Measuring Leaf Angle Distribution and Leaf Area Index of Conifer Canopies Simultaneously on Wide-angle Image*

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Abstract The Leaf Angle Distribution (LAD) and Leaf Area Index (LAI) are important descriptors of the vegetation canopy. But direct field measurement of these variables is very labor-intensive and time-consuming because of the complexity and variation in canopy architecture within and between species, especially for conifers. Upward-looking fisheye photos have been used to provide LAI estimates, but such estimates are subject to errors caused by unknown LAD and clumping of leaves and branches. In this paper, we present our new method on LAD and LAI estimation. The main approach is on how to introduce our intercrown gap probability model into LAI and LAD inversion algorithm, to express the effect of viewing direction on clumping index in normal gap probability model. Two validation experiments have been done. In one of them the estimated LAD (10-degree grouping) fits the directly measured LAD with a correlation coefficient 0.97. Another result is similar. Although the primary results are encouraging, more validation, especially under natural forest, are still needed to incorporate the method into our tree tomography procedure.

Key words Coniferous canopy, Directional gap probability, LAD, Inversion

1 INTRODUCTION

The Leaf Angle Distribution (LAD) and Leaf Area Index (LAI) are important descriptors of the vegetation canopy. But direct field measurement of these variables is very labor-intensive and time-consuming because of the complexity and variation in canopy architecture within and between species, especially for conifers. Upward-looking fisheye photos have been used to provide LAI estimates, but such estimates are subject to errors caused by unknown LAD and clumping of leaves and branches. J. Chen *et al*. recently used least squares inversion to obtain LAI and LAD simultaneously from such fisheye photos. However Chen *et al*. noted that the retrieved LAD accuracies were not high[1]. The reason for the discrepancy may be the assumption of a clumping index that is constant with view zenith angles. Examination of typical fisheye photos reveals that light gaps in a forest stand appear more random at horizon, but are distinctly clumped near nadir. In 1971, Nilson pointed out that this clumping index may be direction dependent[2], but more recent works generally assumed the index to be a constant[3], with a few exceptions, such as J. Chen who noted the clumping index changes with viewing direction because of the structure of whirls in a boreal forest[4].

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By introducing our intercrown gap probability[5] into Chen's method and explicitly expressing the cluming index as a function of viewing zenith angle, we retrieved LAI and LAD estimates more accurately using the same least-square approach. Two validation experiments have been done so far, using a digital wide-angle image gathering system designed for tree-tomography[6]. This consists of a video camera with wide-angle lens and a notebook computer that collects upward-looking digital images under tree canopies. More than 5000 leaves were measured manually for inclination angles in a young sabina nursery in 1995. The estimated LAD (10-degree grouping) fits the directly measured LAD with a correlation coefficient 0.97. An earlier experiment was done in 1994 under a young juniper nursery. In this case, the estimated LAD showed an extremophile distribution, which agreed well with careful observation, but no manual measurements for leaf inclination angles was done.

This paper presents our estimation theory, the directional gap probability model and its application in our algorithm. Our direct and indirect measuring methods for LAD of conifer canopy are introduced. By the validation results, this estimation for LAD of conifer canopy is reasonable, this method is easier and time-saving. It is hopeful to be used in the natural forest stands.

2 DIRECTIONAL GAP PROBABILITY MODEL AND LAD ESTIMATION THEORY

The gap probability or the gap fraction of vegetation canopy stands is the fraction of view in some direction from beneath a canopy. That is the result, in which the light penetrated the canopy, partly absorbed and transmitted by the canopy elements, partly uninterrupted arrive at the viewer on the ground. So the viewed gap fraction contains many information of the architecture of canopy stands. Many methods were developed to extract these architecture parameters from gap fraction. It is obvious that the most important is modeling the procedure of the light transmission when it pass through the canopy, which called the average canopy transmittance theory.

The typical canopy gap probability model is:

$$P_{gap} = e^{-KL/\cos(\theta)} \quad (1)$$

where L is the LAI, K is the coefficient of projection of the leaf area in the solar direction in zenith angle θ. When considering the clumping feature of the leaf elements in the discontinuous canopy, Nilson derived the modified gap probability model from radiation transfer model[3],

$$P(\theta) = e^{-G(\theta) * \Omega * L/\cos(\theta)} \quad (2)$$

where $G(\theta)$ is the projection of the unit element area of canopy surface in the solar direction, L is the LAI, Ω is the clumping index, defined to describe the degree of clumping of the leaf elements within canopy. Based on Nilson's model, J. Chen *et al*. used the least squares inversion method of Norman and Campbell to obtain effective LAI and LAD from fisheye photos of coniferous canopy. Because the Ω in the equation (2) often be taken as a intrinsic parameter of canopy structure, independent on the viewing direction, the estimated result is not ideal. But this works inspired us.

Our main idea is first to described the relativity of the leaf elements clumping index and the viewing direction. As a continuation of our gap probability (P_{gap}) model, assuming azimuthing isotropic and plant surface elements are randomly distribution, we can write the eq. (2) as:

$$P(\theta) = e^{-G_\theta L} \quad (3)$$

where plant surface element are sorted into N groups according to the zenith angle α of their surface normal; G_θ and L are vectors. L is the vector of plant area indices of these N groups, its elements stand for the fractions of effective leaf area with different leaf inclination angle in total effective leaf area. G_θ is defined as a M * N matrix, standing for the group mean projection factors of surface elements along the direction θ to the ground, to describe the relativity between the viewing direction of gap probability and the direction of leaf inclination.

For the mathematical description of the relativity, J. Warren Wilson had presented his theoretical study in 1959[7]. By this theory he used inclined point quadrats method to estimate foliage angle. Based the mathematical description of the relativity of the foliage inclination angle and the viewing direction. We denote the angle between the viewing direction to the nadir direction is α, tocorrespond with the description of foliage element inclination. Then, the matrix G_θ was created. Its elements are:

$$G_{mn}=\begin{cases}\cos(\alpha_n), & \theta\leq\pi/2-\alpha_n\\ \cos(\alpha_n)\cdot(1+(2/\pi)\cdot(\tan(\gamma)-\gamma)) & \text{otherwise.}\end{cases} \quad (4)$$

where,

$$\gamma=\arccos(\cot(\alpha_n)\cdot\cot(\theta_m)) \quad (5)$$

where m and n are the grouping number for viewing direction θ and foliage element normal direction, respectively.

From eq. (3), when modeling the light absorption and albedo of discontinuous canopies, we gave the intercrown gap probability and within-crown gap probability models[5]. Following this idea, we denote within-crown P_{gap} by $P_\theta(n>0)$ and intercrown P_{gap} by $P_\theta(n=0)$. As a first order approximation, for given θ we ignore the difference in path-length by assuming plant surface elements are randomly distribution in space excluding the portion of $P_\theta(n=0)$:

$$P(\theta)=P_\theta(n=0)+P_\theta(n>0) \quad (6)$$

$$P_\theta(n>0)=(1-P_\theta(n=0))\cdot P(\theta\mid n>0) \quad (7)$$

where $P(\theta|n>0)$ is conditional P_{gap} given that its in crown shadows:

$$P(\theta\mid n>0)=e^{-G_\theta L/(1-P_\theta(n=0))} \quad (8)$$

When we can tell gaps and plant surface on a fisheye or wide angle photo clearly, we can sort pixels into M groups according to their viewing zenith angle. Then we can obtain M pairs of estimates for $P_\theta(n=0)$ and $P_\theta(n>0)$ and therefore M simultaneous linear equations,

$$T_m=(P_{\theta m}(n=0)-1)*\ln P(\theta_m\mid n>0)=G_{\theta m}\cdot L \quad (9)$$

We can write this in matrix form:

$$T=GL \quad (10)$$

where G is a M * N matrix, and we can always make $N<M$, then we have:

$$L=(G'G)^{-1}GT \quad (11)$$

Now, considering the effect of viewing direction on the clumping index in P_{gap} model, we give the directional P_{gap} model, which can be used in the processing of fisheye or wide angle photos.

3 MEASUREMENT DATA ACQUISITION AND PROCESSING

In order to validate the directional P_{gap} model, and to apply it in the estimation of LAD and effective LAI, our experiment for getting wide-angle photos was designed on a simulated natural coniferous forest stands, which was planted in the Luancheng experimental station, CAS. The area of the stands is 12 * 12 sq. m., coniferous trees named "*Sabina Chinensis* (*L.*) *Antoine*" were planted with Poission distribution in the spring of 1995. The height of trees were 1.50—2.50 meters. Their crown shape were approximate to cone, and the crowns were in full-grown. Their leaves were in both scaled and thorny leaves growing together. The coverage of the stands was nearly 20 percent.

In the measurement, we use our digital wide-angle image gathering system designed for our tree-tomography[6] to obtain the upward looking wide-angle images for the canopy. The CCD camera of the system is with a wide-angle lens, its standard FOV is 112 degree. The taken pictures were digitized in situ and recorded as images in the hard disk of the notebook computer. The frame was made for mounted the camera to control its posture. The acquisition of images data was done in overcast sky condition, only with diffused skylight. In the stands, we select several viewing points with different openness of canopy to take wide-angle images. In such case, the camera was put on the ground between tree crowns, keeping the axis of lens vertical. The sample of original digital image is shown in Fig. 1.

In the image, the gray of pixels stand for the intensity of the diffused light penetrate the canopy. The center of image is the nadir direction. Other viewing directions can be calculated from the relative coordination of pixels, and the geometric parameters of the lens. By assuming the azimuthal isotropic of canopy, the pixels of image are sorted into M group according to their viewing zenith angles or M contours of equal zenith angle. The number M depends on the resolution of the digital image, as well as the correlation between neighbor contours. The processed image is shown in Fig. 2. fe

Fig. 1 Original image taken by wide-angle camera in sabina nursery

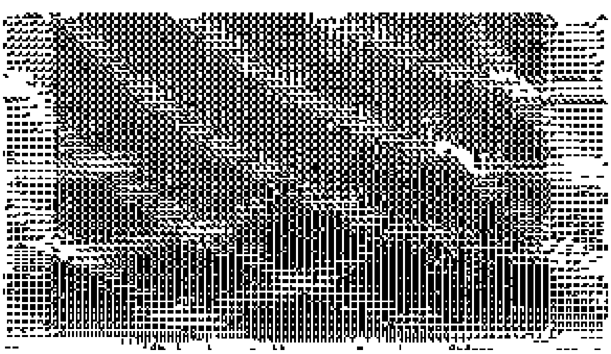

Fig. 2 Image with contours of equal zenith angles (Sabina)

From the image we can calculated the within-crown P_{gap}, $P_\theta(n=0)$, and intercrown P_{gap}, $P_\theta(n>0)$. By eq. (6)—(9), we can get the T_m. By the eq. (4), (5), after given the grouping number M and N, we can get the matrix G_{mn}. Then we can use eq. (11) to invert the effective LAI vector L. To avoid the sensitivity of inversion to noise and correlation in P_{gap} measurements, we introduce a constraint matrix H with N * N elements as J. Chen did[1]. When N=5, the H is:

$$H=\begin{Bmatrix} 1 & -1 & 0 & 0 & 0 \\ -1 & 2 & -1 & 0 & 0 \\ 0 & -1 & 2 & -1 & 0 \\ 0 & 0 & -1 & 2 & -1 \\ 0 & 0 & 0 & -1 & 1 \end{Bmatrix} \quad (12)$$

Then the eq. (11) is changed to,

$$L=(G'G+kH)^{-1}(G'T) \quad (13)$$

where k is adjustable parameter to control the depth of constrain. In our works, when k is changed from 0.5 to 3.5, the distribution of L_{ei} is unchanged, and the total L_e changed a little. For the image shown in Fig. 2, we take k=3.1. Using the model, we take M=14 and N=9 to do the inversion. The inverted LAD is shown in Table 1.

Table 1 Manual measurement and estimated LAD of *sabina* (For M=4, N=9)

θ	LAD		Le
(deg.)	meas.	est.	
5	0.159	0.195	0.247
15	0.144	0.188	0.238
25	0.166	0.173	0.219
35	0.140	0.151	0.192
45	0.139	0.123	0.156
55	0.094	0.090	0.114
65	0.069	0.055	0.070
75	0.051	0.024	0.030
85	0.0383	0.0014	0.0018
total	1.0003	1.0014	1.268
r=0.9717			

To validate the inverted result, we made manual measurement for the leaf inclined zenith angle of scaled leaves. All of the manual measured leaves were in the area of the middle height of tree crowns, because our processed image cover the corresponding area of crowns. When measuring, we selected a branch first, then for every leaf, its inclined zenith angle, length and average width were measured and recorded. Every leaf from the top of the branch to the trunk of the tree was measured in sequence. For easier measuring we cut measured leaves and tried to keep othes in their original place without much changing. All of the manual measurement took four days. More than 5,000 leaves were measured. By the data, the measured LAD was calculated, which is shown in Table 1. It is nearly planophile distribution. Fig. 3

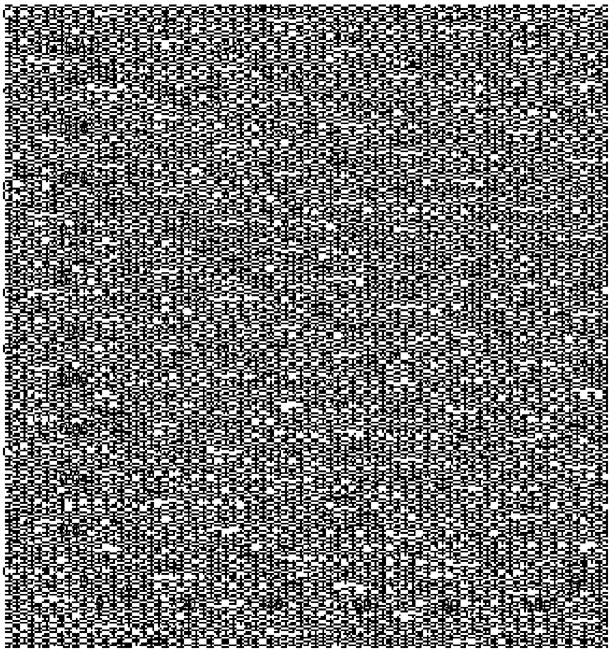

Fig. 3 Comparison between the manual measured and inverted LAD

shows the comparison of manual measured LAD and inverted LAD. The inverted LAD fits the manual measured LAD with a correlation coefficient 0.97.

4 CONCLUSION AND DISCUSSION

1) Our new approach in the application of P_{gap} model shows that it is effectively to consider the viewing direction in the model. Based the definition of within-crown P_{gap} and intercrown P_{gap} in GORT model, we give the mathematical description of the relativity of viewing direction and viewing gap probability. By this way, we can extract more imformations from the wide-angle or fisheye photographs simultaneously, such as LAD and ELAI. The validation based our field measurement data shows the directional P_{gap} model and its inversion algorithm work well.

In order to see if the algorithm can be used in other stands, we made the similar process for another measurement data. The photographs were taken in the juniperus nursery in Yucheng experimental station of Institute of Geography, CAS, in Jun. 1994. The leaves of the coniferous trees are in thorny. A Widelux-35 mm camera with a 135 degree field of view was used. The camera has a curve focusing

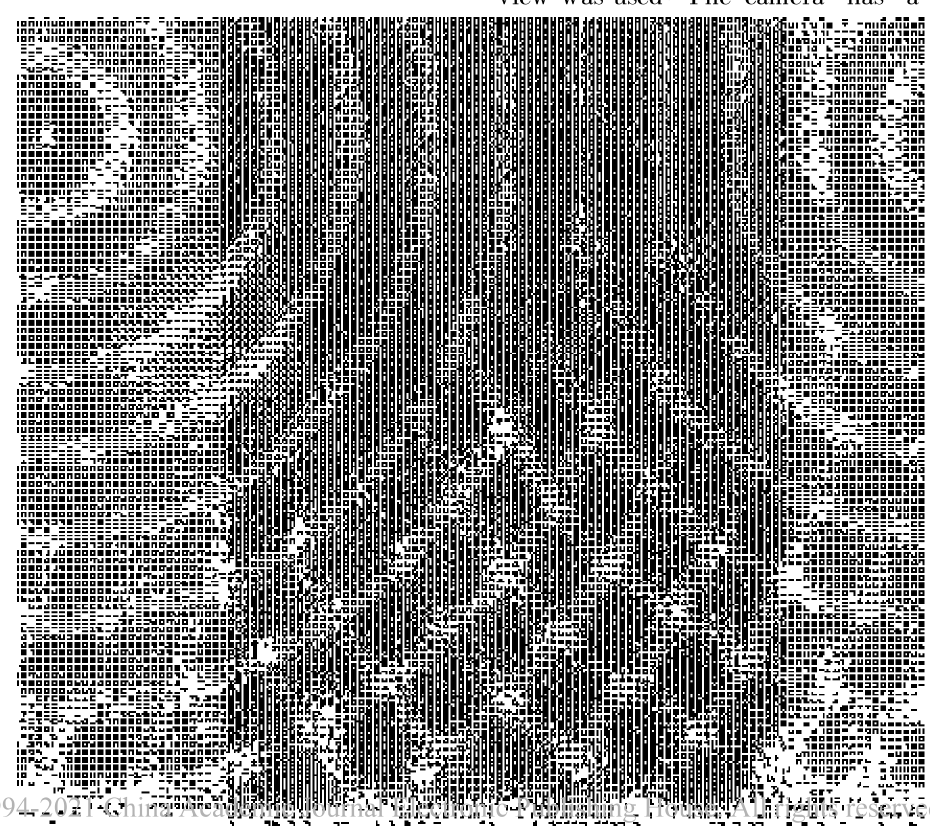

Fig. 4 The image with contours of equal zenith angles (Juniper)

plane, and film exposure is with a gap scanning process. When we took pictures, the camera also was put on the ground, so the upward looking pictures cover ±65 degree zenith angle in camera's scanning direction, and ±25.6 deg. in gap direction. The photographs we used also were taken under overcast sky condition. We took M=19 to get the contours of equal zenith angles, shown in Fig. 4. And took N=9 to do inversion. The estimated LAD is listed in Table 2 and shown in Fig. 5, which is similar with a extremophile distribution. This is agree well with careful observation, but no manual measurement for leaf inclination angle was done.

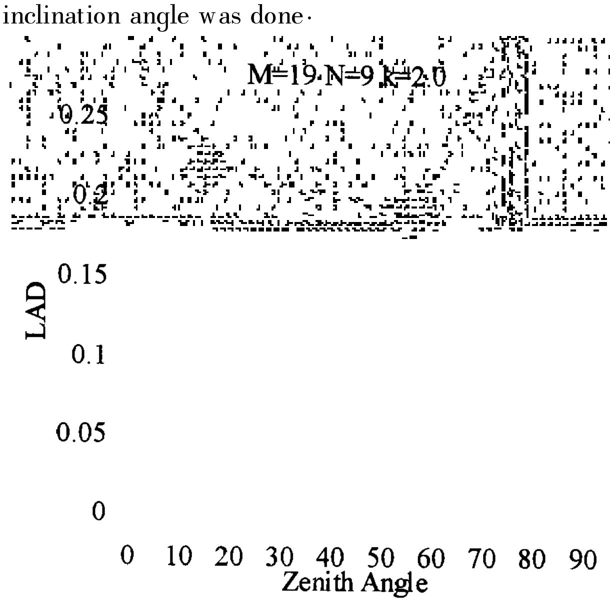

Fig.5 Estimated LAD by model inversion (Juniper)

Table 2 Inverted LAD of juniper (For M=19, N=9)

(deg.)	LAD
5	0.1777
15	0.1580
25	0.1190
35	0.0622
45	0.0092
55	0.0014
65	0.0624
75	0.1661
85	0.2445
total	1.0005

From both validation, we think the method can be used in LAD estimation, although more validation, especially under natural forest, are still needed. We also want to incorporate the method into our tree tomography procedure, to make the reconstruction of the 3-D distribution of FAVD more reliable.

2) In our field experiment in sabina nursery, we took some wide angle images under different openness of canopies, to study the relationship between the canopy openness, the height of canopy layer covered by image and inverted LAD. We selected three kinds of canopy openness by putting the camera in the middle of two trees with different distance. The larger the distance between the two trees, the larger the openness shown. That means the image cover the more high part of the both tree crowns. We have done the same process for the images. The inverted LADs show the high correlation between the image covered part of crowns and its LAD. When images cover much lower part of crowns, where the leaves almost in the shape of thorny, the inverted LADs show approximate extremophile distribution, which looks similar with the LAD of juniper. Fig. 6 are the results. When images cover the higher and top part of the crowns, The inverted LADs show approximate erectophile distribution. In these area of crowns, more leaves are growing upward, to get more light. So the erectophile distribution is also reasonable. The results are shown in Fig. 7. The other case between the two openness was shown in Fig. 2, which have been presented in detail as above.

Based these results, we find that this method is sensitive with the informations of viewing gap probability. For an unique tree species, the LAD may be different because of the openness of canopy and the foliage density within crowns. So we can imagine that our estimated method can be tried to get the LAD of canopy in different height layers, which will be helpful in further studies of BRDF physical model.

3) From Table 1, the estimated effective LAI (ELAI) is $L_e=1.268$. for the canopy of the sabina nursery. We also got the 3-D distribution of FAVD of a sample crown in the nursery by our Tree-tomography algorithm[6]. And we calculated the effective

TPAI (ETPAI) is 7.2895. Our measuring area is S = 12 * 12 sq. m., planted trees number n = 96, measured the average radius of crowns is R = 0.3 m, then the coverage is C = n * π * R * R = 0.1885. So the average ELAI = 1.3741. Comparing this one to the inverted Le, the two results are close to each other.

As a result, our new approach on estimated the LAD and ELAI is feasible, which gives a method in the field simultaneous measurements of canopy architecture parameters. And from the study, we also find some problems to do more works. Such as, the effect of the informations of the measurement included on the model inversion, how to combined this method and the TCT together to make the estimation of canopy architecture parameters more reliable, and in measuring data acquisition using fisheye camera to take the hemispherical photographs to get more informations of canopy, and so on. All of these will be paid attention to in our further studies.

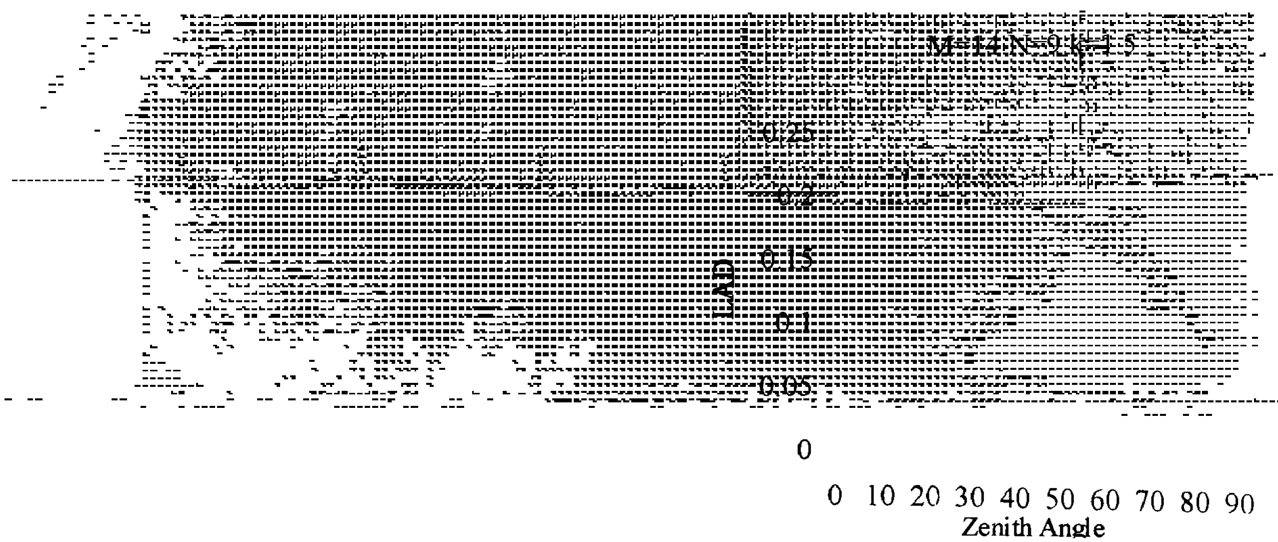

Fig.6 Measured image and estimated LAD in the lower part of the canopy

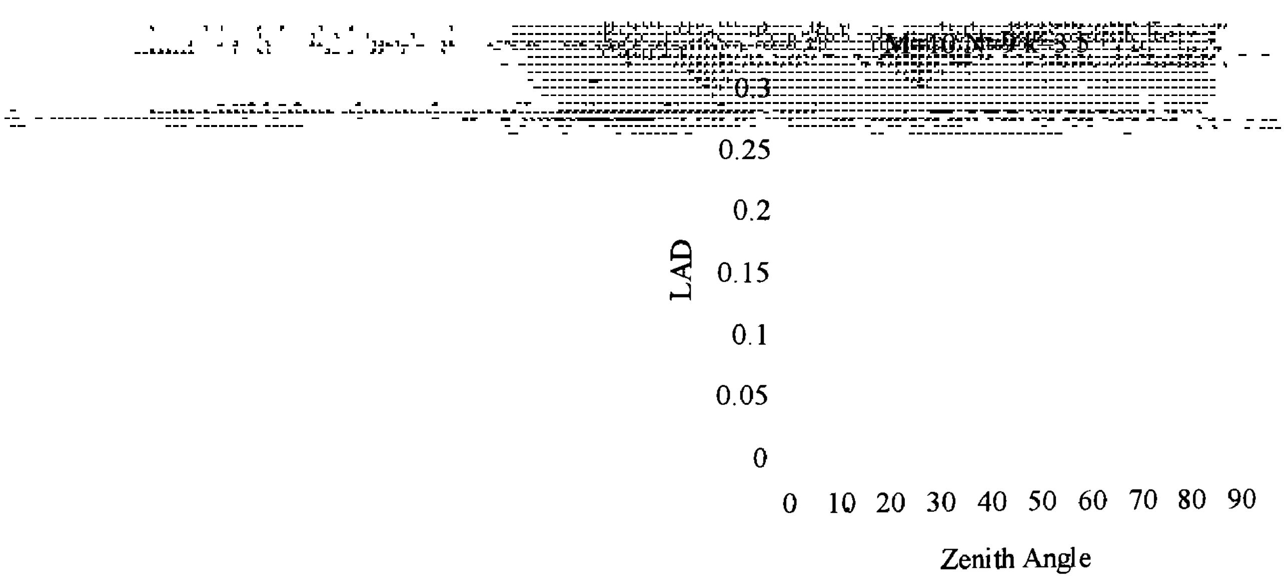

Fig.7 Measured image and estimated LAD for the top layer of the canopy

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用广角图象同时测量针叶树冠层叶角分布和叶面积指数的方法研究

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摘　要　叶面倾角分布（LAD）和叶面积指数（LAI）是植被冠层结构的重要参量。由于植被结构的复杂和千变万化，这些参量的野外直接测量，是十分费力和费时的，特别是对针叶树种就更难进行。底视广角照片已用于LAI的估值，但由于LAD和叶丛、枝的丛集情况未知而导致了估值的误差。J. Chen等近期采用最小平方反演技术从鱼眼象片中同时获取LAI和LAD，他们注意到提取的LAD的精度不高，误差产生的原因可能在于假定对不同的观察方向叶丛集指数为常量。从典型的鱼眼象片中可见，对森林群落，接近水平方向的光间隙是随机的，但接近天顶却明显呈丛集状，Nilson（1971）曾指出这一丛集指数可能是与观察方向有关的，但近期的工作通常将其视作常量，也有一些例外，如J. Chen基于加拿大北部森林的叶丛结构，指出了叶丛集指数随观察方向的变化。

我们将树冠间间隙的概念引入Chen的方法，并将叶丛集指数明确地表示作观察方向天顶角的函数，同样应用最小平方反演，我们提取了满意的LAI和LAD的估计值。我们已用两种针叶树的广角图象进行了验证实验。数字化的底视广角图象用树冠断层象数据采集系统（TCTS）摄取，1995年我们在园柏苗圃中摄取广角图象并同期手工测量的5000余片叶的叶面积叶倾角，LAD的估值结果与直接手工测量值间具有很好的相关性。另一观测目标为桧柏苗圃，估计的LAD呈喜极型分布，这一结果与仔细观察相吻合，但没有进行LAD的手工测量。初步结果总的令人鼓舞，但进一步的验证，特别是对自然林，将这一方法引入我们的树冠断层成象还是十分必要的。

关键词　针叶树冠层，方向间隙率，叶倾角分布，反演