Monitoring forest canopy condition by remote sensing

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CONTENTS

Abstract

This study examines the effects that variations in directional reflectance, illumination, topography and forest species have on the accuracy of remotely sensed data used for assessing forest canopy defoliation. Methods are given for correcting or minimising these variations, and bounds are placed on the errors that remain once these methods are applied. Using these methods, data acquired from airborne sensors should provide ratings of percentage canopy cover that are accurate to within 20%. However, relationships between remotely sensed data and absolute values of canopy cover are generally specific to a forest species, and so obtaining absolute defoliation ratings will be difficult for mixed-species forests. Detection of *change* in percentage canopy cover over time is simpler to assess than the absolute value of canopy cover, and changes of 15% should be detectable irrespective of forest species. Examination of remotely sensed data for a wider range of forest species than studied in this report will be required to confirm these findings. Other parameters that can be readily obtained using remotely sensed data include the area of dead canopy, and the density of conifers (for some conifer types, such as Hall's totara—*Podocarpus cunninghamii* or kaikawaka—*Libocedrus bidwillii*). These parameters can be determined to at least 90% accuracy using data from airborne sensors. Data from satellites will not become useful for rating canopy parameters, including defoliation, until the pixel spatial resolution approaches that of data from airborne sensors: better than about three metres. This is because defoliation in forest is very localised, and larger pixel sizes will almost always cover a combination of defoliated and undamaged forest. The resultant spatial averaging that occurs with larger pixel sizes will substantially reduce the apparent severity of defoliation levels that are recorded.

1. Introduction

The Introduction (Section 1), and Summary and conclusions (Section 6), are written to stand largely independent of the rest of the report. Together, they provide the reader with a good overview of the current status and limitations of determining forest canopy defoliation by remote sensing. The remainder of the report covers in detail some of the more complex issues currently associated with remote sensing of forest canopies. The development and support of meaningful conclusions means that much of this complexity has had to be retained in discussions within the body of the report. This information will be of most relevance to those readers wanting more detail on the technical aspects of remote sensing and accurate data acquisition.

1.1 CANOPY DEFOLIATION AND THE VEGETATION INDEX

Remote sensing is used routinely to quantify forest disease, insect damage, and defoliation in the conifer forests of North America and Europe (e.g., Carter *et al.* 1996, Ekstrand 1996, Lambert *et al.* 1995, and references therein). The basis of the technique is the good correlation that exists between various ratios of red and near-infrared light, and canopy leaf biomass. Such ratios are commonly referred to as vegetation indices. The two most common ratios are (Tucker 1979, Curran 1980):

1. The simple vegetation index: VI = R/IR
2. The normalised difference vegetation index: NDVI = (IR—R)/(IR + R)

   where: R ... red reflectance

   IR .. near-infrared reflectance

In New Zealand, the simplest way of obtaining quantitative data on the red and near-infrared reflectance of forest canopies is to use digitised colour-infrared (CIR) photography. CIR photos record green, red and near-infrared light on film as blue, green and red colour, respectively. Because healthy vegetation reflects green light (about 10% of that incoming), absorbs most red light for photosynthesis, and reflects a very large amount of near-infrared light (about 50% of incoming), such vegetation appears as darker red tones in a CIR print (see Fig. 1). Conversely, dead vegetation reflects all wavelengths of light about equally, and results in grey tones. Colour tonality that is between dark red and grey in a CIR image can therefore be interpreted **qualitatively** as the degree of canopy defoliation.

Quantitative assessment of forest canopy condition can be achieved using vegetation index data that have been calibrated against ground-based measurements of defoliation (percentage canopy cover). However, it is important to note that the relationship between vegetation indices and canopy defoliation depends on the conditions under which remotely sensed data are acquired. The relationship may also vary with vegetation type. Dependence on these conditions must be removed before routine monitoring of canopy condition by remote sensing can occur.

Figure 1. A typical colour-infrared (CIR) scene, showing forest in darker red tones and pasture in the lightest red tones. Blue/grey tones are dead vegetation. Olive green tones are rimu (Dacrydium cupressinum).

1.2 ASSESSING CANOPY CONDITION USING REMOTE SENSING: A NEW ZEALAND EXAMPLE

A study to determine the feasibility of assessing possum damage to indigenous forests from remotely sensed data was undertaken for DOC in 1992 (Investigation Number: 730). Vegetation indices were calculated from digitised large-format CIR aerial photographs, at five sites, for over 100 pohutukawa *(Metrosideros excelsa)* trees on Rangitoto Island. The relationship between the NDVI (or the simple VI) and the canopy percentage leaf cover rating was on average linear and well-correlated (rz>0.67 for linear-linear plots, and >_0.75 for log-linear plots, Trotter 1992a), as shown for one site in Fig. 2 (next page). The study also showed that the relationship between NDVI and percentage cover exhibited some variation between sites, due probably to variations in nutrient availability.

The study indicated that use of CIR imagery for routine monitoring of forest canopy condition, and for producing defoliation-severity maps, would require further investigation and development in three key areas:

- Techniques need to be developed to minimise the effect of intra- and inter-photo variation due to illumination and photographic processing
- The effect of topography and view-angle on the vegetation index needs to be assessed
- The effect of species variation on the relationship between defoliation and the vegetation index needs to be established.

These three areas of investigation form the framework for this study.

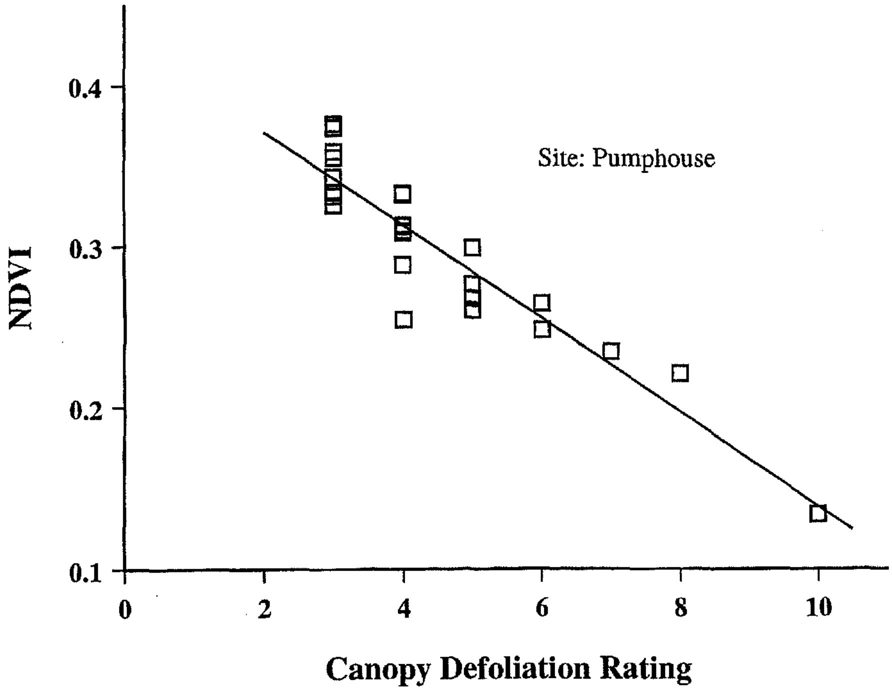

Figure 2. Plot of canopy defoliation cover rating versus the NDVI for pohutukawa (Metrosideros excelsa) forest on Rangitoto island. Ratings of 1 to 10 correspond to percentage leaf covers of 95% to 5%.

2. Objectives

The experimental site was changed during the course of the study, from northern Coromandel to the central North Island, because of difficulties in obtaining photography. The emphasis in the study was also changed (McColl pers. comm.), to reflect initial results indicating that variation in tree species induces much larger errors in estimated defoliation levels than does the effect of topography.

The final objectives for the study were to:

- Develop empirical techniques for radiometrically correcting aerial photographs, to allow vegetation index information derived from individual photos to be mosaiced into maps covering large areas. Exposure/processing/printing variations, hot-spot, and lens fall-off effects are to be investigated, and the accuracy of the corrective techniques evaluated, using existing aerial photography (of Rangitoto Island).
- Define the limits imposed by topographic variation on the accuracy of vegetation indices, in areas with slopes up to 20°.
- Establish the effect of species variation on the vegetation-index/defoliation relationship, using new photography of central North Island forests.
- Provide a vegetation condition map from aerial photography, for two areas of the central North Island forest showing significant species variation. An example of vegetation condition data derived from a satellite image is also to be provided for the same areas.

3. Radiometric correction

3.1 CORRECTION OF EXPOSURE/PROCESSING/PRINTING VARIATIONS IN SINGLE-FILM SURVEYS

When photos are acquired using the same film batch and printed under the same conditions, the ratios of red/near-infrared band data that form vegetation indices should usually compensate for small variations in incoming illumination and/or processing variations. The photos also need to be acquired under skies that are sufficiently clear to minimise variation in incident illumination. This means that shutter speeds remain constant, and the response of the film should remain linear with any minor changes in illumination. Data taken from six digitised CIR photos from the Rangitoto Island study illustrate this point (Table 1). The data show that variations in the exposure/processing/printing sequence are reduced by up to a factor of 10 when band-ratioed vegetation indices (NDVI, and VI) are calculated.

TABLE 1. AVERAGE VALUES OF RED AND NEAR-INFRARED DATA, AND THE CORRESPONDING AVERAGE VI AND NDVI VALUES, EXTRACTED FROM SIX PHOTOS FOR HEALTHY VEGETATION ONLY.

DATA FROM DIGITISED PHOTOS				
	NEAR-INFRARED	RED	VI	NDVI
Data range	145–164	78.0–87.3	0.538–0.532	0.300–0.305
Variation	±6.1%	±5.6%	±0.6%	±0.8%

3.2 CORRECTION OF EXPOSURE/PROCESSING/PRINTING VARIATIONS IN LARGE SURVEYS

When more than one film batch is used, or for surveys repeated over time, a more rigorous approach to correction of exposure/processing/printing variations is required. This is because CIR films show a much wider range of variation in their characteristics than do ordinary colour films. Each film batch is essentially unique in terms of its colour balance and sensitivity. In addition, the film is quite temperature sensitive, and has a relatively short shelf life. These factors exacerbate the normal variations that can be expected from exposure under variable illumination conditions, and are in addition to the variations that arise during the temperature and time-sensitive process of developing and contact printing the film. To eliminate these errors, calibration of all processing steps, and all film batches, is required.

Three calibration steps should be adopted for each film batch if repeatable data are to be obtained from CIR photographs:

- A standardised grey-scale wedge must be exposed onto the film to define its light sensitivity and response. This is available as a commercial service from aerial photographic processors.
- Record film exposure times and incoming illumination intensity at the time of exposure, a step easily implemented by aircraft operators.
- Use the step-wedge brightness and exposure/illumination information to normalise the brightness levels on a photograph to a standard scale.

The last step is performed in an image processing system after the printed photographs (which include the image of the step-wedge) are digitised. It ensures that for all prints, black on the standard step-wedge corresponds to a digital image value of zero, and white to a value of 255. The calibration sequence assumes that aerial operators take steps to ensure that the film is exposed under temperature conditions similar to those at which it was calibrated.

3.3 DIGITAL SENSORS AS ALTERNATIVES TO PHOTOGRAPHIC FILM

An alternative to using CIR film is to use a digital camera. This is strongly recommended for consideration in future surveys. Medium-format CIR digital cameras are becoming available, and need only be calibrated on perhaps a yearly basis (Dymond and Trotter 1997). However, digital cameras must be selected with care if they are to provide quantitative, repeatable data with good dynamic range. Video cameras cannot be recommended, as they offer few advantages over film in terms of dynamic range and accuracy. As with CIR film, operators should take steps to ensure that digital cameras are used at temperatures similar to those at which they were calibrated. An alternative is to use a more expensive, temperature controlled camera. Operators of any camera used for quantitative aerial survey should provide evidence that their systems have been calibrated and used under appropriate conditions.

3.4 CORRECTION OF LENS FALL-OFF

If a camera is pointed at a target of constant brightness, the image will be brighter in the middle than at the edges, an effect known as lens fall-off. This effect is most severe when using wide-angle lenses. Lens fall-off is wavelength dependent, and so may not be completely compensated by ratioing the light intensity recorded at two wavelengths (as occurs in forming vegetation indices). Although lens fall-off can be characterised using a uniformly bright target, such targets are difficult to make. Calibration is therefore a specialised task, and may need to be carried out in an optical laboratory (Dymond and Trotter 1997). Most lenses currently used for aerial survey are not calibrated for lens fall-off. Empirical corrections can be developed (see section 3.5), although there is no substitute for direct calibration if a lens is to be used routinely in quantitative aerial survey.

3.5 AN EMPIRICAL CORRECTION FOR DIRECTIONAL REFLECTANCE AND LENS FALL-OFF EFFECTS

Vegetation does not scatter light equally in all directions (see Fig. 3). More light is scattered back towards the sun than is scattered in other directions, and the shape of the scattering function is also dependent on vegetation type and wavelength (e.g., Kimes *et al.* 1986, Ranson *et al.* 1986). The point of maximum back-scattering in any image occurs when the sun is directly behind the observer, because no shadows are visible from this view. This bright point is known as the hotspot. It can be a problem in quantitative aerial photography, as the amount of light coming from the hotspot and the surrounding area may over-expose the film, resulting in loss of information. Because scattering of light is wavelength dependent, the ratios of data at the two wavelengths used to form vegetation indices do not necessarily compensate for directional scattering.

Because simple, generalised analytical models of directional reflectance do not yet exist, we have developed an empirical correction method as part of this work. The method provides a combined correction for directional reflectance and lens fall-off effects. The basis of the method is that provided a photo covers a uniform target, the variation in the brightness within the photo would represent the combined reflectance/fall-off function. Although real vegetation canopies are not uniform, we can obtain an approximation to this reflectance/fall-off function by averaging the brightness levels from a number of photos from within a given photo run. The resultant averaged reflectance/fall-off image can then be used to normalise any individual photo for variations in directional reflectance and lens fall-off. This method is evaluated below (sections 5.6.2, 5.6.3). It assumes that the directional reflectance properties of different forest canopy types are similar. This

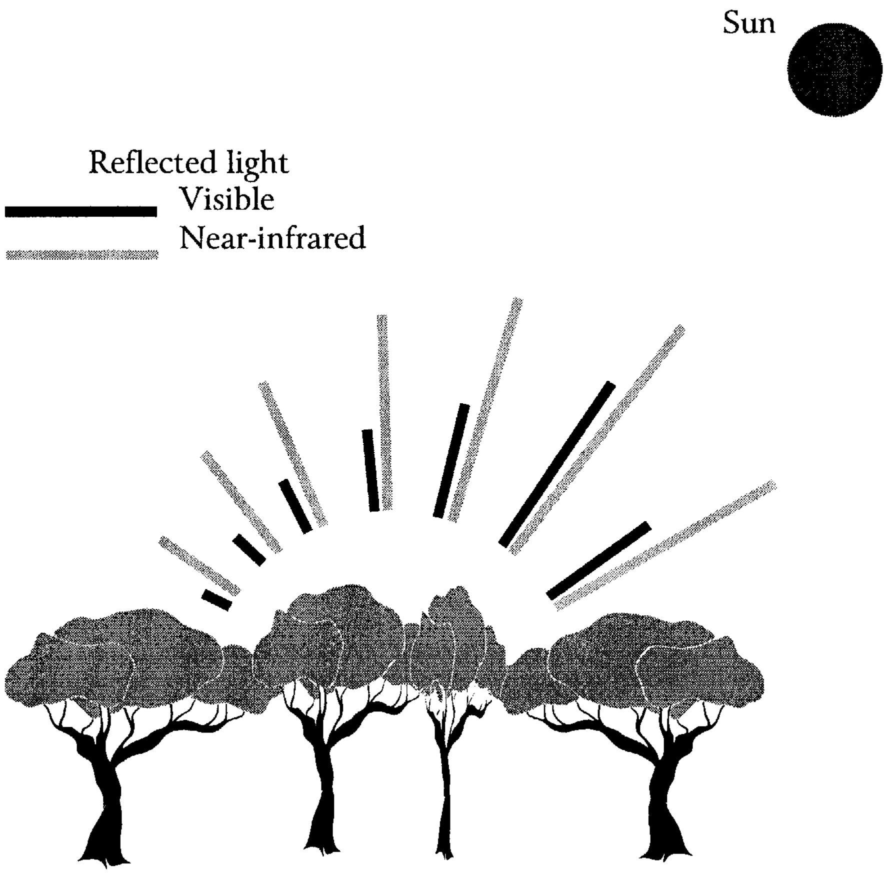

Figure 3. Schematic of light scattering from vegetation. The length of the bars for each wavelength represents the relative amount of light scatted in different directions. More light is scattered back towards the sun than away from it at all wavelengths, and visible light shows a more asymmetric directional scattering function than does near-infrared light.

is expected to be a good approximation for limited view angles and higher sun elevations.

3.6 AN EXAMPLE OF RADIOMETRIC CORRECTION USING THE RANGITOTO DATASET

3.6.1. Formation of the radiometric correction function

The photographic record used here of Rangitoto Island comprises 16 photos acquired on 14 December 1991, at about 3:15 p.m. This corresponds to a sun elevation of 60°, at an azimuth of 290°. The camera lens had a 12″ focal length, giving a relatively narrow field of view of approximately ±22°. The hotspot falls outside the area imaged by the photographs under these imaging conditions since the maximum view-angle is less than the sun zenith angle, although variation in forward/backward scattering is still visible as an asymmetric variation in average brightness within a given photo.

The photos were scanned, and areas with directional reflectance functions grossly different from trees were masked out (i.e., water, grass, and exposed lava). Trees with less than approximately 50% foliage were also masked out, to avoid any chance that lava, visible through sparse foliage, might influence the results. Masked areas were assigned a brightness value of zero and excluded from further analysis. Brightness values in the green, red and near-infrared bands were then averaged using a model constructed using the ERDAS Spatial Modeller. The noise present at the individual pixel level in the brightness-averaged images was considerable, and was not significantly reduced by even a 7 by 7 modal filter with values of zero omitted. The image was therefore broken up into a 10 by 10 array, with an average brightness calculated for each cell of the array.

The averaged brightness image, representing the combined directional reflectance and lens fall-off function (DRLF) for the individual red and near-infrared bands, is shown in Fig. 4. Variations of up to 35% occur in the average brightness of the red band, from the hotspot out to the edges of the image. Variation in the infrared band is slightly smaller, at a maximum 30%, and the image has a significantly larger central area with lower brightness variation than the red band. This is expected because of the more symmetric directional scattering of near-infrared light. The averaged VI and NDVI images show the residual error in these indices resulting from directional reflectance and lens fall-off effects (see Fig. 5). The calculation of vegetation indices as band ratios clearly reduces the error imposed by directional scattering and lens fall-off effects, but does not remove it completely.

If directional reflectance and lens fall-off effects are not corrected, a maximum error in the VI of 12% will occur, or 18% if using the NDVI (Fig. 5). However, this error can be reduced to about 6% for the VI, and 9% for the NDVI, if the outer areas of the photo frame associated primarily with lens fall-off effects are neglected (see Fig. 5). As it is expected that lens fall-off effects would be independently corrected by lens calibration for any system used routinely for acquisition of CIR data in surveys of canopy condition, it is the lower error figures that are of most importance.

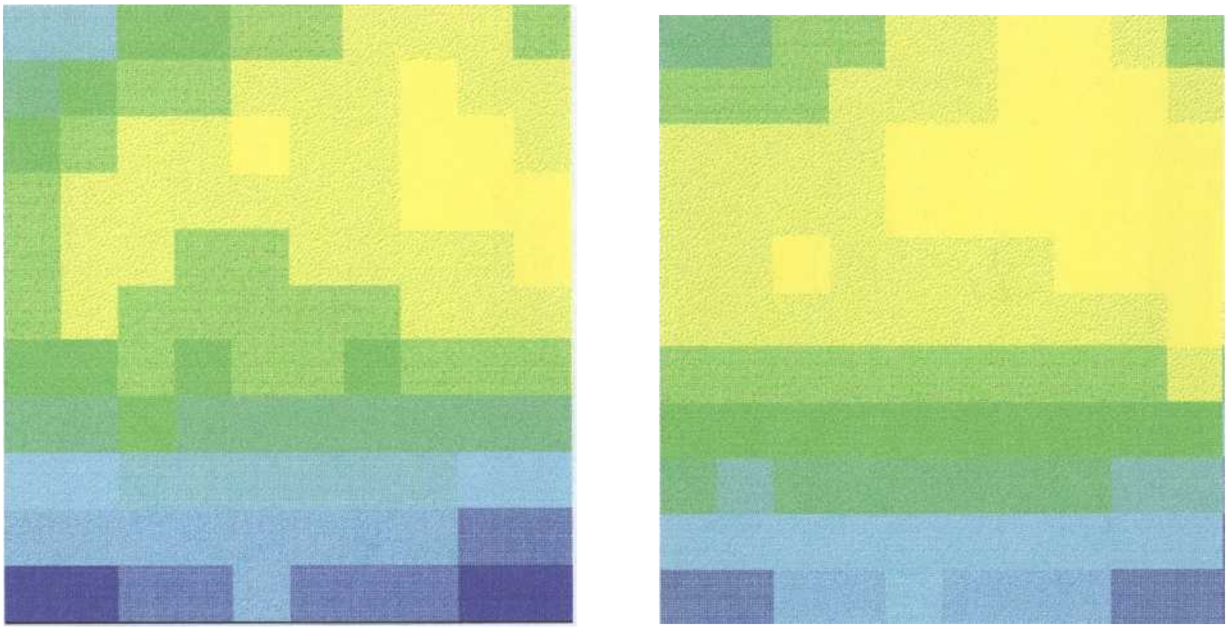

Figure 4. The combined directional reflectance and lens fall-off function (DRLF) for the individual red (left) and near-infrared (right) bands, expressed as average values over a 10 by 10 array covering an image. Each colour step from yellow to dark blue represents a 5% change in the red or infrared data. Variations of up to 35% therefore occur in the red band data.

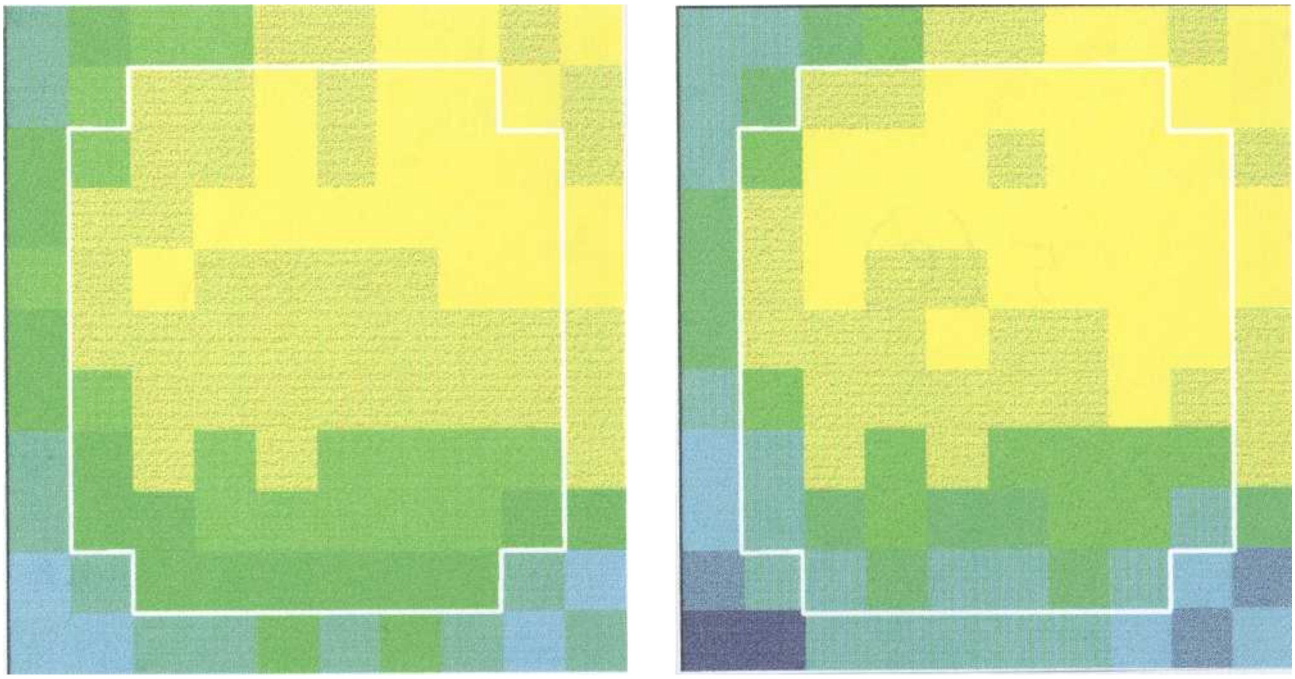

Figure 5. Error in the VI (left) and NDVI (right) that results from using uncorrected red and near-infrared data. Each colour step from yellow to dark blue represents a 2% error. The lens fall-off effect (rather than directional scattering effects) dominates outside the white lines on the images.

3.6.2 Sensitivity of the radiometric correction to formulation conditions

Calculations were performed to determine whether the DRLF was sensitive to the number of photos it was formed from, and whether it was influenced by directional illumination/reflectance effects associated with topography. The DRLF was first calculated under the restriction that the average brightness within an array cell was determined from only those pixels which were contributed to by data from eight or more photos. This was done in an attempt to reduce noise by first averaging the data at the pixel level, before the additional averaging at the cell level. This condition was then relaxed to allow cell averages to be formed from pixels contributed to by four or more photos. No significant differences were found between the DRLFs formed under these two conditions. The effect of topography was evaluated by calculating the DRLF function from only the three photo frames in which the central peak of Rangitoto appeared as a dominant feature. No significant differences were found between this function and that formed from all photos except those covering the peak. This is not a rigorous test of the effect of topography, as slopes on the Rangitoto peak are relatively gentle (<15°). It is nonetheless an encouraging result, and suggests that topographic effects may be averaged out during formulation of the DRLF, even when the DRLF is formed from small numbers of photos.

3.6.3 Accuracy of the radiometric correction

The empirically derived DRLF was used to correct vegetation index data derived from the Rangitoto photography. Six photos containing some common areas appearing in quite different parts of each photo were corrected using the DRLF, and the average vegetation index of each of the areas compared. Fig. 6 shows the approximate location of the areas within a single photo, and the spatial relationship between the group of photos. Table 2 details the variation in the average VI of each area, for the corrected and uncorrected photos. It is clear that the correction made using the DRLF function worked well: differences in the vegetation indices of uncorrected photos are significantly reduced where differences are large, and not made worse where differences are small. The simple VI gives the best performance, both for the corrected and uncorrected data.

3.7 RADIOMETRIC CORRECTION FOR THE HIHITAHI STUDY

A single transect of CIR photography (eight photos) of the Hihitahi area was obtained on 15 February 1994, at 12:10 p.m. This corresponds to a sun elevation of 56°, at an azimuth of 37°. The camera lens used had a 6” focal length, giving a field of view of approximately ±45°. This was a considerably wider field of view than requested, but the opportunity to re-fly the area did not eventuate. The hotspot occurred close to the edge of the photo frame for these wide-angle photos. We note, as it will become important later, that the photos covered a

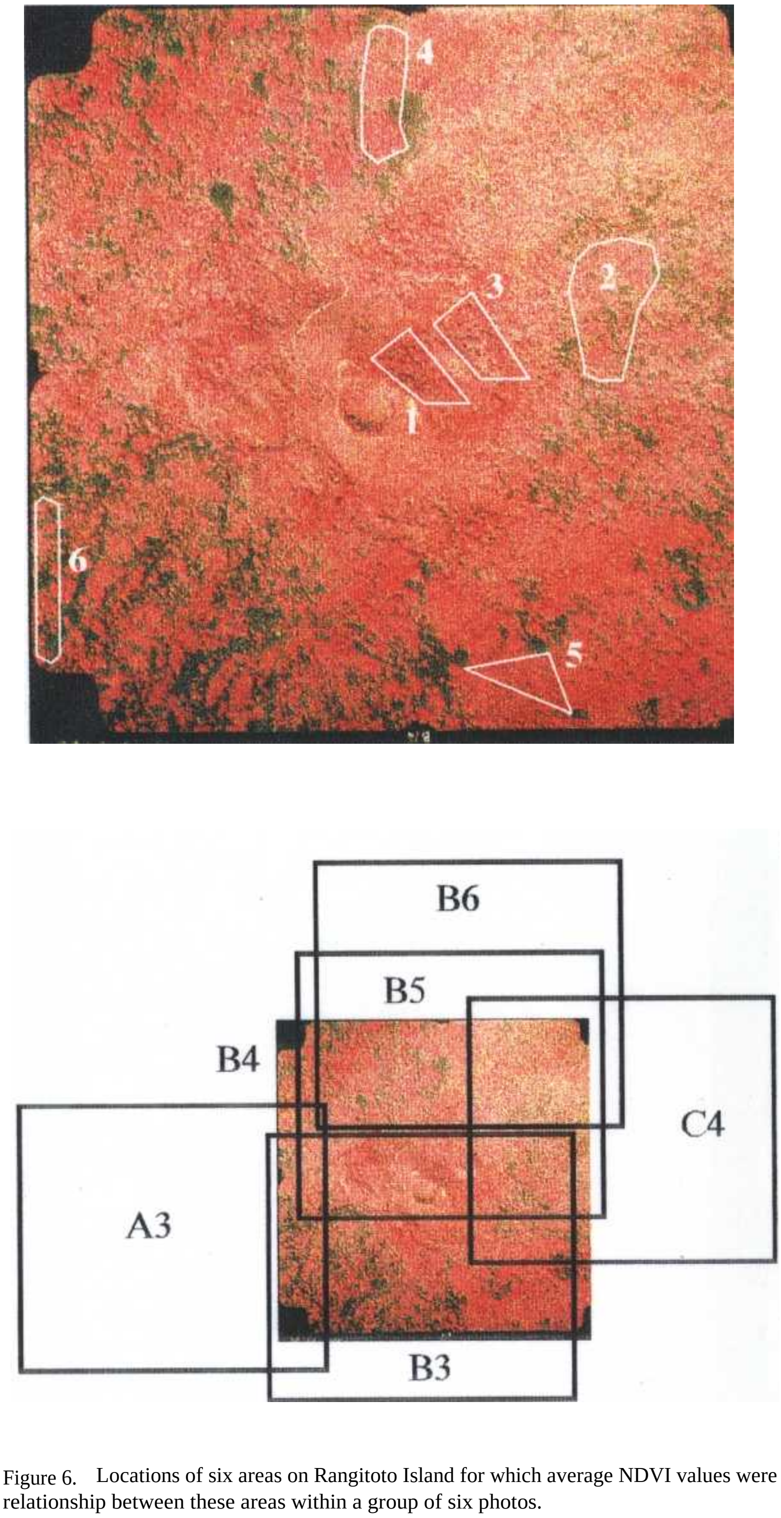

Figure 6. Locations of six areas on Rangitoto Island for which average NDVI values were obtained, and the relationship between these areas within a group of six photos.

TABLE 2. VARIATION IN VEGETATION INDICES WITH VIEW ANGLE, FOR PHOTOS BOTH UNCORRECTED AND CORRECTED FOR DIRECTIONAL REFLECTANCE AND LENS FALL-OFF EFFECTS USING THE DRLF. ALSO SHOWN ARE THE APPROXIMATE VIEW ANGLES AT WHICH SITES 1 TO 6 APPEAR IN THE VARIOUS PHOTOS. THE AIRCRAFT FLIGHT LINE IS IN THE POSITIVE X DIRECTION, AND THE SUN IS APPROXIMATELY IN THE NEGATIVE Y DIRECTION.

PHOTO	SITE	UNCORRECTED VI	CORRECTED VI	UNCORRECTED NDVI	CORRECTED NDVI	VIEW ANGLES (DEGREES X,Y)	
B3	1	0.537	0.540	0.302	0.299	+18	+ 2
B4		0.550	0.560	0.290	0.282	0	+ 2
B5		0.530	0.560	0.307	0.282	−16	0
		Range: 4%	Range: 4%	Range: 6%	Range: 6%		
B3		0.570	0.573	0.274	0.271	+18	+12
B4		0.566	0.573	0.277	0.271	0	+13
B5		0.530	0.570	0.307	0.274	−16	+13
C4	2	0.566	0.577	0.277	0.274	− 4	+12
		Range: 7%	Range: 1%	Range: 11%	Range: 1%		
B3	3	0.533	0.537	0.304	0.302	+20	+ 5
B4		0.540	0.550	0.299	0.290	0	+ 4
B5		0.513	0.540	0.322	0.299	−16	+ 5
C4		0.510	0.537	0.325	0.302	− 3	−20
		Range: 6%	Range: 2%	Range: 8%	Range: 4%		
B4	4	0.543	0.550	0.296	0.290	+18	+ 2
B5		0.540	0.547	0.299	0.293	0	+ 2
B6		0.510	0.537	0.325	0.302	−14	0
		Range: 6%	Range: 2%	Range: 10%	Range: 4%		
B3	5	0.546	0.557	0.293	0.285	0	+14
B4		0.510	0.553	0.325	0.289	−18	+12
C4		0.503	0.536	0.330	0.302	−17	−13
		Range: 8%	Range: 4%	Range: 11%	Range: 6%		
A3	6	0.590	0.597	0.258	0.253	+ 4	+15
B3		0.570	0.590	0.274	0.258	+ 8	−19
B4		0.550	0.583	0.290	0.263	−10	−20
		Range: 7%	Range: 2%	Range: 11%	Range: 4%		
		Mean range: 6.3%	Mean range: 2.5%	Mean range: 9.5%	Mean range: 4.2%		

significant variation in vegetation type, from horopito shrubland, to wineberry, and conifers, with an increasing conifer density towards the west and north.

The DRLF for the Hihitahi photos was calculated in the same way as for the Rangitoto dataset. However, the Hihitahi DRLF was unexpectedly different from that in the Rangitoto study, as the function did not exhibit a relatively smooth variation across the central parts of the photo.

Examination of the Hihitahi photos identified three possible reasons for the DRLF being poorly formed:

- For some photos there appeared to be saturation of the near-infrared data in the vicinity of the hotspot. Measurements on the photos indicate that horopito and wineberry reflect unexpectedly large amounts of near-infrared light, and these species dominate in areas where the hotspot occurs in the three photos at the west end of the transect.
- The systematic variation in conifer density in a north/south direction and east/west direction means that the averaged brightness images from which the DRLF is formed will also contain more systematic variation than is desirable. This is due to conifers reflecting much less light than broadleaf species. An alternative DRLF was formed by first masking out all conifers. Although this improved the appearance of the DRLF, the variation in the average vegetation index of common areas across the edges of corrected photos was still greater in some, but not all, cases than for uncorrected photos. This effect is attributed to saturation of the near-infrared band near the hotspot.
- The final factor contributing to the poorly formed DRLF is considered to be systematic variation in the distribution of wineberry and horopito. These species have a significantly different red spectral response. Unfortunately, masking out one or other of these species left too little data to enable a reliable DRLF to be derived. It is clear from the Hihitahi result that formulating a DRLF for mixed forest types will require that a much larger number of photos be averaged than was available in this study. At least 30 photos are likely to be required to successfully form the DRLF. The success of DRLF formation can be judged by the smoothness of the function, which should decrease monotonically from the hotspot until lens fall-off effects begin to dominate near the edges.

3.8 REVIEW OF FOREST DIRECTIONAL REFLECTANCE AND ILLUMINATION STUDIES

To supplement the conclusions above on the effect of directional reflectance and illumination on values calculated for vegetation indices, we present here a review of this subject from literature published over the past 15 years. There are relatively few studies that deal directly with mature forests, and it is difficult to extrapolate studies on other vegetation canopies to the forest situation. Only three studies have been found that are of direct relevance: Kimes *et al*. (1986), Ranson *et al*. (1986) and Syrén (1994). All used a field-of-view that included a number of trees, which means that their observations are relevant primarily to imagery with larger pixels, such as satellite data.

Kimes *et al*. (1986) and Syrén (1994) have both made measurements on mature monospecific conifer forests with a continuous canopy cover, located on flat sites. Kimes' work indicates that for a continuous canopy, neither the VI nor the NDVI shows variations exceeding 7% for sun elevations from 67° down to 45°, even at view angles of ±60°. For a vertical view, Syrén showed that the sun elevation can vary widely (from 20° to 60°) and yet the NDVI changes only by 4%.

Ranson *et al*. (1986) studied a canopy of variably spaced small trees, placed over backgrounds exhibiting different degrees of contrast with the canopy. They found that for a densely packed canopy, the NDVI could vary by up to 20% if the background was very bright (white in Ranson's study), as the view angle changed from 0° to ±60°. Similar variations were observed at all sun elevations (from 70° to 35°). If the tree density was low and the background bright, the situation most like that of emergents over a lower broadleaved canopy, then variations in the NDVI of up to 60% could occur when changing view angle from vertical to ±60°. These variations are explained by the brightness of the background, the amount of background that is visible with changes in view angle, and the illumination of the background (the better illuminated, the bigger the variation in NDVI with view angle). However, the use of a white background by Ranson is an extreme case, as natural canopies such as broadleaved trees are not as bright as a white reflector. Neither would such large view angles normally be used, even when acquiring airborne data. The data are therefore only useful to illustrate the worst-case scenario. If the view angle is restricted to ±20° (a typical figure for airborne data), and it is assumed that the amount of visible background varies as the tangent of the view angle, then we would expect a variation in the NDVI of 12% as a worst case. Given typical values of reflectance for forest canopy, it is unlikely that variations exceeding 5% would be encountered under restricted view angles, even for pixels which include patches of dead canopy.

Overall, published work suggests that when the pixel size is large, variations in vegetation indices should remain under 10% for limited ranges of sun elevations and view angles. This is the case even when forest types consist of darker conifer emergents over a brighter broadleaved canopy. It would seem that sun elevations of as little as 20° above the angle of the steepest slopes may provide satisfactory results (Syrén *et al*. 1994). However, even this elevation limit may prove quite restrictive in terms of the period during which aerial surveys of steep hill country can be carried out.

3.9 DIRECTIONAL REFLECTANCE AND ILLUMINATION EFFECTS AT SMALL PIXEL SIZES

The observations made in the last section on directional reflectance and illumination effects for forest canopies are appropriate primarily for studies based on satellite data. For such data, the scene components (i.e., individual trees, any lower canopy background, and large shadows) appear as sub-pixel objects. The overall brightness of any particular pixel is determined by the directional reflectance response of the individual components, together with the proportion of each component within the pixel. For airborne data with pixel sizes of a few metres, these scene components will often be resolved individually. This means that directional reflectance and illumination effects will induce larger variations in the brightness of individual pixels in airborne imagery than in satellite imagery, for example, when a fully sunlit pixel changes to being fully shadowed as a result of a change in sun elevation or azimuth.

At pixel scales of a few metres, we can consider an image of a forest canopy to consist of only fully sunlit and fully shaded components, and mixtures of these components. In addition, the canopy can be in various states of defoliation, which will cause variation in the brightness of the sunlit canopy, but will not affect the brightness of the shaded canopy to any significant extent. Variations in sun elevation will alter the proportion of sunlit to shaded canopy, and changes in sun azimuth will alter where the shadows fall. Variations in view angle and direction will also change the observed proportion of sunlit to shadowed canopy. Shadows will tend to be obscured when viewing from the back-scattering direction (i.e., when the sun is behind the viewer), will increase to a maximum proportion of the scene at vertical views, and then decrease again when viewing from the forward-scattering direction. At a given view angle, a greater proportion of shadows will be visible from the forward-scattering than the back-scattering direction. Changes in the view angle/direction will also make different parts of the canopy visible when tall emergents are present over a lower canopy, or in any situation where the canopy shows significant roughness (see Fig. 7).

The accuracy of vegetation indices derived from airborne data can be assessed approximately by considering the behaviour of the scene components. The fully shaded canopy component can be discarded, as it contains no useful data and would normally be masked out as a first step in an analysis. The fully sunlit canopy would be expected to behave similarly to well-illuminated forest, for

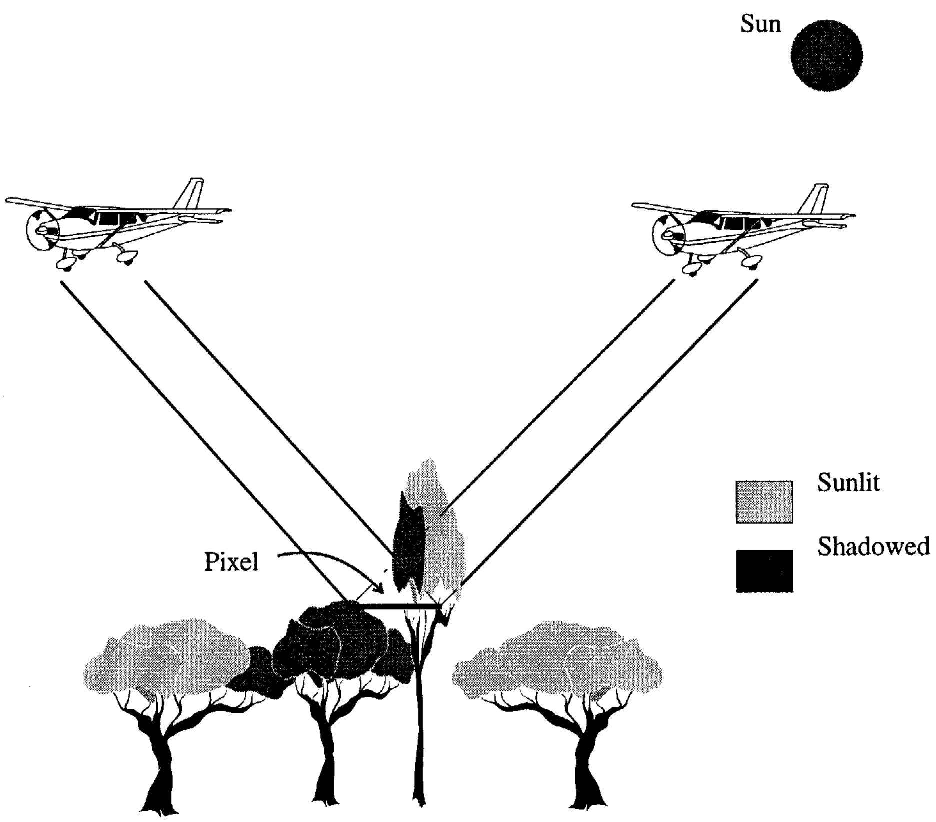

Figure 7. Variation in the area recorded by a pixel with constant geographic location, for different angles of view.

which the measurements made by Ranson *et al*. (1986) and others are relevant (as reported in section 3.7 above). These studies indicate a variation in the NDVI of less than 10% for view angles of up to 60° off-nadir (i.e., off-vertical), over large variations in sun elevation. If view angles are restricted to nadir only, then changes in the NDVI of as little as 4% have been recorded for sun elevation changes from 60° to 20° (Syrén 1994).

Next to be considered is the change in the area of canopy viewed as the view-angle changes. This is an important effect for a canopy that shows a lot of height variation and contains canopy elements of strongly varying brightness, such as bright patches of defoliation or large shadows cast by tall trees (see Fig. 7). A pixel with the same geographic co-ordinates records the reflectance from quite different targets depending upon the angle of view and the relative positions of target features, even at a constant sun elevation. This situation is similar to that investigated by Ranson *et al*. (1986), who found that large variations in the NDVI occurred between nadir and 60° off-nadir views for a canopy of small conifers placed over a highly contrasting background. If differences in the NDVI recorded for the same target in nadir and off-nadir views are to be kept to about 5%, the only possible approach is to restrict view-angles to within ±20°.

An accuracy of 5% will only be obtained at a constant sun elevation. Furthermore, changes in sun azimuth at near-constant elevation, a situation that occurs for about 1.5 hours around midday, will result in the shadows cast by tall trees obscuring different parts of the canopy at different times. Detection of change in vegetation indices between two different dates should therefore not be undertaken on a per pixel basis unless the sun is in a very similar position at the two survey dates. This will generally be difficult to achieve, and an alternative approach is to average changes on an area basis. The area should be sufficiently large that the exact location of shadows is not expected to alter the defoliation data obtained, when data are expressed on the basis of the remaining area of sunlit canopy. An area of about one hectare should be sufficient.

If the sun elevation as well as azimuth changes, the area of canopy affected by large shadows will change as well as the location at which the shadows fall. For example, a decrease in sun elevation of as little as 10° can increase the area of large shadows by up to a factor of two, at the typical sun elevations required to adequately illuminate steep hill country (from 60° to 70°). Even if all identifiable shadows are masked out, the number of pixels containing part of a shadow will also have increased by up to a factor of two. The exact magnitude of this effect on vegetation indices is difficult to establish from published work, although it is unlikely to be as great as that seen with a white background in the studies of Ranson *et al*. (1986). This is because the contrast between the reflectance of vegetation and a white target is much greater than that for vegetation and shadows. The effect of increased shadowing can probably be eliminated by increasing the reflectance threshold for shadow masking, and by restricting view-angles to within ±20°. This view-angle restriction ensures that the proportion of residual shadows appearing as sub-pixel components does not vary greatly across a single photo or image. In addition, vegetation indices should be averaged over areas sufficiently large that a statistically accurate estimate of defoliation within the area is still obtained, even with all shadowed areas masked out.

Continue to next file: DOCTS14a.pdf