Hemiphot.R: Free R scripts to analyse hemispherical photographs for canopy openness, leaf area index and photosynthetic active radiation under forest canopies

Hans ter Steege[1],

[1]Naturalis Biodiversity Center, Leiden, The Netherlands

ABSTRACT

Three R script are presented that allow a full suite of hemispherical photograph analyses (canopy openness, leaf area index, photosynthetic photon flux density) to be carried out for any location on the world. The scripts are free and can be modified as needed. Included are: a source file with all algorithms in functions, a test script, and a script for automated processing several files at once. A full description of the implemented techniques is presented. As the original Pascal versions (Hemiphot/Winphot) have been tested and used substantially, no further tests are presented.

Subjects Ecology, Environmental Sciences, Agrometeorology, Agriculture

Keywords hemispherical photographs, computer analysis, R, PAR, PPFD, LAI

Light is essential for plant growth and the measurement of light is an important element of ecology and evolutionary biology. Arguably, the most precise way to measure light that is available for plant growth (Photosynthetic Active Radiation, PAR) is by means of data loggers and high quality light sensors (being capable of dealing with a large dynamic range). These sensors are expensive, so usually few are available, hampering the collection of large amounts of data. Hemispherical Photograph Analysis (HPA) offers a cheap alternative and allows more vegetation parameters to be estimated. The first programme that was available for such analysis at personal computers was Solarcalc (Chazdon and Field 1987), written for Mac computers, followed by Hemiphot and Winphot for DOS and Windows computers (ter Steege 1997). Several others have been written (Rich 1990, Frazer et al. 1997), some of which commercial. Hemispherical photographs are still widely used for scientific research. Google scholar returned over 33,600 hits (August 10, 2017) with over 1160 for 2016.

The free programmes, that were mostly were written in the 90ties, have mostly 16 bit code that is no longer supported by recent versions of Windows. To enable the free use of HPA, I present a set of three free scripts for the R platform (R Development Core Team 2011) with all algorithms necessary to perform HPA that can be modified as needed. They consist of:

1) Hemiphot.R: a source file that contains function of all necessary algorithms;
2) HemiphotTest.R: A script that demonstrates the use of all functions, including the reading of files, splitting RGB colour channels, thresholding the image, calculating canopy openness, leaf area index (LAI) and PAR, and setting and estimating parameters for batch processing;
3) HemiphotBatch.R: A script that allows the automated analysis of a list of jpeg images;
4) A help file describing the use of the functions.

To be as robust as possible Hemiphot.R depends on one external R library only to read JPEG images: JPEG (Urbanek 2012).

The main process is rather straightforward: a digital image, is taken with overcast sky or in the early morning, perhaps with 1 stop underexposure. The image is loaded and displayed (assuming a jpg image in full colour). A circle encompassing the full hemispherical image is drawn. Typically the centre of the circle will be in the centre of the image with the radius being nearly half the height of the image – this is the default of the programme. The image can be viewed in its 3 colour channels but typically only the blue channel is used for analysis. The reason for this is that leaves have very high absorbance in the blue region resulting in nearly black colour, and both a blue and white sky are very white in the blue channel. The blue channel thus provides the best contrast between sky and leaves (Brusa and Bunker 2014).

Next, the image is converted into a black and white image using a threshold. Proper thresholding is a crucial step in the data handing; if later images are processed as a batch it requires that all images have similar quality with respect to penumbra, halo effects, and other interactions between the canopy and outer light.

With a fixed circle, Hemiphot.R can now estimate canopy openness, LAI and PAR (for one or several days). When PAR is calculated for 1 day the daily course of PAR (direct and diffuse light) can be shown. When PAR is calculated for more than 1 day only the average daily PAR above and below the canopy is given. A general view of the script with 12 solar tracks given for a tropical location is shown in Figure 1.

As all functions are derived from Hemiphot and Winphot 5 (ter Steege 1997), the results of Hemiphot.R are similar. Winphot was extensively tested (Frazer et al. 1997) and (together with Hemiphot) has been used in over 250 publications (Google Scholar, May 2015). I hope that by making the code freely available more people can utilize this cost effective method and modify it to suit their needs.

Methods

Photography

Hemispherical photographs are made with a fish eye lens. The lens should have a lens view of 180 degrees and ideally an equiangular or polar projection (Hill 1924, Herbert 1987). This projection is characterised by a direct relationship between radial distance and zenith angle (Figure 2). Fish eye converters usually give less angle of view and produce more distortion (Anderson 1971, Evans et al. 1974) and should not be used. Despite the higher costs, a true equiangular fish eye lens is preferable. The camera is mounted horizontally on a stable tripod and levelled with a bubble level, a bulls-eye level, or an auto-levelling device. One side of the camera is directed to either the magnetic or true north (note that the metal in the camera may influence the compass). For easy alignment in processing it is recommended that the top of the picture represents the north.

Pictures (normal and 1 stop underexposure) should be taken during a grey overcast sky or early in the morning or late in the afternoon. During bright days a sun near zenith will always produce scattering of light through small holes in the canopy. Days with medium cloud cover but well defined clouds produce an irregularly lighted sky, even if the sun is behind a big cloud.

Canopy Openness

The projection of the sky hemisphere can be thought to consist of 90 concentric rings, dividing the main radius (R, Figure 2) into 90 parts. Each ring corresponds to a circular sphere segment in the sky hemisphere with an arc of 1 degree. The area of all segments is different and will be smaller on those segments nearer to the sky zenith. To obtain canopy openness from a hemispherical photograph we calculate the openness for each of the 90 rings, and correct for the actual area of that segment on the sky hemisphere. The area on a sphere segment defined by a lower angle α1 and an upper angle α2 is given by:

$$A_{\alpha 1-\alpha 2} = 2\pi \cdot R^2 \cdot (\sin\alpha 2 - \sin\alpha 1)$$

Since the total hemisphere has an area of $2\pi R^2$, the fraction of the sky given by each of the rings is given by:

$$A_\alpha = \sin(\alpha + 0.5) - \sin(\alpha - 0.5)$$

As the first ring may include a part of the circle that identifies the image boundary, Hemiphot.R actually uses 89 circles rather than 90. Thus, α runs from 1 to 89. To obtain the total canopy openness of a site we obtain the sum of the openness (O_α) per circle, multiplied by their part in the sky fraction:

$$canopy\_openness = \sum_{a=0.5}^{a=89.5} [O_a \cdot A_a / A_{tot}]$$

Canopy openness is an independent powerful canopy characteristic, not influenced by location of study site. Proper alignment with respect to the geographic north is not important for the calculation of canopy openness.

Leaf area index

The leaf area index (LAI) of a vegetation may be important in a number of studies, including photosynthesis modelling, rain interception, evaporation. The LAI of vegetation is defined as: the amount of leaf area per unit of ground area. LAI is difficult to measure precisely, particularly in forests. Indirect measurement methods are based upon the determination of gap fractions in the foliage. Light has a chance to be intercepted by leaves as it passes through the vegetation. The chance of being intercepted depends on the path length through the vegetation, the foliage density and its orientation. With the assumptions that leaves are small, randomly distributed, have no azimuthal preference and do not transmit light, the gap fraction in the zenithal view angle z can be related to LAI. If we consider the vegetation to consist of many (n) small layers of horizontal leaves, all of which with an equal part of the total LAI, then each layer will have a partial leaf area of L =LAI/n. The chance of a light beam not being intercepted in such a layer is then 1-L. After n layers the chance of still not being intercepted becomes $(1\text{-L})^n$ and the total light intensity relative to that of above the canopy after n layers becomes:

$$I_n = I_0 \cdot (1 - L)^n$$

and in exponential form:

$$I_i = I_0 \cdot e^{n \cdot \ln(1-L)}$$

Usually this formula is given in the form of (Monsi and Saeki 1953):

$$I_i = I_0 \cdot e^{-K \cdot LAI}$$

The gap fraction at a given angle is highly dependent of the leaf angle distribution, however. For instance a vegetation with nearly vertically arranged leaves will show a high gap fraction at z = 0°, whereas a vegetation with horizontally arranged leaves and similar LAI will show a much lower gap fraction at this angle. The gap fraction (T) at z = 67.5° is little affected by leaf angle (Bonhomme and Chartier 1972, Norman and Campbell 1989, Welles and Norman 1991) and is related to LAI as (Bonhomme and Chartier 1972):

$$LAI = 1.1 \cdot -\ln(T_{67.5})$$

On hemispherical photographs this is by far the simplest way to estimate LAI. However, errors at 67.5° will affect the LAI estimated for the total vegetation as seen by the lens. It is better to include more viewing angles to obtain a more accurate estimate of LAI and also be able to estimate mean leaf angle. A method described by Welles & Norman (Welles and Norman 1991), which is used by the Licor LI-2000 Plant Canopy Analyser has been implemented in Hemiphot.R. As in the Plant Canopy Analyser, five viewing angles are used: 7, 23, 38, 53, 68. The gap fractions (T) around each viewing angle, in bands of 13°, are calculated with similar methods as total openness for the hemisphere (see above) and total LAI is then calculated as (Welles and Norman 1991):

$$LAI = 2 \cdot \sum_{z=7}^{z=68} [-\ln(T_z) \cdot W_z \,/\, S_z]$$

where z takes the five values mentioned above, W_z are weights to account for area correction and S_z are the reciprocal path length corrections $1/\cos\theta_z$. For restrictions using this method see (Welles and Norman 1991).

Note that LAI calculations are quite sensitive to small changes in cover, when cover is high. Thus in forest with dense canopy cover halo effects will easily cause an underestimation of the LAI.

Light

Solar geometry

Solar tracks are calculated with standard spherical trigonometry (Gates 1980, List 1984) (Figure 3). Solar altitude (α), the angle of the sun with the horizontal, is calculated as:

$$\sin\alpha = \sin\psi \cdot \sin\delta + \cos\psi \cdot \cos\delta \cdot \cos\eta$$

where ψ is latitude, δ is the declination of the sun and η is the hour angle. Note that solar altitude, sometimes referred to as angular elevation or solar angle, equals ½π - z (z = zenithal angle) and thus sinα = cosz. Sine and cosine (both are required) of solar azimuth (β), the angle of the sun with the north-south axis, are calculated as (Campbell 1981):

$$\sin\beta = -\cos\delta \cdot (\sin\eta \,/\, \cos\alpha)$$
$$\cos\beta = -(\sin\delta - \sin\psi \cdot \sin\alpha) \,/\, (\cos\psi \cdot \cos\alpha)$$

Solar declination is a function of the day in the year and is calculated according as (Campbell 1981, 1985):

$$\delta = 0.39785 - \sin[4.869 + 0.0172 \cdot day + 0.03345 \cdot \sin(6.224 + 0.0172 \cdot day)]$$

where day is the Julian day number, 0.0172 is a constant (2π/365) to convert the Julian day to the day angle. The declination ranges from 23.5° at June 21, the summer solstice, to -23.5° at December 21, the winter solstice. Except for the solstices each declination occurs twice a year. A declination of zero, equinox, occurs on March and September 21.

Direct light

The estimation of direct light requires several steps. First of all an estimate of the amount of radiation on the outer atmosphere is required. This amount, the Solar constant (S_c) is a function of the amount of radiation emitted by the sun and the distance between the sun and the earth and amounts to approximately 1360 W m^{-2} (Gates 1980). The orbit of the earth around the sun is elliptical rather than circular, however, and the sun is not directly in the centre of this ellipse. Consequently, the radiation on the outer part of the atmosphere must be calculated for each day of the year separately (Kreith and Kreider 1978):

$$S_{out} = S_c \cdot [1 + 0.034 \cdot \cos(2\pi \cdot day / 365)]$$

The deviation from 1360 W m-2 is plus or minus 3.4%. The loss of radiation due to atmospheric absorption and scattering must be estimated. Both transmissivity and path length through the atmosphere influence the amount of direct light on a surface normal to the beam (Gates 1980).

$$S_{no} = S_{out} \cdot \tau^M$$

Where τ is the transmissivity of the shortest atmospheric path length (= 1 optical airmass [sun in zenith]). τ is usually between 0.5 and 0.8 but may be as low as 0.4 in the tropics (Whitmore et al. 1993) and mostly taken as 0.6 (Gates 1980), and M is the relative path length in number of optical airmasses, ranging from 1, with the sun in zenith, to around 36 at sunrise and sunset (List 1984). M can be calculated accurately for all solar angles (Kreith and Kreider 1978):

$$M = \sqrt{1229 + (614 \cdot \sin\alpha)^2} - 614 \cdot \sin\alpha$$

M can be corrected for altitude (Kreith and Kreider 1978):

$$M_h = M_0 \cdot p_h / p_0$$

where p_0 is the atmospheric pressure at sea level and p_h is the atmospheric level at altitude h. P_h/p_0 is calculated according to the International Commission of Air Navigation (ICAN) standard atmosphere (List 1984):

$$p_h / p_0 = [(288 - 0.0065 \cdot h) / 288]^{5.256}$$

The airmass is obviously also affected by atmospheric pressure but this effect is neglected in Hemiphot.R. Finally the amount of direct light (S_{dir}) on a horizontal surface should be cosine corrected and is calculated as:

$$S_{dir} = S_{no} \cdot \sin\alpha$$

All values thus far are short wave radiation in W m^{-2} (300-3000 nm). At tropical latitudes approximately 51% of the incoming radiation is PAR (400-700 nm) (Stigter and Musabilha 1982), but this can be as high as 61% under full cloud cover. A factor 4.6 is used to convert W m-2 to μmol m^{-2} s^{-1} (McKree 1981).

Calculation of the amount of direct light at the site of exposure involves the calculation of the location of the sun on a flat projection of the hemisphere, the amount of S_{dir} for a particular day, in steps of 1 to 3 min, and determining if a pixel on that location identifies open sky (white) or obstructed sky (black). The assumption is made if the sun is not obstructed by the canopy, direct light is equal to that of above the canopy and if the sun is obstructed, there is no direct light. This is an obvious simplification as it ignores cloudiness, penumbral effects and scattering within the canopy. As the solar disc is 0.5° degrees, which corresponds to approximately 1 pixel at an image diameter of 360 pixels this works fairly well as an estimate.

Diffuse light

Diffuse light originates from direct light, scattered by the atmosphere. Clear skies scatter differently from clouded skies, due to different properties of both sky types (Gates 1980). For most purposes, under clear sky conditions, the amount of diffuse light on a horizontal surface can be estimated as being 15% of the amount of direct light added to the amount of direct light on that same surface (Gates 1980). However, at low solar altitudes the amount of diffuse light may be much larger (over 50%). Thus a more accurate (empirical) estimation for diffuse light in a clear not dust-free sky is given by (Gates 1980):

$$S_{dif} = S_{out} \cdot (0.271 - 0.294 \cdot \tau^{M}) \cdot \sin\alpha$$

The amount of diffuse light is not distributed equally over the sky hemisphere (Gates 1980). It can be simplified without much loss of accuracy, however, by the Standard Overcast Sky (SOC) in which the illumination (I_z) of an point at zenithal angle z is given by (Anderson 1971):

$$I_z = I_Z \cdot (1 - 2 \cdot \sin\alpha) / 3$$

SOC estimates the sky at zenith (Z) three times as bright as the sky near the horizon. The Uniform Overcast Sky (UOC) assumes that each part of the sky is equally bright (Monsi and Saeki 1953). When gaps are mainly overhead and only diffuse light is present at zenith (often at high latitudes) both sky estimations may result in quite different estimations of the total amounts of light (Madgwick and Brumfield 1969). In reality most diffuse light originates from 10° around the solar disc and both SOC and UOC are poor estimators of instantaneous diffuse light as they neglect the solar angle (Hutchinson et al. 1980), but there errors are small when averaged over longer periods.

In hemispherical photograph analysis often the terms indirect (diffuse) site factor (ISF), direct site factor (DSF), and total site factor (TSF) are used, as introduced by Anderson (1964). The factors are the fractions of direct, indirect or total radiation that will penetrate at a particular site relative to the amount of radiation above the canopy. DSF, ISF and TSF are often strongly correlated (Turner 1990, Whitmore et al. 1993, ter Steege et al. 1994). The indirect site factor is also important in the calculation of diffuse light.

The indirect site factor and finally the amount of diffuse light ($D_u = S_{dif}$ * ISF) at the site of exposure is calculated for the UOC as:

$$D_u = S_{dif} \cdot \sum_{\alpha=0.5}^{\alpha=89.5} [T_\alpha \cdot (A_\alpha / A_{tot}) \cdot \sin\alpha]$$

and for the SOC as:

$$D_u = S_{dif} \cdot \sum_{\alpha=0.5}^{\alpha=89.5} [T_\alpha \cdot (A_\alpha / A_{tot}) \cdot (1 + 2 \cdot \sin\alpha) / 3 \cdot \sin\alpha]$$

Under leaf canopies, diffuse light may also originate from scattering (reflection and transmission) by leaves. Scattered light may represent a large quantity under closed canopies (up to 43%, see (Mitchell and Whitmore 1993)). Multi-layered canopies models which include scattered light do exist (Goudriaan 1977) but such models are not implemented in Hemiphot.R.

Finally direct and diffuse light are added to result in a total amount. Daily totals can be found by summing all instantaneous values per two minutes and multiplying those by 2 times 60 (2 minutes of 60 seconds).

How to use HemiphotR?

To be able to use Hemiphot.R a working version of R (R Development Core Team 2011) needs to be installed on your machine, to be downloaded from the CRAN website (https://cran.r-project.org/). It is best to create a directory for the Hemiphot.R files and scripts. The library JPEG (Urbanek 2012) needs to be installed as well.

The Hemiphor.R files can be downloaded from https://github.com/naturalis/Hemiphot

Load the script ‘HemiphotTest.R’.

The first lines are:

```
### This is the test script for Hemiphot.R
### Here you can test the functions, set the parameters

### clear memory
rm(list = ls())

### set working directory
### need to change to your own settings!
setwd("D:/Documents/R/Hemiphot")
```

In the last line you need to identify the directory where the HemiphotR files and scripts are found.

You then execute:

```
##########          load libraries and source files          ##########

library(jpeg)                          #library for reading and writing jpg's
source("Hemiphot.R")                  #functions to carry out Hemiphot analysis
days = seq(15,360,30)                 #roughly each mid of the 12 months

#######END          load libraries and source files          ##########
```

Which loads the library ‘jpeg’ and the script ‘Hemiphot.R’ with all algorithms.

Then load an image with the next line:

```
##########          load image and plot          ##########
### We assume colour images
im = readJPEG("DSCN0516.jpg", native = F)     #if native = T creates a raster, else an array
```

Here you can use one of your own images, which has to be present in the HemiphotR directory, or the complete path can be given to read the image file.

Then step by step execute the lines in the script, which include the explanation of the functions called.

The output of the test script is given in appendix 1.

The code of the calculations/algorithms can be viewed by loading the source file ‘Hemiphot.R’ and altered, if desired.

If you have a number of images for which you want to calculate openness, site factors, light etc. You can use the test script to determine the values for the standard circle, threshold etc., and fill these in in the proper location in the script 'HemiphotBatch.R':

```
##########          initialize site and image data          ##########

### Location parameters
location.latitude   = 1.487
location.altitude   = 0
location.day        = 150
location.days       = seq(15,360,30)   # roughly each mid of the 12 months

### Image parameters
## determine in Hemiphot.R and fill in here for batch processing
location.cx         = 1504             # x coordinate of center
location.cy         =  975             # y coordinate of center
location.cr         =  900             # radius of circle
location.threshold  = 0.65

### atmospheric parameters
location.tau        = 0.6
location.uoc        = 0.15

#######END          initialize site and image data          ##########
```

Note that site.longitude is not used, as values are calculated for full days or series of full days. Hence longitude does not affect the results here.

References

Anderson, M. C. 1964. Studies of the woodland light climate I. The photographic computation of light conditions. Journal of Ecology **52**:27-41.

Anderson, M. C. 1971. Radiation and crop structure.*in* Z. Sesták, J. Catský, and P. G. Jarvis, editors. Plant photosynthetic production. Manual of methods. Dr. W. Junk N.V. Publishers, The Hague, The Netherlands.

Bonhomme, R. and P. Chartier. 1972. The interpretation and automatic measurement of hemisperical photographs to obtain sunlit foliage area and gap frequency. Israel Journal of Agricultural Research **22**:53-61.

Brusa, A. and D. E. Bunker. 2014. Increasing the precision of canopy closure estimates from hemispherical photography: Blue channel analysis and under-exposure. Agricultural and Forest Meteorology **195–196**:102-107.

Campbell, G. S. 1981. Principles of radiation and temperature relations.*in* O. L. Lange, P. S. Nobel, C. B. Osmond, and H. Ziegler, editors. Physiological Plant Ecology I. Responses to the physical environment. (Encyclopaedia of plant physiology 12A. Springer, New York, USA.

Campbell, G. S. 1985. Soil physics with basic. Transport model for soil-plants systems. Elsevier Science Publishers, Amsterdam, The Netherlands.

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

Evans, C. G., P. Freeman, and O. Rackham. 1974. Developments in hemispherical photography.*in* C. G. Evans, R. Bainbridge, and O. Rackham, editors. Light as an ecological factor II. Blackwell Scientific Publications, Oxford, United Kingdom.

Frazer, G., K. P. Lertzman, and J. A. Trofymow. 1997. A method for estimating canopy openness, effective leaf area index, and photosynthetically active photon flux density using hemispherical photography and computerized image analysis techniques. Pacific Forestry Centre.

Gates, D. M. 1980. Biophysical ecology. Springer Verlag New York Inc, New York, USA.

Goudriaan, J. 1977. Crop meteorology: a simulation study. Pudoc, Wageningen, The Netherlands.

Herbert, T. J. 1987. Area projections of fisheye photographic lenses. Agricultural and Forest Meteorology **39**:215-223.

Hill, R. 1924. A lens for whole sky photographs. Quarterly Journal of the Royal Meteorological Society **50**:227-235.

Hutchinson, B. A., D. R. Matt, and R. T. McMillen. 1980. Effects of sky brightness distribution upon penetration of diffuse radiation through canopy gaps in a deciduous forest. Agricultural Meteorology **22**:137-147.

Kreith, F. and J. F. Kreider. 1978. Principles of solar engineering. Mc Graw Hill, New York, USA.

List, R. J. 1984. Smithsonian meteorological tables. 6th revised edition. Smithsonian Institution Press, Washington DC, USA.

Madgwick, H. A. I. and G. L. Brumfield. 1969. The use of hemispherical photographs to asses light climate in the forest. Journal of Ecology **57**:537-542.

McKree, K. J. 1981. Photosynthetically active radiation.*in* O. L. Lange, P. S. Nobel, C. B. Osmond, and H. Ziegler, editors. Physiological Plant Ecology I. Responses to the physical environment. Springer, New York, USA.

Mitchell, P. L. and T. C. Whitmore. 1993. Use of hemisperical photographs in forest ecology: Calculation of absolute amount of radiation beneath the canopy. Oxford Forestry Institute, Oxford, United Kingdom.

Monsi, M. and T. Saeki. 1953. Über den Lichtfaktor in den Pflanzengesellschaften und seine Bedeutung für die Stoffproduktion. Japanese Journal of Botany:22-52.

Norman, J. M. and G. S. Campbell. 1989. Canopy structure.*in* R. W. Pearcy, J. R. Ehleringer, H. A. Mooney, and P. W. Rundel, editors. Plant physiological ecology. Field methods and instrumentation. Chapman and Hall, London, United Kingdom.

R Development Core Team. 2011. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rich, P. M. 1990. Characterizing plant canopies with hemispherical photographs. Remote Sensing Reviews **5**:13-29.

Stigter, C. J. and V. M. M. Musabilha. 1982. The conservative ratio of photosynthetically active to total radiation in the tropics. Journal of Applied Ecology **19**:853-858.

ter Steege, H. 1997. Winphot 5.0. A programme to analyze vegetation indices, light and light quality from hemispherical photographs. Tropenbos-Guyana reports 97-3.

ter Steege, H., C. Bokdam, M. Boland, J. Dobbelsteen, and I. Verburg. 1994. The effects of man made gaps on germination, early survival, and morphology of Chlorocardium rodiei seedlings in Guyana. Journal of Tropical Ecology **10**:245-260.

Turner, I. M. 1990. Tree seedling growth and survival in a Malaysian rain forest. Biotropica **22**:146-154.

Urbanek, S. 2012. jpeg: Read and write JPEG images. R package. version 0.1-2. . http://CRAN.R-project.org/package=jpeg.

Welles, J. M. and J. M. Norman. 1991. Instrument for indirect measurement of canopy architecture. Agronomical Journal **83**:818-825.

Whitmore, T. C., N. D. Brown, M. D. Swaine, D. Kenedy, C. I. Goodwin-Bailey, and W.-K. Gong. 1993. Use of hemisperical photographs in forest ecology: Measurement of gap size and radiation totals in a Bornean tropical rainforest. Journal of Tropical Ecology **9**:131-151.

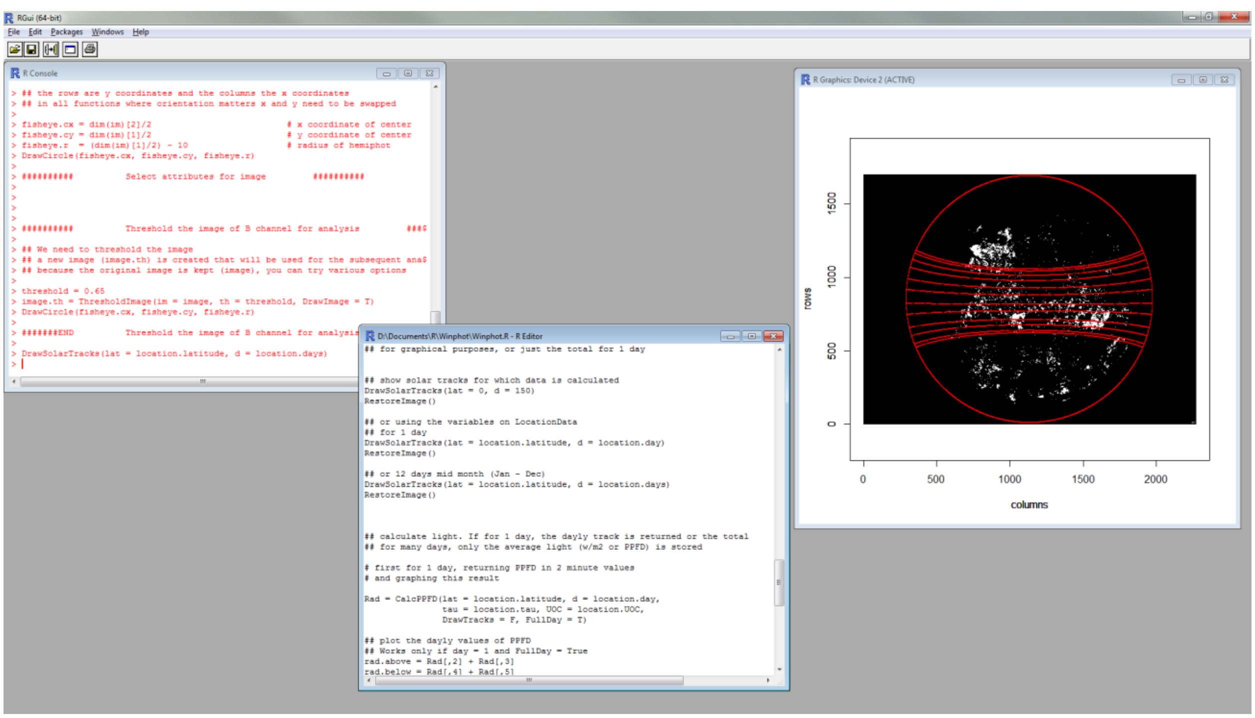


Figure 1. Screenshot of a Hemiphot analysis, with 12 solar tracks.

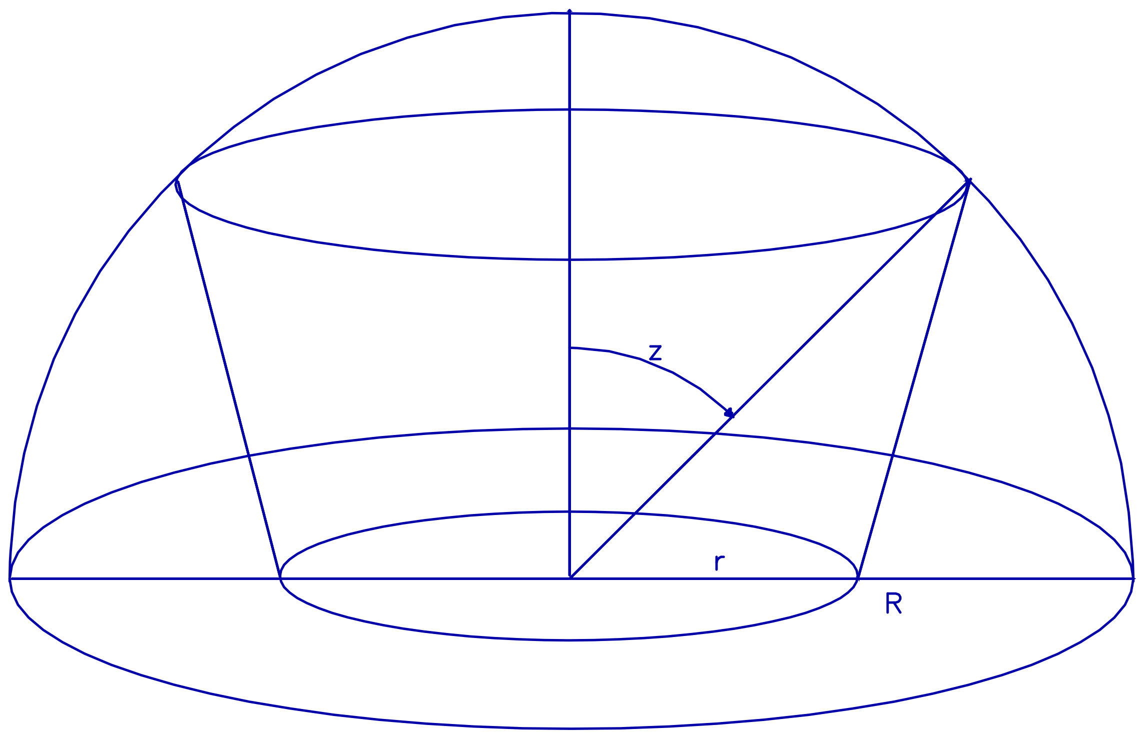


Figure 2. Hill or equidistant projection of the sky hemisphere: z/90 = r/R.

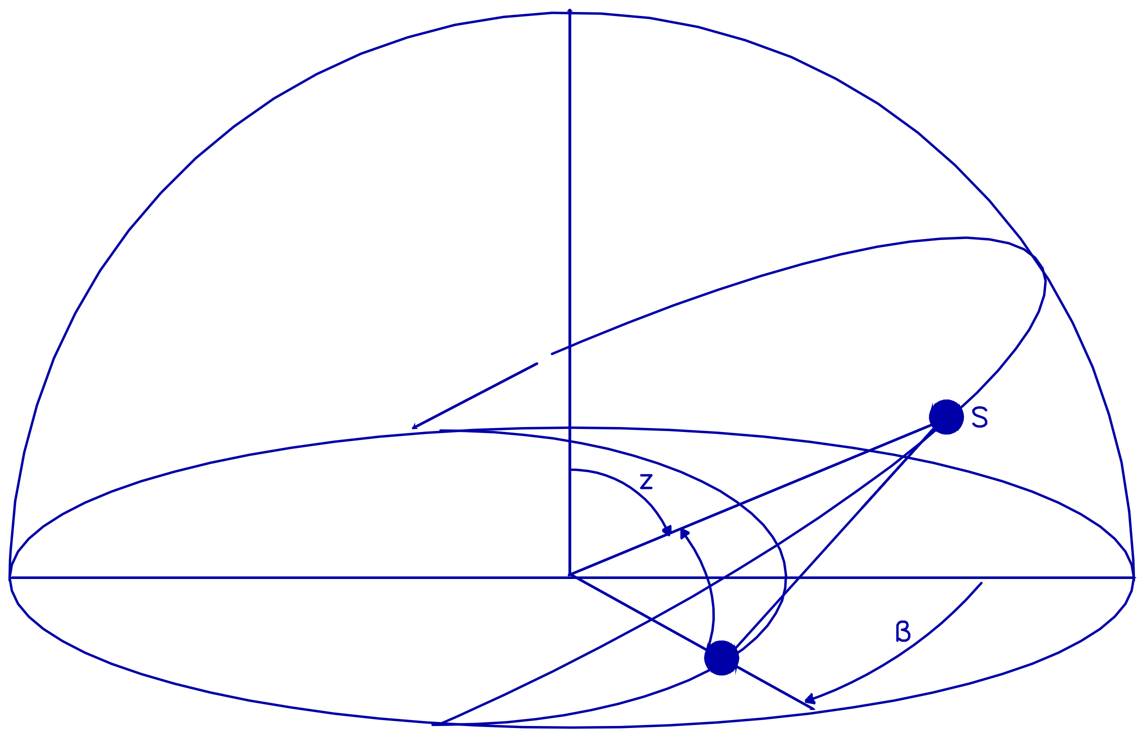
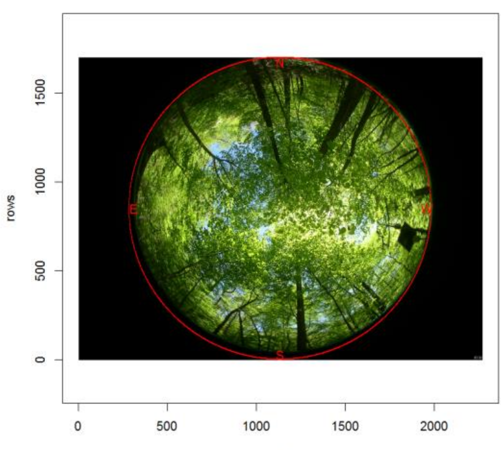


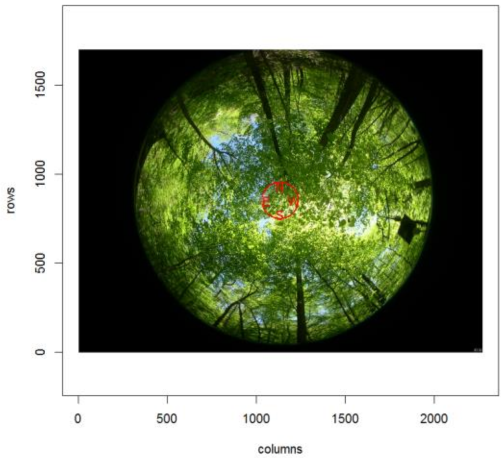
Figure 3. Location of the sun with projections and solar angles.

Appendix: Full run with results from the script 'HemiphotTest.R'

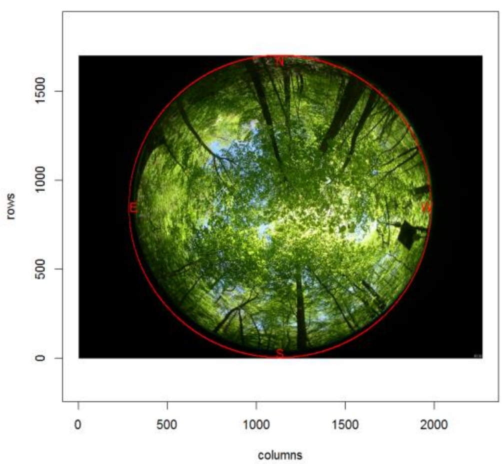
```
> ### This is the test script for Hemiphot.R
> ### Here you can test the functions, set the parameters
>
> ### clear memory
> rm(list = ls())
>
>
> ### set working directory
> ### need to change to your own settings!
> setwd("D:/Documents/R/Hemiphot")
>
>
>
>
>
> ##########          load libraries and source files          ##########
>
> library(jpeg)      #library for reading and writing jpg's
> source("Hemiphot.R")                #functions to carry out Hemiphot analysis
> days = seq(15,360,30)               #roughly each mid of the 12 months
>
> #######END          load libraries and source files          ##########
>
>
>
>
>
> ##########          load image and plot         ##########
>
> ### We assume colour images
> im = readJPEG("DSCN0516.jpg", native = F)     #if native = T creates a raster, else an array
>
>
> ## convert to class HemiphotImage - adding a circle
> im.hemi = Image2Hemiphot(im)

centre of circle (1136, 852)
radius of circle 850

 PlotHemiImage(image = im.hemi, draw.circle = T)                         #note that east and west
are reversed as the image looks upward
```



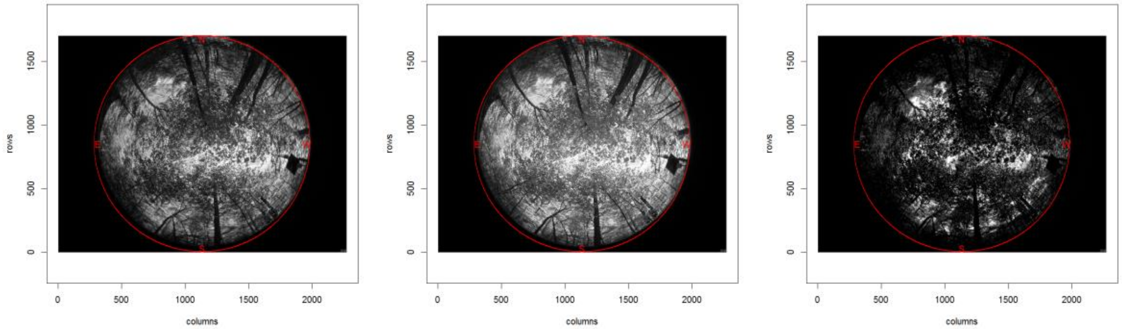
```
> ##adjust circle, if necessary
> im.hemi = SetCircle(im.hemi, cx = 1136, cy = 852, cr = 102)
> PlotHemiImage(im.hemi)
```



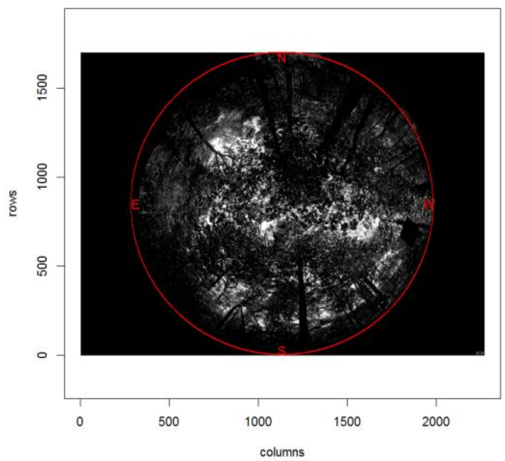

```
## for now use default taken from Hemiphotclass
im.hemi = Image2Hemiphot(im)
PlotHemiImage(im.hemi, draw.circle = T, channel = "")
```




```
#######END          load image and plot         ##########




##########          check RGB channels and choose         ##########

## We check the RGB channels
## R (red) and B (blue) both have high absorption by leaves - leaves are black
## G (green) has high tranmission of light through leaves
## B gives high values for both white and blue sky
## B thus gives best contrast between sky (1) and leaves (0)

PlotHemiImage(im.hemi, draw.circle = T, channel = "R")
PlotHemiImage(im.hemi, draw.circle = T, channel = "G")
PlotHemiImage(im.hemi, draw.circle = T, channel = "B")
```

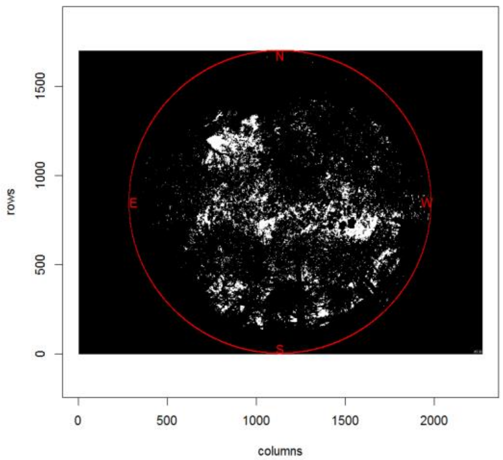



```
## We select the blue channel, as it has strong absorbance with leaves
## leaves will be almost black and sky will be almost white
## under varying conditions (white and blue sky)

im.blue = SelectRGB(im.hemi, "B")
PlotHemiImage(im.blue, draw.circle = T)
```

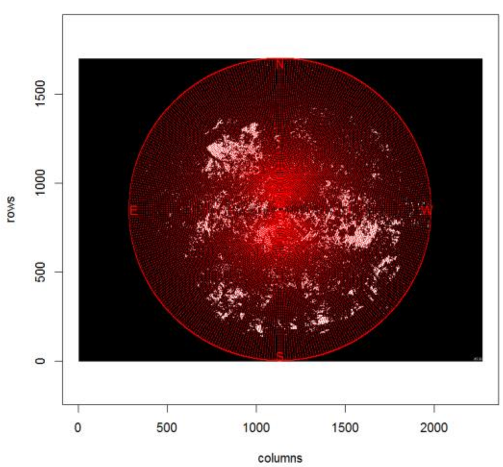



```
#######END          check RGB channels and choose         ##########
```

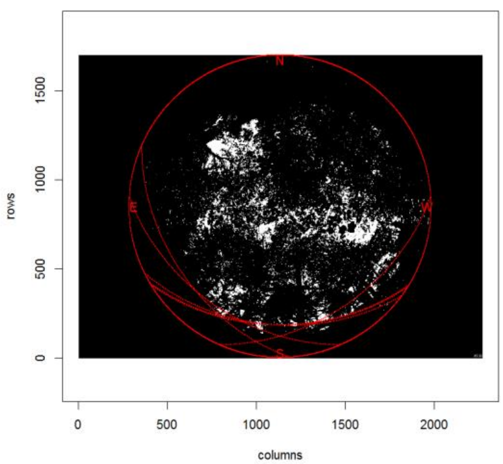
```
##########          Threshold the image of B channel for analysis          ##########

## We need to threshold the image
## a new image (image.th) is created that will be used for the subsequent analysis
## because the original image is kept (image), you can try various options

threshold = 0.48
image.th = ThresholdImage(image = im.blue, th = threshold, draw.image = T)
```



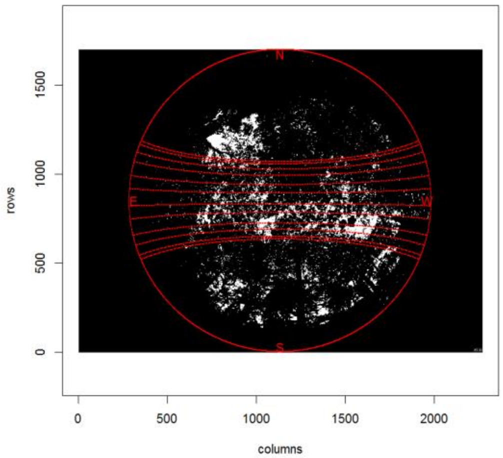

```
#######END          Threshold the image of B channel for analysis          ##########




##########          Main Calculations of Hemiphot.R          ##########


## canopy openess is calculated over 89 circles, each 360 points
## these points can be visualized with draw.circles()

PlotHemiImage(image.th, draw.circle = T)
DrawCircles(image.th[[2]], image.th[[3]], image.th[[4]])
```



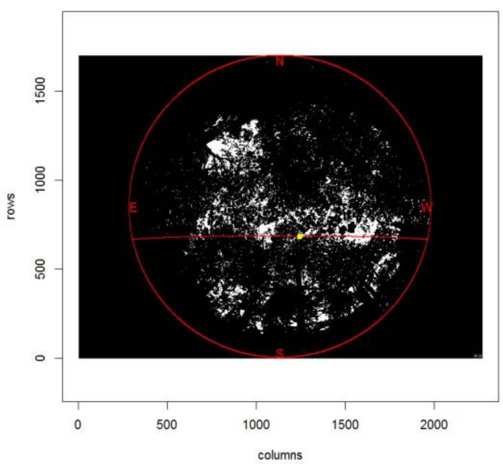
```
PlotHemiImage(image.th, draw.circle = T)
[result not shown]

## calculate canopy cover based on canopy openess of the 89 circles
## the openess by circle is stored in gap.fractions
gap.fractions = CalcGapFractions(image.th)

[1] 0.1438451

canopy.openness = CalcOpenness(fractions = gap.fractions); canopy.openness


## calculate LAI according to Licor's LAI Analyzer
canopy.LAI = CalcLAI(fractions = gap.fractions, width = 6); canopy.LAI

[1] 2.533222

## Photosynthetic Photon Flux Density (PPDF, umol m-1 s-1) P
## is calculated for the variable day.
## Day can either contain 1 or more days
## If one day is selected the PPFD for the full day can be returned
## for graphical purposes, or just the total for 1 day


## show solar tracks for which data is calculated
## see the effect of magnetic correction
DrawSolarTracks(image.th, lat = 52, d = 320, magn.corr = 0)
DrawSolarTracks(image.th, lat = 52, d = 320, magn.corr = 1)
DrawSolarTracks(image.th, lat = 52, d = 320, magn.corr = 5)
DrawSolarTracks(image.th, lat = 52, d = 320, magn.corr = 35)
DrawSolarTracks(image.th, lat = 52, d = 320, magn.corr = -35)
DrawSolarTracks(image.th, lat = 52, d = 320, magn.corr = 55)
```



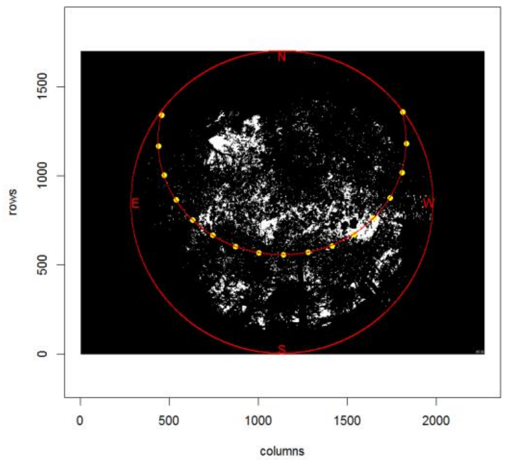
```
## or 12 days mid month (Jan - Dec)
PlotHemiImage(image.th)
DrawSolarTracks(image.th, lat = 0, d = days, magn.corr = 0)
```



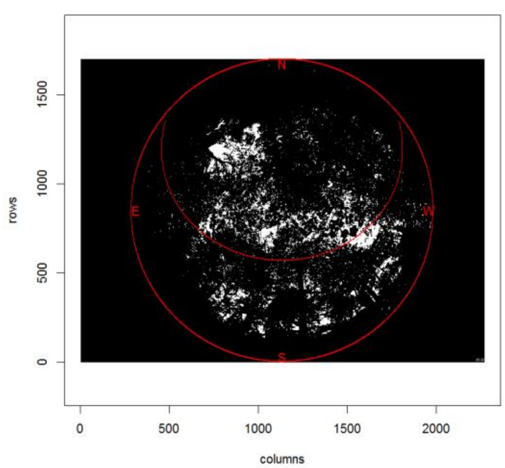

```
## show sunlocation at specified hour
PlotHemiImage(image.th)
DrawSolarTracks(image.th, lat = 0, lon = 0, time.zone = 0,
                d = 300, magn.corr = 0, sun.location = T, h = 12.00)
[result not shown]
PlotHemiImage(image.th)
[result not shown]
DrawSolarTracks(image.th, lat = 5, lon = -58, time.zone = -4,
                d = 300, magn.corr = 0, sun.location = T, h = 12.00)
```



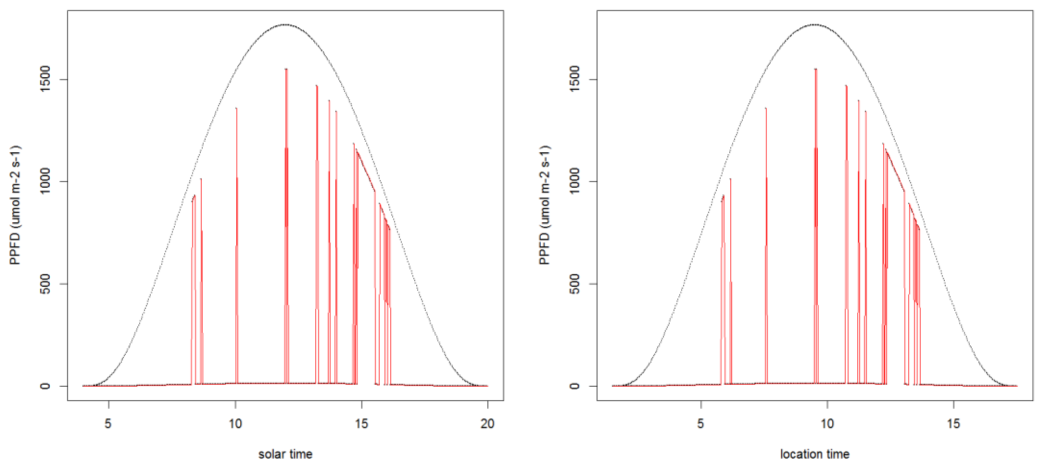

```
PlotHemiImage(image.th)
for(i in 3:21){
  DrawSolarTracks(image.th, lat = 53, lon = 4, time.zone = 0,
                  d = 150, magn.corr = 0, sun.location = T, h = i)
}
```




```
## calculate light. If for 1 day, the dayly track is returned or the total
## for many days, only the average light (w/m2 or PPFD) is stored

# first for 1 day, returning PPFD in 2 minute values
# and graphing this result

PlotHemiImage(image.th)
Rad = CalcPAR.Day(image.th, lat = 53.36, lon = 5.17, time.zone = +1,
                  d = 174, tau = 0.6, uoc = 0.15,
                  magn.corr = 0, draw.tracks = T, full.day = T)
```



```
## plot the dayly values of PPFD
## Works only if day is 1 and full.day is true
PlotPAR.Day(radiation = Rad, real.time = F)
PlotPAR.Day(radiation = Rad, real.time = T)
```




```
# second for 12 days, returning PPFD in 4 fractions
# which is the dayly average of the days sampled
# direct above canopy, diffuse above canopy
# direct below canopy, diffuse below canopy
# when days > 1, FullDay will be ignored

Rad = CalcPAR.Day(image.th, lat = 5, d = days,
                  tau = 0.65, uoc = 0.15,
                  draw.tracks = F, full.day = F)

## show result
Rad

       Solar Time Location Time  DirectAbove DiffuseAbove DirectUnder DiffuseUnder
  [1,]   4.000000      1.509424 2.796753e-02 4.195129e-03      0.0000 2.569561e-04
  [2,]   4.033333      1.542758 4.843374e-02 7.265060e-03      0.0000 4.449926e-04
  [3,]   4.066667      1.576091 8.022145e-02 1.203322e-02      0.0000 7.370472e-04
  [4,]   4.100000      1.609424 1.276552e-01 1.914828e-02      0.0000 1.172852e-03
  [5,]   4.133333      1.642758 1.959475e-01 2.939212e-02      0.0000 1.800298e-03
  [6,]   4.166667      1.676091 2.911746e-01 4.367619e-02      0.0000 2.675213e-03
  [7,]   4.200000      1.709424 4.202136e-01 6.303204e-02      0.0000 3.860779e-03……
```

```
## PAR for 365 days
## may take a few minutes to complete

par(mfrow = c(1,2))

Rad = CalcPAR.Year(image.th, lat = 52, tau = 0.6, uoc = 0.15, magn.corr = 0)
PlotPAR.Year(radiation = Rad)

Rad = CalcPAR.Year(image.th, lat = 0, tau = 0.6, uoc = 0.15, magn.corr = 0)
PlotPAR.Year(radiation = Rad)

par(mfrow = c(1,1))
```