

## 10: ASSESSING MANGROVE LEAF-AREA INDEX (LAI) USING CASI AIRBORNE IMAGERY

### Aim of Lesson

To learn how to assess and map mangrove leaf-area index (LAI) using Compact Airborne Spectrographic Imager (CASI) imagery as an example.

### Objectives

1. To understand what field survey of the mangroves is necessary to calibrate imagery and allow Leaf-Area Index (LAI) to be estimated.
2. To understand how LAI data is derived from field measurements.
3. To learn how to prepare a Normalised Vegetation Difference Index (NDVI) of mangrove areas from CASI imagery
4. To investigate the relationship between NDVI and LAI using UTM coordinate referenced field survey data and use this relationship to create an image of mangrove Leaf Area Index.
5. To learn how to create a palette to display mangrove LAI effectively.
6. To calculate net canopy photosynthetic production from LAI and thus obtain a crude estimate of the mangrove forest primary productivity.

### Background Information

This lesson relates to material covered in Chapters 13 and 17 of the *Remote Sensing Handbook for Tropical Coastal Management* and readers are recommended to consult these for further details of the techniques involved. This lesson describes an empirical approach to mapping mangrove leaf-area index (LAI) using Compact Airborne Spectrographic Imager (CASI) imagery. The mangrove was located on the island of South Caicos.

In the eastern Caribbean the limited freshwater run off of the low dry islands and the exposure of a large portion of the shoreline to intense wave action imposes severe limits on the development of mangroves. They typically occur in small stands at protected river mouths or in narrow fringes along the most sheltered coasts (Bossi and Cintron 1990). As a result most of the mangrove forests in this region are small. Nevertheless they occur in up to 50 different areas where they are particularly important for water quality control, shoreline stabilisation and as aquatic nurseries. Mangroves in the Turks and Caicos Islands are typical of this area but completely different to the large mangrove forests that occur along continental coasts and at large river deltas.

### The *Bilko 3* image processing software

Familiarity with *Bilko 3* is required to carry out this lesson. In particular, you will need experience of using Formula documents to carry out mathematical manipulations of images and Histogram documents to calculate the area of particular features on the imagery. These features are covered in Tutorials 10 and 4 respectively of the *Introduction to using the Bilko 3 image processing software*. A familiarity with the *Microsoft Excel* spreadsheet package is also desirable.

## Image data

A Compact Airborne Spectrographic Imager (CASI) was mounted on a locally-owned Cessna 172N aircraft using a specially designed door with mounting brackets and streamlined cowling. An incident light sensor (ILS) was fixed to the fuselage so that simultaneous measurements of irradiance could be made. A Differential Global Positioning System (DGPS) was mounted to provide a record of the aircraft's flight path. Data were collected at a spatial resolution of 1 m<sup>2</sup> in 8 wavebands (Table 10.1) during flights over the Cockburn Harbour and adjacent areas of South Caicos, Turks and Caicos Islands (21° 30' N, 71° 30' W) in July 1995. Further details are given in Clark *et al.* (1997) and Appendix 1.4.

**Table 10.1.** Band settings used on the CASI for this study.

<b>Band</b>	<b>Part of electromagnetic spectrum</b>	<b>Wavelength (nm)</b>
1	Blue	402.5–421.8
2	Blue	453.4–469.2
3	Green	531.1–543.5
4	Green	571.9–584.3
5	Red	630.7–643.2
<b>6</b>	<b>Red</b>	<b>666.5–673.7</b>
<b>7</b>	<b>Near Infrared</b>	<b>736.6–752.8</b>
8	Near Infrared	776.3–785.4

Geometrically and radiometrically corrected Compact Airborne Spectrographic Imager (CASI) data from bands #6 (red) and #7 (near infra-red) of the area around South Caicos island are provided for the purposes of this lesson as files **Casi\_mangrove#06.dat** and **Casi\_mangrove#07.dat**. These files are unsigned 16-bit integer files (integers between 0 and 65535). This means that there are two bytes needed per pixel rather than the one byte needed for the Landsat TM and SPOT XS images, which are only 8-bit data. Mangrove areas have to be separated from non-mangrove areas and a mask used to set water pixels and non-mangrove land pixels to zero.

## Field survey data

Three species of mangrove, the red mangrove *Rhizophora mangle*, the white mangrove *Laguncularia racemosa*, and the black mangrove *Avicennia germinans* grow with the buttonwood *Conocarpus erectus* in mixed stands along the inland margin of the islands fringing the Caicos Bank. The field survey was divided into two phases. Calibration data were collected in July 1995, accuracy data in March 1996. Species composition, maximum canopy height and tree density were recorded at all sites (Table 10.2). Species composition was visually estimated from a 5 m x 5 m plot marked by a tape measure. Tree height was measured using a 5.3 m telescopic pole. Tree density was measured by counting the number of tree trunks at breast height. When a tree forked beneath breast height (~1.3 m) each branch was recorded as a separate stem (after English *et al.*, 1997). The location of each field site was determined using a Differential Global Positioning System (DGPS) with a probable circle error of 2–5 m.

**Table 10.2.** A summary of the field survey data. Data were collected in two phases; the first in 1995 for the calibration of CASI imagery and the second in 1996 for accuracy assessment. The number of sites at which each type of data was collected during each phase is shown. Category “Other” refers to field survey data for three non-mangrove categories (sand, saline mud crust, and *Salicornia* species).

Purpose of data	Number of sites surveyed	
	Calibration (1995)	Accuracy (1996)
Species composition (%)	81	121
Tree height	81	121
Tree density	81	121
Canopy transmittance	30	18
Percent canopy closure	39	20
Other	37	67

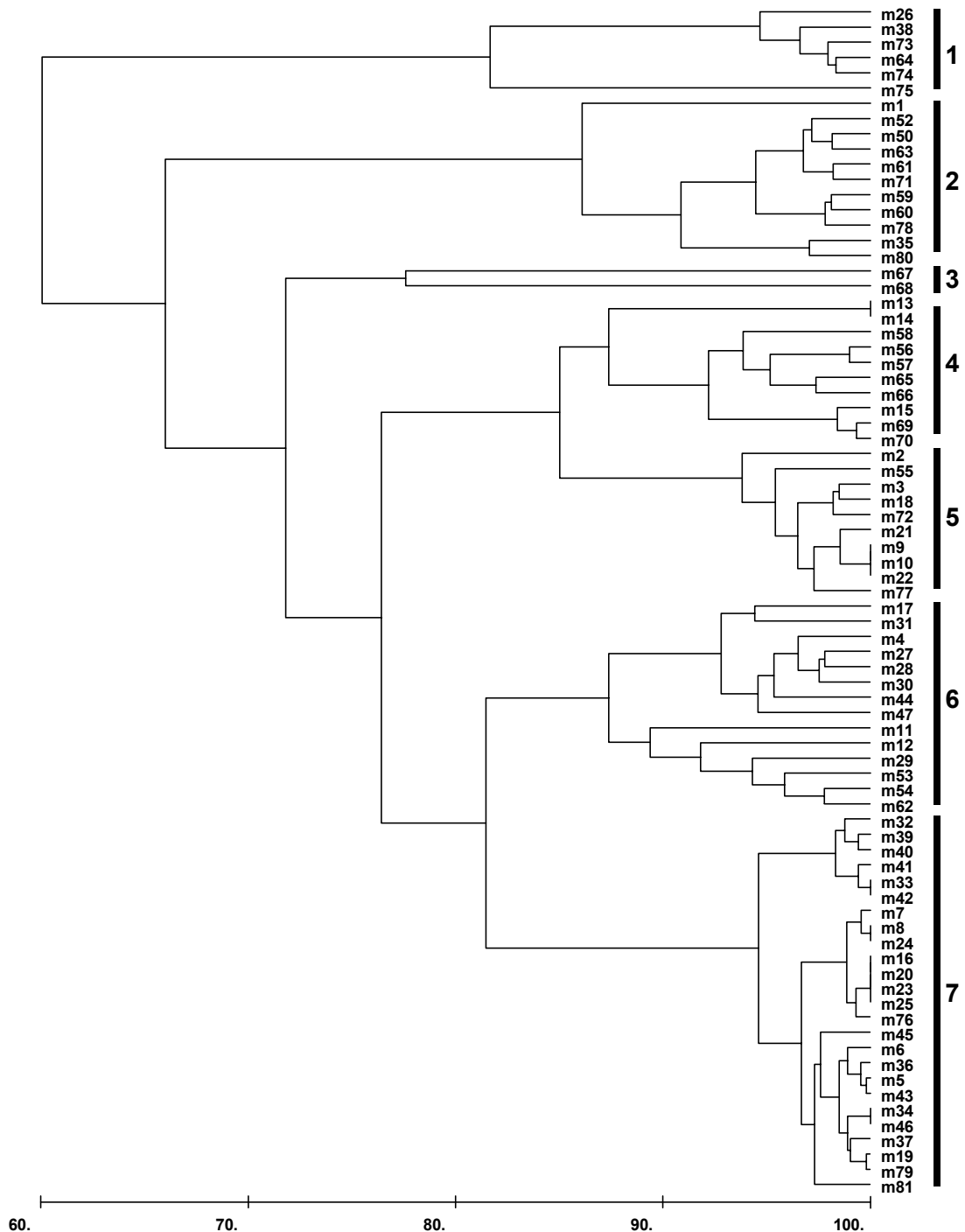
A habitat classification was developed for the mangrove areas of the Turks and Caicos Islands using hierarchical agglomerative clustering with group-average sorting applied to the calibration data. The calibration data were 4<sup>th</sup> root transformed in order to weight the contribution of tree height and density more evenly with species composition (the range of data was an order of magnitude higher for density and height and would cluster accordingly). This identified seven classes, which separated at a Bray-Curtis Similarity of ~85% (Figure 10.1). Categories were described in terms of mean species composition (average percentage of each species), mean tree height and mean tree density (Table 10.3). One category, *Laguncularia* dominated mangrove, was discarded because white mangrove was rare in this area; in both the calibration and accuracy field phases it was observed at only two locations. Three other ground cover types were recorded: (i) sand, (ii) saline mud crust, and (iii) mats of the halophytic succulents *Salicornia perennis* and *S. portulacastrum*. These nine habitat categories (six mangrove, three other) were used to direct the image classification of the CASI data and the collection of accuracy data in 1996.

Two useful ways of describing or modelling the canopy structure of a vegetated area are *leaf area index* (LAI, Box 10.1) and *percent canopy closure*. Both can be estimated from remotely sensed data, which is advantageous in areas where access is particularly difficult or when alternative methods are laborious and difficult to replicate properly over large areas.

### Leaf area index

Many methods are available to measure LAI directly and are variations of either leaf sampling or litter-fall collection techniques. These methods tend to be difficult to carry out in the field, extremely labour intensive, require many replicates to account for spatial variability in the canopy and are thus costly in terms of time and money. Consequently many indirect methods of measuring LAI have been developed (see references in Nel and Wessman, 1993). Among these, are techniques based on gap-fraction analysis that assume that leaf area can be calculated from the *canopy transmittance* (the fraction of direct solar radiation which penetrates the canopy). This approach to estimating LAI uses data collected from beneath the mangrove canopy and was the technique used in this study.

**Figure 10.1.** Dendrogram of 78 mangrove sites using group-average clustering from Bray-Curtis similarities (bottom axis). Seven clusters which are <85% similar were identified. One consisting of sites 67 and 68 was discarded for reasons explained in the text: the other six, were used to direct the supervised classification of the CASI data and an accuracy assessment.



**Table 10.3.** Descriptions for each of the mangrove habitat categories identified in Figure 10.1. N = number of calibration sites in each category.  
Rhiz = *Rhizophora*; Avn = *Avicennia*; Lag = *Laguncularia*; Con = *Conocarpus*.

Habitat Category Description [dendrogram group]	N	Rhiz	Avn	Lag	Con	Tree Height (m) mean (range)	Tree Density (m <sup>-2</sup> ) mean (range)
<i>Conocarpus erectus</i> [1]	6	0	0	0	100	2.4 (1.8–4.5)	0.6 (0.5–1.0)
<i>Avicennia germinans</i> [2]	11	0	100	0	0	2.6 (0.8–6.0)	0.6 (0.2–1.0)
Short, high density, <i>Rhizophora mangle</i> [5]	10	100	0	0	0	1.1 (0.5–2.0)	8.0 (6.0–10.0)
Tall, low density, <i>Rhizophora mangle</i> [7]	25	100	0	0	0	3.7 (2.0–7.0)	0.3 (0.2–0.5)
Short mixed mangrove, high density [4]	10	62	38	0	0	1.7 (0.8–2.5)	8.1 (5.0–15.0)
Tall mixed mangrove, low density [6]	14	56	43	0	1	3.5 (2.0–5.0)	0.6 (0.2–1.2)
<i>Laguncularia</i> dominated mangrove [3]	2	35	5	45	0	3.8 (3.5–4.0)	2.2 (0.5–4.0)
Unclassified	3						

### **Box 10.1. 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 that have been established between it and a range of ecological processes such as rates of photosynthesis, transpiration and evapotranspiration (McNaughton and Jarvis, 1983; Pierce and Running, 1988), and net primary production (Monteith, 1972; Gholz, 1982). 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. 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.

Mangroves are intertidal, often grow in dense stands and have complex aerial root systems that make extensive sampling impractical, with the difficulty of moving through dense mangrove stands and the general inaccessibility of many mangrove areas posing a major logistic problem. Luckily field measurements indicate that there is a linear relationship between mangrove LAI and normalised difference vegetation index (Ramsey and Jensen, 1995; 1996). NDVI can be obtained from remotely sensed data. This means that a relatively modest field survey campaign can be conducted to obtain LAI measurements in more accessible mangrove areas and these used to establish a relationship to NDVI using regression analysis. Once this relationship is known then NDVI values for the remainder of the mangrove areas can be converted to LAI.

### **Measurement of canopy transmittance and calculation of LAI**

LAI is a function of canopy transmittance, the fraction of direct solar radiation that penetrates the canopy. Canopy transmittance is given by the ratio  $I_c/I_o$  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:

$$LAI = \frac{\log_e \left( \frac{I_c}{I_o} \right)}{-k} \times \cos \theta$$

where LAI = leaf area index,  $\theta$  = sun zenith angle (angle between the sun and the horizon; 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 in English *et al.* (1997). For each field site  $\log_e(I_c/I_o)$  was calculated for 80 pairs of simultaneous readings of  $I_c$  and  $I_o$  around the position fix and averaged. A value for  $k$  of 0.525 was chosen as being appropriate to mangrove stands.

Measurements were taken on clear sunny days between 10:00 and 14:00 hours, local time. The solar zenith angle was judged to be sufficiently close to normal (i.e. perpendicular) two hours 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 (PAR) was measured using two MACAM™ SD101Q-Cos  $2\pi$  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 hand-held. 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.

## Lesson Outline

### Creating a Normalized Difference Vegetation Index (NDVI) image

Since NDVI is calculated using near infra-red and red bands there were four options for calculating NDVI from the CASI data with combinations of Bands 5 to 8 (Table 10.4). The relationships between NDVI calculated from Bands 8 and 5 or from Bands 8 and 6, and values of LAI estimated from *in situ* measured canopy transmittance, were not significant. However, there were significant relationships when LAI was regressed against NDVI calculated either from Bands 7 and 6 or 7 and 5 (Table 10.4). NDVI derived from Bands 6 and 7 was deemed most appropriate for the prediction of LAI because (i) it accounts for a much higher proportion of the total variation in the dependent variable, and (ii) the accuracy with which the model predicts the dependence of LAI on NDVI is higher (the standard error of estimate is lower). This is why CASI bands #6 and #7 have been selected for this exercise.

*Activity:* Launch *Bilko* and use **File, Open** to open the 16-bit integer image files **Casi\_mangrove#06.dat** and **Casi\_mangrove#07.dat**. In the **Redisplay Image** dialog box set the **Null value(s):** to zero and initially use an automatic linear stretch for each image. These images show most of the mangroves along the west coast of the southern part of South Caicos Island. Note that the **Casi\_mangrove#06.dat** image in the red part of the spectrum (666.5–673.7 nm) is very dark as mangroves have low reflectances in the red part of the visible spectrum. By contrast, mangroves and other vegetation reflect quite strongly in the near-infrared so that **Casi\_mangrove#07.dat** (recorded in the near-IR at 736.6–752.8 nm) is comparatively bright.

Visually inspect the two images, right-clicking on the images to **Redisplay** them using different stretches, if necessary, to see them more clearly. Note that with a spatial resolution of around 1 m, there is quite a lot of texture visible in the mangrove canopy.

Using both images and the **Edit, Go To** function answer the following question. [*Hint:* you may find it useful to connect the two images as a stacked set.]

*Question:* 10.1. Is the mangrove vegetation thicker and the canopy closure greater at UTM coordinates 236520 E, 2379938 N than at 236600 E, 2379945 N, or is the reverse true? Explain the reasons behind your conclusion. [Both coordinate positions are near the bottom of the image].

**Table 10.4.** Four possible CASI red (Bands 5 and 6) and near-infrared (Bands 7 and 8) band combinations could have been used to calculate NDVI. The results of regressing NDVI, calculated from the four different combinations, on LAI are summarised below.  $R^2$  = coefficient of determination,  $p$  = probability of the F statistic for the model, NS = not significant at the  $p = 0.05$  level of confidence, SE = standard error of the estimate. Degrees of freedom = 1, 29 in all cases. For combinations marked \* the F-test and t-test for the slope estimate were both significant at the 0.001 level of confidence, indicating that they may used to convert NDVI values to LAI.

NDVI equation	$R^2$	Intercept	Slope	p	SE
(Band 8 - Band 5)/(Band 8 + Band 5)	0.22	0.19	0.05	NS	1.93
(Band 8 - Band 6)/(Band 8 + Band 6)	0.12	3.68	2.29	NS	2.18
<b>(Band 7 - Band 6)/(Band 7 + Band 6)*</b>	<b>0.77</b>	<b>0.31</b>	<b>9.76</b>	<b>&lt;0.001</b>	<b>0.99</b>
(Band 7 - Band 5)/(Band 7 + Band 5)*	0.43	1.81	5.71	<0.001	1.69

The next step is to calculate a Normalised Difference Vegetation Index (NDVI) image (Box 10.2) from the CASI bands #6 and #7. In a real life situation you would need to check all possible band-pair combinations and see which was best for predicting LAI. We have done this for you, and you will just work with the band pair that we found to give best results.

**Box 10.2 The use of vegetation indices in the remote sensing of mangroves**

Vegetation indices are complex ratios involving mathematical transformations of spectral bands. As such, vegetation indices transform the information from two or more bands into a single index. For example, the normalised difference vegetation index or NDVI is a common vegetation index calculated from red and infra-red bands. For each pixel in the two wavebands the following is calculated:

$$\text{NDVI} = \frac{\text{infrared} - \text{red}}{\text{infrared} + \text{red}}$$

Since dense vegetation reflects strongly in the near-IR and reflects poorly in the red part of the electromagnetic spectrum, the NDVI can approach a value of 1 in areas of dense vegetation. By contrast areas with little or no vegetation will have similar reflectances in the near-IR and red part of the spectrum or in some cases lower reflectances in the near-IR than red, giving NDVI values approaching 0 or even negative values (with theoretical lower limit of -1).

*Activity:* **Connect** the **Casi\_mangrove#06.dat** and **Casi\_mangrove#07.dat** images as a tiled pair and use the **Selector** toolbar to make sure **Casi\_mangrove#07.dat** (the infra-red image) is image 1 (@1 in a Formula document) whilst **Casi\_mangrove#06.dat** is image 2 (@2 in a formula).

You will now write a simple Formula document to calculate the NDVI for each pixel; this will help you understand better what is being calculated (see Box 10.2). This should be of the form of the equation in Box 10.2. Thus our Formula document equation should look something like this:

$$(@1 - @2) / (@1 + @2) ;$$

*Activity:* Prepare a Formula document to carry out the NDVI. [Ideally, follow best-practice as taught in Tutorial 10 of the *Introduction to using the Bilko 3 image processing software* and use constant statements and comments to make a generic NDVI formula which you can save and easily modify for use with other images.] Since the resultant image will display NDVI on a scale of -1 to +1, use the Formula document **Options!** to select the **Output Image Type:** as 32-bit floating point then **Copy** and **Paste** the formula to the connected images. [You do not need to use special handling for nulls as they are zero on both images.]

*Checkpoint:* If the value of the pixel at coordinate 236395E, 2381050N is 0.810328 then your formula has worked. If it is not, check the formula and re-read the instructions carefully. [To display the UTM coordinates of the cursor on the status bar use the **View, Coords** function.]

To establish a regression relationship that will allow Leaf Area Index (LAI) to be predicted from NDVI, we have noted the NDVI corresponding to 30 ground-truthed points where we have measured LAI in the field. This is done by averaging the NDVI of the nearest nine pixels to the UTM coordinates of the ground-truthing site. The average NDVI is considered to correspond to the recorded LAI. Thus each NDVI value is averaged across a 3.0 m x 3.3 m square on the ground-surface. This allows for some error in the UTM coordinates obtained from the Differential GPS (probable circle error of 2–5 m) during the ground-truthing surveys and corresponds to the approximate area surveyed



as the 80 readings were taken at each site (see section on *Measurement of canopy transmittance and calculation of LAI* above).

The results of this calibration exercise are summarised in Table 10.6 below but the calculation of average NDVI for two sites has been left for you to do. Site 72 has short sparse mangrove and thus a relatively low LAI, whereas site 79 is on the edge of a reasonably dense stand of mangrove and has a much higher LAI. Both sites are towards the south-east of the image.

*Activity:* Save the NDVI image as **Mangrove\_NDVI.dat** and, if you have followed best-practice and created a generic NDVI formula, you may wish to save this as **NDVI.frm**. If UTM coordinates are not displayed on the status bar, select the **View, Coords** command to display them. Scroll to the bottom of the image, which is where the two calibration sites are located. You now need to use **Edit, Go To** to locate site 72 on the image and once you have done this you need to read off (from the status bar) the data values at the coordinates (central pixel) and the eight surrounding pixels and enter these in Table 10.5 below. The central pixel at site 72 should have the value 0.1967 (to 4 decimal places). [*Hint:* Hold down the <Ctrl> key and use the arrow keys to move one pixel at a time.]

**Table 10.5.** Calculating average NDVI for two ground-truthing sites.

[Round values to **4 decimal places**].

<b>Site 72</b>	<b>Site 79</b>
Central pixel: X: 236700, Y: 2379827	Central pixel: X: 236693, Y: 2380127

*Activity:* Use a calculator (or spreadsheet) to work out the average NDVI for sites 72 and 79 and answer the question below.

*Question:* 10.2. What are the average NDVIs at sites 72 and 79 (to **four decimal places**)?

*Activity:* Enter the values (to **two decimal places**) in Table 8.6 (see next page). Congratulations! You now have a complete set of data to calculate the regression relationship between LAI and NDVI.

**Table 10.6.** Calibration data for regression of LAI on NDVI (calculated for CASI bands #7 and #6).

Site	UTM coordinates		NDVI CASI 7/6	Mangrove LAI
	Easting	Northing		
31	237118	2378993	0.70	6.61
33	237105	2378990	0.75	7.32
34	237094	2378986	0.81	8.79
36	237114	2379026	0.63	6.62
37	237103	2379022	0.78	7.83
39	237087	2379071	0.79	6.17
40	237092	2379075	0.73	6.87
43	237115	2379080	0.69	6.96
44	237070	2379373	0.47	2.53
47	237038	2379376	0.75	6.61
52	237026	2379456	0.28	2.52
53	237005	2379491	0.64	5.04
54	236989	2379500	0.63	5.35
56	237008	2379445	0.61	4.76
59	237020	2379567	0.29	2.33
61	236997	2379540	0.42	4.34
62	236978	2379547	0.47	4.96
64	236932	2379588	0.24	1.93
65	236890	2379549	0.47	5.82
66	236872	2379554	0.42	3.74
67	236759	2379649	0.49	6.58
68	236731	2379664	0.43	3.89
71	236718	2379777	0.59	5.59
<b>72</b>	<b>236700</b>	<b>2379827</b>		<b>1.64</b>
73	236723	2379825	0.29	2.33
75	236668	2379932	0.19	1.99
78	236579	2380039	0.35	2.03
<b>79</b>	<b>236693</b>	<b>2380127</b>		<b>5.83</b>
80	236703	2380141	0.61	2.95
81	236728	2380128	0.47	5.05

### Regression of LAI on NDVI

You now need to carry out the regression of Leaf Area Index on NDVI to allow you to map LAI from the CASI imagery. Luckily there is a simple linear relationship between LAI and NDVI defined by the regression equation:

$$\text{LAI} = \text{intercept} + \text{slope} \times \text{NDVI}$$

*Activity:* Open the *Excel* spreadsheet file **Mangrove\_NDVI.xls**. Insert your NDVI values for sites 72 and 79. Examine the graph of LAI against NDVI and note that LAI is roughly ten times NDVI. Use **Tools, Data Analysis** to regress the column of LAI values (Input Y Range:) against the column of NDVI7/6 values (Input X Range:). For the Output Range: just select a cell below the calibration dataset. Note that the regression is very significant, i.e. that NDVI is a good predictor of Leaf Area Index. You only need two pieces of information from the output of the regression analysis, the slope of the regression line and where it intercepts the y-axis. The **intercept** (which should be a small negative number) is labelled as such, whilst the value for the **slope** of the line is labelled “X Variable” in the regression output.

Two alternative approaches are (1) to copy and paste the numerical values for LAI and corresponding NDVI (in columns D and E, rows 3 to 32) into *Minitab* and carry out the regression there, or (2) to right-click on a data point in the graph of LAI against NDVI and select **Add Trendline**; in the **Add Trendline** dialog box select Linear (default) as the trendline type, then click on the **Options** tab and select the **Display equation on chart** checkbox before clicking on OK. Both approaches will give you the slope and intercept of the regression equation.

*Question:* 10.3. What is the intercept and slope of the regression of LAI on NDVI (to 4 decimal places)?

Knowing the relationship between NDVI on the image and LAI measured in the field we can now make an 8-bit (byte) image of Leaf Area Index by applying a Formula document to convert NDVI to LAI. From the graph of LAI against NDVI we know that the maximum LAI we will find is about 10. To spread our LAI measure over more of the display scale (0–255) whilst making it easy to convert pixel values to LAI we can multiply by 10. This means that LAI values up to 2 will map to pixel values between 1 and 20, and so on (see table to right). Thus a pixel value of 56 in the output image will indicate an LAI of 5.6.

LAI range	Pixel values
< 2	1–20
2-4	21–40
4-6	41–60
6-8	61–80
> 8	81–100

The Formula document will thus need to be something like this:

$$(\text{intercept} + \text{slope} * @x) * 10 ;$$

where you substitute the values you obtained in the regression analysis for the *intercept* and *slope* and @x is the NDVI image.

*Activity:* Use **File, New** to open a new Formula document and enter a formula (see above for a model) to carry out the conversion of NDVI to LAI (use constant statements as appropriate to set up input values and make the formula easy to understand). Use the Formula document **Options!** to make sure the output image is an 8-bit unsigned integer and then **Copy** the formula and **Paste** it to the *Mangrove\_NDVI.dat* image you saved earlier. The resultant image will be dark because the highest pixel value is only 100. To see the distribution of mangrove with different levels of LAI, open the Palette document *Leaf\_Area\_Index.pal* whilst the LAI image is the active document. The palette will be automatically applied to the image [assuming **Apply** is checked in the **Open** dialog box] and displays each of the five ranges of LAI in a different shade of green to green-brown. Note that mangrove areas with a Leaf Area Index greater than 8 are very rare.

*Checkpoint:* Note the value of the pixel at *x, y* (column, row) coordinate 324, 1167 in the *Mangrove\_NDVI.dat* image. It should be 0.8333. Use a calculator to work out what its LAI value should be using your equation. It should be 7.8 and thus the pixel value at 324, 1167 on the LAI image should be 78. If it isn't something has gone wrong.

The next stage is to assess the status of the mangroves in the image area. Firstly, you will calculate what proportion of the mangrove area consists of each LAI class. The easiest way to do this is to use *Bilko*'s histogram capabilities. [*Note:* If you originally set the **Null value(s)**: to zero, this should have carried through and the histogram will ignore these values; if you didn't, then you will need to set the null value as zero.]

*Activity:* Check that background pixels (black) of the LAI image are set as null (they will display a “?” in the value panel on the status bar). If they are not, right-click on the image and

use the **Redisplay** option to set zero as the null value. This will mess up the display so, after closing the dialog box, select **Stretch, Clear** to restore the display).

Select all of the image and use **File, New** to bring up a histogram showing the frequencies of pixel values. Position the mouse pointer at 100 on the *x*-axis and holding down the left mouse button drag it until it is over 81. The status bar should indicate that 0.09% of the mangrove pixels are highlighted. Non-mangrove pixels are null and thus ignored. Note the number of pixels and percentage of mangrove pixels between 81 and 100 and record these in Table 10.7 below. Repeat for pixel values of 80 to 61, 60 to 41, 40 to 21 and 20 to 1. Make sure the percentages add up to 100. Now note the total number of mangrove pixels.

From the histogram header one can see that the image is 500 pixels wide and 1325 pixels long. Enter the total number of pixels in the image in Table 10.7. Knowing that each pixel is 1.0 m wide and 1.1 m long, calculate the area of the whole image in hectares (1 ha = 100 x 100 m = 10,000 m<sup>2</sup>). Complete Table 10.7 with all areas recorded in hectares to two decimal places, then answer the questions below.

*Question:* 10.4. What percentage of the image area is mangrove?

*Question:* 10.5. What is the area of the whole image in hectares (to the nearest hectare)?

*Question:* 10.6. What is the total area of mangrove in hectares (to the nearest hectare)?

*Question:* 10.7. How many hectares of mangrove have an LAI > 6 and what proportion of the total mangrove area does this represent?

**Table 10.7.** Analysing the image regarding the status of the mangroves. Record % mangrove pixels and area in hectares to **two decimal places**.

LAI range	Pixel values	Number of pixels	% mangrove pixels	Area (hectares)
< 2	1–20			
2–4	21–40			
4–6	41–60			
6–8	61–80			
> 8	81–100		0.09	
Mangrove total				
Image total				

### Estimation of net canopy photosynthetic production (P<sub>N</sub>)

The approximate net photosynthetic production of the whole mangrove canopy per m<sup>2</sup> of ground area over a day can be described by the following equation:

$$P_N = A \times d \times LAI$$

where A = average rate of photosynthesis (g-C m<sup>-2</sup> leaf area hr<sup>-1</sup>) for all leaves in the canopy, d = daylength (hr), and LAI is the leaf area index already estimated for each pixel (English *et al.* 1997). For mangroves in high soil salinities in the dry season a reasonable estimate for A = 0.216 g-C m<sup>-2</sup> hr<sup>-1</sup> and daylength in the Turks and Caicos is on average about 12 hours. Using this relationship we can make a rough estimate of the net photosynthetic production in each LAI class, indeed, if one had good field data on the average rate of photosynthesis (A) one might in theory make an image where pixel values related to P<sub>N</sub>. For the purpose of this lesson we are just going to make a crude estimate of the

number of tonnes of carbon fixed per hectare each year ( $\text{t-C ha}^{-1} \text{ year}^{-1}$ ) by the mangrove area with an LAI of 6–8.

*Activity:* Let the average LAI of the mangrove area with an LAI of 6–8 be 7. Using the equation estimate the daily net photosynthetic production per  $\text{m}^2$  (in  $\text{g-C m}^{-2}$ ). Convert this to  $\text{t-C ha}^{-1} \text{ year}^{-1}$ . Use your value for the area occupied by mangrove with LAI 6–8 to estimate how many tonnes of carbon are fixed per year by the these mangroves.

*Question:* 10.8. What do you estimate the daily net photosynthetic production of the mangroves with LAI 6–8 in  $\text{g-C m}^{-2}$ ? What is this as an annual production in units of  $\text{t-C ha}^{-1} \text{ year}^{-1}$ ? [Show your working].

*Question:* 10.9. How many tonnes of carbon are fixed per year by the mangroves with LAI 6–8 in the area of the image? [Give your answer to nearest whole tonne C.]

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