



# **FD\_LAI User Manual**

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# 1. Introduction

FD\_LAI is a free software developed by the RAMM research group (RAAdiation Modeling and Measurement, <http://ramm.bnu.edu.cn/>) of the Faculty of Geographical Science of Beijing Normal University. This software is a didactic product made only for pedagogic uses. It can be downloaded at [https://github.com/CloudyCUG/FD\\_LAI](https://github.com/CloudyCUG/FD_LAI) or <http://ramm.bnu.edu.cn/index.php/research?id=18>. For any information, question or bug report, please contact [muxihan@bnu.edu.cn](mailto:muxihan@bnu.edu.cn) or [lyk@mail.bnu.edu.cn](mailto:lyk@mail.bnu.edu.cn).

## 1.1 FD\_LAI usage

FD\_LAI is a software (Operating system: only Windows 10 or 11) used to calculate the Leaf Area Index (LAI) and Clumping Index (CI) from the binary images acquired with a fish-eye camera or with an ordinary digital camera (Yan et al. 2019), and from the transect data measured with tracing radiation and architecture of canopies (TRAC) (Leblanc et al. 2002). The calculation results, *i.e.*, effective LAI (LAI<sub>e</sub>), CI, LAI, are automatically saved in a .txt file named “results\_1DFD” or “results\_2DFD” according to the method selected by the user, which is located in the data directory entered by the user. FD\_LAI can be used to process:

- (1) DHP: digital hemispherical photographs acquired at nadir direction with a fisheye camera;
- (2) DCP: digital cover photographs acquired with an ordinary camera inclined at 0~90° from the vertical direction.
- (3) Transect: transect data acquired with a TRAC instrument.

## 1.2 Hardware and software requirements

The FD\_LAI is a software developed under Microsoft Visual Studio 2017 and can be used on any 64-bit computer working under windows 10 or 11 operating system. It is a compiled version that does not require to install Visual Studio 2017 on the computer. FD\_LAI can be run directly without installation. However, note that FD\_LAI must be located in the same directory as the “gdal203.dll” file to run properly (Fig 1).

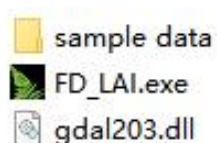


Fig 1. An example to show that FD\_LAI must be located in the same directory as the “gdal203.dll”

file to run properly.

## 1.3 Copyright and limitations of responsibility

The FD\_LAI software and the accompanying documentation described herein are provided as freeware. RAMM research group reserves the right to make changes to this document and software at any time and without notice. RAMM research shall not be liable for any direct, consequently, or other damages suffered by the use of the FD\_LAI software package or its documentation. If the software is used to publish intellectual property rights, the user needs to cite these two articles (Lai et al. 2022; Li and Mu 2021).

## 2. Using FD\_LAI step by step

### 2.1 Choosing the datatype to be processed

FD\_LAI software can process DCP images, DHP images, and TRAC transects. Users select the datatype to be processed in the first dialog interface (Fig 2).

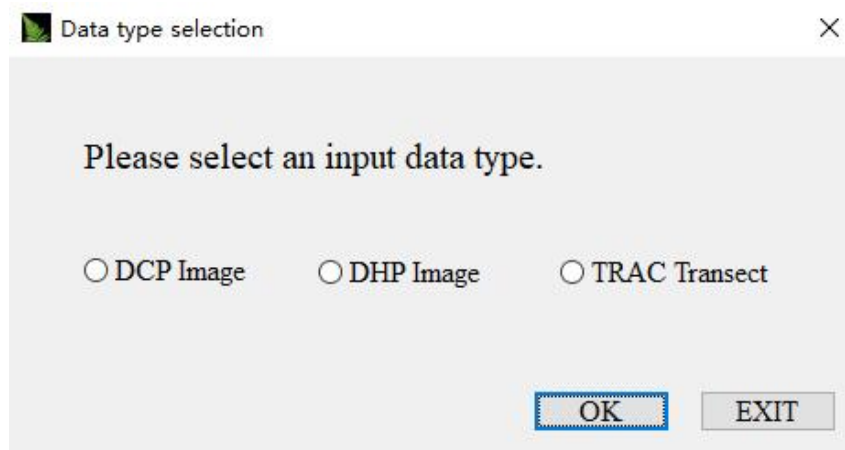


Fig 2. The first dialog interface of FD\_LAI for datatype selection.

FD\_LAI accepts only TIF images, *i.e.*, the image name is suffixed with “.tif” or “.tiff”. The images can be any size. However, all the images to be processed concurrently and stored in a single directory should have the same camera setup and the same inclination angle from the vertical direction. Since the software does not provide classification functions, all images need to be classified in advance and saved as binary images, *e.g.*, 0 for gap pixels and 1 for vegetated pixels. Classification method that accounts for the shadow effect would be a priority for the

downward-looking DCP images, *e.g.*, the SHAR-LABFVC method (Song et al. 2015).

Traditionally, TRAC measurement data is saved in .trc format (Leblanc et al. 2002) and can be opened with Notepad or WordPad (Fig 3(a)). Users need to extract the first column in the TRAC data and save it in .txt format (Fig 3(b)). Users do not need to remove the mark of the beginning of the sub-segment (*i.e.*, 9999 in the data), the FD\_LAI software will automatically skip it during processing.

(a)	9999 2017-08-14 09:12:09	(b)	9999
	1241 1241 1241		1241
	1245 1245 1245		1245
	1250 1250 1250		1250
	1251 1251 1251		1251
	1253 1253 1253		1253
	1254 1254 1254		1254
	1254 1254 1254		1254
	1254 1254 1254		1254
	1253 1253 1253		1253
	1253 1253 1253		1253
	1250 1250 1250		1250

Fig 3. Example of original TRAC data (a) and the first column of the TRAC data (b).

## 2.2 Defining the processing parameters

Once the datatype is selected, another dialog interface will pop up. The user must provide the process parameters that change depending on the datatype selected.

### 2.2.1 Processing parameters for DCP

If the DCP type is selected, the FD\_LAI provides two methods (*i.e.*, 1DFD method and 2DFD method) for calculating the LAI and CI. Both methods require the following parameters (Fig 4).

Fig 4. Parameter input dialog for DCP images.

- (1) **Value of gap pixel:** this parameter is the value of gap pixels of the binary image in the directory, *e.g.*, 0 for gap pixels.
- (2) **Value of vegetated pixel:** this parameter is the value of vegetated pixels of the binary image in the directory, *e.g.*, 1 for vegetated pixels.
- (3) **Leaf projection factor:** this is the value of leaf project function  $G(\theta)$  at zenith angle  $\theta$ . The  $G(\theta)$  is 0.5 if the  $\theta$  is around  $57.3^\circ$  or the leaf angle distribution is spherical.
- (4) **Viewing zenith angle:** the range of the parameter is 0~90 degrees ( $^\circ$ ). It should be the same as the  $\theta$  in  $G(\theta)$ . For DCP images taken vertically up or down, this parameter is 0.
- (5) **Needle-to-shoot area ratio:** this parameter is used to account for within-shoot clumping of conifer species. For flat leaves, needle-to-shoot area ratio is 1. Some typical values are listed in the drop-down list (Fig 5).

Fig 5. The Needle-to-shoot area ratio values for some conifer species are listed in the drop-down list.

- (6) **Woody-to-total area ratio:** when considering the effect of woody component on the measured gap probability, this is needed to convert plant area index (PAI) to LAI (Chen et al. 1997). Some typical values are listed in the drop-down list (Fig 6).

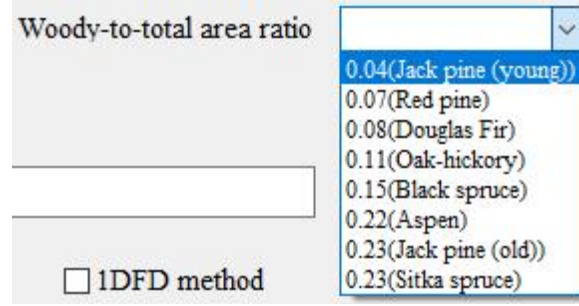


Fig 6. The Woody-to-total area ratio values for some species are listed in the drop-down list.

- (7) **Mean leaf radius (unit: pixel)**: this parameter refers to the number of pixels in the image that the leaf radius occupies when the leaf is treated as a circle. For example, if the area of a leaf is 100 cm<sup>2</sup> and the leaf is regarded as a circle, the radius of the leaf is 5.6 cm. Then, this parameter is  $5.6 \left( = \sqrt{\frac{100}{\pi}} \right)$  if the resolution of the image is 1 cm. The detailed calculation method of this parameter is described in section 2.4.
- (8) **Data file path**: this is the path of the directory containing DCP images. The user can manually enter the path or click the Browsing button to select the path.
- (9) **Optional method**: the FD\_LAI provides two methods for calculating LAI and CI. The user can choose one or two methods to calculate LAI and CI.

Note that these parameters entered by the user are applied to all images in the directory.

### 2.2.2 Processing parameters for DHP

DHP image provides near-hemispheric observations. Traditionally, observations around 57° are extracted to estimate the LAI. By default, the FD\_LAI extracts 55~60° observations from a DHP image to calculate LAI, because  $G(\theta)$  in this particular direction is almost independent of leaf angle distribution and equals to 0.5 (Ross 1981; Wilson 1963). Since the extracted transects are one-dimensional data, 2DFD method cannot be used for DHP images. Thus, the default method of the FD\_LAI is the 1DFD method.

Note that FD\_LAI supports equidistant projection and equisolid projection function. The user needs to select a projection method that is consistent with the fisheye lens used. In addition, DHP images should be acquired at nadir direction, either upward (looking at the sky) or downward (looking at the soil). The center of the images should correspond to the 0° viewing direction, and the field of view should be around 180°.

The parameters required are as follows (Fig 7).

Parameter input

Leaf area index calculation using fractal dimension

Value of gap pixel  Value of vegetated pixel

Needle-to-shoot area ratio  Woody-to-total area ratio

Leaf projection factor (G; 0~1)

Mean leaf radius (unit: pixel)

Data file path (.tif or .tiff)  Browsing...

Fisheye projection ☐ Equisolid ☐ Equidistant

OK EXIT

Fig 7. Parameter input dialog for DHP images.

- (1) **Value of gap pixel:** this parameter is the value of the gap pixel of the binary image in the directory, *e.g.*, 0 for gap pixels.
  - (2) **Value of vegetated pixel:** this parameter is the value of the vegetated pixel of the binary image in the directory, *e.g.*, 1 for vegetated pixels.
  - (3) **Needle-to-shoot area ratio:** this parameter is used to account for within-shoot clumping of conifer species. For flat leaves, needle-to-shoot area ratio is 1. Some typical values are listed in the drop-down list (Fig 5).
  - (4) **Woody-to-total area ratio:** when considering the effect of woody component on the measured gap probability, this is needed to convert plant area index (PAI) to LAI (Chen et al. 1997). Some typical values are listed in the drop-down list (Fig 6).
  - (5) **Leaf projection factor:** this is the value of leaf project function  $G(\theta)$  in  $\theta$  zenith angle. The  $G(\theta)$  in zenith around  $57^\circ$  is almost independent of leaf angle distribution and equals to 0.5
  - (6) **Mean leaf radius:** this parameter refers to the number of pixels in the image that leaf radius occupies when the leaf is treated as a circle. For example, if the area of a leaf is  $100 \text{ cm}^2$  and the leaf is regarded as a circle, the radius of the leaf is 5.6 cm. when the resolution of the observation range of  $55\sim 60^\circ$  in an DHP image is 1 cm, this parameter is  $5.6 (= \sqrt{\frac{100}{\pi}})$ . The detailed calculation method of this parameter is described in section 2.4.
  - (7) **Data file path:** this is the path of the directory containing DHP images. The user can manually enter the path or click the Browsing button to select the path.
- Note that these parameters entered by the user are applied to all images in the directory.



### 2.2.3 Processing parameters for TRAC transects

Since the TRAC transects are one-dimensional data, the default method adopted by the FD\_LAI is the 1DFD method. The parameters required for processing TRAC transects are as follows (Fig 8).

Parameter input

Leaf area index calculation using fractal dimension

Total gap probability (0~1)  Solar zenith angle (0~90)

Needle-to-shoot area ratio  Woody-to-total area ratio

Leaf projection factor (0~1)

Mean leaf radius (unit: pixel)

Data file path (.txt)

Fig 8. Parameter input dialog for TRAC transects.

- (1) **Total gap probability:** this parameter is the value of the fraction of the measured transect occupied by gaps ( $F_m$  in Fig 9) when  $\Lambda$  is 0 in the .fmr file output by the TRAC Android or TRACWin software (Leblanc et al. 2002) (Fig 9).

$\Lambda$	$F_m$	$F_{mr}$	$F_r$
0.0	0.363419	0.202638	0.202638
5.0	0.346672	0.181662	0.197794
10.0	0.330996	0.162027	0.186007
15.0	0.316883	0.144349	0.170416
20.0	0.305322	0.129868	0.153145
25.0	0.293082	0.114537	0.135593
30.0	0.281049	0.099465	0.118643

Fig 9. Example of xxx.fmr file of a measurement. The gap probability of this measurement is the value of  $F_m$ , i.e., 0.363419, when  $\Lambda$  is 0.

- (2) **Solar zenith angle:** the TRAC measures gap probability in the sun's direction. This parameter is recorded in the .lai file output by the TRAC Android or TRACWin software (Leblanc et al. 2002).
- (3) **Needle-to-shoot area ratio:** this parameter is used to account for within-shoot clumping of conifer species. For flat leaves, needle-to-shoot area ratio is 1. Some typical values are listed in the drop-down list (Fig 5).
- (4) **Woody-to-total area ratio:** when considering the effect of woody component on the measured gap probability, this is needed to convert plant area index (PAI) to LAI. Some typical values are listed in the drop-down list (Fig 6).



- (5) **Leaf projection factor:** this is the value of leaf project function  $G(\theta)$  at zenith angle  $\theta$ .
- (6) **Mean leaf radius:** this parameter should be calculated using the area of leaf shadows. However, if the sunlight is regarded as parallel light, this parameter can also be directly calculated by the leaf area. TRAC records the transmitted direct light at a high frequency, *i.e.*, 32 Hz (Leblanc et al. 2002). If TRAC is hand-carried by a person walking at a steady speed of 0.3 m per second, the resolution of this TRAC measurement is about 1 cm. If the area of a leaf is 100 cm<sup>2</sup> and the leaf is regarded as a circle, then this parameter is 5.6 ( $=\sqrt{\frac{100}{\pi}}$ ).
- (7) **Data file path:** this is the file path of the TRAC measurements saved in .txt format. The user can manually enter the path or click the Browsing button to select the path.

## 2.3 Dialog button function

FD\_LAI software contains three kinds of buttons, OK button, EXIT button, and Cancel button.

- (1) OK button: after the user has entered the required parameters, the user can click the OK button to run the program to calculate LAI and CI.
- (2) EXIT button: after the user clicks the EXIT button of the parameter input dialog (Figs 4, 7, 8), the software returns to the datatype selection dialog (Fig 2). If the user clicks the EXIT button of the datatype selection dialog, the FD\_LAI finishes running and close.
- (3) Cancel button: this button appears in the prompt dialog (Fig 10) that pops up after the user clicks the OK button of the parameter input dialog. If the user clicks the Cancel button, the program will not continue to execute, but will return to the parameter input dialog. If the user clicks the OK button, the program continues until all data are processed.

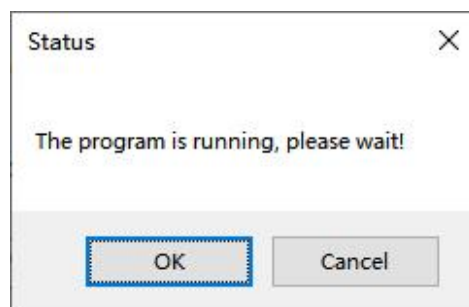


Fig 10. Prompt dialog.

## 2.4 Sample data

Some simulated ortho-DCP images and equidistant projected DHP images are provided in the sample data directory. These images were simulated with large-scale emulation system (LESS) (Qi et al. 2019). The real LAIs of these images have been given in the image name, *e.g.*, “LAI\_0.78.tiff” indicates that the true LAI of the image is 0.78. All images have been processed as binary images, with the pixel values of 1 for leaves and 0 for gaps, respectively. The leaf angle distribution of most DCP images and all DHP images was spherical, except for the scenes with LAI of 1.29, 2.12, 2.59, 2.98, 3.30 and 4.15. However, the leaf projection function (G) could be set to 0.5 when calculating the LAI. In addition, there are not any branch in the simulated scenes, and all trees in the simulated scenes are broadleaf species.

The following describes how to use the FD\_LAI software to estimate the LAI of these simulated data, taking a DCP image generated from a scene with a LAI of 1.58 as an example. According to the description of the scene and data, the following parameters can be easily determined:

- (1) **Value of gap pixel = 0;**
- (2) **Value of vegetated pixel = 1;**
- (3) **Leaf projection factor = 0.5;**
- (4) **Needle-to-shoot area ratio = 1;**
- (5) **Woody-to-total area ratio = 0;**

The only unknown parameter is “**Mean leaf radius**”. This parameter can be calculated when we know the real area of the leaf and the resolution of the image. In addition, if we do not know the real area of the leaf, we can estimate the parameter by extracting the number of pixels occupied by the leaf from the image. The steps are as follows (Fig 11):

- (1) First, load the DCP image in Environment for Visualizing Images (ENVI) software or any other software that can open your image file;
- (2) Then, visually select a complete leaf on the image. Note that this leaf should be approximately perpendicular to the viewing direction to reduce the effect of leaf inclination angle, *i.e.*, the leaf whose shape remains intact on the image.
- (3) Finally, count the pixels occupied by the leaf ( $n$ ) and calculate the “**Mean leaf**

**radius**”, *i.e.*,  $\sqrt{\frac{n}{\pi}}$ .

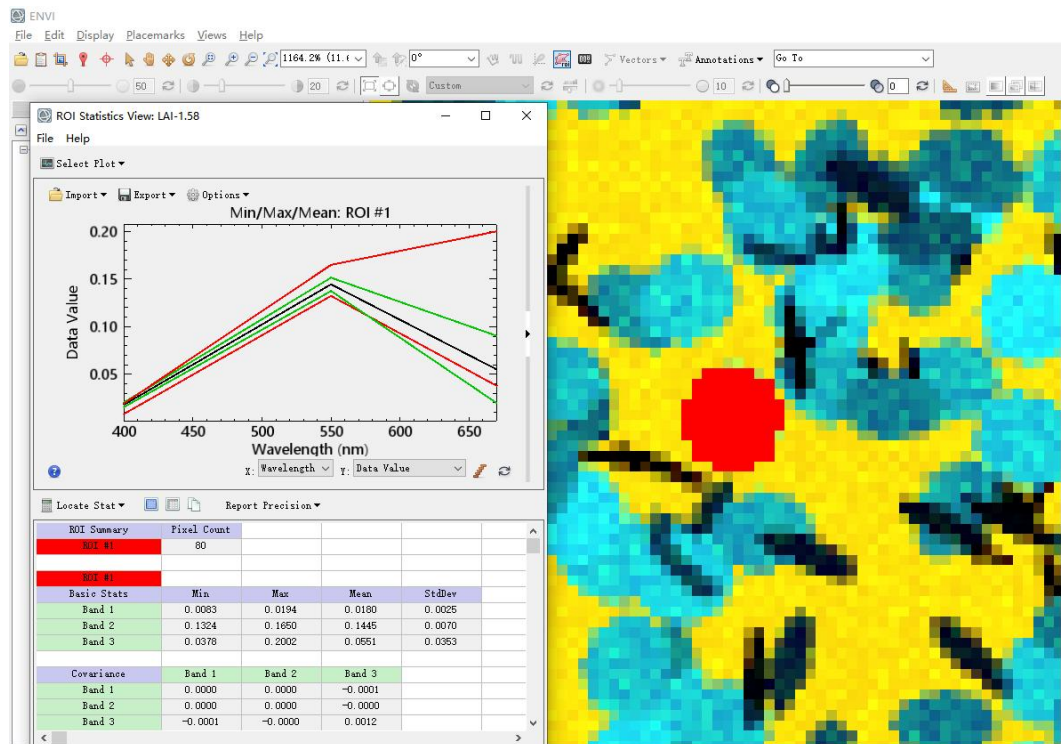


Fig 11. An example showing how to estimate the “Mean leaf radius” with Region of Interest Tool (ROI) of ENVI. Red pixels represent the selected leaf. Since the number of red pixels is 80, the

“Mean leaf radius” is  $5 (= \sqrt{\frac{80}{\pi}})$ .

The number of pixels occupied by the leaf is 80 (Fig 11). Thus, the “**Mean leaf radius**” for the scene with a LAI of 1.58 is 5.0 ( $= \sqrt{\frac{80}{\pi}}$ ). The parameters finally entered in the dialog are shown in Fig 12. The results (including other scenes with “**Mean leaf radius**” of 5) estimated by the FD\_LAI are shown in Fig 13.

The figure shows a dialog box titled 'Parameter input' for 'Leaf area index calculation using fractal dimension'. The parameters are as follows:

- Value of gap pixel: 0
- Value of vegetated pixel: 1
- Leaf projection factor (G; 0~1): 0.5
- Viewing zenith angle (0~90): 0
- Needle-to-shoot area ratio: 1
- Woody-to-total area ratio: 0
- Mean leaf radius (unit: pixel): 5
- Data file path (.tif or .tiff): MFC\FDmethods\64\Release\sample data\DCP\5
- Optional method: ☒ 2DFD method, ☒ 1DFD method

Buttons: OK, Exit

Fig 12. An example of dialog interface after parameter input.

results_1DFD.txt - Notepad (a)				results_2DFD.txt - Notepad (b)			
Image name	LAIe	CI	LAI	Image name	LAIe	CI	LAI
LAI_0.78.tiff	0.779573		0.889022	LAI_0.78.tiff	0.779574	0.9766	0.798254
LAI_1.58.tiff	1.67258		0.964294	LAI_1.58.tiff	1.67258	1	1.67258
LAI_1.09.tiff	1.0884		0.945538	LAI_1.09.tiff	1.0884	0.9334	1.16606
LAI_1.29.tiff	1.09848		0.844457	LAI_1.29.tiff	1.09847	0.7731	1.42087
LAI_1.40.tiff	1.41272		0.958556	LAI_1.40.tiff	1.41272	0.8829	1.60009
LAI_1.68.tiff	1.23576		0.681209	LAI_1.68.tiff	1.23576	0.6307	1.95934
LAI_1.94.tiff	1.93756		0.975447	LAI_1.94.tiff	1.93756	1	1.93756
LAI_2.12.tiff	1.79868		0.704283	LAI_2.12.tiff	1.79868	0.681322	2.63998
LAI_3.52.tiff	2.81455		0.726504	LAI_3.52.tiff	2.81455	0.633561	4.44243
LAI_3.87.tiff	2.27043		0.594486	LAI_3.87.tiff	2.27043	0.63671	3.56588
LAI_5.64.tiff	3.95367		0.767612	LAI_5.64.tiff	3.95368	0.556237	7.10789
LAI_5.86.tiff	4.9601		0.89008	LAI_5.86.tiff	4.9601	1	4.9601
			5.57265				

Fig 13. Estimation results for scenes with “Mean leaf radius” of 5 (file path: XXX\FD\_LAI\sample data\DCP\r=5). (a) and (b) are the results of the 1DFD method and 2DFD method, respectively.

### 3. Theoretical background

#### 3.1 definition and method description

Leaf area index (LAI) is defined as half the total leaf area per unit horizontal ground surface area (Chen and Black 1992; Gonsamo and Pellikka 2008; Leblanc et al. 2005). LAI is an important vegetation structure parameter and has been widely used in climate, ecosystem, and hydrological modeling (Asner et al. 2003; Jonckheere et al. 2004; Stark et al. 2012).

Ground-based LAI estimation methods are generally classified into two categories: direct and indirect. Since the direct method is time-consuming, lab-intensive, and destructive (Daughtry 1990; Gower et al. 1999), the indirect methods are more widely used. Indirect methods are mostly based on the Beer-Lambert Law. This law assumes that leaves are randomly distributed in space and expresses the mathematical relationship between the gap probability and the LAI (Eq. 3.1).

$$P(\theta) = e^{-G(\theta)LAI/\cos(\theta)} \quad (3.1)$$

where  $P(\theta)$  is the gap probability at viewing zenith  $\theta$ ,  $G(\theta)$  refers to the leaf projection function.

In reality, leaves are often clumped in canopies, which is inconsistent with the assumption of the Beer-Lambert Law. The clumping distribution of leaves can seriously affect the accuracy of Beer-Lambert Law in estimating LAI. The underestimation of LAI due to the leaf clumping can be between 30% and 70% for forests (Chen and Cihlar 1995b; Stenberg 1996), and approximately 11% for row crops (Baret et al. 2010). Thus, the difficulty with indirect method lies primarily in how to correct for the clumping effect. A parameter, called clumping index (CI) and

often represented by  $\Omega$  in the formula, is introduced in Beer-Lambert Law to consider the clumping effect (Black et al. 1991; Nilson 1971):

$$P(\theta) = e^{-G(\theta) \cdot \Omega \cdot LAI / \cos(\theta)}. \quad (3.2)$$

Considerable efforts have been exerted to correct for the clumping effect. To obtain relatively accurate LAI estimate, the FD\_LAI software is developed based on two-dimensional fractal dimension (2DFD) method (Li and Mu 2021) and one-dimensional fractal dimension (1DFD) method (Lai et al. 2022).

The theory presented here follows Li and Mu (2021). The 2DFD method introduced the fractal dimension (FD) of DCP images to correct for the clumping effect. The box-counting method (BCM) was used by the 2DFD method to calculate the FD. A formula for the FD and LAI of the scene with randomly and horizontally distributed leaves can be established based on Boolean model. Then, the  $G(\theta)$  and CI were introduced to the formula and the final relationship between FD, LAI, and CI were established for general scenes.

The 2DFD method was proven to be applicable to DCP images. However, it cannot be used with one-dimensional (1D) data such as the data obtained by TRAC or transects extracted from DHP and DCP imagery. Since 1D data account for a large proportion of field measurement data, it is worth exploring how to use this 1D information and establish a relationship between 1D FD, LAI, and CI. To establish the relationship between 1D FD, LAI, and CI for transect data, Lai et al. (2022) derived the relationship between LAI and FD for transects from random and horizontal scenes, based on the principle of BCM and binomial distribution model. The average length of all intersecting segments of a leaf and transect and the number of leaves intersecting the transect were derived to establish the relationship. Then, considering the leaf angle and leaf clumping effect,  $G(\theta)$  and CI were introduced, and the final relationship between FD, LAI, and CI were established for transects of general scenes.

### 3.2 PAI or LAI

Both the 2DFD method and 1DFD method use Beer-Lambert Law to calculate LAI (Eq. 3.2). When considering the effect of woody component on the measured  $P(\theta)$ , the LAI estimate of these two methods should be regarded as the plant area index (PAI), which is the sum of the LAI and the woody area index (WAI) (Neumann et al. 1989). The woody-to-total area ratio ( $\alpha$ ) can be used to convert PAI to LAI as follows (Chen et al. 1997; Zou et al. 2009):

$$LAI = (1 - \alpha) \cdot PAI \quad (3.3)$$

Some typical  $\alpha$  values are as follows (Gower et al. 1999):

- (1) Black spruce (*Picea mariana*): 0.12~0.17;
- (2) Jack pine (young) (*Pinus Banksiana*): 0.03~0.05;
- (3) Jack pine (old) (*Pinus Banksiana*): 0.11~0.34;
- (4) Red pine (*Pinus resinosa*): 0.07;
- (5) Douglas Fir (*Pseudotsuga menziesii*): 0.08;
- (6) Aspen (*Populus tremuloides*): 0.21~0.22;
- (7) Oak-hickory: 0.11;
- (8) Sitka spruce: 0.23;

### 3.3 Needle-to-shoot area ratio ( $\gamma_E$ )

For coniferous species, shoots are identified as foliage when Beer-Lambert Law is used to calculate the LAI (Chen and Cihlar 1995a). However, the needles are also clumped within shoots, rather than randomly distributed. Thus, the overall clumping is affected by clumping at scales larger than the shoots ( $\Omega_E$ ) plus clumping within the shoots (Chen and Cihlar 1995a; Fang 2021; Stenberg et al. 2014). Therefore, the  $\Omega$  in Eq. 3.2 is essentially  $\Omega_E$  for the coniferous forest. To obtain an overall  $\Omega$ , a needle-to-shoot area ratio ( $\gamma_E$ ) is introduced to account for within-shoot clumping (Eq. 3.4). For broad-leaved species,  $\gamma_E$  is equal to 1.

$$\Omega = \frac{\Omega_E}{\gamma_E} \quad (3.4)$$

Some typical  $\gamma_E$  values are as follows (Gower et al. 1999):

- (1) Black spruce (*Picea mariana*): 1.30~1.40;
- (2) Jack pine (*Pinus Banksiana*): 1.20~1.40;
- (3) Red pine (*Pinus resinosa*): 2.08;
- (4) Scots pine (*Pinus sylvestris*): 1.75;
- (5) Douglas Fir (*Pseudotsuga menziesii*): 1.77;

Thus, to obtain the LAI, the results of the 1DFD and 2DFD (PAI) need to be converted as follows:

$$LAI = (1 - \alpha) \cdot PAI \cdot \gamma_E \quad (3.5)$$

## 4. Acknowledgements

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## 5. References

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