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Application note

CIMES: A package of programs for determining canopy geometry and solar radiation regimes through hemispherical photographs

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ABSTRACT

CIMES is a multi-purpose, multi-platform, and free package of programs for the determination of solar radiation regimes and canopy structure attributes using hemispherical photographs. These command-line programs, like a toolbox, offer a unique set of features such as: a variety of approaches to invert gap fraction data, correction for slope (solar radiation and LAI), and different procedures to account for foliage clumping, spherical statistics for gap fraction distribution, photosynthetically active radiation (PAR) interception under clear- and overcast sky conditions, and sun-fleck dynamics. We present the general overview of the programs, the solar radiation regime, and the canopy structure estimates as processed by CIMES software. The most important point of CIMES compared to other software would be to have statistics and estimates for each single photosite including all available theoretical and empirical algorithms, so that anyone working on methods rather than application will have more freedom compared to other software. For application, the batch processing does everything.

1. Introduction

The major physiological processes of vegetation, including photosynthesis and evapotranspiration, are mainly determined by vegetation biophysical attributes that characterize canopy structure, biochemical properties, and solar radiation regimes. Parameters that measure these attributes are useful for applications such as: forestry, agriculture, landscape studies and land management, hydrological, meteorological, and meso-scale weather circulation forecasts. The biophysical parameters, such as fractional photosynthetically active radiation (fPAR), leaf area index (LAI), etc., are the main input for several numerical models of ecophysiology, ecosystem functioning and global change (Gower et al., 1999; Jia et al., 2011).

Radiometric and optical field instruments have been found out to be the only effective means to acquire *in situ* vegetation biophysical parameters (Welles and Cohen, 1996). Among several available optical field instruments, hemispherical (fisheye) photography is becoming a standard, as far as possible used in a multi-instrument and multi-model context (Chen et al., 2006). Hemispherical photography has the advantage over other optical techniques due to:

(i) The effect of radiation reflection and scattering, responsible for positive bias in gap, can be controlled by choosing an appropriate threshold to separate sky from foliage on the digital image,
(ii) The angular information contained in gap fraction data can be analyzed with details over all directions of the hemisphere,
(iii) The angular-dependent foliage clumping can be analyzed easily to all directions of the hemisphere,
(iv) The visual inspection of photographs is a precious aid for the interpretation of canopy structure and parameter estimates,
(v) If hemispherical photographs are acquired with standard procedure, it provides permanent archive which can be reprocessed when improved models become available, and
(vi) Hemispherical photography provides a valuable alternative to other indirect techniques when sunshine is too scarce to allow work with the transmission of a direct beam and when the absence of a large clearing, or a tower, makes reference measurements of full sky radiation impracticable.

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Hemispherical photographs (HP) are taken looking most often upward by means of a fisheye lens, an extreme wide-angle lens (Rich, 1990). The viewing angle typically approaches or equals 180°, so that all sky directions are simultaneously recorded. The resulting photographs record the structure of plant canopies and the sky visible through the canopy holes, or gaps. These features can be measured precisely and used to calculate solar radiation transmitted through (or intercepted by) plant canopies, as well as to estimate parameters of canopy structure, such as LAI. Detailed treatments from field acquisition of HP to theoretical methodologies and procedures have been described thoroughly in the literature (Jonckheere et al., 2004; Weiss et al., 2004).

Various commercial and non-commercial software programs have become available for HP processing and analysis. As the theoretical understanding is developing through a cascade of methodologies, most of the available software programs lack flexibility and hardly any one is designed to analyze HP for multiple purposes and multiple platforms as well. Multiple purposes imply, e.g., the possibility to compare LAI derived from a variety of approaches (Miller (1967), Lang (1986, 1987), and Campbell (1990)), clumping factors from a variety of formulas (modified Chen and Cihlar (1995), Lang and Xiang (1986), and mixed Leblanc et al. (2005)), diffuse sky radiance from heterogeneous clear-sky vs. isotropic overcast radiance models. Multiple platforms mean the user is able to run HP programs on any operating system (Windows, Unix, Linux, Mac OS).

The scope of this application note is presenting an overview and features of a multipurpose and a multi-platform package of programs called 'CIMES', to analyze HP for a wide range of applications, with full-fledged scientific descriptions and flexibility for the scientific community. The overview of the CIMES package of programs is presented, for gap fraction and gap size retrievals, canopy solar radiation regime and canopy structure estimates. For a review and a comparison of CIMES with current available programs and software dealing with HP analysis and processing, see Fournier and Hall (2011). The first section of this article describes the basic steps for acquiring and analyzing HP. The second section gives features of all CIMES programs. The third section describes how gap fractions and gap sizes, the basic data for all HP computation, are retrieved. The forth section provides theoretical and analytical assessments of canopy solar radiation regime through CIMES programs. The subsequent sections describe how canopy structural attributes like canopy openness, LAI, slope effects and clumping factors are derived through CIMES programs.

2. Hemispherical canopy photography

The best performance to retrieve solar radiation regimes and canopy structure from HP starts with careful considerations of the steps needed from planning through processing and finally calculating and archiving. The digital flow follows a prescribed order: (i) *Planning* the fieldwork, (ii) *Acquiring* HP as color images, (iii) *Input* implying image selection, lens calibration, quality control, channel selection, enhancement and registration (size, alignment and orientation), (iv) *Classification* transforming the grayscale image into a binary image for separating foliage from sky, (v) *Extraction* of gap fraction and gap size data, (vi) *Calculation* of solar radiation and canopy structure, (vii) *Output* to spreadsheet or other formats, and finally (viii) *Archival*.

We do not enter into details of each step, which requires careful attention, learning, experiment and skill. Most information about hemispherical photography of plant canopies lies in specialized publications and software manuals (Walter, 2009). A general textbook on hemispherical photography of forest canopies presenting practice, theory and applications will provide all information needed for the beginner (Fournier and Hall, 2011). However, we present some remarks about frequently overlooked procedures: (i) Orientation of the camera on slope, (ii) Exposure, and (iii) Classification.

Measurements on slopes require more care than flat surfaces. A plot should be chosen where slope and aspect are near constant. On sloping ground, two methods can be used for acquiring HP; either the camera is oriented normal to the datum or normal to the slope (Gonsamo and Pellikka, 2008). As a rule, HP should be taken always looking upward to the zenith, i.e. normal to the datum.

Precise exposure depends on multiple factors, in the first instance meteorological conditions. HP should be taken under overcast sky, or diffuse sky near dawn or dusk. Light conditions, film or image exposure, are critical. The 'best' images should offer good contrast between foliage and sky, easily controlled by scrutinizing *in situ* the image histogram, which should display two clearly separated peaks, one at the left hand (black = 0 on the grayscale), and one at the right scale (white = 255, for 8-bit images).

Classifying images into black (foliage) and white (sky) pixels is perhaps the most crucial step in HP techniques. Thresholding of the image for classification, traditionally performed through the visual comparison of gray-toned images, should be replaced systematically by automatic procedures, now easily available (Jonckheere et al., 2005). Although current software may include thresholding capabilities, they propose usually only a single method. In fact, universal all-purpose methods do not exist (Inoue et al., 2011): some work well for dense canopies at the expense of large gaps, while others do best for more open canopies at the expense of small gaps. There are excellent methods used for thresholding medical images, e.g. ImageJ software, which may do a much better job than any of the usual methods for HP. Used with consistency over a set of HP, an adapted method allows automatic thresholding, ensuring objectivity and repeatability in the classification process.

To process and analyze HP, the user is facing the choice between specialized software integrating a graphical user interface (GUI) and non-commercial scripts and programs that follow image preprocessing that may have been undertaken with third-party graphical software. In the first case, all procedures of image input, processing, classification, analysis, calculation and output are performed within a graphical user interface. The main advantage is a well-integrated digital flow that may occur at the expense of flexibility. In the latter case, only extraction of gap fractions and sizes is carried out, followed by calculation using in-house developed scripts or command-line programs.

3. CIMES features

CIMES software, a package of programs (Table 1) that work as a toolbox, corresponds to the non-commercial scripts and programs that follow image pre-processing that may have been undertaken with third-party graphical software. Consequently, the user often requires greater knowledge of the HP acquisition and processing chain (Section 2). In spite of complexities due to the use of external programs, batch analysis of sets of HP is in general easier and allows the processing of many data files in an automated single run.

CIMES software enters step (v) into the digital flow described in Section 2: extraction of gap fraction and size. *Gap fraction* is the proportion of openness for a given set of sky directions, typically either along sun path for calculation of direct radiation or for entire sky for diffuse radiation, sky view factor, LAI, etc. The extraction of gap fractions implies the creation of a sampling grid, or sky map, of hemispherical segments at the intersection of n zenith annuli $\times$ m azimuth sectors (Fig. 1). *Gap size* is the length of sequences of black and white pixels along circular transects, usually one degree in width, at one or multiple zenith directions, over the whole range

Table 1
The complete list and functions of CIMES programs.

Category	Program list and function
Main (core program)	GFA: gap fraction and gap size extraction from oriented digital images
Solar radiation regime assessment	• PARCLR, PARHOR, PARSOC, PARMOD: photosynthetic photon flux density, under clear-sky, overcast sky • SUNEPHEMERIS, SUNFLK: Sun ephemeris, sunfleck dynamics
Canopy geometry assessment	• READPHOT: gap fraction data display in a two-dimensional array • OPENNESS: gap distribution, canopy openness, canopy closure, fraction diffuse light (from isotropic sky luminance) • STATSPH: gap orientation statistics – spherical variance, directions of gap resultant and maximum gap inertia • LAILANG, LAIMLR, TRANSLAI: leaf area index after Lang – mean contact numbers, mean tilt angle, logarithmic averaging, data pooled over transects, grids • LAICMP, LAICAM, LOGCAM: leaf area index (total, sunlit and shaded), extinction coefficients, after Campbell – ellipsoidal x, mean tilt angle, local azimuthal sector values, and global values • CLMPML, PCS: LAI using modified Miller approach, modified Chen and Cihlar, Lang and Xiang, mixed (Leblanc) clumping factors, Pielou 'Coefficient of Segregation' • CMPSH and CMPBSH, CAMSH, LANGSH, CLMPMLSH: short versions of LAICMP, LAICAM, LAILANG and CLMPML for large data sets
Documentation	Detailed features and installation guides; manual file for hemispherical photography, theory, calculation and algorithms descriptions; read-me file and update histories
Miscellaneous	CIMES_GFA_SCRIPT for automatic use of GFA program under Windows environment. These scripts are adaptable to other platform environments

of azimuth angles, essentially for deriving clumping factors or indices (Gonsamo et al., 2010). In the following section, we describe in detail the CIMES program lists (Table 1) followed by CIMES core program (GFA) in Section 4.

CIMES programs have been devised and written since 1982, continuously revised and updated. CIMES package contains command-line programs, which are stand-alone and run independently of each other. Written in C and C++ languages, they ensure portability over any computing system: Windows, Mac OS X (Power PC, G4 and G5, and Intel-based, using Universal Binary), Linux and UNIX. Before running the programs, graphical pre-processing is needed, from steps (iii) and (iv) of the digital flow, using commercial or free graphical software.

Generally speaking, CIMES programs offer an original set of features for digital or digitized HP, allowing for total flexibility and automated processing workflow such as:

- A variety of algorithms to invert gap fraction data
- Local values for zenith annuli and azimuth sectors, and global values
- Selection of any range of zenith and azimuth view angles
- Calculation of several canopy structure variables
- Calculation of several solar radiation variables
- Correction for slope effects (solar radiation, LAI)
- Tools to account for foliage clumping
- Spherical statistics of gap fractions
- Ability to batch processing for sets of HP
- Output for spreadsheet and other formats
- Flexibility of command-line toolbox
- Multiplatform use: Windows, Mac OS, UNIX, Linux.

Programs of CIMES package are presented in Table 1. All programs have been tested on the Alpha Server 4000 under Digital Unix (True64 Unix), the PC under Microsoft Windows 95/98/2000, NT, XP, Linux (Ubutu), and Mac OS X (G4 and Intel-based, using Universal Binary format).

Programs such as CAMSH, CMPSH (plus CMPBSH), LANGSH and CLMPMLSH ('SH' for 'short') work the same way as LAICAM, LAICMP, LAILANG, CLMPML, respectively. The only difference: the output is organized in a single line. This allows the user to: (i) process easily dozens or hundreds of data files in only one run (batch mode), and (ii) display results in a spreadsheet format like Excel™. See USAGE in the appropriate parts of the user's manual and program documentation.

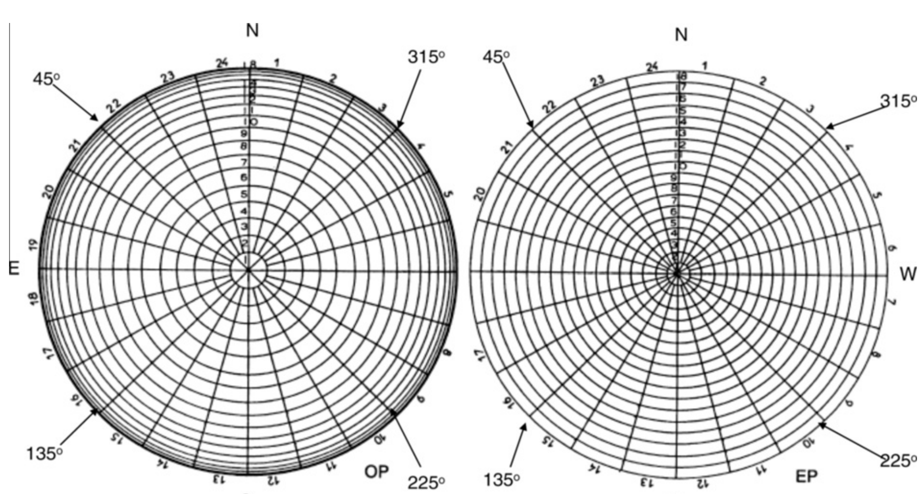

Fig. 1. Sky maps for two different geometric distortions of fisheye lenses. Sky divisions constitute the sampling grid for gap fraction extraction. Zenith annuli intersect azimuth sectors, defining segments of the object hemisphere projected onto the image plane. The examples show 18 zenith annuli 5° in width and 24 azimuth sectors 15° in width (24 × 18 = 432 segments). OP: orthographic projection, EP: equidistant (polar) projection. Both figures are represented the same size. N: North, S: South, E: East, and W: West. Note the inversion of E and W.

4. Gap Fraction Analysis (GFA)

Extraction of oriented gap fraction and size is the task of the core program of CIMES, GFA, for 'Gap Fraction Analysis'. GFA processes image files in BMP format only. Except a CIMES program called SUNEPHEMERIS, a utility, all remaining 21 programs use gap fraction data and/or gap size data created by GFA (Table 1). Image files can be supplied to the program either as gray-toned, or as binary files previously thresholded through appropriate software. Two geometric distortions of the fisheye lens are taken into account by GFA: the polar projection, by far the most common (Herbert, 1987), and the orthographic projection (Fig. 1). GFA is interactive, i.e. calls for entering the image file name, projection geometry (polar or orthographic), coordinates {x,y} of three points of the image circle (horizon), threshold value, magnetic declination, the choice for deriving either gap fraction (indicating numbers of zenith annuli and azimuth sectors) or gap sizes (indicating range of zenith angles and step, in degrees, usually 1).

GFA scans the pixel map of the oriented image from zenith through horizon, i.e. from the center through the circumference of the image, starting north moving westward. The number of zenith annuli and azimuth sectors determines the total number of sky divisions (segments). The choice of those numbers is important for the angular resolution of the analysis, which may affect all calculation (Gonsamo et al., 2010).

The program creates two alternative ASCII files: (i) gapfract.txt, for gap *fractions*, (ii) gapsize.txt, for gap *sizes*. These text files are created in overwrite mode, *not* in append mode.

5. Calculation of solar radiation regimes of forest canopies

Historically, the first use of HP was deriving 'light climate' in the pioneering works of Evans and Coombe (1951) and Anderson (1964). Only the Photosynthetically Active Radiation (PAR), a part of solar radiation in the 400–700 nm wavelengths, is considered here.

Six of the CIMES programs (Table 1) are used to calculate various outputs related with solar radiation regimes of forest canopies with appropriate input variables (Table 2). Direct (solar beam irradiance) and diffuse (sky irradiance) components of PAR are calculated separately. Direct component is calculated as the sum of all direct radiation originating from non-obscured sky directions along the sun path, whereas diffuse component is calculated as the sum of all diffuse radiation (scattered from the atmosphere) originating from any non-obscured sky directions of the hemisphere. The sum of direct and diffuse components gives 'global' or 'total' PAR. The Photosynthetic Photon Flux Density (PPFD) is expressed either in quantum (μmol m^{-2}, mol m^{-2} d^{-1}) or in energy units (W m^{-2}, MJ m^{-2} d^{-1}). Site factor is the radiation penetrating a canopy as a fraction of that incident on the canopy, all measurement conditions being identical. This notion applies to direct, diffuse and total radiation; hence direct (DSF), diffuse or indirect (ISF) and total (TSF) site factors. All CIMES programs deriving solar radiation regimes use the same command-line input frame:

[program file] [parameter file] [gap fraction file] [output file]↵.

There are several input parameters, assumptions and equations required for solar radiation calculations programs (parameter file). Table 2 presents the important input parameters required to run the programs. Some parameters (condensable water, air turbidity), not easily available, may be found on a regional scale from meteorological or climatological stations, and used as a guess or for sensitivity analyses. All the models and algorithms for specific calculation are described in the respective program's manual with extensive literature review.

Numerous textbooks (Robinson, 1966; Gates, 1980; Ross, 1981; Iqbal, 1983; Varlet-Grancher et al., 1993) and international journals have published models, theoretical and empirical equations describing fluxes of shortwave solar radiation and PAR and their use in ecology and ecophysiology. Some particular algorithms, barely found in other commercial software, are used in CIMES programs for the calculation of: (i) PAR scattered by foliage through the canopy (Norman et al., 1971; Flerchinger and Yu, 2007), and (ii) ground-reflected radiation (Dogniaux, 1976). Daily incident and transmitted values are expressed with respect to horizontal and according to topography.

Program PARCLR computes PAR, intercepted and transmitted by canopies, under clear-sky conditions. Using a heterogeneous clear-sky radiance distribution model (Grant et al., 1996) is a particular feature of the program, different from most common available software, which use isotropic sky-radiance models like uniform overcast (UOC), or standard overcast (SOC). The program uses gap fraction data from hemispherical photographs. Thus, combined with heterogeneous clear-sky radiance and azimuthal canopy data, PARCLR takes into account all radiation and structural heterogeneities for PAR estimates (Wang et al., 2006).

Program PARHOR presents a detailed account of hourly estimates of incident PAR and solar data for each selected day. PARHOR is a companion program of PARCLR. PARHOR is useful for understanding how some geometric, topographic and atmospheric variables and parameters are associated in PARCLR program.

Program PARMOD is based on Campbell ellipsoidal model of leaf angle distribution (Campbell, 1990), from which LAI, mean tilt angle, ellipsoidal extinction coefficient and shape-parameter *x* are derived first. Scattering is estimated after Flerchinger and Yu (2007), explicitly based on these parameters. LAI and the ratio of diffuse to total PAR serve also as parameter input to an alternative model of radiation scattering by Norman (1979), for comparison. Contrarily to PARCLR, which provides azimuthal data estimates encompassing all sky and canopy heterogeneities, program PARMOD smoothes out these heterogeneities (Walter, 1993).

Program PARSOC computes incident and transmitted PAR under standard overcast sky conditions, with two options: moderately and heavily overcast. PARSOC takes into account the influence of latitude on the angular distribution of SOC (Steven and Unsworth, 1980). A slightly modified version of (Norman et al., 1971) algorithm is used for deriving PAR upwelling.

Program SUNFLK analyses sun-fleck dynamics beneath canopies, for any day and latitude from gap fraction data. Sun-fleck dynamics play an important role for animal life, micro-fauna and flora, undergrowth plants – including seeds, seedlings, saplings – and soil processes as well (Chazdon, 1988; Pearcy, 1990). The underlying hypotheses are: parallel beam of sun radiation, absence of penumbral effects, and opacity of foliage to PAR.

Table 2
Overview of the main input data required for solar radiation calculations using CIMES.

Category	List of input parameters
General data	Image ID, geometric correction, channel (RGB), number of zenith rings, number of azimuth sectors, zenith view angle
Topographic data	Slope, aspect, topographic mask, and altitude
Geographic data	Orientation, magnetic declination, latitude, longitude, time zone
Biological data	Leaf reflectance and transmittance, soil reflectance, seasonal period
Atmospheric data	Cloudiness index, spectral fraction, beam fraction, condensable water, air turbidity
Astronomic data	Solar constant, year (leap), days of year, solar time step, time integration
Calculation options	Sky radiance models, radiation units

A utility program, SUNEPHEMERIS, computes commonly required data related to the sun and the photoperiod on an hourly basis. For all CIMES solar radiation programs, except SUNFLK, values are calculated on a daily-integrated basis, the time resolution being hourly. For SUNFLK the time resolution is 3 min, meaning that the sun's position is calculated for every 3 min.

The problem of time resolution vs. spatial resolution of the gap-fraction sampling grid (sky map) is of concern. Results may change significantly according to the sky map resolution, a problem often overlooked (Gonsamo et al., 2010). The resolution of the gap-fraction sampling grid should be as close as possible to 18 zenith annuli by 24 azimuth sectors for programs PARCLR, PARHOR and PARSOC, since the time resolution is hourly. The sky map for SUNFLK should be adjusted to the finer time resolution. Thus, a sky map 36 by 144 is adapted, with sky segments 2.5° zenith × 2.5° azimuth angular widths. Solar radiation regimes are highly determined by canopy structure, the matter of the next sections.

6. Canopy structure

Canopy structure, or architecture (Ross, 1981; Gower et al., 1999), is generally understood as the spatial and temporal arrangement of vegetation components or elements, at various scales. The geometric approach to canopy structure quantifies the area, pattern and orientation of plant components such as leaves, trunks, flowers and fruits, and the size, morphology and dispersion of gaps which separate them (Welles and Cohen, 1996). The statistical analyses of these properties lead to such a reduction of data that only a few synthetic descriptors are retrieved, such as canopy openness (CO), canopy closure (CC), leaf area index (LAI), mean tilt angle or average leaf inclination angle (ALIA), and canopy element clumping index (CI).

Canopy geometry is defined by three sets of basic properties with respect to plant, or canopy, elements: (i) spatial dispersion (random, clumped, regular), (ii) angular distribution (planophile, plagiophile, erectophile, extremophile, spherical, ellipsoidal, and conical based on the de Wit's terminology), and (iii) areal extension (leaf, wood, bark, plant or canopy element area and density) (Nilson, 1971; Andrieu and Baret, 1993; Bréda, 2003; Fournier, 2003). CIMES provides insight into connected aspects of forest structure often overlooked, which may deeply affect estimates of parameters: (i) the size, morphology and spatial dispersion of canopy gaps, (ii) the LAI and angular distribution of foliage, (iii) the effects of landform on LAI and leaf angle distribution, and (iv) the non-randomness of canopy element distribution (foliage clumping).

In the following sections, we present algorithms and calculation of canopy indices of structure, such as total gap (TG), canopy openness (CO) and closure (CC), and site openness (SO). The calculation of this first group of attributes does not need theoretical assumptions, except that of 'black' leaves, i.e. leaves supposed to be opaque to incoming solar radiation. Conversely, LAI, ALIA, and CI, the second group, need consideration about model assumptions, in particular for the 1-D gap fraction inversion model described by Nilson (1971), and commonly envisaged. The next section presents the first group of canopy indices, followed by the section describing the second group of canopy indices.

6.1. Size, morphology and spatial dispersion of canopy gaps

Gap fraction in any particular direction of the canopy is the fraction of open sky not obstructed by canopy elements. Gap fraction ranges from 0 (completely obstructed sky) to 1 (completely open sky). There is always an implied area over which gap fraction is taken. Thus, gap fraction is computed from a digital image classified into black (B) and white (W) pixels separating canopy elements and sky:

$$P_o(\theta, \varphi) = P_W/(P_B + P_W) \quad (1)$$

where θ is the mid-point of zenith angle and φ is the mid-point of azimuth angle of a portion of the hemisphere projected to the image plane, P_B is the number of black pixels, and P_W is the number of white pixels contained in that segment (Fig. 1). Therefore, in hemispherical photography, gap fraction represents the relative proportion of open sky contained in any defined region on the projected image plane. The projected image plane is divided into elements of a sampling grid, according to the geometric distortion of the fisheye lens (Fig. 1). CIMES utility program called READPHOT displays in a matrix form the oriented gap fraction data sampled on the grid of the projected image plane. Total gap (TG) is nothing but the mean gap fraction over the selected range of zenith and azimuth angles, usually for the entire hemisphere. Canopy openness (CO) originates in the need to correct gap fraction data obtained from the hemisphere projected onto the image plane, for the geometric distortion produced by the fisheye lens. CO is a good indicator of basic canopy structure and the potential penetration of solar radiation. CO is equivalent to the sky view factor (SVF) used by architects for urban planning and by foresters. CO may be defined (Frazer et al., 1997) as:

$$\mathrm{CO} = \sum_{1}^{N} P_o(\theta, \varphi) \cdot [(\cos\theta_1 - -\cos\theta_2)/n] \quad (2)$$

where θ_1 is the smallest zenith angle, θ_2 is the largest zenith angle of a segment of the hemisphere, n is the number of divisions of azimuth angles, N is the total number of segments used in the application. CO takes into account the morphology and orientation of gaps. In order to obtain this structural canopy attribute for undistorted size and shape of gap, the image must be projected back to the object sky hemisphere (Fig. 1). Canopy closure, or cover, is the complement to canopy openness (CC = 1 − CO). Other formulas for both CO and CC, not detailed here, are available in CLMPML program. CC may be expressed over the whole hemisphere, or for any selected zenith view angle (for example 15°, 25°). On slopes, CO and CC are calculated discarding the topographic shading. Site openness includes the topographic shading (Frazer et al., 1997). All CIMES programs compute TG, CO, CC, and SO for the whole range of zenith angles or for a limited zenith view angle.

Jupp et al. (1980) were the first to introduce gap orientation statistics, useful to interpret the spherical gap distribution. Indeed, each direction cosine of the hemisphere is weighted by a gap fraction. These gap-weighted vectors are used to define a spherical resultant whose direction (spherical mean) should be near the zenith in most canopies. The spherical variance measures the concentration of gaps about that direction. In a canopy whose gap distribution is close to the Poisson model, the direction of the resultant and the direction of maximum inertia should be identical. The higher the spherical variance, the more dispersed the gaps about the resultant. The spherical variance is inversely related to ALIA and to LAI. Program STATSPH does these gap orientation statistics computations. As far as we know, CIMES is the only HP software performing these computations.

The next section describes algorithms and calculations of leaf area and clumping indices implemented in CIMES programs.

6.2. Leaf area index

LAI may be defined as one half the total surface area of green leaves per unit horizontal surface area (Chen and Black, 1992), also quoted as hemi-surface area index (HSAI, Norman and Campbell, 1989). For recent presentations of underlying theory and applications, see Jonckheere et al. (2004), Weiss et al. (2004) and Fournier and Hall (2011).

Using optical field instruments such as hemispherical photography, LAI is derived from inversion of gap fractions. Considering the Poisson model of gap frequency distribution, the canopy is assumed to be closed and horizontally homogeneous, with plant elements oriented at random with respect to azimuth. Moreover, the canopy elements are assumed small in size and spatially distributed at random within the canopy volume considered. Deviation from randomness of foliage distribution can be expressed by a constant factor, the clumping index. Furthermore, the canopy elements are assumed opaque to solar radiation ('black leaves'). Thus, the canopy looks like a horizontally homogeneous layer with foliage varying in density only along the vertical axis. A 1-D light extinction model in vegetation canopies is the Poisson model (Nilson, 1971). Although unrealistic, due to clumping effects, random canopy models are the most commonly used, with various degrees of sophistication.

A general expression for estimating LAI by gap fraction inversion may be written as:

$$\mathrm{LAI} = \frac{-\ln(P_0(\theta)) \cdot \cos\gamma}{G(\theta) \cdot \Omega(\theta) \cdot \cos\beta} \tag{3}$$

where LAI is the leaf area index, $P_0(\theta)$ is the mean gap fraction at zenith angle θ, $G(\theta)$ is the angle-dependent extinction coefficient per unit leaf area measured at incidence angle θ of a ray of light, $\Omega(\theta)$ is the angle-dependent canopy clumping index, $\cos\gamma$ is a correction factor for path length, and $\cos\beta$ is a correction factor for ground slope β. Eq. (3) may be simplified, considering a random canopy with $\Omega(\theta) = 1$ and a spherical distribution of leaf angles with $G(\theta) = 0.5$. The product $\mathrm{LAI} \times \Omega(\theta)$ is the 'effective' leaf area index, $\mathrm{LAI_e}$. In fact, LAI in Eq. (3) is a 'plant area index' LAI_p, no distinction being made between photosynthetic and non-photosynthetic surfaces.

CIMES programs are based on varying assumptions about leaf angle distributions and mathematical techniques to invert LAI from gap fraction measurements. We group these programs according to approaches by Miller (1967), Lang (1986, 1987) and Campbell (1990).

6.3. Miller approach

From Gap Fraction Analysis, Miller's theorem applies to integral estimated over $\pi/2$. As most gap fraction data are retrieved over a zenith view angle $<\pi/2$, the discrete approximation:

$$\mathrm{LAI} = -2 \cdot \frac{\sum_{i=1}^{n} \ln[P_0(\theta_i)] \cdot \frac{\cos\theta_i}{\Omega(\theta_i)} \cdot \sin\theta_i \Delta\theta_i}{\sum_{i=1}^{n} \sin\theta_i \Delta\theta_i} \tag{4}$$

may be used, as in CLMPML, CLMPMLSH and PCS, where n is the number of zenith angles being used. The formula uses a $\sin\theta_i \Delta\theta_i$ weighting, normalized to the sum of 1, for each angle-dependent estimation of LAI, between the limits of the integral. This property, among other considerations, allows the calculation over a more restricted zenith angle range. For example, calculation may be applied over 55°–60° of zenith angle. This range of angles brackets the sun's beam incidence angle $\theta_b = 57°.3$ (≈ 1 radian), where the mean projection of leaf area $G(\theta)$ and the extinction coefficient $K(\theta)$ are virtually independent of the leaf angle distribution. Other useful ranges of zenith angles where the G becomes independent of leaf angle distribution can be found in Gonsamo et al. (2010).

6.4. Lang approach

From Eq. (3), the following expression can be derived:

$$-\cos\theta \cdot \ln P_0(\theta) = \mathrm{LAI} \cdot G(\theta) = \kappa(\theta) \tag{5}$$

where $\kappa(\theta)$ is the mean contact number. The mean contact number is determined by the overlapping of projected areas of leaves on a plane perpendicular to the direction of the ray of light, which penetrates the canopy along a given path length. Lang (1986, 1987) argued that LAI and ALIA may be recovered from the inversion of Eq. (5), using the relationship:

$$\kappa(\theta) = a + b \cdot \theta \tag{6}$$

where a and b are empirical regression parameters. Using original Miller's integral for flat leaves with symmetry about azimuth yields:

$$\mathrm{LAI} = 2. \int_0^{\pi/2} \kappa(\theta). \sin\theta d\theta \tag{7}$$

By substituting (6) into (7):

$$\mathrm{LAI} = 2 \cdot (a + b) \tag{8}$$

Eq. (8) is the exact solution to Miller's integral. This simple plot yields the effective LAI (LAI_e). The mean leaf inclination angle can be derived from the slope b, by using a polynomial regression.

CIMES program LAIMLR uses this procedure described by Lang (1987), whereas programs LANGLAI and LANGSH rely on a graphical procedure described in detail by Lang (1986). A great advantage of these approaches is the possibility to estimate statistical reliability of LAI and ALIA, derived from the goodness-of-fit of the regression.

6.5. Campbell approach

Campbell method relies on the ellipsoidal distribution function of leaf angles (Campbell, 1990). The ellipsoidal distribution function assumes that the leaf angles in the canopy are "distributed like the angles of normals to small area elements on the surface of an ellipsoid". The 'shape parameter' x may be defined as the ratio of vertical to horizontal foliage area projections, which describes the shape of the distribution. For example, if $x = 1$, leaves have a spherical distribution. The canopy tends to be 'horizontal' or planophile, when $x > 1$ and 'vertical' or erectophile, when $x < 1$ (Fig. 2). The shape parameter determines an ellipsoidal extinction coefficient $K_e(\theta)$ and a normalized ellipse area. A non-linear constrained least-squares technique finds values of x and LAI. ALIA can be derived as a function of x. Programs LAICAM, LAICMP, CAMSH, CMPSH, CMPBSH use Campbell approach.

For conventional use of CIMES program to calculate LAI, we have recently developed TRANSLAI program that uses data pooled over transects or grids, for processing pooled gap fractions or contact numbers from a certain number of single photosites covering the same plot. The good point of CIMES would be to have statistics for each single photosite, so that anyone working on methods rather than application will have more freedom compared to other software. For application, the batch processing does everything.

6.6. Leaf area index corrected for slopes

Many forest remnants on Earth are located on hilly or highly dissected terrain, even though the effect of landform on LAI estimates has scarcely been envisaged (Frazer et al., 1997; Walter and Torquebiau, 2000; Gonsamo and Pellikka, 2008; Courbaud et al., 2003; Duursma et al., 2003). Plain observations show that forest architecture may be deeply modified by slope. On steep slopes, trees usually bear asymmetric crowns expanded downslope, and shade intolerant trees tend to lean either down-slope or upslope. Not only is forest architecture altered by landforms, but also forest dynamics and diversity. One major determinant of such changes, among others, is linked to the modified radiation regime (Courbaud et al., 2003).

Usual computation of LAI is based on the inversion of gap fractions, generally averaged over azimuth, whether arithmetically or

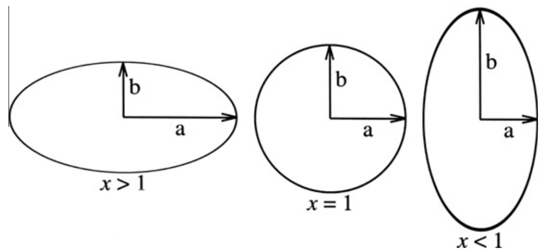

Fig. 2. Parameter x of the ellipsoidal leaf angle distribution function. From left to right: $x = a/b$ translates into leaf angle distributions characterizing 'horizontal', 'spherical' and 'vertical' canopies, respectively. a: Vertical projection, and b: Horizontal projection of foliage.

logarithmically, for fixed path lengths. This is valid only for flat ground (Frazer et al., 1997; Walter and Torquebiau, 2000; Gonsamo and Pellikka, 2008). Furthermore, the assumption of azimuthal isotropy of gap frequency distribution used in the Poisson model is strongly violated for slopes. The azimuthal averaging over the whole range of angles is no longer acceptable. Depending on the severity of the slope and vegetation characteristics, canopies appear increasingly opaque upslope, whereas gaps are more and more conspicuous down-slope. For a given zenith angle, the path lengths travelled by a ray of light through a uniform canopy parallel to the slope plane are lengthened upslope and shortened down-slope. We hypothesize variable path lengths influence LAI estimates, whether from radiation transmission or from optical measurements.

To derive LAI 'corrected for slope', zenith angles θ about zenith (Eq. (4)) are replaced by incidence angles γ about the normal vector to the slope. The angular distance $\cos\gamma$ from sun's beam, or probe, or center of a given hemisphere portion to the normal vector of the terrain slope, is calculated as:

$$\gamma = \arccos(\cos\theta\cos\beta + \sin\theta\cos(\omega - \omega')\sin\beta) \quad (9)$$

where β is the ground slope, ω is the azimuth of a pixel and ω' is the azimuth of the ground slope. The value of $\cos\gamma$ presents negative and positive results, according to azimuth. Values of $\cos\gamma < 0$ correspond to parts of the sky hemisphere hidden by the slope ('topographic shading', upslope, assuming a uniform plane), while values of $\cos\gamma \geqslant 0$ correspond to free parts of the hemisphere, with canopy upslope and down-slope to horizon. Normalizing path lengths for the horizontal allows for estimating corrected LAI and leaf inclination angles be always referred to the horizontal. All CIMES programs for canopy structure integrate, at least, the correction for topographic shading. LAI and ALIA are always corrected for slope, under the assumption of the canopy parallel to a regular slope.

6.7. Clumping of canopy elements

Foliage element clumping seems to be the main factor causing errors in indirect LAI estimation. The underestimation errors caused by clumping could not be satisfactorily addressed including correction factors or adapting radiation models. In order to 'adjust', or 'correct', effective LAI for clumping, several ways have been explored: the finite length averaging method, the azimuthal segmentation of the hemisphere, the spatial auto-correlation of gaps, the gap size and gap fraction distributions, adaptive fit of gap distribution to the negative binomial. Adapted models such as the Markov model or the negative binomial model are not compatible with the data measured by optical field instruments and are not in an operational form.

There are several ways to test canopies for randomness: (i) by using a dispersion index, e.g. the relative variance of contact numbers (the ratio variance/mean) in unit distances of penetration from determined directions of the hemisphere (Campbell and Norman, 1989), (ii) by comparing the actual gap frequencies with frequencies predicted by the Poisson model (Bonhomme and Chartier, 1972; Walter and Torquebiau, 1997), and (iii) by performing a run-test on sequences of black and white pixels along circular transects for each zenith angle (Pielou, 1962; Walter et al., 2003; Gonsamo and Pellikka, 2009).

Clumping indices correspond to $\Omega(\theta)$ in Eqs. (3) and (4). They are written Ω for an angular integrated value. Generally, unless otherwise stated, clumping indices derived from HP are valid only at the whole canopy scale (crowns, trees, tree clumps). They do not account for finer scales like conifer shoots (needles), leaf clumps, whorls, branches, which need other techniques (Chen et al., 2006). The study of clumping at various scales, particularly in conifer forests and heterogeneous vegetation like open- forests and tree savanna, needs as indicated above, multi-instrument and multi-model approaches.

GFA core program extracts either gap fraction or gap size data, allowing for estimates of angle-dependent clumping indices. Programs LAILANG and LAICAM compare actual gap frequencies with frequencies predicted by the Poisson model. Program PCS calculates Pielou's angle-dependent 'coefficient of segregation' (PCS), a run-test on sequences of black and white pixels.

Programs LAIMLR and LOGCAM calculate the most widely used Lang and Xiang (1986) 'finite length, or logarithmic gap fraction averaging' method, using variable azimuthal segmentations of the hemisphere. A modified application of this procedure is available in LAICMP and CMPSH programs. We acknowledge that the increasing areas of the hemisphere from zenith to horizon encompass spatial dimensions incompatible with the theory of Lang and Xiang. We agree with van Gardingen et al. (1999) that "methods of setting the number and size of each segment, based on the size of foliage elements have not proved to be practical for the analysis of hemispherical images." Implemented in all CIMES LAI programs, Lang and Xiang widely used clumping index (CI_{LX}) is calculated as the ratio of log mean gap fraction to mean log gap fraction over a determined range of zenith angles.

On digital images, sequences of black and white pixels represent foliage and sky, respectively. These data can be used to derive a Ω following Chen and Cihlar gap size distribution theory (Chen and Cihlar, 1995). Chen and Cilhar's clumping index (CI_{CC}) originates in the methodology introduced by the TRAC instrument and provides a detailed record of the canopy geometry at each zenith angle and for the whole canopy as well. In programs CLMPML and CLMPMLSH and PCS, Chen and Cihlar's method is proposed, modified by Leblanc et al. (2005). Leblanc et al. (2005) combined Lang and Xiang with Chen and Cihlar approaches, using gap size and logarithm. This method is implemented in programs CLMPML and CLMPMLSH as a combined index (CLX).

Comparative analyses about clumping index have been presented in Walter et al. (2003), Leblanc et al. (2005), and recently by Gonsamo and Pellikka (2009).

7. Conclusions

Hemispherical photography is a close-range remote sensing technique. Used as stand-alone or in a multi-instrument and multi-model context, it is becoming a standard approach to estimate canopy solar radiation regimes and to characterize plant canopy structure. Several commercial and free software programs have become available for HP analysis. The technique has been applied for diverse use in ecology, meteorology, forestry, and agriculture. The general overview and features of the CIMES package and solar radiation calculations were presented in this paper. The examples provided demonstrate the self-explanatory and multiple-parameterretrieval-in-one-run designs used for the software package. All the CIMES programs can be automated.

CIMES provides unique tools for calculation of size, morphology and spatial dispersion of canopy gaps, gap orientation statistics, and sectorial calculation of canopy structures and non randomness. Most of these futures are developed or implemented for first time in CIMES programs. The new algorithms such as sectorial calculation of clumping index gives the hierarchical stepwise canopy gap non randomness estimates in a hierarchical way from azimuthal iteration. A unique way to account for terrain topography for calculation of canopy structure and solar radiation is also developed in CIMES programs.

CIMES package of programs provides a wide range of options for doing an exhaustive analysis from HP. As the algorithms for both solar radiation and canopy structure assessments are evolving with the understanding of science, it allows a wide range of model assumptions and algorithms to be used, which in turn require further research and development, particularly through sensitivity analyses. It also provides different ways for rigorous corrections, which otherwise are ignored and overlooked by other HP software. Above and beyond, the most important point of CIMES compared to other software would be to have statistics and estimates for each single photosite including all available theoretical and empirical algorithms, so that anyone working on methods rather than application will have more freedom compared to other software. For application, the batch processing does everything. Finally, it has been also extensively validated, reviewed and evaluated by the user community on various operating systems.

CIMES Package: All CIMES programs are accessible via http://equinoxe.u-strasbg.fr/cimes, http://jmnw.free.fr, or permanent email (jmnw@free.fr) to the second author. The source code, written in C++ and C, is also available on request to the second author.

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