FD_LAI User Manual

Version 1 updated June, 10th 2022

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1. Introduction

FD_LAI is a free software developed by the RAMM research group (RAdiation 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 or http://ramm.bnu.edu.cn/index.php/research?id=18. For any information, question or bug report, please contact muxihan@bnu.edu.cn or lyk@mail.bnu.edu.cn.

1.1FD_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 (LAIe), 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).

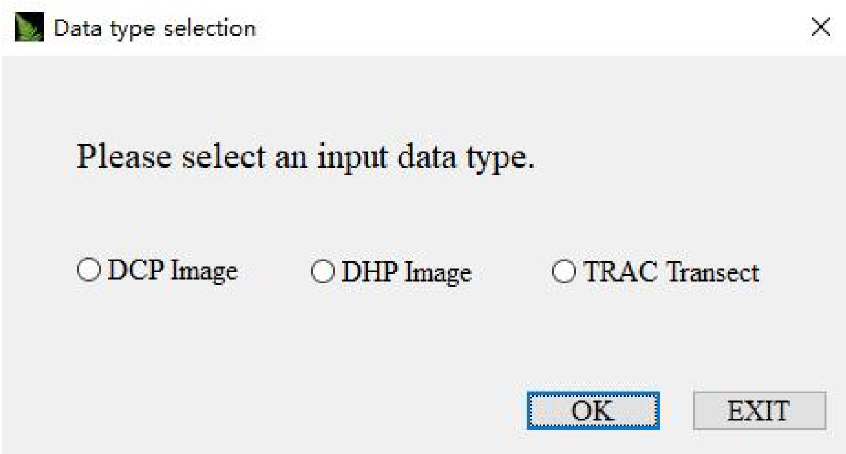


Fig 2. The first dialog interface of FD_LAI for datatype selection.

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
1241 1241 1241
1245 1245 1245
1250 1250 1250
1251 1251 1251
1253 1253 1253
1254 1254 1254
1254 1254 1254
1254 1254 1254
1253 1253 1253
1253 1253 1253
1250 1250 1250
```

(b)

```
9999
1241
1245
1250
1251
1253
1254
1254
1254
1253
1253
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).

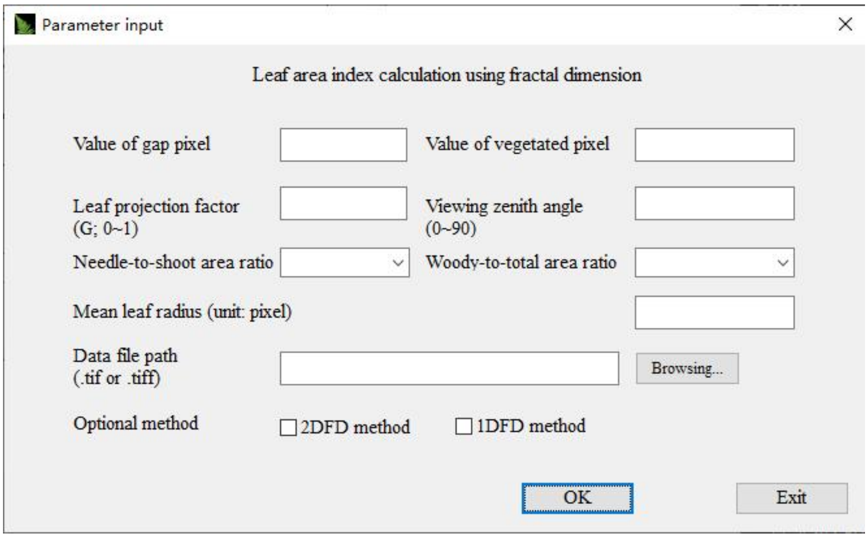


Fig 4. Parameter input dialog for DCP images.

(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 θ. The $G(\theta)$ is 0.5 if the θ is around 57.3° or the leaf angle distribution is spherical.

(4) **Viewing zenith angle**: the range of the parameter is 0~90 degrees (°). It should be the same as the θ in $G(\theta)$.

(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).

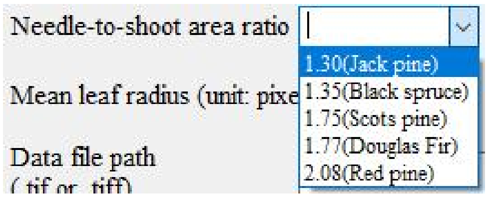


Fig 5. The Needle-to-shoot area ratio values for some conifer species are listed in the drop-down list.

(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).

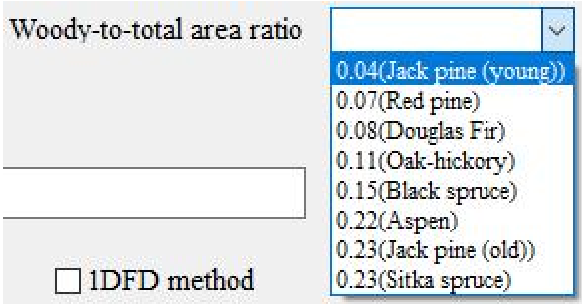


Fig 6. The Woody-to-total area ratio values for some species are listed in the drop-down list.

(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^2 and the leaf is regarded as a circle, the radius of the leaf is 5.6 cm. Then, this parameter is 5.6 ($=\sqrt{\frac{100}{\pi}}$) 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).

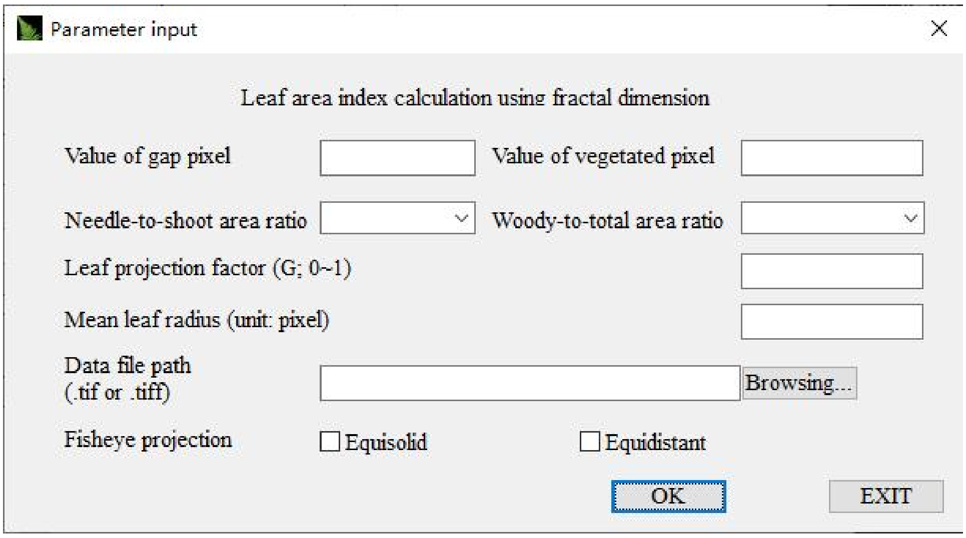


Fig 7. Parameter input dialog for DHP images.

(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 θ zenith angle. The $G(\theta)$ in zenith around 57° 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 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 55~60° 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).

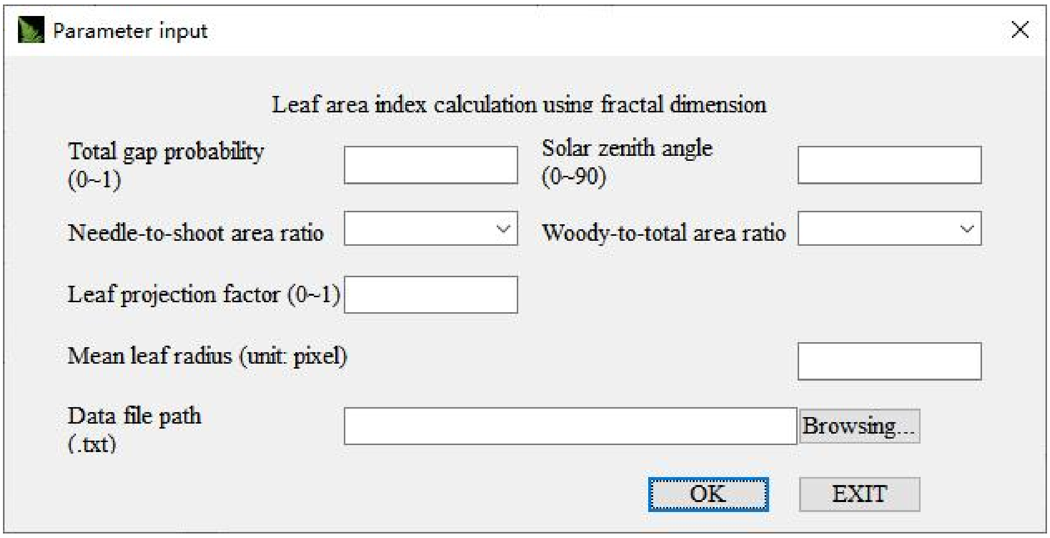


Fig 8. Parameter input dialog for TRAC transects.

(1) **Total gap probability**: this parameter is the value of the fraction of the measured transect occupied by gaps (Fm 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	Fm	Fmr	Fr
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 Fm, *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 θ.

(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^2 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.

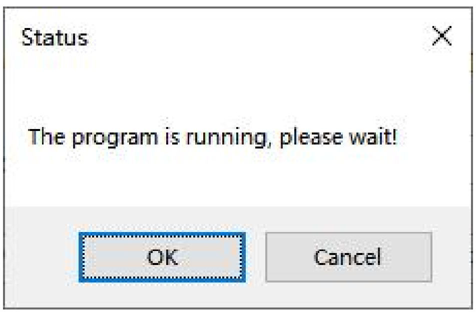


Fig 10. Prompt dialog.

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.*, $\sqrt{\frac{n}{\pi}}$.

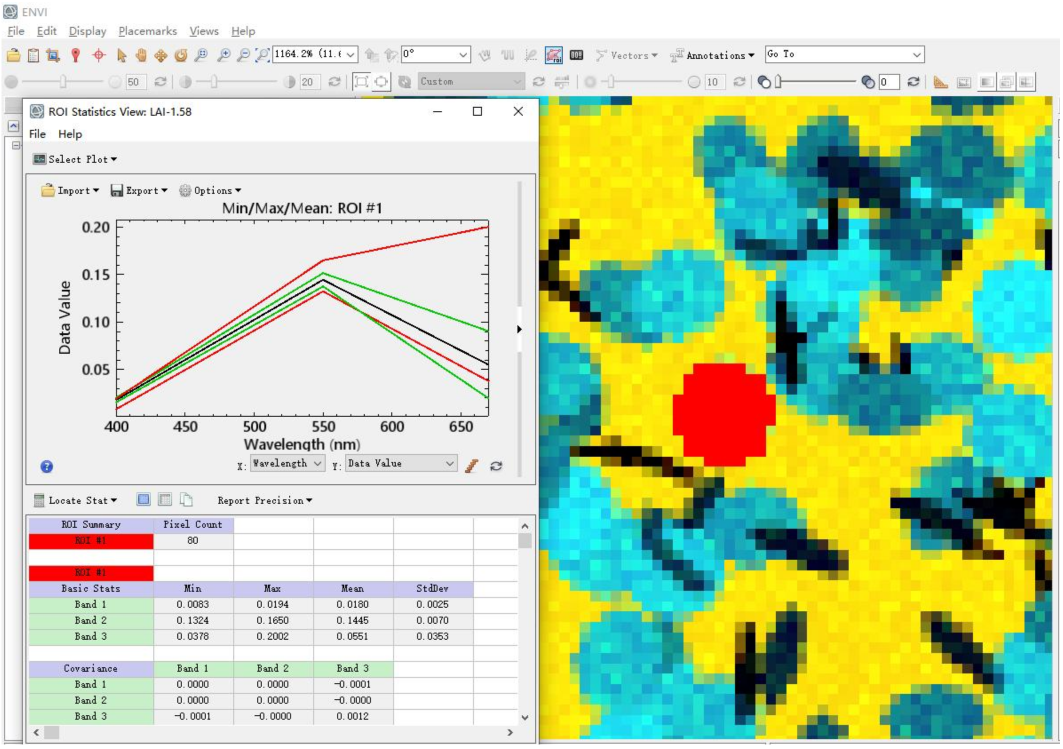


Fig 11. An example showing how to estimate the “Mean leaf radius” with Region of Interest Tool (ROI) of ENVI. Red pixels represent the selected leaf. Since the number of red pixels is 80, the “Mean leaf radius” is 5 ($=\sqrt{\frac{80}{\pi}}$).

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.

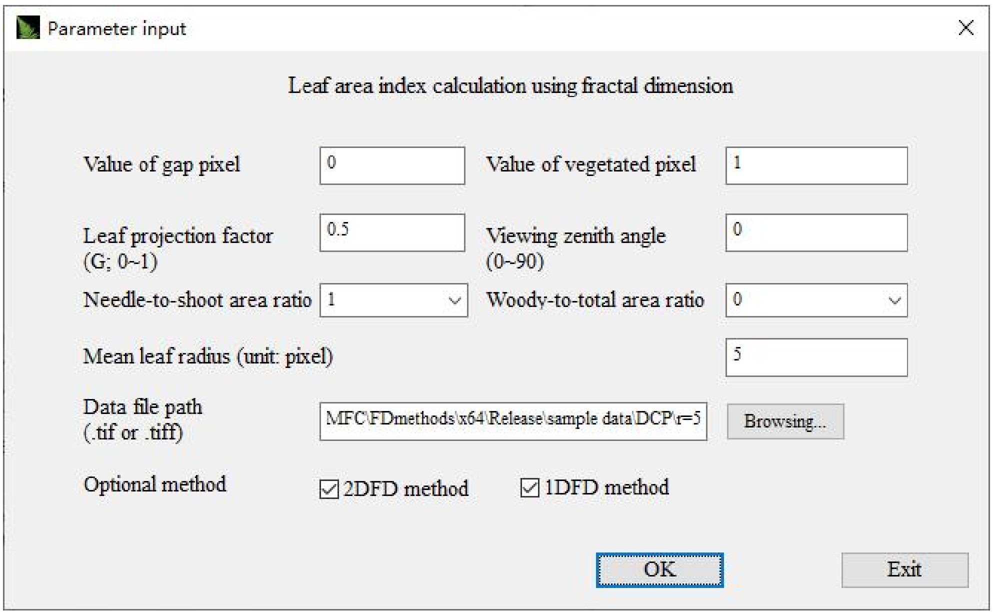
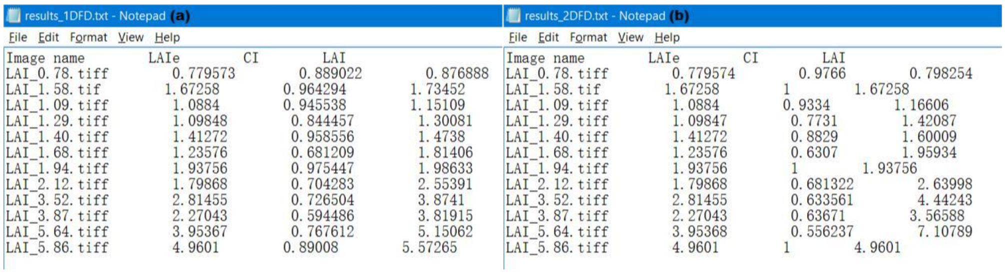


Fig 12. An example of dialog interface after parameter input.



results_1DFD.txt - Notepad (a)

Image name	LAIe	CI	LAI
LAI_0.78.tiff	0.779573	0.889022	0.876888
LAI_1.58.tif	1.67258	0.964294	1.73452
LAI_1.09.tiff	1.0884	0.945538	1.15109
LAI_1.29.tiff	1.09848	0.844457	1.30081
LAI_1.40.tiff	1.41272	0.958556	1.4738
LAI_1.68.tiff	1.23576	0.681209	1.81406
LAI_1.94.tiff	1.93756	0.975447	1.98633
LAI_2.12.tiff	1.79868	0.704283	2.55391
LAI_3.52.tiff	2.81455	0.726504	3.8741
LAI_3.87.tiff	2.27043	0.594486	3.81915
LAI_5.64.tiff	3.95367	0.767612	5.15062
LAI_5.86.tiff	4.9601	0.89008	5.57265

results_2DFD.txt - Notepad (b)

Image name	LAIe	CI	LAI
LAI_0.78.tiff	0.779574	0.9766	0.798254
LAI_1.58.tif	1.67258	1	1.67258
LAI_1.09.tiff	1.0884	0.9334	1.16606
LAI_1.29.tiff	1.09847	0.7731	1.42087
LAI_1.40.tiff	1.41272	0.8829	1.60009
LAI_1.68.tiff	1.23576	0.6307	1.95934
LAI_1.94.tiff	1.93756	1	1.93756
LAI_2.12.tiff	1.79868	0.681322	2.63998
LAI_3.52.tiff	2.81455	0.633561	4.44243
LAI_3.87.tiff	2.27043	0.63671	3.56588
LAI_5.64.tiff	3.95368	0.556237	7.10789
LAI_5.86.tiff	4.9601	1	4.9601

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).

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

where $P(\theta)$ is the gap probability at viewing zenith θ, $G(\theta)$ 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 Ω in the formula, is introduced in Beer-Lambert Law to consider the clumping effect (Black et al. 1991; Nilson 1971):

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

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 (α) can be used to convert PAI to LAI as follows (Chen et al. 1997; Zou et al. 2009):

$$LAI = (1-\alpha)\cdot PAI \tag{3.3}$$

Some typical α 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 (*Populous tremuloides*): 0.21~0.22;
(7) Oak-hickory: 0.11;
(8) Sitka spruce: 0.23;

3.3 Needle-to-shoot area ratio ($\boldsymbol{\gamma_E}$)

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 (Ω_E) plus clumping within the shoots (Chen and Cihlar 1995a; Fang 2021; Stenberg et al. 2014). Therefore, the Ω in Eq. 3.2 is essentially Ω_E for the coniferous forest. To obtain an overall Ω, a needle-to-shoot area ratio (γ_E) is introduced to account for within-shoot clumping (Eq. 3.4). For broad-leaved species, γ_E is equal to 1.

$$\Omega = \frac{\Omega_E}{\Upsilon_E} \tag{3.4}$$

Some typical γ_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:

$$LAI = (1 - \alpha) \cdot PAI \cdot \Upsilon_E \tag{3.5}$$

4. Acknowledgements

Appreciation is sincerely expressed to the people who helped test the software: Linyuan Li from Beijing Forestry University, Yuequn Bian and Yaoyao Chen from Beijing Normal University.

5. References

Asner, G.P., Scurlock, J.M., A. Hicke, J. (2003). Global synthesis of leaf area index observations: implications for ecological and remote sensing studies. *Global Ecology and Biogeography, 12*, 191-205.

Baret, F., de Solan, B., Lopez-Lozano, R., Ma, K., Weiss, M. (2010). GAI estimates of row crops from downward looking digital photos taken perpendicular to rows at 57.5 zenith angle: Theoretical considerations based on 3D architecture models and application to wheat crops. *Agricultural and Forest Meteorology, 150*, 1393-1401.

Black, T.A., Chen, J.-M., Lee, X., Sagar, R.M. (1991). Characteristics of shortwave and longwave irradiances under a Douglas-fir forest stand. *Canadian Journal of Forest Research, 21*, 1020-1028.

Chen, J.M., Black, T. (1992). Defining leaf area index for non-flat leaves. *Plant, Cell & Environment, 15*, 421-429.

Chen, J.M., Cihlar, J. (1995a). Plant canopy gap-size analysis theory for improving optical measurements of leaf-area index. *Applied optics, 34*, 6211-6222.

Chen, J.M., Cihlar, J. (1995b). Quantifying the effect of canopy architecture on optical measurements of leaf area index using two gap size analysis methods. *IEEE transactions on geoscience and remote sensing, 33*, 777-787.

Chen, J.M., Rich, P.M., Gower, S.T., Norman, J.M., Plummer, S. (1997). Leaf area index of boreal forests: Theory, techniques, and measurements. *Journal of Geophysical Research: Atmospheres, 102*, 29429-29443.

Daughtry, C.S. (1990). Direct measurements of canopy structure. *Remote sensing reviews, 5*, 45-60.

Fang, H. (2021). Canopy clumping index (CI): A review of methods, characteristics, and applications. *Agricultural and Forest Meteorology, 303*, 108374.

Gonsamo, A., Pellikka, P. (2008). Methodology comparison for slope correction in canopy leaf area index estimation using hemispherical photography. *Forest Ecology and Management, 256*, 749-759.

Gower, S.T., Kucharik, C.J., Norman, J.M. (1999). Direct and indirect estimation of leaf area index, fAPAR, and net primary production of terrestrial ecosystems. *Remote Sensing of Environment, 70*, 29-51.

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

Lai, Y., Mu, X., Li, W., Zou, J., Bian, Y., Zhou, K., Hu, R., Li, L., Xie, D., Yan, G. (2022). Correcting for the clumping effect in leaf area index calculations using one-dimensional fractal dimension. *Submitted to Remote Sensing of Environment*

Leblanc, S.G., Chen, J.M., Fernandes, R., Deering, D.W., Conley, A. (2005). Methodology comparison for canopy structure parameters extraction from digital hemispherical photography in boreal forests. *Agricultural and Forest Meteorology, 129*, 187-207.

Leblanc, S.G., Chen, J.M., Kwong, M. (2002). Tracing radiation and architecture of canopies. *TRAC Manual. Version, 2*

Li, W., Mu, X. (2021). Using fractal dimension to correct clumping effect in leaf area index

measurement by digital cover photography. *Agricultural and Forest Meteorology, 311*, 108695.
Neumann, H., Den Hartog, G., Shaw, R. (1989). Leaf area measurements based on hemispheric photographs and leaf-litter collection in a deciduous forest during autumn leaf-fall. *Agricultural and Forest Meteorology, 45*, 325-345.
Nilson, T. (1971). A theoretical analysis of the frequency of gaps in plant stands. *Agricultural meteorology, 8*, 25-38.
Ross, J. (1981). *The radiation regime and architecture of plant stands*. Springer Science & Business Media
Song, W., Mu, X., Yan, G., Huang, S. (2015). Extracting the green fractional vegetation cover from digital images using a shadow-resistant algorithm (SHAR-LABFVC). *Remote Sensing, 7*, 10425-10443.
Stark, S.C., Leitold, V., Wu, J.L., Hunter, M.O., de Castilho, C.V., Costa, F.R., McMahon, S.M., Parker, G.G., Shimabukuro, M.T., Lefsky, M.A. (2012). Amazon forest carbon dynamics predicted by profiles of canopy leaf area and light environment. *Ecology letters, 15*, 1406-1414.
Stenberg, P. (1996). Correcting LAI-2000 estimates for the clumping of needles in shoots of conifers. *Agricultural and Forest Meteorology, 79*, 1-8.
Stenberg, P., Mõttus, M., Rautiainen, M., Sievänen, R. (2014). Quantitative characterization of clumping in Scots pine crowns. *Annals of botany, 114*, 689-694.
Wilson, J.W. (1963). Estimation of foliage denseness and foliage angle by inclined point quadrats. *Australian Journal of botany, 11*, 95-105.
Yan, G., Hu, R., Luo, J., Weiss, M., Jiang, H., Mu, X., Xie, D., Zhang, W. (2019). Review of indirect optical measurements of leaf area index: Recent advances, challenges, and perspectives. *Agricultural and Forest Meteorology, 265*, 390-411.
Zou, J., Yan, G., Zhu, L., Zhang, W. (2009). Woody-to-total area ratio determination with a multispectral canopy imager. *Tree Physiology, 29*, 1069-1080.