

Estimating leaf area index of mangroves from satellite data

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Abstract

The relationship between the normalised difference vegetation index (NDVI) and leaf area index (LAI) was modelled for mangroves growing on the Caicos Bank, Turks and Caicos Islands. NDVI values were used to predict LAI with this model and a thematic map of LAI produced from satellite data for the whole Bank. Mangrove LAI ranged between 0.8 and 7.0, with a mean of 3.96. LAI data, estimated from in situ measurements of canopy transmittance for a set of sites independent of those used to derive the LAI/NDVI model, were used to test the accuracy of this image. Accuracy was defined as the proportion of accuracy sites at which the LAI value (as estimated from field measurements) lay within the 95% confidence interval for the predicted value of LAI. The accuracy of this map was high (88%) and the mean difference between predicted and measured LAI was low (13%). Remote sensing is thus demonstrated as a powerful tool for estimating the spatial distribution of LAI for whole mangrove ecosystems. This information can be obtained rapidly compared to alternative methods of measuring LAI and can minimise the logistical and practical difficulties of fieldwork in inaccessible mangrove areas. © 1997 Elsevier Science B.V.

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1. Introduction

The canopy structure of a vegetated area is frequently described in terms of leaf area index (LAI). LAI is defined as the single-side leaf area per unit ground area, and as such is a dimensionless number. The importance of LAI stems from the relationships which have been established between it and a range of ecological processes (rates of photosynthesis, transpiration and evapotranspiration (McNaughton and Jarvis, 1983; Pierce and Running, 1988); net primary production (Monteith, 1972; Norman, 1980; Gholz, 1982; Meyers and Paw, 1986; Meyers and Paw, 1987); rates of energy exchange between plants and the atmosphere (Botkin, 1986; Gholz et al., 1991)). Measurements of LAI have been used to predict future growth and yield (Kaufmann et al., 1982) and to monitor changes in canopy structure due to pollution and climate change (Waring, 1985; Gholz et al., 1991). The ability to estimate leaf area index is therefore a valuable tool in modelling the ecological processes occurring within a forest and in predicting ecosystem responses.

Many methods have been used to measure LAI directly and are variations of either leaf sampling or litterfall collection techniques (Clough et al., 1997 and in Chason et al., 1991). Leaf sampling involves the destructive harvesting and measurement of leaf area for all leaves within a vertical quadrat down through the entire canopy. Litterfall collection is better suited to deciduous forests which have a single leaf fall as opposed to evergreen canopies (Chason et al., 1991). All direct methods are similar in that they are difficult, extremely labour intensive, require many replicates to account for spatial variability in the canopy and are therefore costly in terms of time and money. Consequently, many indirect methods of measuring LAI have been developed (see Nel and Wessman, 1993). Techniques based on gap-fraction analysis assume that leaf area can be calculated from the canopy transmittance (the fraction of direct solar radiation which penetrates the canopy). They have been used successfully to estimate LAI of terrestrial forest canopies (Pierce and Running, 1988; Chason et al., 1991; Ellsworth and Reich, 1993; Nel and Wessman, 1993) and mangroves (*Rhizophora apiculata*, Clough et al., 1997).

This approach to measuring LAI uses data collected from along transects beneath the forest canopy (e.g., at 10 m intervals along 300–400 m transects in coniferous forests, Nel and Wessman, 1993). Mangroves are intertidal, often grow in dense stands and have complex aerial root systems which would make this sampling regime impractical. Clough et al. (1997) estimated LAI from a ground area of 900 m², their objective being a comparison between an estimation of mangrove LAI based on gap-fraction analysis with a direct collection method. To measure the LAI of mangroves over large areas would require measurements at many different locations, an extremely time-consuming process. The difficulty of moving through dense mangrove stands and the general inaccessibility of many mangrove areas clearly pose a problem in this respect.

Remotely sensed data provide a synoptic view of large coastal areas and are collected uniformly in time and space, in a nonintrusive manner. Furthermore, the interception, scattering and emission of radiation is closely related to the canopy structure of vegetation (Mather, 1987). If the spatial aspects of LAI can be indirectly estimated from the spectral signature of mangrove forests, many of the problems associated with

obtaining LAI values for entire mangrove forests might be avoided. This paper describes a method by which an indirect estimation of mangrove LAI based upon gap-fraction analysis is used as ground-truthing information to calibrate remotely sensed data. Thematic maps of LAI for the entire area covered by mangroves are derived without the need for large numbers of ground measurements to a high level of accuracy.

2. Methods

2.1. Study area

Fieldwork was carried out around South Caicos (21°30'N 71°30'W) and the eastern edge of the Caicos Bank, Turks and Caicos Islands, British West Indies. Three species of mangrove, *Rhizophora mangle* (Linnaeus), *Laguncularia racemosa* (Gaertner) and *Avicennia germinans* (Stearn) grow with *Conocarpus erectus* (Gaertner) in mixed stands along the inshore (western) margin of the islands fringing the Caicos Bank. Measurements of canopy transmittance were taken from 61 sites on South Caicos and Nigger Cay during two field trips in July 1995 and March 1996. The positions of these sites were recorded using a Trimble 4000 differential GPS.

2.2. Satellite imagery

Landsat Thematic Mapper (Landsat TM, path 9 row 45, date 22/11/1990) and multispectral Système Pour l'Observation de la Terre (SPOT XS, K 643, J306, date 27/3/1995) imagery were georeferenced to Ordnance Survey maps of the Turks and Caicos Islands (Series E8112 DOS 309P). A subset was removed from the TM scene which included the Caicos Bank. The SPOT image covered the northeastern quarter of the Caicos Bank. In this area, both images were cloud free.

2.3. Calculation of LAI

LAI is a function of canopy transmittance, the fraction of direct solar radiation which penetrates the canopy. Canopy transmittance is given by I_c/I_o where I_c = light flux density beneath the canopy and I_o = light flux density outside the canopy. LAI can then be calculated, and corrected for the angle of the sun from the vertical, using the formula

$$\text{LAI} = [\text{Log}_e(I_c/I_o)/k] \cos(\theta\pi/180)$$

where LAI = leaf area index, θ = sun zenith angle in degrees (this can be calculated from time, date and position), k = canopy light extinction coefficient, which is a function of the angle and spatial arrangement of the leaves. The derivation of this formula is given by English et al. (1994). Nel and Wessman (1993) and Clough et al. (1997) should be consulted for a full discussion of the assumptions on which this model is based. For each field site, $\text{Log}_e(I_c/I_o)$ was calculated for pairs of simultaneous readings and averaged. A value for k of 0.525 was chosen as being appropriate to mangrove stands (B. Clough, personal communication). Two more sensors inside

collimating tubes would have been required to measure diffuse radiation simultaneously with the readings of I_c and I_o (see Chason et al., 1991; Nel and Wessman, 1993). No attempt was made to correct for diffuse radiation because (i) uncorrected measurements have been shown to yield estimates of LAI similar to direct methods (Clough et al., 1997), (ii) uncorrected measurements would under estimate, rather than over estimate LAI, (iii) the cost of extra detectors was high, and (iv) a drastic reduction in mobility through the mangroves would result from a system of four inter connected detectors and cables.

2.4. *Measurement of canopy transmittance*

Measurements were taken on clear sunny days between 1000 and 1400 h, local time. The solar zenith angle was judged to be sufficiently close to normal 2 h either side of noon for directly transmitted light to dominate the radiation spectrum under the canopy. At other times the sun is too low and diffuse light predominates. Photosynthetically active radiation was measured using two MACAM™ SD101Q-Cos 2π PAR detectors connected to a MACAM™ Q102 radiometer. One detector was positioned vertically outside the mangrove canopy on the end of a 40 m waterproof cable and recorded I_o . The other detector recorded I_c and was connected to the radiometer by a 10 m waterproof cable. If the mangrove prop roots and trunk were not too dense to prevent a person moving around underneath the canopy this detector (which was attached to a spirit level) was handheld. If the mangroves were too dense, then the I_c detector was attached to a 5.4 m extendible pole and inserted into the mangrove stand. The spirit level was attached to the end of the pole to ensure the detector was always vertical. All recordings of I_c were taken at waist height, approximately 0.8 m above the substrate. Eighty pairs of simultaneous readings of I_c and I_o were taken at each site, from within an area of 20×20 m (the size of a SPOT XS pixel) around the position fix. Both detectors were calibrated against each other by MACAM technicians immediately before and after data collection. There was no drift in their measurement of PAR during fieldwork.

2.5. *Image processing techniques*

After geometric and radiometric correction, mangrove areas were separated from non-mangrove areas using the following processing steps. Firstly, submerged areas were removed from the Landsat TM image using infrared band 5 as a mask. Then, following the method of Gray et al. (1990), the visible and infrared bands were ratioed, 3:5 and 5:4. A five-band image was created using original bands 3, 4, 5 and ratios band 3:band 5 and band 5:band 4. Principal components analysis was applied to this image. Principal components 1, 2 and 4 (corresponding to bands 3, 4 and ratio 3:5) were selected because (i) they account for > 90% of the variability in the data, and (ii) visual interpretation of a false colour composite of these principal components provided the best discrimination between mangrove and non-mangrove vegetation. This image was resampled to a pixel size of 20 m and recoded to produce a mangrove/non-mangrove mask.

Using the near infrared band 3 of SPOT, submerged areas were masked from the XS

scene. Non-mangrove areas were then masked out using the mangrove mask derived from processing the Landsat TM data. Field measurements suggest a linear relationship between mangrove LAI and of normalised difference vegetation index, NDVI (Ramsey and Jensen, 1995, 1996). NDVI is calculated using near infrared and red bands ((Near Infrared-Red)/(Near Infrared + Red), see Rouse et al., 1973; Jensen et al., 1991). Values of LAI estimated from in situ measurements of canopy transmittance were regressed against values of NDVI derived from SPOT XS (Band 3 – Band 2)/(Band 3 + Band 2). The equation of this linear regression model was then used to calibrate the NDVI image into a thematic map of LAI.

Why was it necessary to use both SPOT XS and Landsat TM imagery? Mangroves in the Turks and Caicos Islands grow in relatively small patches and linear stands along inlets typical of the eastern Caribbean islands. It was therefore desirable to take advantage of the superior spatial resolution of SPOT XS in calculating NDVI. Landsat TM data were necessary because experiments conducted by the authors have shown that the band ratioing/principal components analysis technique fails to discriminate satisfactorily between mangroves and *Acacia* scrub (the dominant terrestrial vegetation in the Turks and Caicos Islands) when applied to SPOT XS data (Green et al., 1997). However this is possible using Landsat TM, a fact which is probably attributable to the superior spectral resolution of Landsat TM.

3. Results

3.1. The relationship between NDVI and LAI

Fig. 1 is a scatter plot of in situ LAI values against the NDVI information derived from the SPOT XS data for 29 field sites surveyed in 1995. A linear regression was fitted to these data and a good coefficient of determination obtained ($R^2 = 0.74$, $p < 0.001$, $n = 29$). The F -test for the model and t -test for the slope estimate were both significant at the 0.001 level of confidence, which indicates that the relationship did not occur by chance and may be used to convert NDVI values to LAI.

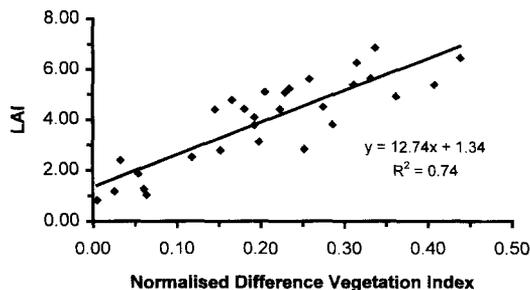


Fig. 1. A scatter plot of leaf area index (LAI) estimated from in situ measurements of canopy transmittance against normalised difference vegetation index (NDVI) derived from SPOT XS data for 29 sites near South Caicos, Turks and Caicos Islands. A linear regression has been fitted to the data and is significant at the 0.001 confidence level.

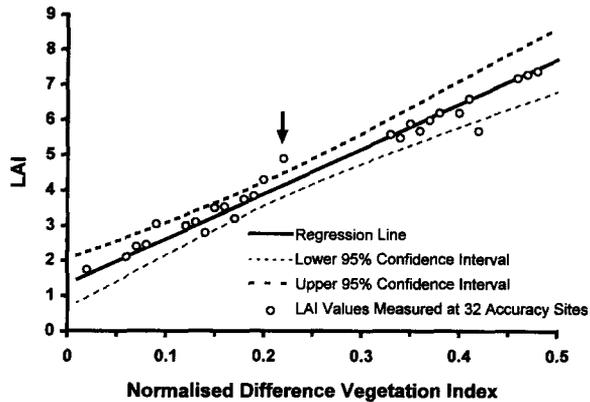


Fig. 2. A plot of the 95% confidence intervals of the regression model. In situ measured values of LAI for 32 sites have been superimposed over this plot. The accuracy of the LAI image was defined as the proportion of 1996 sites at which the LAI value lay within the 95% confidence interval for that value of NDVI. For example, accuracy site number 16 (indicated by an arrowhead) has a NDVI of 0.22. At this NDVI, the 95% confidence interval of a predicted value of LAI is 3.81–4.48. However, LAI at that site was calculated from measurements of canopy transmittance at 4.9. Therefore, the estimation of LAI at accuracy site number 16 was not accurate. LAIs of 28 accuracy sites lie between the appropriate confidence intervals. The accuracy of a thematic map of LAI which was created using the regression model to convert NDVI to LAI would therefore be 88%.

3.2. Calculation of LAI

The model was then used to estimate values of mangrove LAI for the entire image. LAI ranged from 0.83 to 8.51, with a mean value of 3.96. However, values of LAI greater than 7.0 should be treated with caution because the highest calibration point in

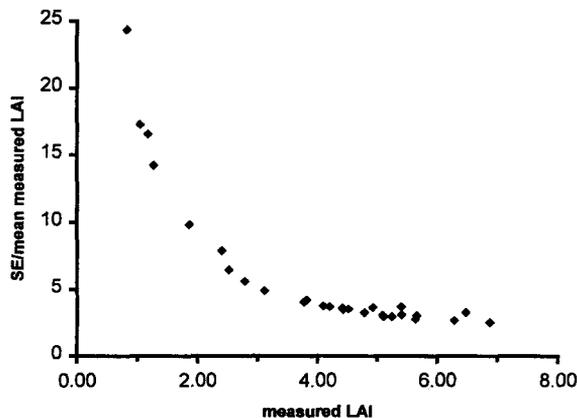


Fig. 3. The precision of the LAI prediction. Precision is inversely proportional to the values used to measure it: standard error/mean (Andrews and Mapstone, 1987). Hence high values of precision are found at low values of this ratio. The standard error of predicted values of LAI have been calculated as a percentage of measured LAI and are plotted against measured LAI. The precision of LAI prediction is high (> 90%) for LAI values greater than 1.5.

the regression model was only 7.0. This produced a thematic image of LAI for the mangrove areas of the Caicos Bank. Field data from 32 accuracy sites surveyed in 1996 were used to test the accuracy of this image. The 95% confidence intervals of values of LAI predicted from NDVI were calculated for the regression model (Zar, 1996). The accuracy of the LAI image was defined as the proportion of 1996 sites at which the value of LAI estimated from in situ measurements of canopy transmittance lay within the 95% confidence interval for that value of NDVI. Fig. 2 shows that the thematic maps of LAI are highly accurate; 88% of the LAIs predicted from NDVI were within the 95% confidence interval. The mean difference between predicted LAI and the value estimated from field measurements was only 13% for the accuracy sites.

An estimate of the precision of the LAI prediction was obtained by expressing the standard error of a predicted LAI value as a percentage of LAI estimated from in situ measurements of canopy transmittance. Fig. 3 shows that the precision is more than 90% for values of LAI of 1.5 and above.

4. Discussion

A technique is presented here by which thematic maps of mangrove LAI can be derived accurately and precisely from remotely sensed satellite data. Clough et al. (1997) have previously published LAI values for mangroves from the west coast of peninsular Malaysia. They obtained indices ranging from 2.2 to 7.4 (mean 4.9) by direct measurement, and a mean value of 5.1 when LAI was estimated indirectly from light transmission measurements over four transects. Values of LAI derived from satellite data of Caribbean mangroves (0.83–7.00, mean 3.96) compare well with their findings and other published values for mangrove LAI (Table 1).

The lower LAI values reported here reflect the inclusion of some sites with sparse mangroves and more open canopies. Care should be taken when interpreting low (< ~ 1.5) values of LAI derived from remotely sensed data, especially if the understorey vegetation is not uniform. The spectral signature of such sites will contain a larger proportion of light that has been reflected from the understorey than if the canopy was denser. Ground cover beneath sparse mangrove sites was variable in the TCI. White sand, dark organic detritus and dense green mats of the succulent *Salicornia perennis* were all recorded, ground covers with presumably very different optical properties. The

Table 1
Values for mangrove leaf area index recorded by different authors

Reference	Habitat	Leaf area index		
		Minimum	Maximum	Mean
Araújo et al. (1997)	Mangrove	3.0	5.7	—
Clough et al. (1997)	Mangrove	2.2	7.4	4.9
Cintrón and Schaeffer-Novelli, 1985	Mangrove	0.2	5.1	—
Cintrón et al., 1980	Mangrove	—	—	3.8
Present paper	Mangrove	0.8	7.0	4.0

LAI of mangroves with relatively open canopies might be underestimated if they were growing over white sand, or over estimated if dark organic detritus covered the sediment. LAI values higher than previously published probably reflect the inclusion of especially dense mangrove areas.

Notwithstanding this, satellite data can be used to estimate mangrove LAI with considerable precision in the range 1.5–7.0. The extent to which LAI obtained in this way can be used to model ecological processes in mangrove forests may only be limited by the availability of supporting data. If the appropriate data exist then LAI may be used to produce thematic maps of, e.g., rates photosynthesis, transpiration, respiration and nutrient uptake. Such thematic maps could then be combined with other spatial data in a GIS for the management of mangrove areas.

The major advantage of this method is that estimates of LAI for large areas of mangrove (a SPOT XS scene covers 3600 km²) can be obtained without the need for extensive field effort in areas where logistical and practical problems can be severe. *Rhizophora mangle*, in particular, grows extremely densely in the Turks and Caicos Islands and access to the interior of mangrove thickets is physically impossible in many cases. Remote sensing is therefore the only way that LAI can be estimated nondestructively. In addition, the LAI data is obtained relatively quickly; the field measurements presented here required a team of two working for a total of 34 person days, processing time another 22 person days.

Although two types of satellite imagery were used in this case, this may not be necessary in every instance. As already mentioned, SPOT XS was deemed necessary because mangroves in the TCI do not grow in stands covering large areas. In regions where mangroves form forests of more than a few km², LAI can undoubtedly be estimated from Landsat TM alone, which would reduce the processing time by about half and the financial cost of acquiring imagery by about 40%.

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