

Article

A Study on Wavelet Transform-Based Inversion Method for Forest Leaf Area Index Retrieval

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Abstract: Leaf Area Index (LAI) is one of the key parameters for characterizing leaf density, vegetation growth status, and canopy structure. Rapid, objective, and accurate acquisition of forest LAI is of great significance for studying forest ecosystems and forestry production. This study focuses on the core issue of accurately segmenting leaf elements from background elements in hemispherical photography used for forest LAI measurement, with a particular focus on meeting the real-time requirements of embedded platforms. The differences in grayscale values and frequency characteristics between leaf regions, trunk regions, and sky regions in vegetation canopy images were leveraged to decompose, process, and reconstruct such images using a 9/7 wavelet-based transformation method, achieving efficient and precise segmentation of leaf regions. Effectively addresses the issue of LAI overestimation caused by trunk regions in traditional threshold-based segmentation methods. Through the extraction of canopy gap fraction, rapid LAI measurement was enabled. Comparative experimental results showed that the proposed inversion method exhibited a high correlation with the LAI-2200C measurement results ($r = 0.897$, $RMSE = 0.431$), fully verifying its accuracy across different forest ecological environments. This study provides strong support for the development of portable, high-precision LAI measurement devices and holds practical application value and broad application prospects.

Keywords: Leaf Area Index; hemispherical photography; image segmentation; wavelet transform



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1. Introduction

Forests are an essential part of global vegetation, widely distributed across various climatic and soil conditions. They play an irreplaceable role in maintaining ecological balance, preserving biodiversity, regulating the climate, and providing resources for humanity [1–3]. As a key component of Earth's life-support system and sustainable human development, forests face increasing challenges due to rapid population growth, urbanization, and modernization [4–6]. Balancing forest ecological protection with technological advancements has become a pressing issue. Strengthening forestry research, advancing forestry science and technology, and improving forest monitoring and assessment are crucial research topics in forestry and environmental protection [7–9]. Efficient vegetation information statistics are a key aspect of this process. They are vital for understanding forest vegetation growth, accurately assessing forest ecological quality, scientifically formulating conservation strategies, and optimizing forestry production layouts [10–12].

The Leaf Area Index (LAI) is one of the fundamental parameters describing canopy structure. It is defined as half the total leaf surface area per unit ground area [13]. LAI reflects leaf quantity, distribution, and canopy density and is crucial for studying plant

growth, photosynthesis, transpiration, and crop yield [14,15]. It has broad applications and research value in forestry and agriculture [16]. Accurate measurement and analysis of LAI enable a better understanding of plant health and growth, providing a scientific basis for forestry and agricultural management [17–20].

The measurement methods for LAI primarily include direct and indirect approaches [21]. The direct measurement method involves collecting plant leaf samples, measuring their area, and calculating the total leaf area per unit of land to determine LAI. Although this method is accurate, it is labor-intensive, and the collection of leaf samples can cause some damage to the plants. It is typically suitable for small-scale or specific-area measurements and is difficult to apply over large areas [22]. In contrast, the indirect measurement method estimates LAI by measuring parameters such as canopy reflectance and transmittance using remote sensing technology and optical instruments, combined with mathematical models [23,24]. This approach offers advantages such as fast measurement speed, wide coverage, and the ability to conduct large-scale measurements quickly without damaging trees, saving both labor and resources. As a result, it is widely used for LAI measurement [25].

Measurement methods based on radiative transfer models estimate LAI indirectly by simulating light transmission characteristics within plant canopies. Common instruments include TRAC, AccuPAR, and the LAI-2000 series plant canopy analyzers [26–28]. These instruments provide high measurement accuracy and are suitable for various types of vegetation, geographical regions, and ecosystems [29]. However, radiative transfer models often rely on certain assumptions (e.g., uniform canopy structure, single leaf morphology), which may reduce their applicability in complex environments, thereby affecting the accuracy of LAI estimation [30,31]. Additionally, radiative transfer models are highly sensitive to environmental factors such as light conditions, weather, and atmospheric conditions [32,33]. They require high-precision optical sensors to capture the optical properties of plant canopies, which often come with high costs and technical requirements, increasing the barrier to their use [34].

In recent years, the hemispherical photography-based LAI measurement method has gained significant attention among researchers, driven by advancements in image processing technology [34]. This approach involves capturing canopy images from beneath the vegetation using a fisheye lens-equipped camera. By applying image segmentation techniques, the method distinguishes leaf areas (target pixels) from gaps (sky pixels) and estimates LAI using radiative transfer models or empirical models. Compared to traditional radiative transfer model-based methods, hemispherical photography offers the advantage of permanently documenting vegetation dynamics, providing valuable visual data for long-term research and enabling the tracking of canopy changes over time [35–37]. Additionally, it is more cost-effective and easier to operate than high-precision optical sensors, making it a practical choice for large-scale ecological monitoring.

The integration of artificial intelligence and automated image analysis software has further enhanced the efficiency of this method [38], enabling rapid processing of large datasets and the extraction of canopy structural information for LAI estimation. However, challenges remain in practical applications. Image segmentation accuracy can be compromised by variable lighting conditions and image quality, particularly in dense forests or complex ecosystems, where distinguishing between leaf and sky pixels becomes difficult [39–41]. These limitations highlight the need for continued refinement of the technique to improve robustness and reliability in diverse environmental conditions.

The accuracy of vegetation image segmentation algorithms significantly impacts the precision of hemispherical photography-based LAI measurements. Currently, commonly used image segmentation algorithms primarily include traditional segmentation algorithms based on low-level image features (such as grayscale, color, and spatial information) [42,43]

and deep learning-based segmentation algorithms. The traditional segmentation algorithms are relatively simple in structure and computationally efficient, but they are sensitive to factors such as image noise and lighting variations, resulting in limited adaptability to complex scenes and segmentation accuracy [44,45]. Additionally, these algorithms struggle to effectively distinguish between leaf region and trunk region, often resulting in an overestimation of the LAI [21]. In contrast, deep learning-based segmentation algorithms utilize convolutional neural networks to automatically learn high-dimensional image features, making them well-suited for segmentation tasks in complex scenes and with a higher accuracy. However, these algorithms require substantial computational resources during both training and inference, necessitating high-performance computing hardware. Moreover, the performance of these models heavily depends on the quality and quantity of annotated datasets. Yet, there is currently no publicly available standardized annotated dataset, which limits the further application and development of these algorithms to some extent. As a result, deep learning-based methods remain largely in the experimental research phase and are not yet practical for rapid field measurements [46,47].

This study introduces a wavelet-based segmentation paradigm addressing these methodological gaps. By integrating wavelet transforms [48–50] with dynamic optimization techniques, this approach establishes a novel framework for vegetation analysis, effectively bridging the gap between computationally intensive deep learning methods and oversimplified traditional algorithms. The main contributions of this paper are as follows:

- (1) Through multi-scale 9/7 wavelet decomposition, the algorithm simultaneously analyzes grayscale textures and frequency-domain features of canopy components, effectively handling complex forest textures while suppressing noise artifacts [51].
- (2) A novel dynamic optimization suppression method improves segmentation precision by adaptively adjusting coefficient thresholds, overcoming the limitations of traditional threshold segmentation methods, and enabling more accurate differentiation of trunk regions, thereby improving the accuracy of LAI measurements.
- (3) Experimental validation against LAI-2200C benchmark measurements demonstrates enhanced accuracy across diverse ecosystems. Comparative analysis reveals significant improvements over traditional color-based segmentation in handling mixed-pixel scenarios and structural interference.

2. Materials and Methods

2.1. Study Area and Data Source

2.1.1. Study Area

The study selects three forest ecosystems from different geographic regions within China as study areas: Jiangshanjiao Experimental Forest Farm, Forestry Academy of Heilongjiang Province (43°85' N, 128°95' E), Qianyanzhou Subtropical Forest Ecosystem Observation Station, Chinese Academy of Sciences (26°75' N, 115°06' E), and the Qingshui River campus of the University of Electronic Science and Technology of China in Chengdu, Sichuan Province (30°75' N, 103°93' E). The study area map is shown in Figure 1. The Jiangshanjiao observation station mainly includes temperate mixed forests of larch, red pine, white birch, and mountain ash, while the Qianyanzhou station mainly consists of subtropical evergreen broadleaf forests of oil tea, citrus, and fir trees. The observation site at the University of Electronic Science and Technology includes subtropical evergreen broadleaf forests with camphor, nanmu, and Osmanthus trees.

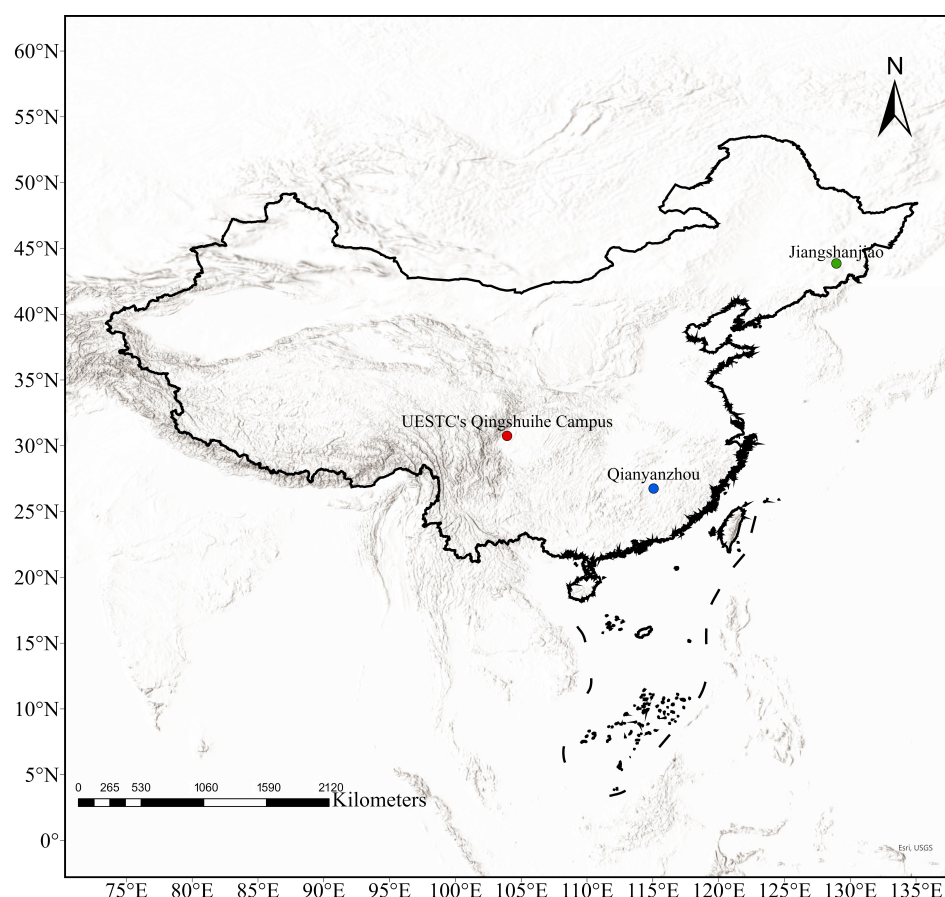


Figure 1. Image of the study area location.

The three study areas are located in Northeast, Southeast, and Southwest China, each differing significantly in climate, soil types, etc., with diverse vegetation types, densities, and heights, aiming to comprehensively evaluate the stability, adaptability, and accuracy of the inversion method proposed in this study when dealing with different vegetation types under varying ecological conditions. An overview of the study areas is shown in Table 1.

Table 1. Overview the study area.

SN	Area Name	Vegetation Type	Climate Type	Landform Type
1	Jiangshanjiao Station, Heilongjiang, China	coniferous and broad-leaved mixed forest	Temperate monsoon climate	Low mountain and hilly landform
2	Qianyanzhou Station, Jiangxi, China	evergreen broad-leaved forest	Subtropical monsoon climate	Red Soil Hills
3	Qingshuihe Campus of UESTC, Sichuan, China	evergreen broad-leaved forest	Subtropical monsoon climate	Plain

2.1.2. Data Collection

This experiment employs a self-developed vegetation image acquisition system, synchronized with the LAI-2200C instrument (LI-COR, Lincoln, NE, USA), to capture high-resolution canopy images, as illustrated in Figure 2. The vegetation image acquisition device is an embedded device that integrates image capture and storage functions. It is equipped with an STM32F767 microprocessor, a CMOS image sensor OV2640, and a 160° ultra-wide-angle fisheye lens (in comparison, the LAI-2200C has a field of view of 148°), capable of capturing images with up to 2 million pixels. The device is designed to be

compact and lightweight, supporting both independent and synchronized collection with the LAI-2200C. During synchronized collection, the device is secured to the optical probe of the LAI-2200C using Velcro straps to ensure the alignment of the fisheye lens center with the center of the optical sensor of the LAI-2200C.



Figure 2. Experimental data collection. (a) LAI-2200C; (b) LAI-2200C measurement principle; (c) Experimental equipment connection diagram; (d) Experimental site map.

When measuring, the vegetation image acquisition device and LAI-2200C are connected via a cable, and each time the LAI-2200C takes a measurement, the vegetation image device synchronously captures a hemispherical canopy image, which is stored to the TF card of the device. This method ensures that measurements are taken at the same time and location for the same target, effectively reducing the influence of environmental factors on the results and enhancing data accuracy and reliability.

Under relatively ideal weather conditions (overcast, low wind speed, no rainfall) [21], measurements were conducted in flat areas within the experimental zone using a 6×3 grid sampling method. Specifically, six sample points were collected along the diagonal direction of each sampling area at equal intervals, with a minimum spacing of 10 m between sampling points. During the data collection process, it is essential to rigorously adhere to the measurement standards of the LAI-2200C to ensure the reliability of the data and the quality of the images [52]. As shown in Figure 3, the green background represents the sampling area, and the red dots indicate the sample collection points. To minimize single-measurement errors and ensure the stability and accuracy of the data, each sample point was measured three times. As shown in Figure 3, the green background represents the sampling area, and the red dots indicate the sample collection points. To minimize single-measurement errors and ensure the stability and accuracy of the data, each sample point was measured three times.

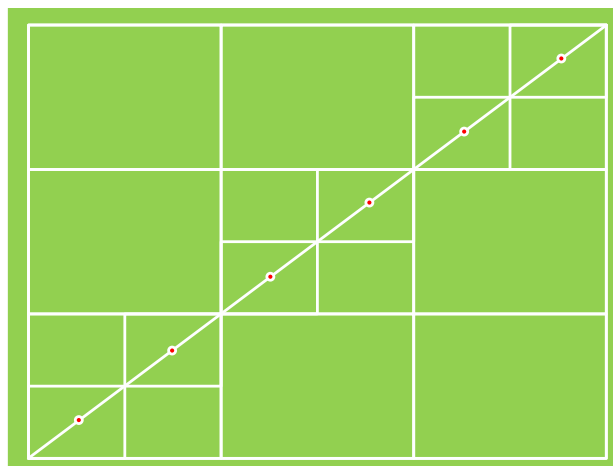


Figure 3. Schematic diagram of sample point collection.

2.1.3. Dataset

This study collected 60 sets of data, with 20 sets from each study area. Each data set includes one LAI-2200C measurement file and 21 vegetation canopy hemispherical images (3 images are of the outside vegetation, and 18 are of the vegetation canopy). The sample data is shown in Figure 4, where Figure 4a represents the images of the Chinese fir forest collected in Qianyanzhou, and Figure 4b represents the images of the mixed conifer-broadleaf forest collected in Jiangshanjiao. The LAI-2200C measurement file contains information such as firmware version, file creation time, GPS log, and LAI calculation results [47]. It is important to note that during the measurement process, the LAI-2200C computes the overall LAI of the area by averaging the results of each sample point within a specific sampling region, and generates a measurement file based on this data. In this study, the arithmetic mean of the LAI calculated from the 18 vegetation canopy images was used to represent the measurement results of the inversion method proposed in this paper. This approach ensured a comprehensive consideration of all sample data, effectively reflecting the overall variation in the LAI across the sampling area and providing an objective benchmark for evaluating the performance of the inversion method.

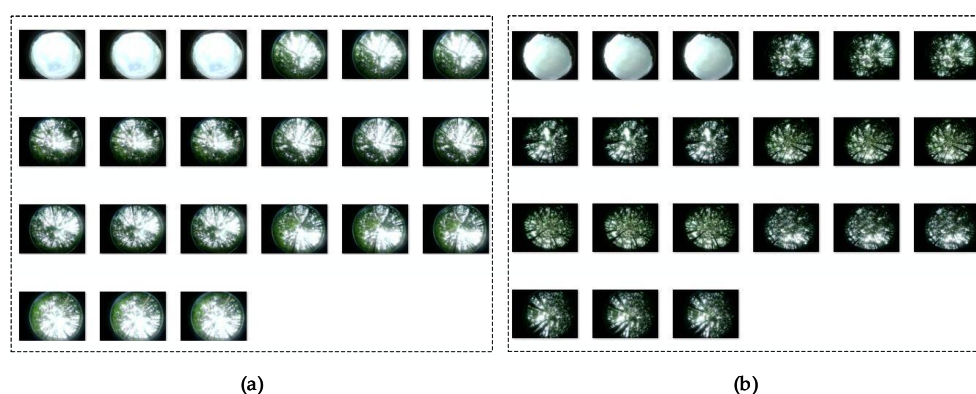


Figure 4. Sample data example. (a) Chinese fir forest; (b) mixed conifer-broadleaf forest.

2.2. Principles of Wavelet Image Decomposition and the 9/7 Wavelet

Common frequency analysis methods include the Fast Fourier Transform (FFT), Wavelet Transform, and Hilbert–Huang Transform (HHT) [53]. The FFT lacks spatial information, making it unsuitable for extracting boundary features [54]. Although the HHT handles nonlinear and non-stationary data well [55], its high computational complexity and the absence of significant nonlinear or dynamic characteristics in canopy images limit

its practical applicability. In contrast, the wavelet transform is a highly useful technique in image processing. By using wavelet transform, images can be decomposed into different scales and frequency components, enabling information extraction in both spatial and frequency domains, as illustrated in Figure 5.

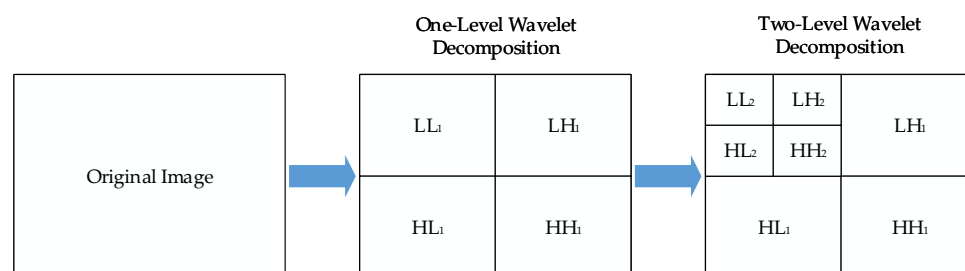


Figure 5. Schematic diagram of image wavelet decomposition.

The first wavelet transform of the image generates four subbands: low-low (LL_1), low-high (LH_1), high-low (HL_1), and high-high (HH_1), each representing image features at different frequencies and directions. The LL_1 subband captures low-frequency information, reflecting the image's main structure and background, while LH_1 , HL_1 , and HH_1 represent high-frequency details and edges in horizontal, vertical, and diagonal directions. Further wavelet transformation of LL_1 yields additional subbands for finer feature extraction and improved segmentation accuracy.

In wavelet image decomposition, selecting the appropriate transformation method and basis function is key to effective image processing. For LAI measurement, deeper wavelet decomposition is employed to enhance high-frequency leaf features while suppressing low-frequency background interference. The 9/7 wavelet transform is a high-precision, energy-concentrated wavelet transform method with relatively low computational complexity and excellent compression performance. It effectively retains image details and has good edge preservation capability, making it highly suitable for complex background and edge-blurring image segmentation tasks. Additionally, the 9/7 wavelet transform can be efficiently implemented using only basic addition, subtraction, and bit-shift operations, significantly simplifying the computational process and minimizing storage requirements. This computational efficiency makes the 9/7 wavelet transform particularly well-suited for deployment on resource-constrained microprocessor platforms, enabling high-performance, real-time image processing.

2.3. Imaging Region Extraction

Fisheye lenses typically consist of a group of very short focal length convex lenses. When light passes through them, it refracts at different angles. The refracted light is projected onto the image in a circular field of view, as shown in Figure 6a. Due to misalignment during installation, the circular field of view is not exactly centered on the photo. The position of the circular region's center and its radius must be determined. A white background image is captured using the vegetation image acquisition device, and this fisheye image is then binarized, as shown in Figure 6b. Next, morphological operations are performed to smooth the boundaries and extract the boundary points, yielding the circle's center (840, 634) and radius $R = 660$, as shown in Figure 6c.

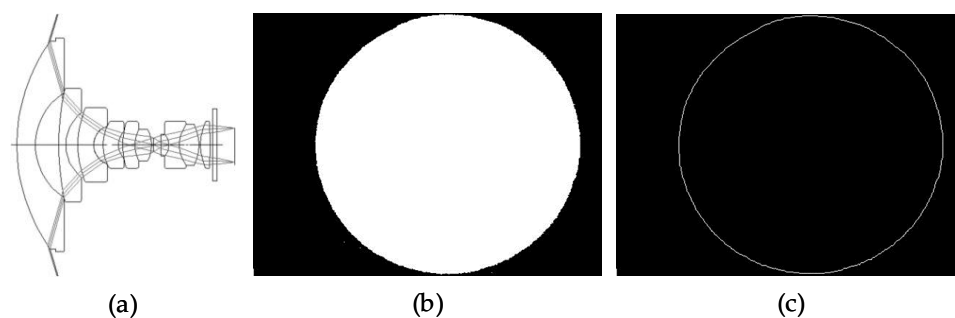


Figure 6. Image area extraction. (a) Schematic diagram of fisheye lens imaging; (b) Binary image; (c) Imaging area boundary.

According to the equidistant projection model of the fisheye lens, a Cartesian coordinate system is established with the center of the circular imaging area as the origin. The zenith angle θ of any pixel (x, y) on the image is calculated using the following formula:

$$\theta = 90^\circ \frac{\sqrt{x^2 + y^2}}{R} \quad (1)$$

2.4. Analysis of Vegetation Canopy Image Feature

The hemispherical photography method involves capturing canopy images from below the plant canopy using a camera equipped with a fisheye lens, with a viewing angle range from 180° to 200° , where the foreground is vegetation and the background is the sky, as shown in Figure 7a. The canopy image consists of three regions: the leaf area, the trunk area, and the sky area, which exhibit significant differences in grayscale and frequency. The leaf area has a higher reflectance, finer texture, and is primarily concentrated in high-frequency bands after wavelet transformation. The trunk area is typically darker, with the lowest grayscale and weaker reflection, mainly concentrated in low-frequency bands. The sky area is well-lit, with the highest grayscale, generally appearing in the canopy gaps, and corresponds to the image's low-frequency information.

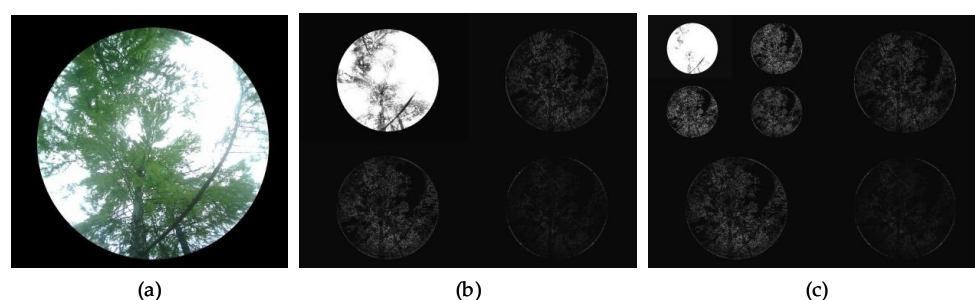


Figure 7. Wavelet decomposition results. (a) Vegetation canopy image; (b) One layer decomposition result; (c) Second level decomposition results.

The wavelet decomposition results of the vegetation image in Figure 7a are shown in Figure 7b,c. After the first wavelet decomposition, the LL_1 component retains much of the structural information, with the leaf, trunk, and sky regions still clearly visible. This demonstrates that the first wavelet transformation effectively preserves the image's low-frequency information and presents the main structure of the image. The HL_1 and LH_1 components contain significant boundary information for the leaf and trunk areas, with sparse leaf information. After a second wavelet decomposition, the high-frequency information is increasingly decomposed, and the leaf area information in the LL_2 component decreases, while trunk and sky information is largely preserved. A substantial amount of leaf information is decomposed into HL_2 , LH_2 , and HH_2 parts, displaying high brightness, while

the trunk and sky areas appear in black, with significant grayscale differences between adjacent regions. The wavelet decomposition results of the vegetation image show that the frequency information differs significantly across the regions. The leaf area typically exhibits strong high-frequency features, while the trunk and sky areas are concentrated in low-frequency components.

2.5. LAI Extraction

The LAI inversion method based on hemispherical photography involves two key steps: image segmentation and LAI extraction. Image segmentation focuses on distinguishing different regions within the image, such as leaf area, trunk area, and sky area. LAI extraction is performed by estimating the proportion of the leaf area in the image.

2.5.1. Image Segmentation

Accurate segmentation of leaf areas is critical for precise LAI measurement, as it provides the foundational data required for reliable calculations. To achieve this, wavelet decomposition is applied to the vegetation image, with an emphasis on suppressing low-frequency components. This suppression minimizes the influence of background elements (e.g., trunks and sky) on leaf area segmentation, thereby enhancing the grayscale contrast between leaf regions and other parts of the image. The improved contrast facilitates the effective use of image segmentation algorithms, enabling more accurate extraction of leaf areas and ultimately contributing to higher precision in LAI estimation.

Fixed Coefficient Suppression

The vegetation image is decomposed using two layers of 9/7 wavelet transform. The pixel values within the effective imaging area of the LL_2 subband from the second wavelet decomposition are normalized:

$$f(x, y)_{LL_2-NDH} = \frac{f(x, y)_{LL_2}}{255} \quad (2)$$

where $f(x, y)_{LL_2}$ is the original grayscale pixel value of the image, ranging from $[0, 255]$, and $f(x, y)_{LL_2-NDH}$ is the normalized pixel value, ranging from $[0, 1]$. A coefficient I is applied to globally suppress the grayscale values of the normalized LL_2 subband:

$$f(x, y)_{LL_2-I} = f(x, y)_{LL_2-NDH} \cdot I \quad (3)$$

The purpose of global grayscale suppression is to enhance the high-frequency components by reducing the low-frequency components, thereby highlighting the edges and details of the leaf area. During this process, the grayscale values of the low-frequency components (trunk and sky areas) are lowered, making the leaf area more distinct in the subsequent image segmentation process. After suppression, the LL_2 subband $f(x, y)_{LL_2-I}$ is reconstructed with the other subbands using the inverse 9/7 wavelet transform. Finally, Otsu's method is used to perform automatic threshold segmentation, yielding clear image segmentation results.

Global grayscale suppression was applied to the vegetation image shown in Figure 8a using coefficients $I = 0.01, 0.02$, and 0.03 . The segmentation results are displayed in Figure 8, where the trunk and sky regions are marked in white, and the leaf areas are marked in black. It is important to note that smaller suppression coefficients result in stronger suppression effects on the image.

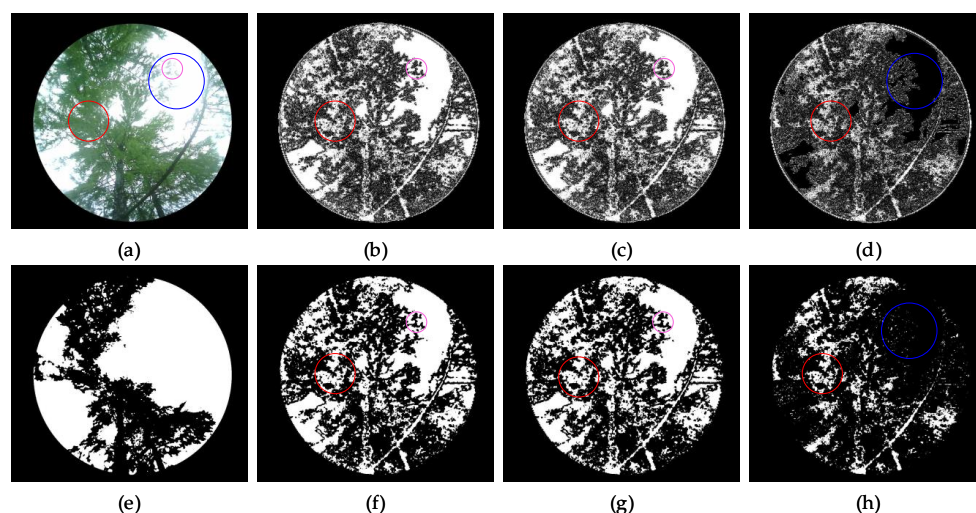


Figure 8. Fixed coefficient suppression algorithm segmentation results. (a) Original image; (b–d) Reconstructed images with $I = 0.01, 0.02, 0.03$; (e–h) Otsu’s segmentation of (a–d). (Red circle: leaf-as-sky errors; Blue circle: sky-as-leaf errors; Pink circle: restored leaf areas).

By comparing the segmentation results, the following five observations can be made:

- (1) When the vegetation image is directly processed using Otsu’s method, some brighter leaf areas are misclassified as the sky regions, and some darker trunk areas are misclassified as leaf areas due to insufficient grayscale contrast.
- (2) After the wavelet transformation of the image, Otsu’s method accurately segments the trunk area.
- (3) When the suppression coefficient is too small ($I = 0.01, 0.02$), some leaf areas with subtle grayscale variations are misclassified as sky regions, as shown in the red-circled areas in Figure 8b–d. This occurs because these leaf areas, located in the low-frequency components, experience excessive suppression, reducing their grayscale values to levels similar to other low-frequency areas, resulting in misclassification.
- (4) As the suppression coefficient increases, the grayscale suppression of low-frequency components weakens, improving the contrast between the leaf area and the sky area, thereby enhancing the leaf area segmentation.
- (5) When the suppression coefficient is excessively large ($I = 0.03$), the sky region is erroneously classified as part of the leaf area, as illustrated in the blue-circled region of Figure 8d. This misclassification arises because the high grayscale values of the sky are inadequately suppressed, diminishing the grayscale contrast between the sky and the leaf area, ultimately resulting in segmentation errors.
- (6) The foliage of vegetation typically shows strong continuity in its distribution. However, during the image acquisition process, certain leaf regions may appear blurred due to a bright background. Wavelet transformation can effectively restore these blurred areas, recovering leaf details that were originally obscured by the bright background, as illustrated in the pink-circled regions in Figure 8b,c.

When collecting vegetation images in natural environments, factors such as weather conditions, leaf density, and distribution differences result in significant global grayscale variations across different vegetation images. The low-frequency components of the image may include the leaf area, sky area, and trunk area. Due to these variations in grayscale distribution, the same suppression coefficient may produce inconsistent results across different images, leading to under-suppression or over-suppression in some images, affecting the accuracy of segmentation results. Therefore, when applying grayscale suppression,

it is beneficial to consider a suppression scheme based on the image's grayscale mean to improve segmentation accuracy.

Grayscale Mean-Based Suppression

By iterating through all pixel points, the arithmetic mean of the normalized grayscale image is calculated using the following formula:

$$\overline{f(x,y)_{LL_2-NDH}} = \sum f(x,y)_{LL_2-NDH} / N \quad (4)$$

where N represents the number of pixel points within the effective imaging area. Global grayscale suppression is applied to the normalized LL_2 subband using the coefficient I as follows:

$$f(x,y)_{LL_2-I} = \overline{f(x,y)_{LL_2-NDH}} \cdot f(x,y)_{LL_2-NDH} \cdot I \quad (5)$$

The suppressed LL_2 subband is then reconstructed with the other subbands using the inverse 9/7 wavelet transform. Finally, Otsu's method is used to segment the reconstructed image automatically.

Subsequently, the suppressed LL_2 subband, denoted as $f(x,y)_{LL_2-I}$, along with the other subbands, is reconstructed into an image using the inverse 9/7 wavelet transform. Finally, Otsu's method is employed to perform automatic threshold segmentation on the reconstructed image, yielding clear and precise image segmentation results.

For the vegetation image shown in Figure 9a, global grayscale suppression is applied with coefficients $I = 0.01, 0.02, 0.03$, with the segmentation results shown in the Figure 9.

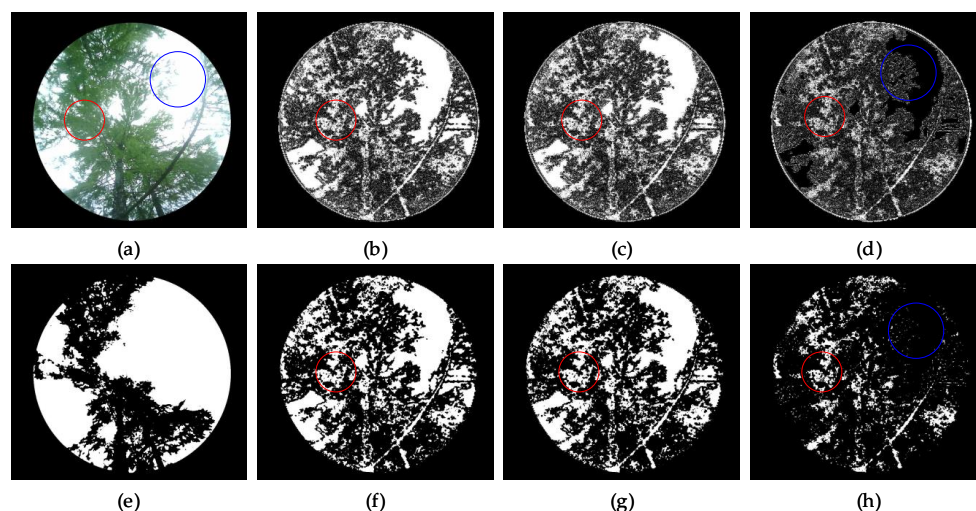


Figure 9. Grayscale mean-based suppression segmentation results. (a) Original image; (b–d) Reconstructed images with $I = 0.01, 0.03, 0.04$; (e–h) Otsu's segmentation of (a–d). (Red circle: leaf-as-sky errors; Blue circle: sky-as-leaf errors).

Segmentation results show that the grayscale mean-based suppression algorithm still provides good segmentation results. However, some leaf areas with smooth grayscale transitions are still misclassified as sky regions. Compared with the fixed coefficient global suppression algorithm, the following two differences were observed:

- (1) When the suppression coefficient does not exceed $I = 0.03$, the sky region is correctly segmented without misclassification.
- (2) When the suppression coefficient increases to $I = 0.04$, the sky region is misclassified as part of the leaf area.

The analysis of the two suppression algorithms yields the following conclusions:

- (1) The trunk area in vegetation images generally has the lowest grayscale values. Even with a high suppression coefficient, it is correctly identified without misclassification.
- (2) When the suppression coefficient is too small, the suppression effect on low-frequency components becomes overly strong, causing some leaf areas with subtle grayscale variations to be excessively suppressed. This makes them indistinguishable from the sky, leading to misclassification.
- (3) When the suppression coefficient is too large, the sky area is not effectively suppressed, reducing the contrast between the sky and leaf areas. This results in the misclassification of the sky as part of the leaf area.
- (4) An appropriate suppression coefficient enhances the grayscale contrast between the leaf area, sky, and trunk, thereby improving segmentation accuracy.

Thus, there is an optimal suppression coefficient. If the coefficient is too low, it can effectively identify the sky area; however, if it is too high, the ability to recognize the sky decreases, though misclassification of the leaf area improves. Based on this analysis, a dynamic optimal suppression algorithm is proposed to ensure accurate segmentation results under various conditions.

Dynamic Optimization Suppression

Dynamic optimization suppression is an algorithm that dynamically adjusts the suppression coefficient. Through multiple dynamic iterations, the algorithm gradually approaches the optimal suppression coefficient to adapt to the grayscale characteristics of different vegetation images, enabling more accurate image segmentation. The algorithm process is shown in Figure 10.

Suppression coefficients $I1$ and $I2$ are defined such that:

$$I2 = I1 + C \quad (6)$$

where C is a positive increment. These coefficients are applied to globally suppress the normalized $I1$ and $I2$ subband:

$$f(x, y)_{LL_2-I1} = \overline{f(x, y)_{LL_2-NDH}} \cdot f(x, y)_{LL_2-NDH} \cdot I1 \quad (7)$$

$$f(x, y)_{LL_2-I2} = \overline{f(x, y)_{LL_2-NDH}} \cdot f(x, y)_{LL_2-NDH} \cdot I2 \quad (8)$$

The suppressed LL_2 subbands $f(x, y)_{LL_2-I1}$ and $f(x, y)_{LL_2-I2}$ are then reconstructed with other subbands using the 9/7 inverse wavelet transform, yielding reconstructed grayscale images $f(x, y)_1$ and $f(x, y)_2$. Finally, Otsu's method is applied for automatic threshold segmentation to obtain clear segmentation results.

White pixels (sky and trunk regions) are labeled as 1, and black pixels (leaf regions) as 0. The number of white pixels in $f(x, y)_1$ and $f(x, y)_2$, denoted $f(x, y)_{1-W}$ and $f(x, y)_{2-W}$ are counted. The difference between the two images is calculated as:

$$Index = f(x, y)_{1-W} - f(x, y)_{2-W} \quad (9)$$

During execution, the algorithm repeats or terminates based on the value of $Index$. If iteration is required, $I1$ increases by a step size ΔI :

$$I1 = I1 + \Delta I \quad (10)$$

when $I1$ is small, the segmentation results of $f(x, y)_1$ and $f(x, y)_2$ are similar ($Index \approx 0$). As $I1$ increases, $f(x, y)_2$ may misclassify sky regions as leaf regions earlier than $f(x, y)_1$,

causing $f(x,y)_{2-W}$ to decrease sharply while $f(x,y)_{1-W}$ remains stable. A sudden increase in *Index* indicates optimal suppression coefficients have been reached, terminating the optimization.

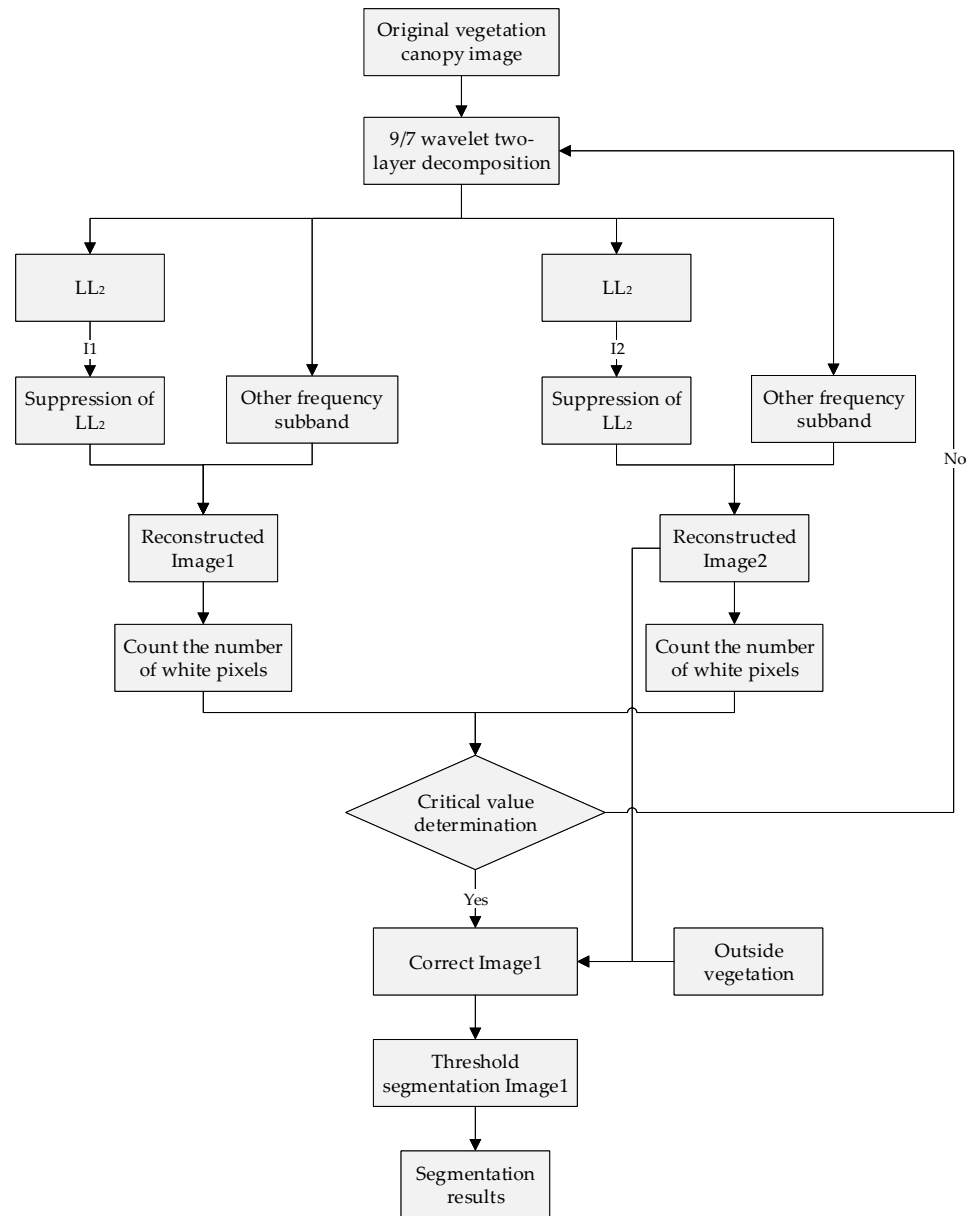


Figure 10. Dynamic optimization suppression algorithm process.

To address potential misclassification of leaf regions as sky in $f(x,y)_1$ (due to small $I1$), $f(x,y)_2$ is used to correct $f(x,y)_1$. A pure sky image (vegetation-free) is normalized:

$$f(x,y)_{sky-NDH} = \frac{f(x,y)_{sky}}{255} \quad (11)$$

where $f(x,y)_{sky}$ is the original grayscale (range: $[0, 255]$). $f(x,y)_{sky-NDH}$ represents the normalized pixel value, scaled to the range $[0, 1]$. By iterating through all pixel points, the arithmetic mean of the normalized grayscale values for the vegetation-free image is calculated as follows:

$$\overline{f(x,y)_{sky-NDH}} = \sum f(x,y)_{sky-NDH} / N \quad (12)$$

For each white pixel in $f(x, y)_1$, if the corresponding pixel in $f(x, y)_2$ is black (non-trunk) and the original pixel's grayscale is less than $\overline{f(x, y)}_{sky-NDH}$, the pixel is corrected to black (leaf region).

Segmentation Performance Evaluation

To objectively compare the three 9/7 wavelet-based image segmentation algorithms, three evaluation metrics are used: Difference Index between Regions (DIR), Within-Region Variance Consistency (Ui), and Maximum Contrast within Regions (Z_{eb}). The definitions of these metrics are detailed below.

DIR quantifies the grayscale or texture differences between distinct regions in an image. A higher DIR value indicates greater inter-region differences and better segmentation performance. The DIR is defined as:

$$DIR = \frac{1}{C_M^2} \frac{\sum_{i=1}^{M-1} \sum_{j=i+1}^M |f(R_i) - f(R_j)|}{g_{\max} - g_{\min}} \quad (13)$$

where $M = 3$ (leaf, trunk, and sky regions); C_M^2 is the number of region combinations; $g_{\max}$ and $g_{\min}$ are the maximum and minimum grayscale values in the effective image area; $f(R_i)$ is the average grayscale of region i .

Ui evaluates the uniformity of grayscale distribution within a region. A higher Ui value indicates lower intra-region variability and better segmentation. Ui is defined as:

$$Ui = 1 - \frac{2}{N} \sum_{R_k \in I} \frac{\sum_{i \in R_k} (f_i - \frac{1}{N_k} \sum_{i \in R_k} f_i)^2}{(\max_{i \in R_k} f_i - \min_{i \in R_k} f_i)^2} \quad (14)$$

where N is the total number of pixels in the effective area of the vegetation image; R_k denotes the k -th segmented region; N_k is the pixel count of region and f_i represents the grayscale value of pixel i . Due to the inherent elemental heterogeneity of leaf regions, the Ui metric is computed exclusively for assessing consistency within the sky and trunk regions.

The Z_{eb} metric quantifies grayscale value differences within a specific region of an image. It focuses on intra-region brightness contrast, evaluating the intensity of texture, detail, or variation. In vegetation image processing, Z_{eb} is used to assess contrasting differences between regions. A smaller Z_{ebk} value indicates lower maximum contrast variability in the k -th region, signifying better segmentation for that region. Similarly, a smaller Z_{eb} value reflects better overall segmentation performance. Z_{ebk} is defined as:

$$Z_{ebk} = \frac{1}{N_k} \sum_{\substack{i \in R_k \\ j \in W(i) \cap R_k}} \max(f_i - f_j) \quad (15)$$

where Z_{eb} is defined as:

$$Z_{eb} = \frac{1}{N} \sum_{k=1}^M N_k Z_{ebk} \quad (16)$$

where $M = 3$: Total number of regions (leaf, trunk, sky); R_k is the k -th segmented region; N_k refers to the total pixels in region; f_i is the grayscale value of pixel i and $W(i)$ means the neighborhood of pixel i .

2.5.2. LAI Extraction

LAI Extraction Method

The hemispherical photography-based LAI inversion method relies on vegetation parameter retrieval algorithms derived from canopy gap fraction theory, grounded in

the Beer-Lambert theorem [56] and probabilistic models of leaf distribution. The core formula is:

$$LAI = -\frac{\ln p_0(\theta) \cos \theta}{G(\theta)} \quad (17)$$

where θ : Zenith angle; $p_0(\theta)$: Gap fraction (porosity); $G(\theta)$: Projection function.

Miller proposed a simplified formula eliminating $G(\theta)$ [57,58]:

$$LAI = -2 \int_0^{\frac{\pi}{2}} \overline{\ln(p_0(\theta))} \cos \theta \sin \theta d\theta \quad (18)$$

In practical processing, to improve measurement efficiency, n equidistant zenith angles are typically selected. For each angular ring, the average canopy gap fraction is measured, and the results are weighted and summed to compute the final LAI. The discretized formula is:

$$LAI = -2 \int_0^{\frac{\pi}{2}} \overline{\ln(p_0(\theta))} \cos \theta_i \sin \theta_i d\theta \quad (19)$$

where $W_i = \sin \theta_i d\theta$: Weighting factor for angle θ_i ; $d\theta = \pi/2n$: Angular interval between adjacent angles; $\bar{W}_i$: Normalized weighting factor, satisfying $\sum_{i=1}^n \bar{W}_i = 1$. This leads to the fast-calculation formula for multi-angle LAI inversion:

$$LAI = 2 \sum_{i=1}^n \frac{\overline{\ln[p_0(\theta_i)]}}{1/\cos \theta_i} \cdot \bar{W}_i \quad (20)$$

In this study, five zenith angles are selected: 7°, 23°, 38°, 53°, and 68° (identical to the LAI-2200C instrument). The normalized weighting factors for each angle are provided in Table 2.

Table 2. Weight Factors.

θ_i	$d\theta$	$W_i = \sin \theta_i d\theta$	$\bar{W}_i$
7°	12.5	0.0266	0.0427
23°	12.5	0.0852	0.1369
38°	12.5	0.1343	0.2157
53°	12.5	0.1742	0.2798
68°	12.5	0.2023	0.3248

Evaluation of LAI Extraction Results

To assess the performance of the comparative experiments, three statistical metrics were selected: correlation coefficient r , and p -value [59]. The r measures the strength and direction of the linear relationship between datasets. A larger absolute r value indicates stronger correlation. The formula for r is:

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \quad (21)$$

where: x_i : Predicted value, i.e., the inversion result from the Dynamic Optimization Suppression method. $\bar{x}$: Mean of the predicted values (average of the inversion results from the Dynamic Optimization Suppression method). y_i : True observed value, i.e., the measurement from the LAI-2200C. $\bar{y}$: Mean of the true observed values (average of the LAI-2200C measurements). n : Total number of observation points ($n = 60$ in this study).

The p -value is used to test whether there are statistically significant differences between variables. If $p > 0.05$, no statistically significant difference exists between the datasets. If $p < 0.05$: A statistically significant difference is observed. The p -value is typically derived

from statistical hypothesis testing. Different statistical tests correspond to distinct p -value calculation formulas. In this study, T-test is employed to compute the p -value.

3. Results

3.1. Suppression Algorithm Segmentation Results and Evaluation

3.1.1. Dynamic Optimization Suppression Algorithm Reconstruction Results

Set the suppression coefficient $I1 = 0.02$, $I2 = I1 + 0.001$ and an increment of 0.001. Using the dynamic optimization suppression method to decompose, reconstruct, and repair the vegetation image shown in Figure 11a. The final output result is shown in Figure 11d. In Figure 11a, the leaf area within the red circle was misclassified as the sky area in Figure 11b. Using Figure 11c to repair Figure 11b, the result in Figure 11d correctly identifies the leaf area within the red circle. Meanwhile, the reconstruction results of other similar areas in Figure 11d also show varying degrees of improvement. Therefore, the dynamic optimization suppression method effectively handles complex vegetation images, reduce misclassification, and optimize the overall segmentation effect through the correct step.

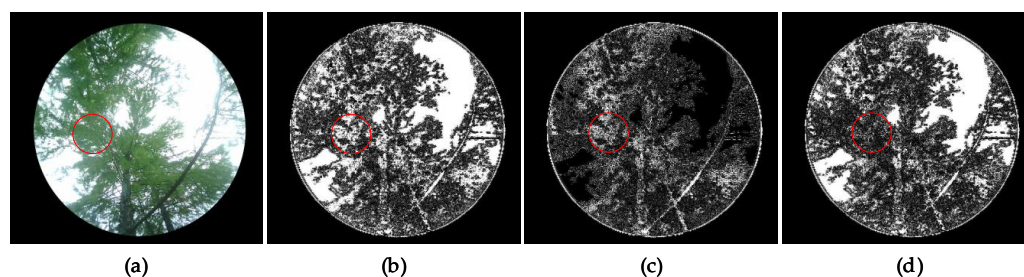


Figure 11. Results of dynamic optimization suppression method. (a) Original image; (b) Reconstruct image ($I1$); (c) Reconstruct image ($I2$); (d) The final output image.

3.1.2. Comparison of Segmentation Results of Three Suppression Algorithms

The vegetation images were processed using the three wavelet transform-based segmentation algorithms described earlier, followed by segmentation using the Otsu's method. The results are shown in Figure 12. Otsu's method suffers from misclassification in images with complex backgrounds or regions with unclear contrast differences. The fixed coefficient suppression algorithm and grayscale mean-based suppression algorithm experience over-suppression, resulting in less accurate segmentation, as shown in the red circle area. The dynamic optimal suppression algorithm significantly improves the misclassification situations, providing better segmentation results compared to the fixed coefficient suppression algorithm and the grayscale mean-based suppression algorithm, thus further improving the segmentation accuracy.

3.1.3. Evaluation of Segmentation Results Using Three Suppression Algorithms

To objectively evaluate the segmentation results of the three suppression algorithms, the fixed coefficient suppression algorithm ($I = 0.01, 0.02$), the grayscale mean-based suppression algorithm ($I = 0.01, 0.02$), and the dynamic optimization suppression algorithm were applied to a single vegetation image (shown in Figure 12a) as well as to ten randomly selected vegetation images. The evaluation indicators for these experiments are summarized in Tables 3 and 4.

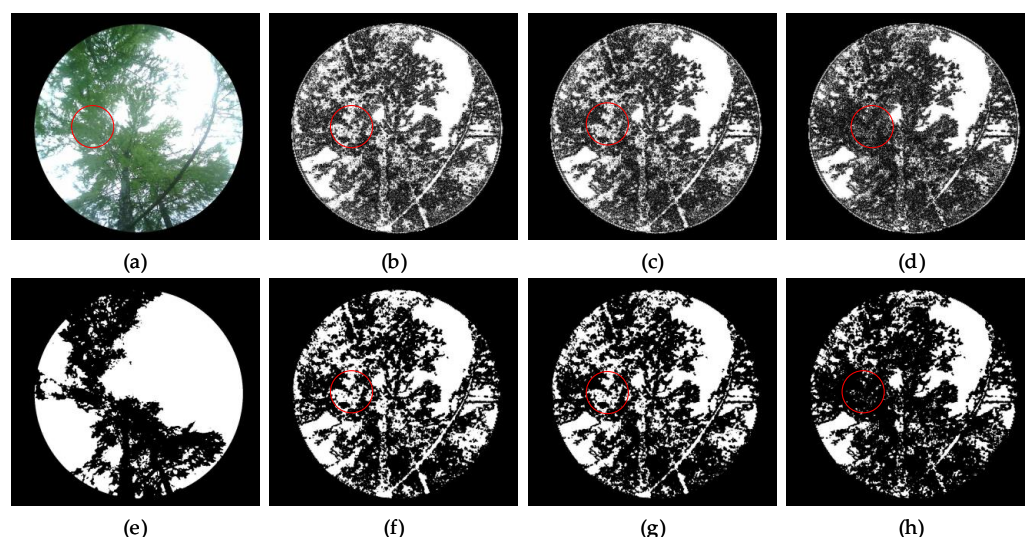


Figure 12. Comparison of segmentation results. (a) Original vegetation image; (b) Fixed coefficient suppression algorithm ($I = 0.02$); (c) Grayscale mean-based suppression algorithm ($I = 0.02$); (d) Dynamic optimization suppression algorithm; figures (e–h) show the Otsu's method segmentation results of figures (a–d).

Table 3. Evaluation of Single Sample Reconstruction Results.

	Fixed Coefficient Suppression Algorithm		Grayscale Mean-Based Suppression Algorithm		Dynamic Optimization Suppression Algorithm
	0.01	0.02	0.01 g	0.02 g	-
DIR	0.6077	0.6272	0.6487	0.6663	0.7859
Ui	0.978	0.9774	0.9799	0.9798	0.9835
Z_{eb}	1.4856	1.5141	1.3049	1.2796	0.9549
Z_{eb_leaf}	23.6957	23.403	22.9683	22.7328	20.9293
Z_{eb_sky}	0.5266	0.4819	0.4625	0.4266	0.4256
Z_{eb_tree}	2.638	2.6618	2.4393	2.4062	2.2444

Table 4. Evaluation of Multi-Sample Reconstruction Results.

	Fixed Coefficient Suppression Algorithm		Grayscale Mean-Based Suppression Algorithm		Dynamic Optimization Suppression Algorithm
	0.01	0.02	0.01 g	0.02 g	-
DIR	0.6437	0.6537	0.6668	0.6723	0.7481
Ui	0.9442	0.9437	0.944	0.944	0.9589
Z_{eb}	2.6149	2.6527	2.4204	2.414	2.1597
Z_{eb_leaf}	35.2194	35.135	34.2992	34.2531	33.1133
Z_{eb_sky}	1.986	1.9812	1.9371	1.9312	1.7034
Z_{eb_tree}	2.9535	2.9765	2.7295	2.7167	2.4775

3.2. Results and Evaluation of LAI Extraction

The dynamic optimal suppression algorithm's inversion results (abbreviated as LAI-9/7WT) were plotted with the LAI-2200C measurement results on the x -axis and y -axis, respectively, and linear fitting was performed to calculate the r and p -values, as shown in Figure 13. The correlation coefficients for the three test sites were 0.939 (Chengdu), 0.967 (Jiangshanjiao), and 0.931 (Qianyanzhou), with an overall correlation coefficient of 0.897, and p -values all far less than 0.001. The experimental results indicate a highly significant

correlation between the inversion method designed in this paper and the LAI-2200C measurement results.

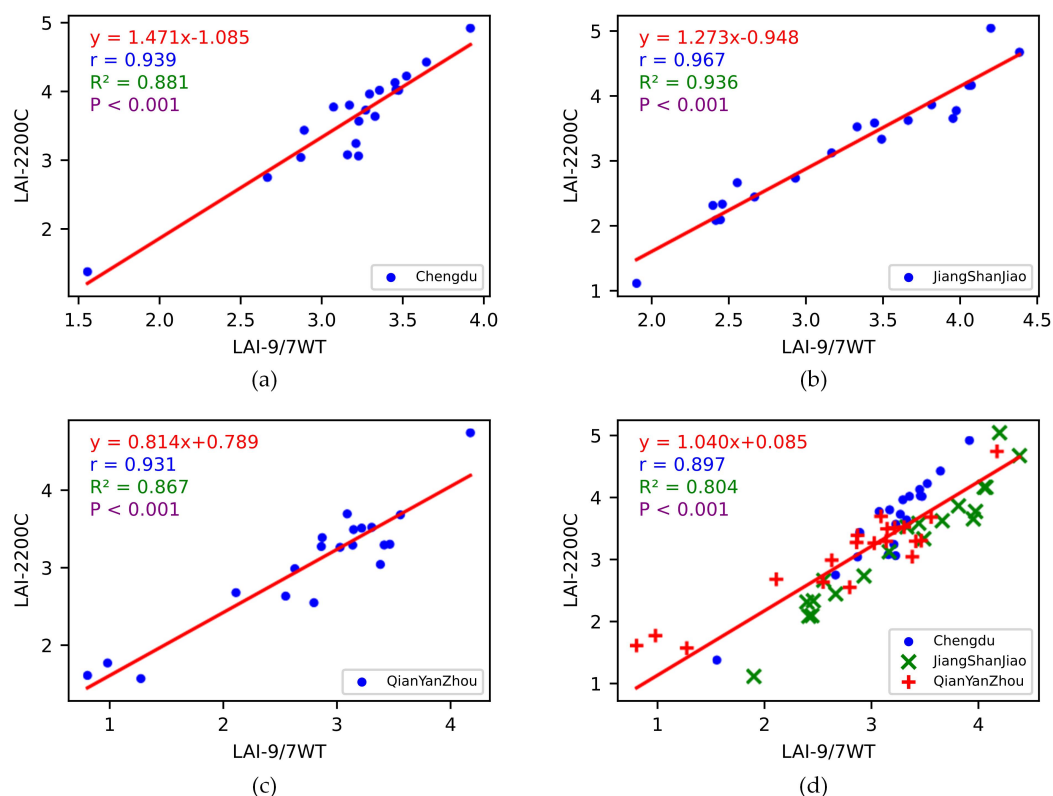


Figure 13. Correlation analysis of LAI values. (a) Chengdu; (b) JiangshanJiao; (c) QianYanZhou; (d) All.

The boxplot of LAI value distribution in the testing area (Figure 14) and the statistical data table of the boxplot (Table 5) are as follows. The median, 75th percentile, and 25th percentile of the three regions are close to LAI-2200C, indicating that the measurement of the dynamic optimization suppression algorithm has a similar distribution. This is consistent with the conclusion reflected in the correlation analysis.

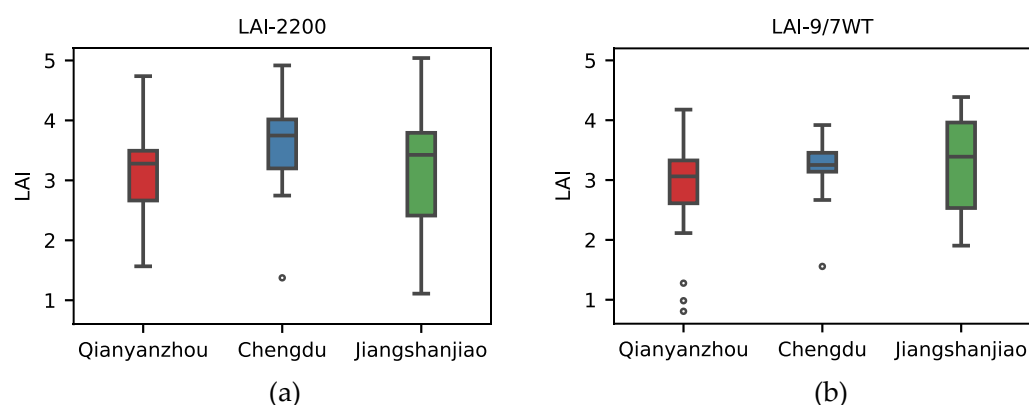


Figure 14. Boxplot of the LAI value. (a) LAI-2200C; (b) LAI-9/7WT.

Table 5. Boxplot data sheet of the LAI value.

Study Area			LAI-2200C	Dynamic Optimization Suppression Algorithm
Chengdu	median		3.748	3.252
	75th percentile and 25th percentile	75th percentile	4.016	3.456
		25th percentile	3.199	3.140
		Difference	0.817	0.316
	extremum	maximum	4.917	3.919
		minimum	1.374	1.557
Jiangshanjiao	median		3.425	3.391
	75th percentile and 25th percentile	75th percentile	3.792	3.961
		25th percentile	2.412	2.533
		Difference	1.38	1.428
	extremum	maximum	5.040	4.387
		minimum	1.110	1.904
Qianyanzhou	median		3.279	3.061
	75th percentile and 25th percentile	75th percentile	3.494	3.328
		25th percentile	2.664	2.612
		Difference	0.83	0.716
	extremum	maximum	4.738	4.177
		minimum	1.566	0.807

Using the value of LAI-2200C as the true value, calculate the variance performance index of the inversion value of the dynamic optimization suppression algorithm, as shown in Table 6.

Table 6. Analysis of LAI value Error.

	Chengdu	Jiangshanjiao	Qianyanzhou	ALL
RMSE	0.533	0.318	0.415	0.431
MAE	0.461	0.234	0.358	0.351

3.3. Comparison of Image Segmentation Results

Currently, commonly used image processing algorithms include the fixed threshold methods, the traditional Otsu's method and the improved Otsu's method [60]. Among these methods, the improved Otsu's method performs the best. Four typical forest vegetation canopy images were selected, and processed using the dynamic optimization suppression algorithm to decompose, reconstruct. Then, the images were segmented using the fixed threshold method (th = 175), the traditional Otsu's method, and the improved Otsu's method. The results are shown in Figure 15.

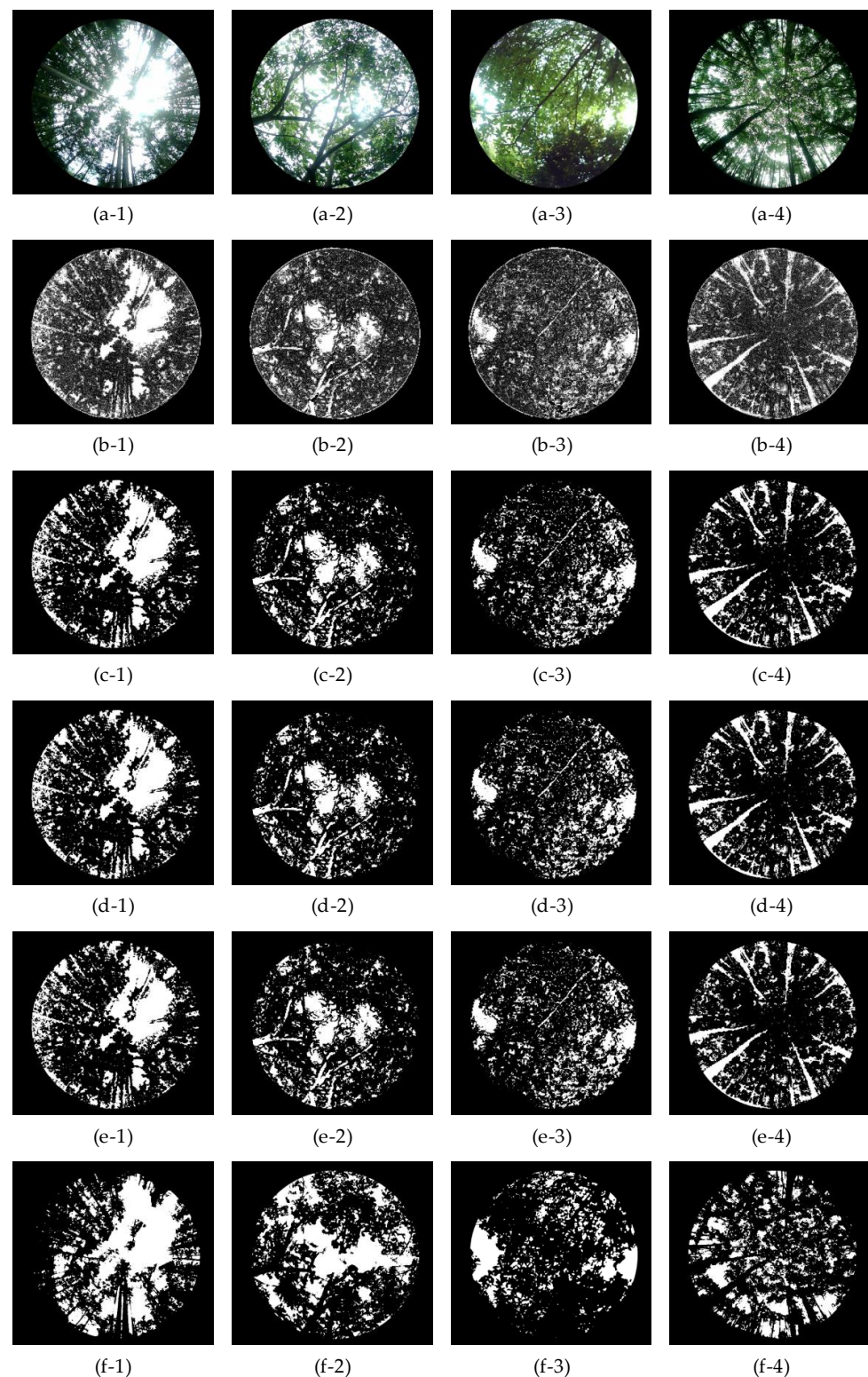


Figure 15. Dynamic optimization suppression algorithm segmentation results. (a1–a4) Original images; (b1–b4) Wavelet-reconstructed images; (c1–c4) Fixed-threshold segmentation on wavelet images; (d1–d4) Otsu’s method on wavelet images; (e1–e4) Improved Otsu’s method on wavelet images; (f1–f4) Improved Otsu’s method on Original images.

4. Discussion

4.1. Discussion on Wavelet Transform-Based Segmentation Algorithms

The fixed coefficient suppression algorithm, when processing images, produces consistent suppression effects on all images due to the fixed suppression coefficient, leading to over-segmentation or misclassification in some images.

The grayscale mean-based suppression algorithm dynamically adjusts based on grayscale mean, improving the image segmentation effect. However, its flexibility is limited, and it has limitations when dealing with complex backgrounds or detailed regions.

The dynamic optimal suppression algorithm dynamically adjusts the suppression coefficient based on image characteristics and performs well for different types of vegetation images. Additionally, using the reconstruction results to repair misclassification can more accurately separate the leaf area, avoid over-suppression issues, and significantly improve the segmentation accuracy and stability. Future work could continue to explore how to further optimize the algorithm to ensure its adaptability and reliability in large-scale or different environments.

Based on the evaluation indicators presented in Tables 3 and 4, the dynamic optimization suppression algorithm achieves the best segmentation results for the vegetation image. It demonstrates the highest region difference index DIR, indicating the greatest distinction between regions, and the highest variance consistency index U_i , reflecting minimal internal variation. Furthermore, it exhibits the lowest contrast indices Zebk and Zeb, signifying minimal contrast variation within regions. In conclusion, the dynamic optimization suppression algorithm achieves the best segmentation results for this vegetation image.

4.2. Instrument Selection for Comparison

Among indirect measurement instruments, the LAI-2200 series, developed by the U.S. company LI-COR, occupies a crucial position in plant physiology and ecological research due to its efficiency, non-destructive nature, and wide applicability [29].

The LAI-2200C uses a fisheye optical sensor (vertical field of view of 148°) to measure projected light at five zenith angles (7° , 23° , 38° , 53° , 68°) on the canopy, using a vegetation canopy radiation propagation model to calculate the LAI. As a high-precision LAI measuring instrument, the LAI-2200C has been widely used worldwide and is the instrument of choice for researchers in plant physiology and ecology. Its measurement results are widely recognized within the industry for their high reliability and accuracy and are regarded as the industry standard.

4.3. Analysis and Discussion of LAI Inversion Results

The experimental results show that the LAI extracted by the inversion method designed in this paper is overall smaller than the LAI-2200C measurement results, which is similar to other studies. This discrepancy occurs because the LAI-2200C assumes that tree leaves are optical black bodies, absorbing all light and neglecting reflection and refraction effects between leaves. In reality, tree leaves have certain reflective and transmissive properties, which affect the light propagation within the canopy and consequently the gap rate measurement. This leads to a smaller gap rate and an overestimation of the LAI in the LAI-2200C measurements. Moreover, the LAI-2200C is sensitive to all shading objects in the field of view, including leaves, stems, and branches [61], which are all included in the measurements, causing an overestimation of the LAI.

In this paper's designed inversion method, the trunk area is treated as a non-leaf area. During actual measurements, the trunk may block some leaf areas, resulting in an underestimation of the leaf area, and thus the extracted LAI is smaller. Therefore, in practical applications, the LAI-2200C measurement results can be combined with the image-based

inversion method through weighted averaging or data fusion techniques to obtain more accurate LAI values or verified using destructive sampling or other independent methods (e.g., ground LiDAR) [62–64].

4.4. Suppression Coefficient Selection

This paper compares the segmentation results of different suppression coefficients and selects the suppression coefficient parameters based on experience, especially the initial values $I1$ and $I2$, and increment ΔI for the dynamic optimal suppression algorithm, which is not universally applicable. In setting the suppression coefficients $I1$ and $I2$, $C = \Delta I$, meaning that the increment of $I2$ compared to $I1$ is the same as the increment for $I1$ itself:

$$I2 = I1 + C = I1 + \Delta I \quad (22)$$

This parameter design borrows from the iterative computing idea, simplifying the computational load. In actual execution, the segmentation result of suppression coefficient $I2$ is used as the segmentation result for $I1$ in the next iteration, thus only recalculating the new suppression coefficient $I2$'s result, which reduces computational load by half compared to when $C \neq \Delta I$.

The advantage of the dynamic optimal suppression algorithm is its ability to adjust the suppression coefficient based on image characteristics, but this process relies on understanding and prior knowledge of image properties. To enhance the algorithm's adaptability, future research could use automated parameter optimization, machine learning, and multi-scale analysis methods to automatically determine the suppression coefficient parameters, further improving the algorithm's applicability and reliability.

4.5. Image Segmentation Method Comparison and Discussion

As shown in Figure 15, the improved Otsu's method delivers relatively effective segmentation results. However, certain errors remain in areas of high brightness, where leaf regions are erroneously classified as sky regions. Additionally, the method misclassifies trunk areas as leaf regions during segmentation, potentially resulting in an overestimation of LAI.

The wavelet transform significantly improves the contrast of the target areas, allowing the segmentation algorithms to more accurately separate the leaf area from the background. Furthermore, the reconstructed images processed through wavelet transformation effectively restore leaf details lost or blurred due to overexposure in the original images, thereby further enhancing the accuracy of measurement results. This approach results in noticeably improved accuracy compared to applying these algorithms directly to the original images. Moreover, the segmentation results become more consistent after wavelet transformation, allowing for the use of simpler threshold-based segmentation algorithms. Therefore, combining wavelet transformation with image segmentation algorithms can significantly reduce the complexity of segmentation and improve both efficiency and accuracy. Future research should focus on optimizing and refining wavelet transformation algorithms to further enhance their performance.

While the segmentation accuracy of the wavelet transformation method represents an improvement over traditional threshold-based segmentation techniques, it remains inferior to the accuracy achieved by deep learning-based methods [46,47]. Deep learning approaches utilize complex network architectures and large datasets for training, enabling the effective extraction of high-dimensional features and semantic information from images, thereby delivering more precise segmentation [65,66]. However, due to current limitations in vegetation datasets and computational hardware resources, deep learning methods are not yet practical for rapid measurements in field environments [67,68].

4.6. Limitations and Improvement Measures Discussion

The image processing algorithm proposed in this paper performs well with the data from the three selected forest experimental areas. However, due to the limited dataset, it is not possible to determine if the algorithm will still show good segmentation results when processing more diverse tree species datasets. Therefore, it is necessary to collect image datasets from various regions and forests with different vegetation types. By comparing the differences between the LAI extracted from different tree species and the actual values, the applicability of the inversion method proposed in this paper can be evaluated. Furthermore, conducting a more in-depth analysis of potential influencing factors, such as tree structure features, leaf morphology, and distribution, will help better understand how these factors affect the LAI inversion results. Once these influencing factors are fully understood, the inversion method can be further optimized and improved to enhance its accuracy and robustness.

The image processing algorithm proposed in this paper is currently implemented on a PC. If this algorithm is to be migrated to a microprocessor platform (such as embedded systems, Raspberry Pi and FPGA) [69,70], the primary task is to evaluate the algorithm's operating speed and resource usage, including processing time, memory usage, and other key indicators. To improve the running efficiency on microprocessors, optimization of both the code (e.g., reducing unnecessary computations, using more efficient algorithms) and hardware (e.g., utilizing specific hardware acceleration features, optimizing memory access patterns) will be necessary.

5. Conclusions

To address the demand for fast and accurate measurement of LAI in forest ecosystems, this paper proposes a LAI inversion method based on the 9/7 wavelet transform. This method focuses on the core issue of accurately segmenting leaf elements from background elements in vegetation canopy images. By utilizing differences in grayscale and frequency features between the leaf area, trunk area, and sky area, the 9/7 wavelet transform is used to decompose, process, and reconstruct vegetation images. This approach efficiently and accurately segments leaf regions, even in complex backgrounds and under varying lighting conditions, while minimizing the influence of trunk regions. By extracting the canopy gap rate, rapid LAI measurement is achieved.

To validate the effectiveness of the proposed inversion method, vegetation canopy images were collected synchronously using the LAI-2200C in three forest experimental areas from different geographic regions. The LAI values for 60 sampling areas were calculated using the proposed method and compared with the LAI-2200C measurements. The results show that the proposed method is highly correlated with the LAI-2200C measurements ($r = 0.897$, $RMSE = 0.431$), indicating that it has high accuracy under different environmental conditions and is a reliable LAI measurement method. As the technology continues to mature and expand, it is expected to have a profound impact on sustainable agriculture, ecological protection, and addressing climate change.

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