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ESTIMATION OF LEAF AREA INDEX FROM BIDIRECTIONAL SPECTRAL REFLECTANCE DATA BY INVERTING A CANOPY REFLECTANCE MODEL

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ABSTRACT

A technique for estimating the leaf area index from bidirectional canopy reflectance (CR) data, in the infrared region, e.g., in band 4 of a Thematic Mapper (TM), is described. It involves inversion of a CR model which accurately represents the reflectance from the canopy. A method for remotely collecting this CR data using an aircraft based TM is described. The bidirectional CR's, for a black spruce (*picea mariana*) canopy, for 7 solar/view directions, as measured using this technique, are given. A very preliminary analysis of the data from a point of view of estimating LAI by inversion of a CR model is given. This analysis suggests that for an acceptably accurate estimation of LAI, one will require bidirectional CR's for many more than 7 solar/view directions.

I. INTRODUCTION

It is now very well established that the reflectance, in the visible and infrared regions, from a vegetation (crop, grassland, and forest) canopy is strongly correlated to the agronomic, architectural, and spectral parameters of the canopy. Remote sensing of vegetation relies on this correlation. The agronomic parameters include the densities and orientations of vegetation components like leaves, stems, branches, and bark. The architectural parameters include spatial distributions, both in horizontal and vertical directions, of vegetation components. The spectral parameters include reflectances and transmittances of these components. In addition, the canopy reflectance (CR) depends upon the ground (soil, moss, disintegrated vegetation etc.) reflectance and the relative fraction, SKYL, of the diffused incident solar radiation.

During the last quarter of a century, many models (see Ross, 1981; Goel, 1982; and Smith, 1983 for reviews of these models) at different levels of complexity, have been proposed to provide a realistic relationship between important canopy parameters and canopy reflectance. With these CR models one can, in principle, calculate the canopy reflectance as a function of the illumination and view directions (bidirectional CR), using the measured values of the canopy parameters, ground reflectance, and incident diffused radiation. A desirable application of these models is the estimation of important agronomic parameters like leaf area index (LAI) from the measured bidirectional CR's by carrying out such calculations in "reverse", i.e., by inverting a CR model.

One of the authors and his collaborators (Goel and Strebel, 1983; Goel, Strebel and Thompson, 1984; Goel and Thompson, 1984a,b,c) have investigated the possibility of such an estimation, using CR data in the infrared region, for a set of solar/view directions. We have shown that such an estimation is, in principle, possible, at least for a homogenous canopy. Specifically, we have shown that at least for three CR models - the Suits model (Suits, 1972), the SAIL model (Verhoef and Bunnik, 1981), and the CUPID model (Norman, 1979), there is a one to one relationship between the canopy parameters and the bidirectional CR. That is, all the canopy parameters can be estimated uniquely using only CR data, provided of course these models accurately represent the measured CR's. We also applied this canopy reflectance model inversion technique to field measured CR's for a set of view directions. We have shown (Goel and Thompson, 1984c) that one can estimate quite accurately the leaf area index (LAI) as well as the average leaf inclination angle (ALA) for a homogenous fully covered soybean canopy, using CR data for about 50 view directions, provided that the other canopy parameters like leaf reflectance and transmittance, soil reflectance and fraction of diffused skylight are known.

The obvious general question is: Can one use the inversion technique to estimate LAI for an <u>inhomogenous canopy</u> such as that for a <u>forest</u> using <u>remotely sensed</u> bidirectional <u>CR</u> data and some (ground) measured ancillary data on spectral and architectural parameters of the canopy? As part of our continuing investigations to address this question, we have collected part of such a data set. The main purpose of this paper is to present the methodology for collecting the remotely sensed bidirectional canopy reflectance and for measuring ancillary parameters and to present a very preliminary analysis of the data from the point of view of estimating LAI by inversion of a canopy reflectance model.

In section II we briefly review the general procedure for estimating agronomic parameters from the bidirectional spectral reflectances using inversion of a CR model. We highlight the strengths and limitations of the technique.

In section III we describe the technique for remotely sensing the bidirectional canopy reflectance. In this technique, the collection of the raw data essentially involves flying an aircraft, equipped with an appropriate sensor, in a maze pattern, registration of the sensed images to a common base, and calibration of the raw data. The technique was used for collecting data on a boreal forest site in the Superior National Forest, on July 13, 1983, using a NASA Ames Research Center C-130 aircraft equipped with a Thematic Mapper (TM) sensor. Seven flight lines were flown at 1615 M altitude (giving 4 M resolution) in various azimuthal headings. From this data 7 images of a scene approximately 2.0 KM square were produced. Each image represents different zenith and azimuthal view angles and when processed in the manner described in section III, allowed the measurement of bidirectional reflectance characteristics of stands of black spruce, birch, and aspen in the scene. These seven images were rotated and registered to a common base, using a tiepoint registration approach included in the Vicar software developed at the Jet Propulsion Laboratory and converted to run with the CMS operating system at the Earth Resources Research Division Computer system at NASA Johnson Space Center. The raw sensor data was then calibrated to produce the bidirectional canopy reflectance data for 7 sets of solar/view directions. The resulting values for these CR's are given for 4 stands of black spruce--two of high density, one of high to medium density, and one of low density (sparsely populated trees).

In section IV we give a very preliminary analysis of the data. This analysis, as to be expected, shows that because of the complexity and inhomogenity of the black spruce canopy, LAI can not be uniquely determined with just 7 bidirectional CR's and the available ancillary data. It appears that for low density stands, larger values of CR's as compared to those for high density stands, could only be accounted for by factors like differences in the nature of the background reflectance, shadowing and nonhomogenous nature of the black spruce canopy. This preliminary analysis suggests that to estimate LAI, one will require more than 7 images. With these additional measurements and some improvements on the CR model (e.g., inclusion of shadow effects), so that it represents more accurately the CR of a forest canopy, one should be able to estimate not only LAI but also bark area index, branch area index, and possibly also the leaf angle distribution of the crown part of the forest canopy.

II. BASIC PROCEDURE FOR LAI ESTIMATION FROM THE CANOPY REFLECTANCE DATA

The procedure for estimating LAI or any other agronomic variable from the canopy reflectance data has two key ingredients:

(1) a canopy reflectance (CR) model which represents canopy reflectance accurately, and

(2) a procedure for inverting the CR model.

There are a number of CR models which have been proposed. Some of these models are rather complex and comprehensive but not very comprehensible and there are others which are rather simple and comprehensible but less realistic and comprehensive. In all of these models, the canopy reflectance depends upon the following types of parameters:

spectral parameters: reflectance and transmittance of vegetation components (leaf, stem, branch, bark etc.) and reflectance of ground cover or soil

agronomic parameters: densities and orientations of vegetation components

canopy architecture: spatial (horizontal and vertical) distribution of vegetation components solar parameters: solar zenith, θ_s, and azimuth, ψ_s, angles and fraction of incident diffused light, SKYL

viewing parameters: view zenith, θ_v, and azimuth, ψ_v, angles.

The wavelength, λ, dependence of the CR is implicit in the dependence of spectral parameters and to some extent of SKYL on λ.

Let R_i be the crop reflectance for a given set of canopy parameters and the solar/view direction parameters, $\theta_s(i)$, $\psi_s(i)$, $\theta_v(i)$, and $\psi_v(i)$ for $i=1,\ldots,n$, where $\{\theta_s(i),\psi_s(i),\theta_v(i)$ and $\psi_v(i)$, $i=1,\ldots,n\}$ is a set of solar/view angles.

Let R'_i be the measured crop reflectance for the same set of solar/view angles. We define a merit function, F, by

$$F = \sum_i w_i(R_i-R'_i)^2 \qquad (2.1)$$

Here, the summation is over the number of solar/view angles, and the canopy parameters appear as unknowns. The w_i's are weight factors which could all be set equal to 1, or be given unequal values to reflect the relative importance and accuracy of the various observed CR's. The values of the canopy parameters which are to be estimated from the observed CR data, R'_i, are those for which the function F is minimum will exist and be unique.)

Thus the basic procedure for estimating the canopy parameters from the bidirectional CR data is to find the minimum of F. To do so we start with an initial guess for the unknown canopy parameters, calculate F using the CR model, and use a method to choose successive values for the canopy parameters until the computed F takes on a minimum value. In principle, this procedure is straightforward. However, in practice one runs into the problem of slow convergence to the optimum values for the canopy parameters. This convergence can be so slow that one can erroneously conclude that one has obtained the optimal values of the parameters, even though one may be quite far from doing so. (This may be referred to as the local trapping problem.)

Through careful investigation of the path of convergence to the minimum for a set of canopy parameters, we have developed a procedure which avoids the local trapping problem and seeks the global minimum of F. This procedure is described in detail in Goel and Thompson (1984a).

As the CR model becomes more realistic in representing CR, it naturally becomes more complex and involves a larger number of canopy parameters. It is obvious that to determine this larger number of unknown canopy parameters, the number, n, of bidirectional CR's also increases. The value of n must at least be equal to the number of unknown canopy parameters. In practice, however, because of the errors in the measurement of CR's and inadequacy of even the most comprehensive CR model in representing the canopy reflectance, n should be considerably larger than the number of unknowns.

In our studies to date we have chosen 3 models, alluded to in the Introduction, all for one layer spatially homogenous canopies. For one of these representative models, the SAIL model (Verhoef and Bunnik, 1981), with single vegetation component (leaf) in the canopy, the crop reflectance depends upon the following parameters:

spectral parameters: ρ, τ, and ρ_s

illumination source parameters: θ_s, SKYL

view direction parameters: θ_v and ψ

agronomic parameters: LAI and LAD

Here ρ and τ are the leaf reflectance and transmittance, respectively, and ρ_s is the soil reflectance. SKYL is the diffused fraction of the incident solar radiation. θ_s and θ_v, respectively, are the solar and view zenith angles, and ψ is the relative aximuthal angle ($0° \le \psi \le 180°$) between the solar and view directions.

Though SAIL model uses fractions of leaves at discrete leaf angles (typically 9), it is convenient to represent the LAD by a continuous distribution, the beta distribution, characterized by two parameters μ and ν. Elsewhere (Goel and Strebel, 1984), we have shown that this distribution approximates rather well LAD for various canopy types (planophile, erectophile, plagiophile, uniform, spherical, etc.), as well as measured LAD for soybean, wheat, blue grama, and sorghum canopies. More recently (Goel, unpublished result) we have also found that it also represents well the branch angle and needle angle distributions for a balsam fir canopy as measured by Jon Ranson (unpublished data) at Purdue University.

For the LAD application, the beta probability density function on the leaf inclination angle interval 0° to 90° is given, in terms of the Gamma function (Γ), by

$$f(\theta,\mu,\nu) = \frac{1}{(360)(90)} \frac{\Gamma(\mu+\nu)}{\Gamma(\mu)\Gamma(\nu)} \times (1-0/90)^{\mu-1}(0/90)^{\nu-1} \qquad (2.2)$$

Here μ and ν are two parameters related to the average leaf inclination angle, $<\theta>$, and its second moment, $<\theta^2>$, by

$$<\theta> = (90)(\nu/\mu+\nu) \qquad (2.3a)$$

$$<\theta^2> = (90)^2\nu(\nu+1)/(\mu+\nu)(\mu+\nu+1) \qquad (2.3b)$$

The function $f(\theta,\mu,\nu)$ represents the fraction of leaves per unit leaf zenith angle per unit leaf azimuth angle. Thus the fraction of leaves in a zenith angle interval L_1 to L_2 is given by 360 times the integral of $f(\theta,\mu,\nu)$ between L_1 and L_2. If this is a small interval around an angle $\bar{\theta}$, this fraction can be approximated by $360f(\bar{\theta},\mu,\nu)$ times the length of the interval.

With the above representation of LAD, the following 7 canopy parameters determine the reflectance from a one-component, one-layer, homogenous canopy, for a given set of incident radiation and viewing directions.

$$LAI,\mu,\nu;\rho,\tau;\rho_s, \text{ and SKYL} \qquad (2.4)$$

In developing the procedure for estimating canopy parameters from the CR data, we mostly used error free simulated CR data. That is we chose a certain set of values for the seven canopy parameters and used them to calculate the canopy reflectances, R_i'. The parameters were then "forgotten" and these calculated reflectances were taken as the observed ones. These "error free" or "perfect" observed reflectances were used in Eq.(2.1) for the purpose of minimizing F to obtain the canopy parameters. The calculated canopy parameters are then compared with the forgotten parameters. We found that the simple SAIL model is mathematically totally invertible, i.e., the calculated values of all the canopy parameters occuring in the SAIL model are the same as their forgotten values. That is, there is a one to one correspondence between the canopy parameters and the bidirectional canopy reflectance as calculated by using the model.

Though all the canopy parameters can be estimated accurately using only bidirectional "simulated" error free CR data, the estimated values could be quite sensitive to changes in the values of CR's. A detailed sensitivity analysis (Goel and Thompson, 1984b,c) showed that the agronomic canopy parameters LAI and ALA may be determinable with acceptable accuracy only when the other canopy parameters, in particular, the leaf spectral parameters are known and for such a case the accuracy level of LAD is at best marginal.

To see how these inferences bear out with measured CR data, we used the CR data for a fully covered homogenous soybean canopy collected by the investigators at Purdue Univ. (Ranson et al., 1981). They collected 12 data sets. Each of these sets was collected over a period of about 15 minutes with solar zenith and azimuth angles almost constant (for a data set) and view zenith angle varying from 0° to 60° and view azimuth angle varying from 0° to 315° (about 50 solar/view directions in each data set). Each of these CR data sets was inverted to determine LAI, μ, and ν, using measured values of ρ,τ,ρ_s, and SKYL (Goel and Thompson, 1984c). The esimated value of LAI was 3.09±0.19 as compared to the measured value of 2.87±0.44. The estimated value of ALA was 55.1°±1.8 as compared to the measured value of 51.9° for the whole canopy and 60.4° for top 20% of the canopy. Also the estimated LAD was closer to the measured LAD for the top 20% of the canopy than for the whole canopy, though the agreement was not as good as for LAI and ALA.

We should add that though the estimated agronomic parameters were somewhat different than the measured ones, one should not conclude that the inversion technique for estimating the canopy parameters from the CR data is failing. On the contrary, it worked very well and did what it is supposed to do - namely determine canopy parameters for which a given CR model fits best, in the least square sense, to the observed bidirectional CR data. This is simply seen by a lower value of root mean square error (RMS) between R_i' (observed CR's) and R_i (calculated CR's) for the estimated values of agronomic parameters than between R_i' and R_i for the measured values of the agronomic parameters. This RMS measure between two sets of canopy reflectances, R_a and R_b, is defined by

$$RMS = [\Sigma(R_a-R_b)^2/N_{obs}]^{1/2} \qquad (2.5)$$

where N_{obs} is the number of solar/view directions in each of the two data sets and the summation is over all of these directions.

Though the inversion technique seems to work rather well for estimating LAI for a homogenous soybean canopy from ground based measured CR's for about 50 solar/view directions, it should be emphasized that it is not expected to work so well for an inhomogenous black spruce canopy, with aircraft based measured CR's for only 7 solar/view directions (There are many more than 7 variables which determine CR's). Inspite of these expectations, we any how tried the technique for a black spruce canopy, in order to get an assessment of the potentials of the technique for practically estimating LAI of such a canopy from remotely sensed data. We now describe the methodology for measuring the bidirectional CR data and spectral parameters of the vegetation elements.

III. MEASUREMENTS

As noted in the Introduction, the bidirectional CR for varying zenith and azimuth view angles, required for estimating LAI through a CR model inversion, was collected using a C-130 aircraft. This aircraft was equipped with a NS-001 aircraft scanner (Richard, et al., 1978). The method employed to obtain a range of view and sun angles was to fly a set of lines at different aircraft headings over a specified position on the ground. A range of view zenith angles is present in the data due to the position of the target in reference to the nadir position of the viewing sensor. Different view azimuth angles result from different aircraft headings as the sensor is flown over the scene. A range of sun zenith and azimuth angles is obtained due to the time differences in flying various lines.

The data set reported in this paper is based upon 7 flight lines, flown at an elevation of approximately 5300 feet over a small portion of the Superior National Forest in Northern Minnesota, on July 13, 1983. The NS-001 scanner has a maximum scan angle of 50 degrees from nadir with a 2.5 milliradian incident field of view (IFOV). At an altitude of 5300 feet (1615 meters) this will result in a 4.0 meter ground resolution element. The scan angle introduces significant across track variations in ground resolution and radiometric conditions as observed by the sensor. In preparing the data set, extensive use was made of computer software developed by the staff of the Goddard Institute for Space Studies. This software was used in extraction of data from tapes as well as correction for the ground resolution just noted. Following the extraction and ground resolution correction, the data from lines 2-6 were registered to line 1 which was chosen as a reference. Registration was performed using a tiepoint registration approach using Vicar systems program converted to run with the CMS operating system. Approximately 10-20 tiepoints (well spaced across the image) were required in order to attain a registration within 4-6 pixels. The reference flight line was flown at an aircraft heading of 357 degrees or only 3 degrees from true north-south. The registration step was included in data set preparation for 2 reasons, first to insure that the data from any specific site in the larger extracted scene would be present in all flight lines and second to insure that spectral data extracted and used as input data for the model inversion would come from the same site in reference to the ground in all 7 flight lines.

Though scanner data was collected over stands of black spruce, birch, and aspen and also over Kanza Prairie grassland, we have so far only processed it for 4 black spruce (*picea mariana*) sites labeled as 14, 15, 57, and 58, near Lake Jeanette.

Scanner data from these 4 sites was processed further as follows. A 4 pixel by 4 pixel area was chosen and the mean of the 16 spectral values, in counts, was computed. For each of the 4x4 pixel areas, the mean view zenith angle was computed based upon geometry of the sensor. View azimuth was determined from aerial photographs plotted on maps of the area. Sun zenith and azimuth were determined from the year, day and time of the data acquisition together with the latitude and longitude of the ground truth sites. Tables 3.1 summarizes the solar and view directions for the 4 sites and 7 flight lines.

Table 3.1. Solar/view angles

Flt. Line	θ_s	ψ_s	ψ_v	θ_v for site 14	15	57	58
1	56	94	357	4.2	3.9	7.1	-34.1
2	54	97	357	35.2	34.9	37.8	- 0.5
3	51	100	357	-19.8	-20.3	-16.0	-48.2
4	49	103	320	20.4	22.2	9.9	-18.8
5	47	105	319	-19.2	-15.3	-27.1	-46.2
6	44	110	231	24.1	27.1	3.6	37.5
7	42	114	232	-27.5	-24.6	-42.6	-10.2

Note that the view zenith angles are negative as well as positive. In reality no sign is necessary for the zenith angles as by normal convention zenith is measured from straight up and down. In our case the sign is for orientation purposes only. A negative (positive) zenith view angle implies that the aircraft flew on the left (right) side of the pixel. The zenith angles can be taken to be positive and the view azimuth angles are determined by adding or subtracting 90 degrees from the aircraft heading depending upon if the view zenith is positive or negative.

The next step in obtaining bidirectional CR from NS-100 raw data (channel counts) is to convert them into upwelling radiance by using a calibration procedure. This procedure used the results of laboratory calibration of the sensor, prior to flight, which was performed by NASA Ames Research Center. These data are used in computing a responsivity value and a dark level value for each scan line for each channel and are recorded on the processed data tape along with the spectral counts.

The following equation is used to calculate radiance:

$$\text{radiance} = a\,(\text{counts}-b) \qquad (3.1)$$

where a and b are two constants (responsivity and dark level respectively) which depend upon the wavelength band. In Table 3.2 are given the values of these constants for site 14 for band 4.

Table 3.2. Values of constants a and b in Eq. (3.1), for band 4, to convert counts to radiance (μwatts/cm^{2}Srμm)

Flt.	Band 4	
Line	a	b
1	69.0	11.9
2	68.6	12.0
3	68.7	12.0
4	68.1	12.0
5	68.1	12.0
6	68.1	12.0

In order to simplify the computation, we used a mean set of values for a and b. The Statistical Analysis System (SAS) package was used to calculate a mean set of values for a and b over a subset of data known to be from a homogenous black spruce canopy. Relative error, (RE), of radiance, due to using a mean calibration for each flight line, was calculated for a 90% confidence limit. This error is defined by

$$RE = (I_i - I_{ij})/I_i \qquad (3.2)$$

where I_i is the mean radiance for channel i and I_{ij} is the radiance for scan line j for channel i. In Table 3.3 are given these relative errors.

Table 3.3. Relative error (%) of radiance due to using a mean calibration for each flight line

Flt.	Band					
Line	1	2	3	4	6	7
1	2.5	5.0	1.50	0.25	2.5	30.0
2	5.0	5.0	1.25	1.00	1.5	50.0
3	3.2	2.4	0.60	0.24	4.0	28.0
4	3.0	3.2	1.00	0.20	5.0	100.0
5	4.8	1.6	0.80	0.15	3.2	12.0
6	2.0	1.2	2.00	0.80	2.0	16.0

The values in Table 3.3 probably are overestimates of the relative errors since about 1500 lines were sampled to estimate the variance of a and b and only about 512 lines were in the area of the test site.

From Tables 3.2 and 3.3, one can see that a and b do not vary significantly from flight line to flight line in the visible and near infrared bands and the relative error of radiance due to using a mean calibration is <±1.0%. Therefore to simplify the computations further, we used a=68.42 and b=12 for all the flight lines and for all sites.

To calculate reflectance factor, one also needs the downwelling irradiance. This was estimated by using an atmospheric scattering model (Dave, 1980) and is approximately given by $26400\cos\theta_s \times (0.975)^{\sec\theta_s}$ Thus the reflectance factor is given by

$$CR = \frac{68.62(\text{count}-12)}{26400\ \cos\theta_s \times (0.975)^{\sec\theta_s}} \qquad (3.3)$$

Here the path radiance due to the atmosphere between the aircraft and the ground target is approximated to be equal to zero in band 4 (0.76-0.90μm). This atmospheric model also gives the fraction of diffused skylight, SKYL, for band 4, as 7.54%.

Using Eq.(3.3) and the measured channel count, the measured bidirectional CR's for various flight lines, for various sites are as given in Table 3.4. This table also gives the corresponding view zenith and azimuth angles.

Table 3.4. Measured bidirectional CR's and ψ_v. θ_v is as given in Table 3.1 except that all signs are now positive.

	Site 14		Site 15		Site 57		Site 58	
	ψ_v	R	ψ_v	R	ψ_v	R	ψ_v	R
1	267	.1342	267	.1455	267	.1314	87	.3535
2	267	.1459	267	.1413	267	.1326	87	.2803
3	87	.2168	87	.2242	87	.1908	87	.3708
4	230	.1481	230	.1609	230	.1499	50	.2985
5	49	.1905	49	.1897	49	.2189	49	.3041
6	141	.2444	141	.2459	141	.2112	141	.3396
7	322	.1450	322	.1362	322	.1369	322	.2174

The CR values in Table 3.4, together with the view angles and solar angles (see Table 3.1) will constitute the data set for the analysis given in the next section.

We conclude this section by pointing out that the reflectance from typical understories were also collected on the ground. For band 4 a typical value for understory or background reflectance is 22.61%. This is the value we will be using in our analysis which we now describe.

IV. RESULTS AND DISCUSSION

As noted in section II, to obtain the agronomic parameters from the bidirectional CR's, the first step is to select a CR model which is likely to accurately represent the reflectance from the canopy under consideration. Since the number of solar/view directions for which CR's were measured is only 7, it is mandatory to choose a model which has a minimum number of parameters and is still somewhat realistic.

On agronomic basis, a realistic model of black spruce canopy should preferably have two layers, with top layer representing the tree crown with predominance of needles, twigs, and branches, while the bottom layer representing the stems, with bark as the predominant vegetation component. For such a model, the minimum set of canopy parameters (assuming canopy to be spatially homogenous) are:

2 spectral parameters, ρ and τ, per vegetation component

1 vegetation density (e.g., LAI) parameter per component per layer

2 angular distribution parameters, μ and ν, per component per layer

background reflectance and SKYL.

Even if we assume only 3 vegetation components (combine twigs and branches into one category), the total number of canopy parameters is 26! Further simplifying assumptions are therefore necessary.

We first made the following assumptions and simplifications

(1) The angular distribution of bark is vertical and it does not transmit any radiation (bark transmittance, $\tau_B=0$).

(2) We combined needles, branches and twigs into one category and call the vegetation component as leaf

(3) The top layer of the canopy consist of only leaves while the bottom layer consists of only bark.

With these assumptions, the CR model will consist of following 9 parameters:

leaf reflectance, ρ, and transmittance, τ
2 parameters μ and ν for leaf angle distribution
leaf area index, LAI
bark reflectance, ρ_B
bark area index, BAI
ground reflectance, ρ_S, and SKYL.

Even for this simplified model, the number of parameters is larger than the number of observations. Thus LAI can not be estimated using only CR data (this any how is not practically possible even for a larger number of CR observations because of the high sensitivity of estimated value of LAI to changes in the CR, see section II). Therefore, one must keep some of the above canopy parameters fixed at their measured values in the inversion process.

We kept SKYL and ground reflectance fixed at their measured values of 0.2261 and 0.0754, respectively. We also kept leaf reflectance, ρ, and transmittance, τ, and bark reflectance, ρ_B, fixed at the values of 0.59, 0.14, and 0.315, respectively, reported in the literature (Woolford, 1983).

With 5 parameters fixed, we carried out the inversion process for the remaining 4 agronomic parameters, LAI, BAI, μ and ν, using the SAIL model. We assumed that the canopy has 2 layers, with top layer consisting of only leaves while the bottom layer consisting of only bark. In Table 4.1 are given the values of estimated agronomic parameters (including the average leaf angle, $<\theta>$, as calculated by using estimated values of μ and ν), percentage difference, PD, between calculated and observed CR's and the RMS error, defined by Eq.(2.5), between calculated and observed CR's. The difference PD is defined by

$$PD = 100 \text{ (calculated CR-observed CR)/ (observed CR)} \qquad (4.1)$$

Table 4.1 Estimated values of the canopy parameters, percentage difference (PD) between calculated and measured CR's, and the RMS error. Values of the parameters fixed in the inversion process are: $\rho=0.59$, $\tau=0.14$, $\rho_B=0.315$, $\tau_B=0$, $\rho_S=0.2261$, SKYL=0.0754, bark vertically inclined. Two-layer SAIL model was used.

Flt. Line	% Difference, PD, for Site			
	14	15	57	58
1	-1.3	-3.9	-15.4	1.8
2	-3.8	-5.6	- 2.6	6.0
3	-4.4	-3.4	- 6.8	- 2.6
4	1.9	6.5	- 5.8	5.6
5	-2.4	-0.2	6.9	- 5.3
6	6.3	2.8	16.3	5.2
7	2.3	-2.9	- 2.4	-11.7

Param.	Values for Site			
	14	15	57	58
RMS	0.0076	0.0068	0.0173	0.0165
LAI	3.01	2.05	0.92	1.98
BAI	0.23	0.32	0.69	10.79
μ	0.66	1.24	1.01	3.05
ν	4.96	5.96	3.50	3.73
$\langle\theta\rangle$	79.4	74.5	69.8	49.5

We note that the model seems to fit the data for sites 14 and 15 rather well as indicated by < 7% values of PD and low values of RMS error. However, we do not know whether the values of LAI and BAI are reasonable or not, because ground truth data though collected has not yet been completely analyzed to give the measured values of these parameters. The fit to CR data for sites 57 and 58 is somewhat worse (higher values of PD and RMS error). Also for site 58, the value of LAI is higher than that for site 57 and the value of BAI is rather large. This seems to be contradictory to ground truth-site 58 has the smallest density of the 4 sites. However, such numbers for LAI and BAI are consistent with the highest CR's for site 58 (see Table 3.4) if observed CR is only due to interaction of solar radiation with the vegetation in the manner incorporated in the SAIL model. It appears to us that for site 58 because of its low density, the shadow effects (shadow of a tree on itself, on other trees and on ground) are important. Such effects are known to increase CR in a low density site as compared to a high density site.

We also note that a one-layer SAIL model in which bark and leaves are all taken in one layer fits the observed CR data somewhat better (lower values of PD and RMS errors) than the 2-layer model used in the above analysis and the values of agronomic parameters, LAI and BAI, are significantly higher.

The sensitivity of the estimated values of LAI and other agronomic parameters to the model is expected because of the small number of CR observations; 7 data points are not enough to differentiate between any two models. It is imperative to increase the number of CR observations i.e., the number of flight lines if one hopes to estimate LAI with any acceptable level of accuracy. Also, for thinly populated tree stands, it appears that one needs to also modify the CR model to include the shadow effects. We are pursuing such a strategy and hope to report the results in a future communication.

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