und geschlossenes Kronendach, berechnet durch die Programme HemiView (HV), Gap Light Analyzer (GLA), hemIMAGE (hI) und Winphot (Wp). R^2 ist das Bestimmtheitsmaß. * bedeutet Signifikanz auf dem 5 % Niveau, und ** auf dem 1 % Niveau.

Tab. 9: *Linear regression coefficients for the comparison of the cosine-corrected global solar radiation transmittances associated with the two types of canopy condition estimated using the programmes HemiView (HV), Gap Light Analyzer (GLA), hemIMAGE (hI) and Winphot (Wp). The two canopy conditions are canopy gaps and closed canopies. R^2 is the coefficient of determination. * indicates significance at the 5 % level, and ** at the 1 % level.*

Condition	Variable	Intercept	Slope	R^2	p-value	n
Canopy gaps	HV vs GLA	-0.007*	0.987**	0.989	0.000**	39
	HV vs hI	-0.009**	1.010**	0.990	0.000**	39
	HV vs Wp	-0.052**	1.333**	0.952	0.000**	39
	GLA vs hI	-0.002	1.020**	0.995	0.000**	39
	GLA vs Wp	-0.044**	1.358**	0.973	0.000**	39
	hI vs Wp	-0.041	1.330**	0.975	0.000**	39
Closed canopies	HV vs GLA	-0.003	1.013**	0.981	0.000**	39
	HV vs hI	-0.002	1.012**	0.955	0.000**	39
	HV vs Wp	-0.005	1.101**	0.921	0.000**	39
	GLA vs hI	0.002	0.990**	0.955	0.000**	39
	GLA vs Wp	-0.002	1.090	0.944	0.000**	39
	hI vs Wp (Fig. 4c)	0.000	1.068**	0.929	0.000**	39

The linear regression analysis of all of the non-cosine-corrected solar radiation transmittance values obtained for both the gaps and the closed canopy conditions also demonstrated strong relationships between the estimates produced by the two programmes ($n = 39$; $R^2 > 0.922$; $p < 0.01$ for all). This meant that both computed very similar results with respect to the transmittance of solar radiation irrespective of canopy condition (Table 10 and Fig. 5).

4 Discussion

4.1 Canopy structure and solar radiation transmittance

All of the comparisons of both variable types, namely canopy structure and below-canopy solar radiation environment, calculated using the different programmes revealed a high level of agreement, with no statistically discernable differences between the results produced. Irrespective of canopy

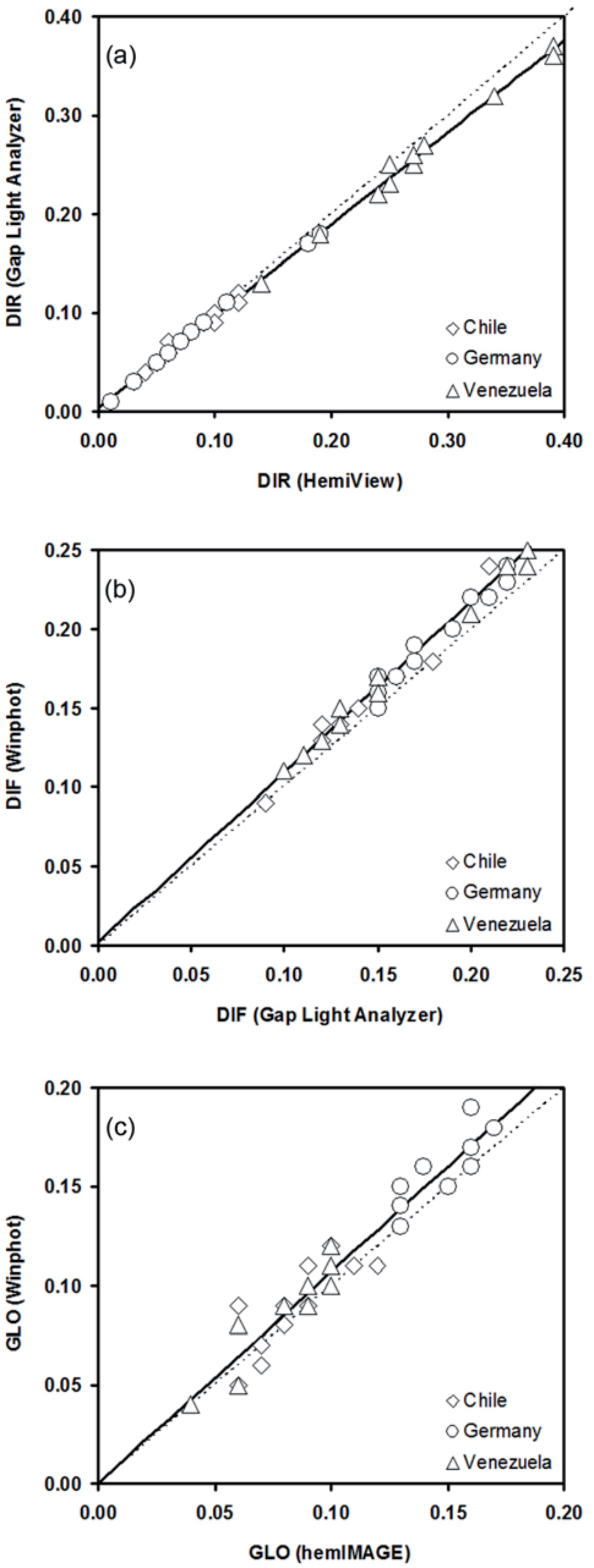

Abb. 4: Scatter plots der Beziehungen zwischen der

(a) cosinus-korrigierten transmittierten direkten Einstrahlung (DIR) in Kronendachlücken unter Verwendung von HemiView und Gap Light Analyzer

(b) cosinus-korrigierten transmittierten diffusen Einstrahlung (DIF) unter Verwendung von Gap Light Analyzer und Winphot, und

c) cosinus-korrigierten transmittierten globalen Einstrahlung (GLO) bei geschlossenem Kronendach, berechnet durch hemIMAGE und Winphot.

Die durchgezogenen Linien entsprechen den Gleichungen in Tabelle 7 (Fig. 4a), 8 (Fig. 4b) und 9 (Fig. 4c). Die unterbrochenen Linien sind Referenzlinien des Verhältnisses von 1:1.

Fig. 4: *Scatter plots of the relationships between*

(a) the cosine-corrected direct solar radiation transmittances (DIR) in canopy gaps estimated using HemiView and Gap Light Analyzer,

(b) the cosine-corrected diffuse solar radiation transmittances (DIF) in canopy gaps estimated using Gap Light Analyzer and Winphot and

c) the cosine-corrected global solar radiation transmittances (GLO) under closed canopies estimated using hemIMAGE and Winphot.

The solid lines correspond to the equations in Tables 7 (Fig. 4a), 8 (Fig. 4b) and 9 (Fig. 4c). The broken lines represent a 1:1 reference.

condition, the results produced by all four software packages proved to be almost similar.

The outputs of the four programmes almost always revealed a strong positive relationship ($R^2 > 0.859$) with respect to the evaluation of the two contrasting canopy conditions (gap and closed canopy). This coincided with the findings of FRAZER et al. (1997), who compared the canopy architecture (percent open sky and effective plant area index) of different forest chronosequences in British Columbia using Hemiphot and PAMAP GIS.

However, a comparison of the effective plant area index derived for both canopy gaps and under closed canopy conditions, calculated by HemiView and Winphot on the basis of ellipsoidal leaf angle distributions (Le-E), revealed only weak correlations.

Tab. 10: Lineare Regressionskoeffizienten zum Vergleich der nicht cosinus-korrigierten direkten, diffusen und globalen transmittierten Einstrahlung für Kronendachlücken und geschlossenes Kronendach, berechnet durch die Programme HemiView (HV) und hemIMAGE (hI). R^2 ist das Bestimmtheitsmaß. * bedeutet Signifikanz auf dem 5 % Niveau, und ** auf dem 1 % Niveau.

Tab. 10: *Linear regression coefficients for the comparison of the non-cosine-corrected direct, diffuse and global solar radiation transmittances associated with the two types of canopy condition estimated using the programmes HemiView (HV) and hemIMAGE (hI). The two canopy conditions are canopy gaps and closed canopies. R^2 is the coefficient of determination. * indicates significance at the 5 % level, and ** at the 1 % level.*

Condition	Variable	Intercept	Slope	R^2	p-value	n
Non-cosine-corrected direct solar radiation transmittances						
Canopy gaps	HV vs hI (Fig. 5a)	-0.001	0.968**	0.996	0.000**	39
Closed canopies	HV vs hI	0.007	0.895**	0.922	0.000**	39
Non-cosine-corrected diffuse solar radiation transmittances						
Canopy gaps	HV vs hI	0.000	0.989**	1.000	0.000**	39
Closed canopies	HV vs hI (Fig. 5b)	0.000	0.989**	1.000	0.000**	39
Non-cosine-corrected global solar radiation transmittances						
Canopy gaps	HV vs hI	-0.015**	1.139**	0.967	0.000**	39
Closed canopies	HV vs hI (Fig. 5c)	0.002	1.008**	0.951	0.000**	39

This may have been linked to the plant area index calculations, which are quite sensitive to small changes in cover. Therefore, in environments with dense cover, the computed plant area indexes might underestimate the actual situation (Ter Steege 1996). However, the hemispherical photographs input into each programme had the same format and resolution. The contrasting findings may have been due to different gap-fraction inversion procedures or mathematical algorithms used by the programmes, resulting in the calculation of different values. This can be observed in the different parameters featured in the equations incorporated into Winphot and HemiView (Eqs. 4 and 5, respectively). These calculate the extinction coefficient given in Eq. 3 and finally, by successive iterations, until the best effective plant area index (Le) is obtained from Eq. 1. Furthermore, the mean leaf angle estimated in both conditions, under both canopy gaps and closed canopy, showed variations. The weaker relationship was found for the canopy gaps (R^2 = 0.332), which indicates a high variability between the programmes (Fig. 3). The mean leaf angle variable can show the distribution of the ellipsoidal leaf angle distribution parameter (ELADP) in Eqs. 3, 4, 5 and 6. Its values are near to 0.0 when all canopy elements are vertical (90°). This was predominantly the case in the canopy gaps, as estimated by HemiView, and contrasted with the results obtained from the same hemispherical photographs with Winphot. Values near 1.0 show that the canopy has a spherical distribution, and values of ELADP $\rightarrow \infty$ when the canopy elements are more horizontal (0°).

The contrasting results may also have derived from the assumption of a random distribution of canopy elements, leading to either an under- or an overestimation in the calculation of the plant area indexes. This possibility has been described for conifer forests (Rich et al. 1999, Walter et al. 2003) and for forests with discontinuous canopies (Walter et al. 2003). The hemispherical photographs made in the gaps fall into the latter category. This can also be observed in Fig. 3, where the estimated values of mean leaf angle under closed canopy conditions were more closely related (R^2 = 0.612). However, both Gap Light Analyzer and Winphot also calculate the effective Le-75 on the basis of the assumption that canopy elements are randomly distributed. Yet, in this case (Table 5), the resulting values were strongly positively correlated (R^2 = 0.859). It would appear, therefore, that the contrasting results were not linked to the assumption of a random distribution of canopy elements.

Additional data relating to, for example, foliage clumping, the shading effects of branches and boles, slope corrections, etc., must be incorporated in order to improve estimates of plant area index. This is required because accurate estimates of plant area indexes are necessary in studies of forest ecology (Frazer et al. 2000, Walter and Torquebiau 2000, Walter et al. 2003). Coops et al. (2004) stated that a more accurate estimate of the effective plant area index can be achieved by comparing the estimates with actual leaf quantity measurements, or other direct leaf area index measurements (refer to Jonckheere et al. 2004). LAI measurements may, therefore, prove important as a method of calibration (Jonckheere et al. 2004), and calibration of the estimates of plant area index from hemispherical photographs might be made with those derived from allometric models.

Through the regression analysis, strong relationships were found when all of the outputs of solar radiation transmittances were compared (Tables 7, 8, 9 and 10, and Figs. 4 and 5), indicating that the results are comparable. Thus, it does not matter which program is used to estimate the below-canopy solar radiation from hemispherical photographs.

Finally, and in spite of the fact that the length of the vegetation period in Winphot was set to only 7 days for both the German and the Chilean forest, the results computed did not differ from those calculated on the basis of the complete length of the respective vegetation periods using the other programmes.

4.2 Other aspects requiring consideration when selecting a programme

All four of the software packages evaluated (HemiView, Gap Light Analyzer, hemIMAGE and Winphot) are Windows-based programmes. The minimum system requirements of each are

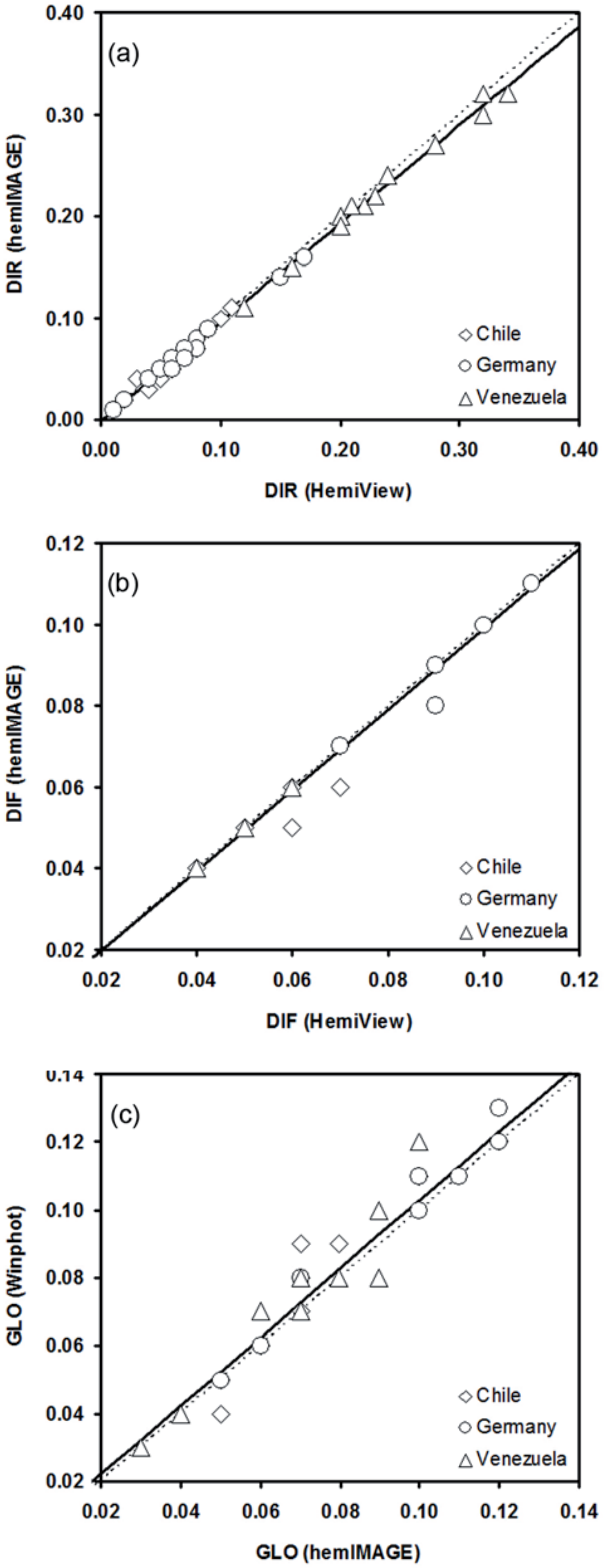

Abb. 5: Scatter plots der Beziehungen zwischen der

(a) nicht cosinus-korrigierten transmittierten direkten Einstrahlung (DIR) in Kronendachlücken unter Verwendung von HemiView und hemIMAGE,

(b) nicht cosinus-korrigierten transmittierten diffusen Einstrahlung (DIF) bei geschlossenem Kronendach unter Verwendung von HemiView und hemIMAGE.

Die unterbrochenen Linien sind Referenzlinien des Verhältnisses von 1:1.

Fig. 5: *Scatter plots of the relationships between*

(a) the non-cosine-corrected direct solar radiation transmittances (DIR) in canopy gaps estimated using HemiView and hemIMAGE,

(b) the non-cosine-corrected diffuse solar radiation transmittances (DIF) under closed canopies estimated using HemiView and hemIMAGE and c) the non-cosine-corrected global solar radiation transmittances (GLO) under closed canopies estimated using HemiView and hemIMAGE.

The solid lines correspond to the equations in Table 11. The broken lines represent a 1:1 reference.

Microsoft Windows 3.1 or later (Winphot), Microsoft Windows 95 or later (HemiView and Gap Light Analyzer), and Windows NT 4.0 or later (HemiView and Gap Light Analyzer). Other considerations in relation to the software system requirements are listed in Table 11.

One of the difficulties encountered using the programmes concerned the image file formats supported. hemIMAGE requires GIF files saved in the grey scales format (Brunner 2002), Winphot accommodates both BMP and PCX (Ter Steege 1996), whereas Gap Light Analyzer supports most common graphics formats, with the exception of compressed TIFF, GIF and newer formats like FlashPix (Frazer et al. 1999). The commercial product, HemiView, supports the following image formats: BMP, JPG, PCX, TIFF, TARGA and PCD (Rich et al. 1999). The latter two programmes can also support colour photographs. However, not all of the aforementioned file formats are produced by digital cameras. Graphics editing software such as Adobe Photoshop or the free image manipulation programme 'GIMP' is, therefore, necessary to convert the digital hemispherical photographs to the supported file formats. This can potentially increase the time needed for the analysis of hemispherical photographs.

The hemIMAGE software requires that all images are quadratic in shape (Brunner 2002), so that the programme can calculate the boundaries of the circular fisheye image and the zenith position. This, too, means that a graphics editing software is required. Winphot also requires a graphics editor, for the conversion of the images to be analysed to the required formats (refer to Ter Steege 1996). Incorporated within Winphot, Gap Light Analyzer and HemiView are registration or alienation processes to determine correctly the horizon on each photograph (Frazer et al. 1999, Rich et al. 1999, Ter Steege 1996). Therefore, in the case of these three programmes, the cropping procedure is not necessary. However, it was not tested whether these alienation processes rendered the image preparation less subjective, and easier, or whether they improved the accuracy of the subsequent analysis of the images.

Another factor often highlighted as a source of error associated with hemispherical photography relates to the classification and distinction of visible sky from obscured sky, commonly referred to as threshold setting. The programmes Gap Light Analyzer, Winphot and HemiView have an inbuilt interactive threshold setting tool, which can be applied to the complete photography or to a segment thereof (Frazer et al. 1999, Rich et al. 1999). However, there are also problems associated with this technique, caused by unevenness in the light conditions within hemispherical photographs (Rich et al. 1999). Manual threshold setting procedures have also been criticised for their subjectivity, with human interpretation considered a major source of error (Inoue et al. 2004, Ishida 2004, Nobis and Hunziker 2005, A. Brunner, personal communication). Automatic thresholding methods have been developed in recent times (Ishida 2004, Nobis and Hunziker 2005), which might eliminate this source of error. This may negate the need for the use of graphics editing software and interactive threshold setting tools.

A correction for lens distortion is integrated into the hemIMAGE, Gap Light Analyzer and HemiView software. The latter two programmes allow the user to input a new, user-defined lens distortion (Frazer et al. 1999, Rich et al. 1999). In hemIMAGE any new calibrations must be entered into the programme code by the programmer (Brunner 2002). Winphot, alternatively, assumes a polar or equiangular projection and lens options cannot be set (H. Ter Steege, personal communication). In this context, all lens calibrations used are very close to the polar or equiangular projection, and differences in the results produced by this setting procedure should not be expected.

The four programmes evaluated allow the user to store different file variables. Different configurations for site (latitude, longitude, altitude, time zone, magnetic correction for true north, slope, aspect), the time period (a specific day, growing season, year, etc.) and for the radiation models (universal overcast model, standard overcast model, percentage of both diffuse and direct radiation, etc.) can be saved. These stored settings can also be used later for further analysis of the images (Ter Steege 1996, Frazer et al. 1999, Rich et al. 1999, Brunner 2002).

All of the results generated by the three free programmes are saved as text files with different formats, all of which can be opened in a spreadsheet application like Microsoft Excel for further analysis (Ter Steege 1996, Frazer et al. 1999, Brunner 2002). The spreadsheets generated by the commercial software HemiView can be saved directly as MS Excel 5.0 files (Rich et al. 1999).

All four programmes were generally user friendly, but in each case it was necessary to understand the functions, tools and programme-specific characteristics to begin analysing the hemispherical photographs. Although each is accompanied by a user manual (Ter Steege 1996, Frazer et al. 1999, Rich et al. 1999, Brunner 2002), not all aspects are covered in the manuals. Brunner (2002), for example, assumed that the readers and users are familiar with the basic steps involved in the analysis of hemispherical photographs. Each manual includes a list of references or a bibliography, allowing readers and users to consult source literature directly.

Another positive aspect was the effective contact with the authors of the free software, and the almost immediate feedback to queries. Various requests made during both the configuration stage and the analysis of the results were answered more or less promptly. Communication with the makers of the commercial software, HemiView, proved somewhat more problematic and it was not possible to solve the issues with the treatment of the outlier in figure 3a.

Conclusions: It was possible to demonstrate that the characterisation of forest environment using digital hemispherical photographs, evaluated using a commercial software package (HemiView) and free software packages (Gap Light Analyzer, hemIMAGE and Winphot), resulted in similar estimates of the most commonly used canopy structure and solar radiation variables. Thus, irrespective of canopy condition and latitude, the results produced by all four software packages proved to

Tab. 11: Anforderungen der Programme an die 4 untersuchten PC-Systeme. Ein '-' bedeutet, dass keine Angaben zu den Voraussetzungen gegeben wurden.

Tab. 11: *Programme system requirements. A '-' means that no indication of the programme requirements has been given.*

Programme	Minimum operating system	Minimum RAM	Minimum hard disc	Minimum video display
HemiView	Microsoft Windows NT 4.0 Microsoft Windows 95	16 MB	10 MB	16 colour VGA
Gap Light Analyzer	Microsoft Windows NT 4.0 Microsoft Windows 95	64 MB	-	4 MB of 600 x 800 true-colour
hemIMAGE	-	-	-	-
Winphot	Microsoft Windows 3.1	-	-	-

be very similar. However, accurate estimates of forest canopy structure and below-canopy solar radiation environments are needed, and in the case of some variables the outputs of the programmes deviated, especially the outliers. This may lead to greater bias in the analysis of vegetation patterns in the forest. The calculation of the effective plant area index should be viewed with caution, as the comparison of the computed outputs with HemiView and Winphot revealed varying estimates. Moreover, the outline of the contrasting methods employed for the analysis of hemispherical photographs provided here might be used to develop a standard protocol for the evaluation of hemispherical photographs made in broadleaf forests, because the outputs of all four programmes were very similar.

Acknowledgements

This study was financed by the Chilean FONDEF Project D02I1080, the EU-financed 'Natural Management of Beech Forests in Europe' (Nat-Man) project, the German Academic Exchange Service (DAAD), the Association of Friends of the University of Freiburg (Verband der Freunde der Universität Freiburg i. Br.), the Dr.-Leo-Ricker Foundation in Freiburg (Dr.- Leo-Ricker-Stiftung in Freiburg i. Br.) and the International Ph.D. Programme 'Forestry in Transition' of the Faculty of Forest and Environmental Sciences of the University of Freiburg. Logistical and field work support were provided by the Wildlife Conservation Society in Chile (WCS), Programa de Bosques Patagónicos of the University of Chile, Gerencia de Gestión Ambiental of the CVG – EDELCA in Venezuela, the Canaima National Park (Eastern Sector) of the INPARQUES in Venezuela and the administration of the Hainich National Park in Germany. The authors would like to extend their gratitude to all of the organisations above, and to Mr. Joaquín Soto, owner of the forest in the Río Cóndor (Tierra del Fuego, Chile).

References

Anderson, M.C. (1964): Studies of the woodland light climate I. The photographic computation of light conditions. J. Ecol. **52**: 27-41.

Anderson, M.C. (1966): Stand structure and light penetration. II. A theoretical analysis. J. Appl. Ecol. **3**: 41-54.

Barnes, B.V., Zak, D.R., Denton, S.R., Spurr, S.H. (1998): Forest Ecology. 4th Edition John Wiley & Sons, Inc, New York: 774 pp.

Barrie, J., Greatorex-Davies, J.N., Parsell, R.J. & Mars, R.H. (1990): A semi-automated method for analyzing hemispherical photographs for the assessment of woodland shade.Biol. Conserv. **54**: 327-334.

Becker, P., Erhardt, D.W., Smith, A.P. (1989): Analysis of forest light environments. Part I. Computerized estimation of solar radiation from hemispherical canopy photographs. Agric. For. Meteorol. **44**: 217-232.

Bellow, G., Nair, P.K.R. (2003): Comparing common methods for assessing understory light availability in shaded-perennial agroforestry systems. Agric. For. Meteorol. **114**: 197-211.

Brunner, A. (2002): Hemispherical photography and image analysis with hemIMAGE and Adobe Photoshop, Horsholm, Denmark. http://statisk.umb.no/ina/ansatte/andrb.php

Butler-Manning, D. (2008): Stand structure, gap dynamics and regeneration of a semi-natural mixed beech forest on limestone in central Europe – a case study. Freiburger Forstliche Forschung, Vol. 38, Freiburg i. Br.: 253 pp.

Campbell, G.S. (1986): Extinction coefficients for radiation in plant canopies calculated using an ellipsoidal inclination angle distribution. Agric. For. Meteorol. **36**: 317-321.

Canham, C.D., Denslow, J.S., Platt, W.J., Runkle, J.R., Spies, T.A., White, P.S. (1990): Light regimes beneath closed canopies and tree-fall gaps in temperate and tropical forests. Can. J. For. Res. **20**: 620-631.

Chan, S.S., Mccreight, R.W., Walstad, J.D., Spies, T.A. (1986): Evaluating forest vegetative cover with computerized analysis of fisheye photographs. For. Sci. **32**: 1085-1091.

Chazdon, R.L., Field, C.B. (1987): Photographic estimation of photosynthetically active radiation: Evaluation of a computerized technique. Oecologia **73**: 525-532.

Clearwater, M.J., Nifinluri, T., Van Gardingen, P.R. (1999): Forest fire smoke and a test of hemispherical photography for predicting understory light in Bornean tropical rain forest. Agric. For. Meteorol. **97**: 129-139.

Comeau, P. (2000): Measuring light in the forest. Extension Note 42. Ministry of Forest Research Program, British Columbia. http://www.for.gov.bc.ca/hfd/pubs/Docs/En/En42.htm

Comeau, P., Gendron, F., Letchford, T. (1998): A comparison of several methods for estimating light under a paper birch mixed wood stand. Can. J. For. Res. **28**: 1843-1850.

Coops, N.C., Smith, M.L., Jacobsen, K.L., Martin, M., Ollinger, S. (2004) Estimation of plant and area index using three techniques in a mature native eucalypt canopy. Austral Ecol. **29**: 332-341.

Engelbrecht, B.M., Herz, H.M. (2001): Evaluation of different methods to estimate understorey light conditions in tropical forests. J. Trop. Ecol. **17**: 207-224.

Evans, G.C., Coombe D.E. (1959): Hemispherical and woodland canopy photography and the light climate. J. Ecol. **47**: 103-113.

Ferment, A., Picard, N., Gourlet-Fleury, S., Baralato C. (2001): A comparison of five indirect methods for characterizing the light environment in a tropical forest. Ann. For. Sci. **58**: 877-891.

Frazer, G.W., Trofymow, J.A., Lertzman, K.P. (1997): A method for estimating canopy openness, effective plant area index, and photosynthetically active photon flux density using hemispherical photography and computerized image analysis techniques. 73 pp. Can For Serv, Pac For Cent. Inf Rep No BC-X-373.

Frazer, G.W., Canham, C.D., Lertzman, K.P. (1999): Gap Light Analyzer (GLA): Imaging software to extract canopy structure and gap light transmission indices from true-colour fisheye photographs, users manual and program documentation. 36 pp. Simon Fraser University, Burnaby, British Columbia, and the Institute of Ecosystem Studies, Millbrook, New York.

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**: 249-263.

Gendron, F., Messier, C., Comeau, P.G. (1998): Comparison of various methods for estimating the mean growing season percent photosynthetic photon flux density in forest. Agric. For. Meteorol. **92**: 55-70.

Hale, S.E., Edwards, S. (2002): Comparison of film and digital hemispherical photography across a wide range of canopy densities. Agric. For. Meteorol. **112**: 51-56.

Hernández, L., Castellanos, H. (2006): Crecimiento diamétrico arbóreo en bosques de Sierra de Lema, Guyana Venezolana: primeras evaluaciones. Interciencia **31**: 779-786.

Holst, T., Hauser, S., Kirchgässner, A., Matzarakis, A., Mayer, H., Schindler, D. (2004): Measuring and modelling plant area index in beech stands. Int. J. Biometeorol. **48**: 192-201.

Inoue, A., Yamamoto, K., Mizoue, N., Kawahara, Y. (2004): Effects of image quality, size and camera type on forest light environment estimates using digital hemispherical photography. Agric. For. Meteorol. **126**: 89-97.

Ishida, M. (2004): Automatic thresholding for digital hemispherical photography. Can. J. For. Res. **34**: 2208-2216.

Jennings, S.B., Brown, N.D., Sheil, D.(1999): Assessing forest canopies and understorey illumination: canopy closure, canopy cover and other measures. Forestry **72**: 59-73.

Jonckheere, I., Fleck, S., Nackaerts, K., Muys, B., Coppin, P., Weiss, M., Baret F. (2004): Review of methods for in situ leaf area index determination. Part I. Theories, sensors and hemispherical photography. Agric. For. Meteorol. **121**: 19-35.

Machado, J., Reich, P.B. (1999): Evaluation of several measures of canopy openness as predictors of photosynthetic photon flux density in deeply shaded conifer-dominated forest understory. Can. J. For. Res. **29**: 1438-1444.

Monteith, J.L., Unsworth, M.H. (1990): Principles of environmental physics (2nd edition). Edward Arnold, London: 291 pp.

Nobis, M. (2005): SideLook 1.1. Imaging software for the analysis of vegetation structure with true-colour photographs. http://www.appleco.ch

Nobis, M., Hunziker, U. (2005): Automatic thresholding for hemispherical canopy-photographs based on edge detection. Agric. For. Meteorol. **128**: 243-250.

Norman, J.M., Campell, G.S. (1989): Canopy structure. pp. 301-325. In: Pearcy, R.W., Ehleringer, J.R., Mooney, H.A., P.W. Rundel (eds): Plant Physiological Ecology: Field Methods and Instrumentation. Chapman and Hall, London.

Promis, A. (2009): Natural small-scale canopy gaps and below-canopy solar radiation effects on the regeneration patterns in a Nothofagus betuloides forest – A case study from Tierra del Fuego, Chile. Ph.D. dissertation, University of Freiburg i. Br.: 186 pp.

Rich, P.M. (1990): Characterizing plant canopies with hemispherical photographs. Instrumentation for studying vegetation canopies for remote sensing in optical and thermal infrared regions. Remote Sens. Rev. **5**: 13-29.

Rich, P.M., Clark, D.B., Clark, D.A., Oberbauer, S.F. (1993): Long-term study of solar radiation regimes in a tropical wet forest using quantum sensors and hemispherical photography. Agric. For. Meteorol. **65**: 107-127.

Rich, P.M., Wood, J., Vieglais, D.A., Burek, K., Webb, N. (1999): Guide to HemiView: Software for analysis of hemispherical photography. Delta-T Devices, Ltd., Cambridge, England: 79 pp.

Roxburgh, J.R., Kelly, D. (1995): Uses and limitations of hemispherical photography for estimating forest light environments. New. Zeal. J. Ecol. **19**: 213-217.

Smith, W.R., Somers, G.L. (1993): A system for estimating direct and diffuse photosynthetically active radiation from hemispherical photographs. Comput. Electron. Agric. **8**: 181-193.

Sokal, R.R., Rohlf, F.J. (2000): Biometry. The principles and practice of statistics in biological research. Third Edition. W.H. Freeman and Company, New York: 863 pp.

Ter Steege, H. (1996): Winphot 5.0: A programme to analyze vegetation indices, light and light quality from hemispherical photographs. Tropenbos Guyana Reports 95-2, Tropenbos Guyana Programme, Georgetown Guyana.

Wagner, S. (1996): Übertragung strahlungsrelevanter Wetterinformation aus punktuellen PAR-Sensordaten in grossen Versuchsflächenanlagen mit Hilfe hemisphärische Fotos. Allg. Forst. Jagdztg. **167**:34-40.

Walter, J.-M.N. (1989-2006): CIMES. A package of programs for the assessment of canopy geometry through hemispherical photographs. Manual. Université Louis Pasteur, Strasbourg.

Walter, J.-M.N., Torquebiau, E.F. (2000): The computation of forest leaf area index on slope using fish-eye sensors. C.R. Acad. Sci. Paris, Life Sciences **323**: 801-813.

Walter, J.-M.N., Fournier, R.A., Soudani, K., Meyer, E. (2003): Integrating clumping effects in forest canopy structure: An assessment through hemispherical photographs. Can. J. Remote Sens. **29**: 388-410.

Welles, J.M., Norman, J.M. (1991): Instrument for indirect measurement of canopy architecture. Agron. J. **83**: 818-825.

Wood, J. (2001): Canopy light calculation. HemiView application note.

submitted: 23.09.2009
reviewed: 01.03.2010
accepted: 28.03.2010

Addresses of the authors:

Dr. Alvaro Promis,
Universidad de Chile,Departamento de Silvicultura y Conservación de la Naturaleza, Santa Rosa 11315, La Pintana,Casilla 9206,Santiago, Chile.
E-mail: alvaro.promis@gmail.com

Dr. Stefanie Gärtner,
University of Alberta, Department of Renewable Resources, Edmonton, Alberta, T6G 2H1, Canada.

Dr. David Butler-Manning,
Albert-Ludwigs-Universität Freiburg, Fakultät für Forst- und Umweltwissenschaften, Waldbau-Institut,
Tennenbacher Str. 4, D-79085 Freiburg i. Br., Deutschland.

Ph.D. Student Cristabel Durán-Rangel,
Universität Freiburg, Forstwissenschaftliche Fakultät, Waldbau-Institut,Tennenbacher Str. 4, D-79085 Freiburg.
Centro de Investigaciones Ecológicas de Guayana, Universidad Nacional Experimental de Guayana, Calle Chilmex, Puerto Ordaz, Venezuela.

Prof. Dr. Dr. h.c. Albert Reif,
Albert-Ludwigs-Universität Freiburg, Fakultät für Forst- und Umweltwissenschaften, Waldbau-Institut,
Tennenbacher Str. 4, D-79085 Freiburg i. Br., Deutschland.

Dr. Gustavo Cruz,
Universidad de Chile,Departamento de Silvicultura y Conservación de la Naturaleza, Santa Rosa 11315, La Pintana,Casilla 9206,Santiago, Chile.

Dr. Lionel Hernández,
Centro de Investigaciones Ecológicas de Guayana, Universidad Nacional Experimental de Guayana, Calle Chilmex, Puerto Ordaz, Venezuela.