CALCULATION OF LEAF AREA INDEX AND OTHER CANOPY INDICES FROM GAP FRACTION: A MANUAL FOR THE LAICALC SOFTWARE

by

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ABSTRACT

LAICALC is a computer program that calculates leaf area index (LAI) and other canopy indices from gap fraction measurements. Gap fraction, the proportion of unobstructed sky for a range of zenith angles, can be measured by a variety of techniques, including hemispherical photography and optical sensors. Various canopy indices can be calculated from gap fraction based on inversion models. The LAICALC software, written in the "C" programming language and available on PC and UNIX platforms, performs five main calculations: 1) effective leaf area index (LAIeff), 2) leaf angle distribution, 3) mean tilt angle, 4) extinction coefficients as a function of zenith angle, and 5) skyview factor. A flexible configuration file specifies the format of input data, the calculations to be reported, and the format of output. Thus, LAICALC serves as a general-purpose gap fraction analysis program, useful for convenient calculation of canopy indices.

1.0. INTRODUCTION

1.1. Gap Fraction Methods

Understanding the organization and function of plant canopies is of central importance when conducting many types of comparative ecological studies or when developing biophysical earth system models involving water and carbon balance (Mooney et al. 1987, Baldocchi et al. 1988, McNaughton 1989, Ehleringer and Field 1992). Yet characterizing plant canopies presents many challenges, largely because of their complex geometry, and because of the difficulties of obtaining meaningful quantitative indices that relate back to fundamental processes such as light interception, transpiration, and photosynthesis. One fruitful approach involves measurement of gap fraction, the proportion of unobscured sky in a set of sky directions as seen from beneath a plant canopy. Recent advances in theory permit calculation of a useful array of canopy properties from gap fraction measurements, including light extinction coefficients, leaf area index (LAI), and leaf angle distribution (Norman and Campbell 1989, Chen and Black 1992). A variety of techniques can be employed to obtain gap fraction measurements, such as linear arrays of light sensors (e.g., the Decagon Sunfleck Ceptometer, Welles 1991, Decagon 1995), hemispherical light sensors (e.g., the Licor LAI-2000 canopy analyzer, Gower and Norman 1991, Welles 1991, Li-Cor 1994), hemispherical photography (Rich 1989, 1990, Chen et al. 1991), and imaging hemispherical sensors (e.g., the CID CI-100 Canopy Analyzer, CID 1995). This manual serves as a comprehensive reference for the software program LAICALC, which provides as a general-purpose means for calculating canopy indices from gap fraction measurements obtained from any of these measurement sources.

1.2. Overview

This manual includes a summary of relevant theory and details concerning installation and operation of LAICALC. The canopy indices calculated by LAICALC include both measures of light transmission/interception properties (extinction coefficients, skyview factor...) and geometry/material distribution (LAI, leaf angle distribution...). A brief description, calculation formulae, and references to the primary literature are provided for each of the canopy indices calculated by LAICALC. Currently versions of LAICALC are available for PC and UNIX platforms, and a Macintosh version will be forthcoming. Installation of LAICALC simply involves copying the executable and configuration files to an appropriate directory. Operation of PC and UNIX versions of LAICALC is by command line arguments. LAICALC inputs gap fraction values from an ASCII input file and outputs calculated indices to an ASCII output file. An ASCII configuration file enables flexible specification of input and output formats.

2.0. THEORY

2.1. Gap Fraction

All of the calculations for LAICALC depend on accurate measures of gap fraction as a function of zenith angle (i.e., measured as an angle relative to the zenith). The sky can be divided into a series of zenith angle ranges, which are also referred to as annuli. Each annulus can be described by a minimum and maximum zenith angle, or by the center zenith angle and the total range. The latter (center angle, range) is the standard representation used by LAICALC. Within a given annulus, gap fraction is the proportion of unobscured sky as seen from a position beneath a plant canopy. Values of gap fraction vary between zero and one -- totally open sky within an annulus yields a gap fraction of zero, while completely obscured sky yields a gap fraction of one. It is generally assumed that plant canopies are isotropic, such that foliage distribution is symmetrical as a function of azimuth angle (i.e., measured as an angle relative to north). Thus gap fraction for a portion of each annulus should generally be the same as gap fraction for the whole annulus. For this reason some instruments (e.g., the Licor LAI-2000 canopy analyzer) can get reliable gap fraction measurements even from a restricted portion of each annulus.

2.2. Leaf Area Index

Leaf area index (LAI) is widely used to describe the photosynthetic and transpirational surface of plant canopies. LAI can be simply defined as the amount of leaf surface area per unit ground area, and has broad applications in ecophysiology, water balance modeling, and characterization of vegetation-atmosphere interactions. LAI values are calculated following a simple attenuation law:

GAP_FRACTION(theta) = e -[G(theta) LAI / cos(theta)]

where LAI refers to the LAI, GAP_FRACTION refers to gap fraction, theta refers to the zenith angle, and G(theta) refers to the mean projection coefficient factor (Chen and Black 1992). This equation can be inverted to calculate LEAF_AREA in each of a series of projected directions (see Sections 2.4 and 2.5). The LAI is then computed as follows:

LAI = [SUM across all theta] LEAF_AREA(theta)

where LEAF_AREA(theta) is the leaf area normal to a given zenith angle (see Section 2.5).

Note two important issues: First, we advocate the definition of LAI as half of the total leaf area per unit ground surface area (after Lang et al. 1991 and Chen and Black 1992), as opposed to the projected area, which does not work well for all leaf shapes. Second, these calculation of LAI assume a random distribution of canopy elements, such that gap fraction should be observed for a small enough annulus that randomness can be assumed. LAI calculated in this manner is actually better termed "effective LAI" (LAIeff), since it does not account for non-random distribution of foliage. Chen et al. (1991) suggests that a clumping factor can be used to account for this non-random distribution, such that LAIeff is simply multiplied by a stand-specific clumping factor to calculate a more realistic LAI. In practice, LAI and LAIeff are nearly identical in broadleaf canopies (i.e., clumping factors are near unity); however, in conifer canopies, where there is strong clumping, it becomes necessary to estimate the clumping factor by either direct of indirect means (Chen and Cihlar 1995, Chen et al. 1995).

2.3. Extinction Coefficients

The extinction coefficient (EXTINCTION_COEFFICIENT) is given by the projection coefficient G(theta) divided by the path length traveled, and can be used to calculate the rate of light extinction as a function of zenith angle:

EXTINCTION_COEF(theta) = PROJECTION_COEF(theta)/cos(theta).

2.4. Mean Contact Number

Mean contact number is the average number of contacts per unit path length for a given zenith angle (Miller 1967). This is calculated as follows:

MEAN_CONTACT_NUMBER = - ln(GAP_FRACTION(theta)) cos(theta)

where GAP_FRACTION is gap fraction and theta is zenith angle.

2.5. Leaf Angle Distribution

Leaf angle distribution refers to the leaf area at each angular orientation (Chen et al. 1991):

LEAF_AREA(theta) = (A'A + gH)-1 (A'a)

where A = extinction coefficient of the canopy
H = constraint matrix
g = scalar deciding the importance of the constraint
a = negative log gap fraction.

2.6. Mean Tilt Angle

The mean tilt angle or mean foliage inclination is calculated by the following equation (Lang 1986):

MEAN_TILT_ANGLE = a + b x + c x2 + d x3 + e x4 + f x5

where a = 56.81964
b = 46.84833
c = -64.62133
d = -158.6914
e = 522.0626
f = 1008.149
x = slope of a line fitted between the projection coefficient and the angle in degrees.

2.7. Mean Tilt Angle Error

The standard error of the mean tilt angle (MTA_ERROR) is calculated as follows:

MTA_ERROR = a + b x + c x2 + d x3 + e x4 + f x5

where a = 56.81964
b = 46.84833
c = -64.62133
d = -158.6914
e = 522.0626
f = 1008.149
x = standard error added to the slope of a line fitted between the projection coefficient and the angle in degrees.

2.8. Skyview Factor

Skyview factor is the proportion of unobscured sky, weighted appropriately to account for angle of incidence on a horizontal plane (Reifsnyder 1967). As such, it serves as a reasonable estimate of diffuse light under a canopy and as a standardized site factor to compare overall openness of different canopies. The term "skyview factor" is equivalent to the "indirect site factor" with a cosine correction (ISFC) and an isometric (uniform) diffuse illuminance distribution (Rich 1989, 1990), and is also equivalent to "diffuse transmission coefficient" (e.g., CID 1994). The calculating formula for skyview factor is as follows:

SKYVIEW_FACTOR = (SUM across all annuli) 2 ANGLE_RANGE GAP_FRACTION sin(theta)

where ANGLE_RANGE is the angle range for each annulus;
GAP_FRACTION is the gap fraction for each annulus;
theta is the center angle for each annulus.

3.0. INSTALLATION

3.1. Hardware Requirements

3.1.1. PC platform:

Computer System: IBM PC compatible.
Processor: 80386 or higher Intel x86 compatible.
Math Coprocessor: required (i.e. when using an 80386 or 80486SX processors without built in coprocessor).
RAM: 640 K (exact memory required depends on the number of zenith angle ranges measured for gap fraction).
Operating System: MS-DOS 3.1 or higher (or PC-DOS or Novell DOS).
Notes: LAICALC does a large number of floating point calculations using matrices. Processing speed improves greatly when using a fast processor. Thus, an 80486DX 33MHz or faster processor is recommended. Also, LAICALC is currently limited to the DOS 640 K memory limit. It is highly recommended that the system configuration in config.sys maximize DOS memory when analyzing a large number of input zenith angle ranges, in particular when more than ten zenith angle ranges are used. If LAICALC does not have enough memory, it will report an error message and exit.

3.1.1. UNIX platform:

Computer System: UNIX Workstation (tested on SUN SPARC 2).
Operating System: should run under any implementation of UNIX; however the program will need to be compiled by a "C" compiler appropriate for the particular implementation (tested on SUN OS 3.1).

3.2. Software Installation

There is no installation program for LAICALC. Simply copy the two required files laicalc.exe (laicalc without the *.exe suffix for UNIX version) and laicalc.cnf from diskette to your hard drive. Note that although it is assumed you will be running LAICALC from a hard drive, this is not mandatory. LAICALC can be run from a floppy drive; although this will slow down program execution considerably. laicalc.exe is the executable program file, and laicalc.cnf is the ASCII configuration file. For ease of use, laicalc.exe and laicalc.cnf should generally be in the same directory.

4.0. OPERATION

4.1. Command Line Arguments

LAICALC is operated by command line arguments. This provides a straightforward way to run LAICALC using DOS batch capabilities. The format for usage of LAICALC is as follows:

laicalc <input_file> [-o <output_file>] [-c <config_file>]

<input_file> gives the name of the file containing input gap fraction data as a function of zenith angle range. By convention, input files are generally given a *.gap suffix (see Section 6.0 for input file format).

-o <output_file> specifies a filename to which the output will be written. Note, this is optional. If the -o option is not specified then the output of LAICALC will be displayed on the screen. Alternatively the screen output can be redirected to a file using the DOS redirection character '>' followed by <output_filename>. By convention, output files are generally given a *.lai suffix (see Section 5.3 for output file options).

-c <config_file> specifies which configuration file to used. Note, this is optional and typically will not be used. If the -c option, then LAICALC will use the default configuration file LAICALC.CNF. By convention, configuration files are generally given a *.cnf suffix (see Section 5.0 for configuration file format).

Example: In a case where the input file called tree.gap is in the current directory on the c: drive, the output is to be saved to d:\output, and the configuration file is in the d:\config directory, the following command line parameters would be used to run LAICALC:

```
laicalc tree.gap -o d:\output\tree.lai -c d:\config\laicalc.cnf
```

4.2. Batch Operation

DOS batch files can simplify the use of LAICALC. Batch files are especially useful for applications where large numbers of input files are used or where a repeated series of calculations are to be performed.

Example: In a case where first gap fraction is calculated from a *.out file using an awk program and then LAI calculations are performed, the following commands are contained in the batch file lcalc.bat:

```
awk -f gap.awk %1.out > %1.gap
laicalc %1.gap -o %1.lai
```

Thus, entering

```
lcalc site1
```

first performs awk calculations on site1.out to produce the gap fraction output in the file site1.gap; and then site1.gap is used as input to LAICALC to produce output in the file site1.lai.

5.0. CONFIGURATION FILE FORMAT

5.1. Overview of Configuration File Format

Options for LAICALC are specified using the configuration file. The default name of the configuration file is LAICALC.CNF (as noted in Section 3.2). Options can be specified in any order within the configuration file, and option names are specified within square brackets. In general, when an option involves a single argument, the argument is placed on the line immediately following the option name.

Example:

```
[OUTPUT_DELIMITER]
TAB
```

When an option involves a list of arguments, the option name is followed by the list of arguments, with each argument on a separate line, and the end of the list designated with [END] on its own line:

Example:

```
[ANNULUS]
7.5 15
22.5 15
37.5 15
52.5 15
67.5 15
[END]
```

A detailed explanation of all configuration options follows.

5.2. Input and Output Delimiters

[INPUT_DELIMITER]: This option specifies the delimiter character that is used in the input file containing the gap fractions. Typically this will be a space, comma, tab, or bar. These four commonly used delimiters may specified in the configuration file by using one of the following: COMMA, TAB, SPACE, or BAR. In addition, any ASCII character can be used as a delimiter by specifying the ASCII character code. A table of ASCII character codes can be found in the online help for Microsoft's QBASIC interpreter that comes with MS-DOS.

Example:

```
[INPUT_DELIMITER]
SPACE
```

specifies that a space is to be used as the input delimiter.

[OUTPUT_DELIMITER]: This option specifies the delimiter character that is used in the output file containing the gap fractions. As for input delimiters, output delimiters can be specified as COMMA, TAB, SPACE, or BAR, or as any ASCII character code. Note that the input and output delimiters do not have to be the same.

Example:

[OUTPUT_DELIMITER]
COMMA

specifies that a comma is to be used as the output delimiter.

5.3. Output Options

Output from LAICALC is printed as fields separated by spaces, commas, tabs, or other delimiters. This output is readily converted into any of the popular databases or spreadsheets for storage and analysis. Each field contains one of the specified output calculations. Each row in the output corresponds to a record that contains the output calculations for a given set of gap fractions in the input file.

LAICALC recognizes various descriptors for specification of output fields. These include the following variables:

LABEL: the label associated with a given set of gap fraction measurements;
LAI: the effective leaf area index;
GAMMA: the importance constraint used in calculating LAI;
MEAN_TILT_ANGLE: the mean tilt angle (mean leaf inclination);
MTA_ERROR: the standard error of the mean tilt angle;
SKYVIEW_FACTOR: the skyview factor, i.e., proportion unobstructed sky weighted by angle of incidence to a horizontal plane.

The following descriptors have different values associated with each zenith angle range (annulus). The n after each descriptor represents a number corresponding to each of the annulus for which calculations are being performed, with n=1, corresponding to the innermost annulus, (smallest zenith angle range) and n=maximum_annulus, corresponding to the outermost annulus. If [ZENITH_AVERAGING] is performed (see Section 5.5) the total number of annuli corresponds to the number after averaging.

EXTINCTION_COEFn: the extinction coefficient for a given annulus n;
PROJECTION_COEFn: the projection coefficient for a given annulus n;
MEAN_CONTACT_NUMBERn: the mean contact number for a given annulus n.

Similarly, one last descriptor, accounting for leaf angle distribution, has different values associated with different zenith angle ranges.

RELATIVE_LEAF_AREAn: the proportion of the total leaf area that corresponds to a given range of zenith angles n.

In this case, however, the n refers to angle ranges that span all zenith angle ranges from zero to 90 degrees. The number of zenith angle ranges will be the same as the number of annuli, but will commonly correspond to a different range For example, if five annuli at 15-degree intervals from zero to 75 degrees are used for the calculations, then each angle class would have a range of 18 degrees (90/5 degrees).

Example: For a case with gap fraction measurements from five annuli, an output file containing the record label, leaf are index, mean tilt angle, and the extinction coefficients for all five annuli would specified as follows:

```
[OUTPUT_FIELDS]
LABEL
LAI
MEAN_TILT_ANGLE
EXTINCTION_COEF1
EXTINCTION_COEF2
EXTINCTION_COEF3
EXTINCTION_COEF4
EXTINCTION_COEF5
[END]
```

The first line of the output file can optionally contain a list of all output data field labels by using the option [FIELD_LABELS] with the argument ON, for including the field label list, or OFF, for not including the field label list.

Example: For the preceding example, specifying that field labels are to be displayed,

```
[FIELD_LABELS]
ON
```

would lead to the following first line of the output file (assuming an output delimiter of SPACE):

LABEL LAI MEAN_TILT_ANGLE EXTINCTION_COEF1 EXTINCTION_COEF2 EXTINCTION_COEF3 EXTINCTION_COEF4 EXTINCTION_COEF5

5.4. Zenith Angle Ranges (Annuli)

The section in the configuration file denoted [ANNULUS] specifies the center angle and range of each annulus for which calculations are performed. The order is from small to large zenith angles (from the zenith toward the horizon), and angles are given in degrees. Thus, the argument list for [ANNULUS] consists of a pair of center angle and range values for each annulus. As for other argument lists, the end of the list is indicated by [END].

Example: For gap fraction measurements measured at 5-degree intervals from zero to 75 degrees, each annulus is specified by the center angle of each annulus (2.5, 7.5...) and the range of the annulus (5) as follows:

[ANNULUS]
2.5 5
7.5 5
12.5 5
17.5 5
22.5 5
27.5 5
32.5 5
37.5 5
42.5 5
47.5 5
52.5 5
57.5 5
62.5 5
67.5 5
72.5 5
[END]

5.5. Zenith Range Averaging Option

[ZENITH_AVERAGING]: This feature allows ranges of zenith angles (annuli) to be grouped together (using a weighted average) for calculation, which is useful to compare canopy indices from different instruments, or to save memory when a large number of annuli are measured. The argument for [ZENITH_AVERAGING] is the number of adjacent annuli that are to be grouped. For example, if gap fraction values are measured for 15 annuli, but only 5 aggregated annuli are to be used for calculation, then [ZENITH_AVERAGING] should have the value 3 (15 original annuli / 3 adjacent annuli grouped = 5 calculation annuli). Note that zenith averaging uses a sin weighting to account for increase in hemispherical area with increase in zenith angle. Also note that zenith averaging can only be performed when each annulus has the same total range and the number of original annuli can be divided by the zenith averaging value with no remainder.
Example: For instance, for gap fraction measurements taken from fifteen annuli at five-degree intervals fm zero to 75, clumping these into just five 15-degree ranges would require a zenith averaging of three:

[ZENITH_AVERAGING]
3

This would permit direct comparison with measurements by the Licor LAI-2000 canopy analyzer.

6.0. INPUT FILE FORMAT

The format of input files is relatively simple. LAICALC assumes that the first entry on a line is the identifying label. The label should be one word that uniquely identifies the set of gap fractions that follow. The gap fraction measurements follow the label on the same line, in order of increasing zenith angle. All entries in the input file must be delimited with an ASCII character (e.g. a comma), and the [INPUT_DELIMITER] variable in the configuration file (see Section 5.2) must specify this delimiter character.

Example: For gap fraction measurements using five annuli, and from three different sites which you refer to as SITE-A, SITE-B, and SITE-C, the contents of the input file would resemble the following:

SITE-A,0.5,0.3,0.25,0.1

SITE-B,0.9,0.75,0.6,0.3

SITE-C,0.76,0.65,0.5,0.2

Note that no spaces should occur within the label.

7.0. CONCLUSION

LAICALC provides a convenient means for calculating a suite of common canopy indices from gap fraction data. The program is written generically, such that it can use gap fraction data from any source. The configuration design permits a high degree of flexibility of specification of customized output.

8.0. ACKNOWLEDGMENTS

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