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4. Topographic correction

4.1 TOPOGRAPHIC EFFECTS IN IMAGERY: A REVIEW OF RECENT WORK

The topographic effect can be defined as the variation in the amount of reflected light from a surface, with changes in slope and aspect. In images of hill country, this effect manifests itself as a **visual impression** of topographic relief, although there is nothing in the remote sensing process which directly captures relief information. As stated in section 1.3 of this report, the topographic effect received only limited study in this investigation. We have confined ourselves to a review of the available literature published during the last 15 years, plus some experimental work to verify our conclusions.

Topographic correction is a topic of ongoing debate in the remote sensing literature, and there is as yet no consensus on the most appropriate correction method. Topography can alter the amount of light reflected by a given target by up to 30% at low sun angles (Leprieur and Durand 1988). Yet automated identification of targets in remotely sensed imagery relies on there being a **constant** relationship between a given target type and the amount of reflected light. Although the topographic effect is therefore a particular problem in studies which use absolute values of reflected light (e.g., vegetation identification), the use of ratios of bands in vegetation indices is generally assumed to provide a significant reduction in the topographic effect (e.g., Crippen 1988). However, there are few measured data that support this assumption. Reported studies generally show significantly less variation with topography in the visible bands than in the near-infrared, implying only a partial topographic suppression is to be gained by band ratios (Ekstrand 1996, Lepriuer and Durand 1988, Smith *et al*. 1980). This apparent wavelength dependence of the topographic effect also implies that the NDVI, rather than the simple VI, might be more resistant to topographic effects.

Only three published studies provide useful data on reflectance from forest canopies as a function of topography: Ekstrand 1996, Leprieur and Durand 1988, Smith *et al*. 1980. All these studies use nadir-viewing satellite data. However, available evidence indicates that the topographic and directional reflectance effects are independent (Woodham and Gray 1987), and thus the conclusions drawn may be applied to any view angle. To discuss these studies, we must introduce the term incidence angle: the angle between the sun and the normal to the slope. The incidence angle describes how well a particular combination of slope and aspect is illuminated. An incidence angle of 0° occurs when the slope is at right angles to the sun and is fully illuminated, while an angle of 90° or greater indicates the slope is in full shadow.

For a conifer forest illuminated at a sun elevation of 38°, studies show that a maximum error of 7% in the NDVI, and 13% in the VI, over a range of incidence angles from 37° to 78° (Ekstrand 1996). Smith *et al*. (1980) found the average error to be only about 4% for both the VI and NDVI, for a similar range of incidence angles, at a sun elevation of 53°. Leprieur and Durand (1988) have also measured reflectance from conifer forests at a sun elevation of about 50°, but over an incidence angle range of 15° to 60°. Their data show errors in the NDVI of 5% (10% for the VI). To put these results in context, incidence angles in the range 15° to 80° would be encountered in hill country with slopes up to 30°, at a sun elevation of 50°.

In summary, these studies indicate that the effect of topography on vegetation indices is less than 10% for continuous forest canopies, provided that the sun elevation is kept at least 20° above the largest slope angle. As with directional reflectance effects, this restriction on sun elevations will impose significant limits on the period available for aerial surveys.

4.2 TOPOGRAPHIC EFFECTS OBSERVED AT HIHITAHI

Topographic effects reported in the literature for forest (see above) were compared with a small set of vegetation index data obtained from wineberry (*Aristotelia serrata*) canopy on the opposite sides of steep gullies at Hihitahi. Slopes on which the patches were located varied in angle from 20° to near 30°, and were oriented approximately at right-angles to the direction of the sun. This means that the slopes had a variation in incidence angle from about 30° up to near 90°, patches of canopy were selected for their visual uniformity, and data were extracted from the digitised large format CIR photos. Directional reflectance effects are not expected to influence the pairs of vegetation indices formed from this data, as the pairs occur in close proximity. The vegetation indices measured for nine pairs of wineberry canopy patches are given in Table 3, and show variations similar to those encountered in other studies with a similar range of incidence angles (e.g., Ekstrand 1996). Some of the variation will no doubt be due to small differences in canopy composition between the pairs of patches.

TABLE 3. AVERAGED VEGETATION INDICES FOR NINE PAIRS OF WINEBERRY (*Aristotelia serrata*) CANOPY PATCHES LOCATED ON OPPOSING ASPECTS ORIENTED APPROXIMATELY AT RIGHT-ANGLES TO THE DIRECTION OF THE SUN, AT HIHITAHI. FIGURES IN BRACKETS ARE STANDARD DEVIATIONS.

SOUTH FACING		NORTH FACING		DIFFERENCE (%)	
NDVI	VI	NDVI	VI	NDVI	VI
0.40 (0.02)	2.31 (0.11)	0.35 (0.02)	2.09 (0.08)	10 (2)	11 (2)

5. Effect of variation in forest species

The purpose of this part of the study was to determine the relationship between vegetation indices and the levels of defoliation in a range of tree species. The study was carried out in two parts. The first was to determine whether the relationship between defoliation and vegetation indices was linear for species other than the previously studied pohutukawa forest. The second was to determine how variable the relationship was likely to be for the more important species found in a conifer/broadleaved forest undergoing decline.

5.1 RATING THE LEVEL OF CANOPY DEFOLIATION IN INDIVIDUAL TREES: THE HOROPITO STUDY

The first part of the study was carried out at Horopito, in farmland immediately adjacent to the south-west boundary of the Tongariro National Park. The area was chosen primarily because of the requirement that single trees be both readily accessible from the ground and unambiguously identifiable in aerial photos. Kamahi (*Weinmannia racemosa*) and black maire (*Nestegis cunninghamii*) were the species chosen for study. Both species show symptoms of decline in this area, although only kamahi is highly preferred as a food source by possums. The trees selected for rating were generally those standing as isolated individuals surrounded by pasture.

A transect of six 1:10 000 scale photos was acquired along the park boundary, at a sun elevation of 54°. Selected areas were enlarged to 1:2500 scale on a colour photocopier, for use as maps in the field. Canopy condition rating was performed from the ground on 80 trees, using the percentage leaf cover assessment method (Payton *et al*. 1997). The trees to be rated were selected by an independent observer who took no part in assigning the ratings. Only the observer had access to the 1:2500 scale photo-enlargements during the ground survey. A wider range of canopy defoliation levels were rated than the previous study on Rangitoto Island (Trotter 1992a, Trotter 1992b), with the sample including both undamaged and dead trees.

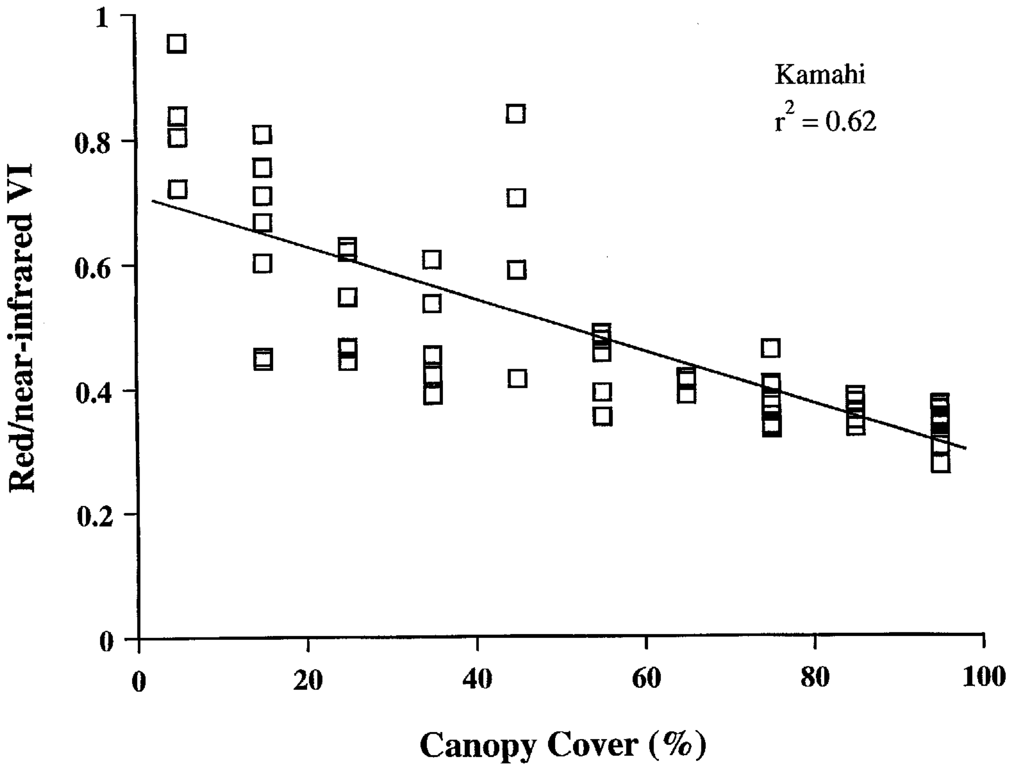
Red, green and near-infrared data for the trees rated for defoliation were extracted from a single digitised CIR photo of the site, using the ERDAS Imagine image processing system. The photo had been digitised at 400 dpi, equivalent to a ground pixel size of 0.6 m. No radiometric correction to the image was required, as the site occupied only a small area on the photo, with negligible change in any view-directional effects. The site was on ground not exceeding 5° in slope, so topographic effects were insignificant.

Table 4 shows the results of linear and log-linear regression analysis for individual bands, and for various band ratios including those commonly used as vegetation indices. Examples of these relationships are shown in Fig. 8. As expected, ratios of red and infrared reflectance were most strongly related to the percentage canopy cover, although green/infrared ratios also performed well (see Table 4). The relationship between percentage canopy cover and the simple red/infrared or green/infrared VIs was the same for the kamahi and black maire datasets. That is, the slopes and intercepts of the regression lines for percentage canopy cover versus the simple VIs agreed within their 95% confidence intervals (Table 5). The green/red VI also shows some promise as a measure of percentage canopy cover if estimates can be averaged over larger areas (Fig. 9), although its predictive accuracy at the individual tree level is not as good as ratios that include infrared reflectance. Similar comments apply to the green band, although band ratios are preferred for estimation of canopy condition due to the partial cancellation of directional reflectance and topographic effects that ratios provide.

On average, there is a good relationship between ground surveyed defoliation and the red/infrared (or green/infrared) vegetation index, although the relationship is not as strong at the individual tree level as expected. Ground-based ratings are thought to be accurate to a defoliation level of ±10% defoliation (Payton *et al*. 1997). However, whether ground observers can visually integrate the variable level of defoliation that occurs within individual trees to arrive at an accurate figure for the whole tree is uncertain, especially at intermediate defoliation levels. Where visual integration is simple (i.e., for trees that are either undamaged or completely dead), the standard deviations in the corresponding vegetation indices show a range of about 10%. This is significantly smaller than the figures of up to 20% found at intermediate

TABLE 4. RESULTS OF LINEAR AND LOG-LINEAR REGRESSION OF REFLECTANCE DATA AGAINST PERCENTAGE CANOPY COVER RATINGS FOR KAMAHI (*Weinmannia racemosa*) AND BLACK MAIRE (*Nestegis cunninghami*). THE LOG-LINEAR REGRESSIONS GENERALLY SHOW HIGHER VALUES OF R^2, ALTHOUGH THE GAINS OVER LINEAR-LINEAR REGRESSION ARE SMALL.

DEPENDENT VARIABLE	R^2 (KAMAHI)	R^2 (MAIRE)
G	0.34	0.49
R	0.21	0.31
IR	0.34	0.20
G/R	0.36	0.57
G/IR	0.49	0.75
R/IR	0.62	0.81
(IR–R)/IR+R)	0.67	0.79
1n(G)	0.40	0.54
1n(R)	0.24	0.48
1n(IR)	0.36	0.41
1n(G/R)	0.42	0.59
1n(G/IR)	0.56	0.80
1n(R/IR)	0.68	0.79
1n[(IR–R)/IR+R)]	0.70	0.82



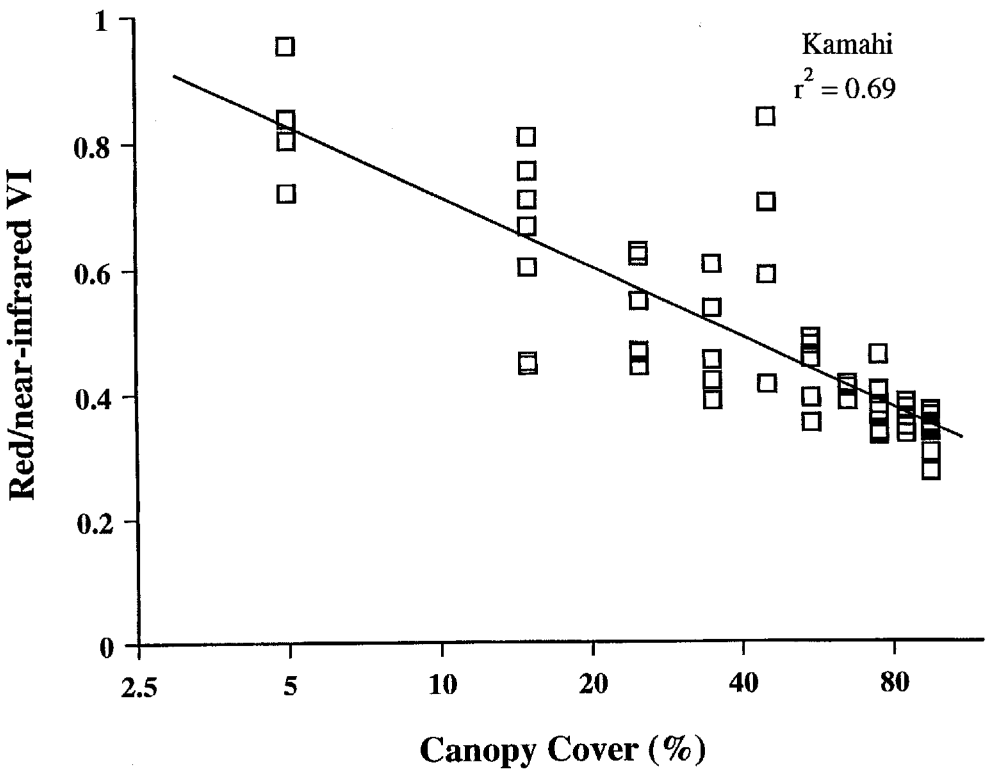


Figure 8. Linear (top) and log-linear (bottom) relationships between the red/near-infrared simple VI and percentage canopy cover, for individual kamahi trees.

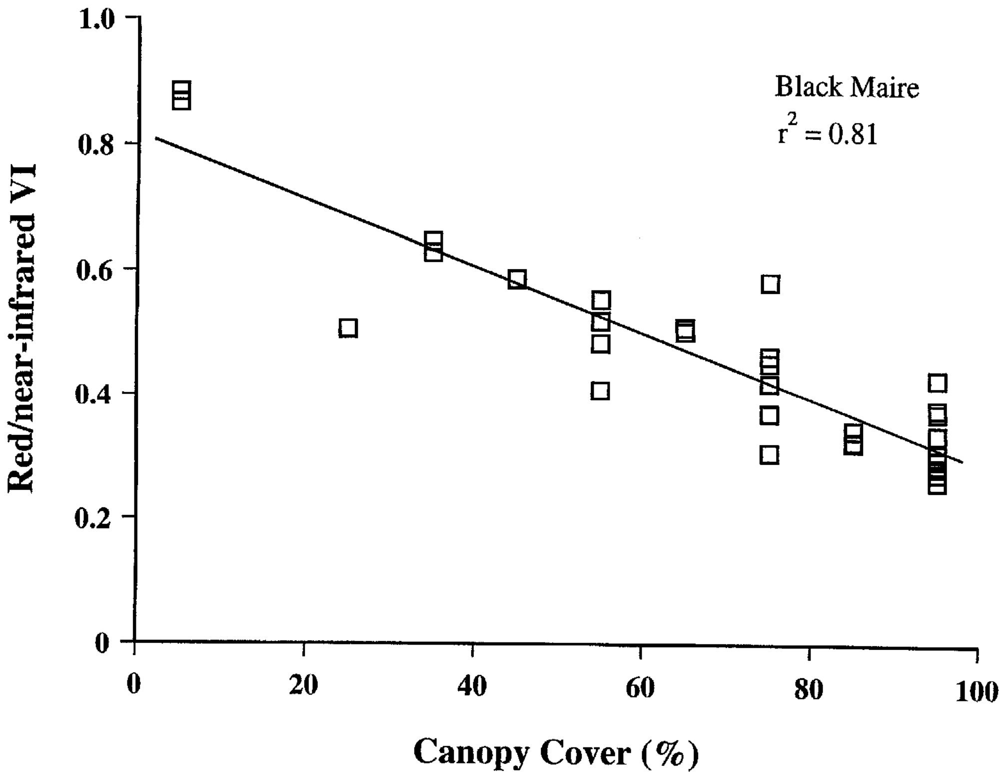
defoliation levels, which are likely to be more difficult to assess from the ground. It should also be noted that remote sensing obtains data which are biased towards the upper part of the canopy, whereas ground-based ratings take into account either the whole canopy volume for smaller trees or may perhaps be biased towards the lower portion of the tree for taller forest. This may be responsible for some of the differences observed between ground-based and remote sensing assessments of defoliation. Future studies will need to try and resolve the source of the variation that exists between ground-measured and vegetation-index-estimated defoliation levels for partially defoliated trees.

The relationships between either the red/infrared VI or red/green VI, and defoliation, indicate that highly defoliated trees ($\leq$5% canopy cover) should be easily and accurately separable from other trees by automated data processing. To test this, a simple classification for dead canopy was done on the central part of one the frames of CIR 1:10 000 scale imagery, without shadow masking. Areas classified as dead were checked against visual assessments made under a stereoscope, and one hundred pixels automatically classified as dead were visually checked against the original imagery. None were visually associated with other than dead canopy. Neither shadows, nor any canopy with the slightest red tinge on the image, were classified as dead. It seems probable that dead canopy can be detected with at least a 95% accuracy using this method. Figures 8 and 9 suggest that a red/infrared or red/green VI should also accurately identify dead vegetation, provided shadows are masked out (as these can give spurious VI values due to noise in low magnitude data). Identification of dead canopy based on a red/green VI would be expected to offer advantages in terms of reduced topographic, illumination and directional scattering effects, due to the similarity of the wavelengths that comprise this VI.

TABLE 5. RELATIONSHIP BETWEEN THE RED/NEAR-INFRARED VEGETATION INDEX (VI) AND THE PERCENTAGE CANOPY COVER (PCC) IN KAMAHI AND BLACK MAIRE TREES.

SPECIES	NO. OF SAMPLES	REGRESSION EQUATION	R^2
Kamahi	48	VI = –0.0042PCC + 0.71 1n(VI) = –0.16PCC + 1.1	0.62 0.68
Black maire	32	VI = –0.0053PCC + 0.82 1n(VI) = –0.15PCC + 1.07	0.81 0.83

Confidence intervals (95%) for the slope and intercept of the non-log transformed regression are 0.0001 and 0.07 respectively. The higher r^2 values for the maire probably reflect the size of the dataset rather than any improvement in the reliability of the relationship. Similar trends are evident in the relationship between the green/red VI and the percentage canopy cover, albeit at a much lower value of r^2.



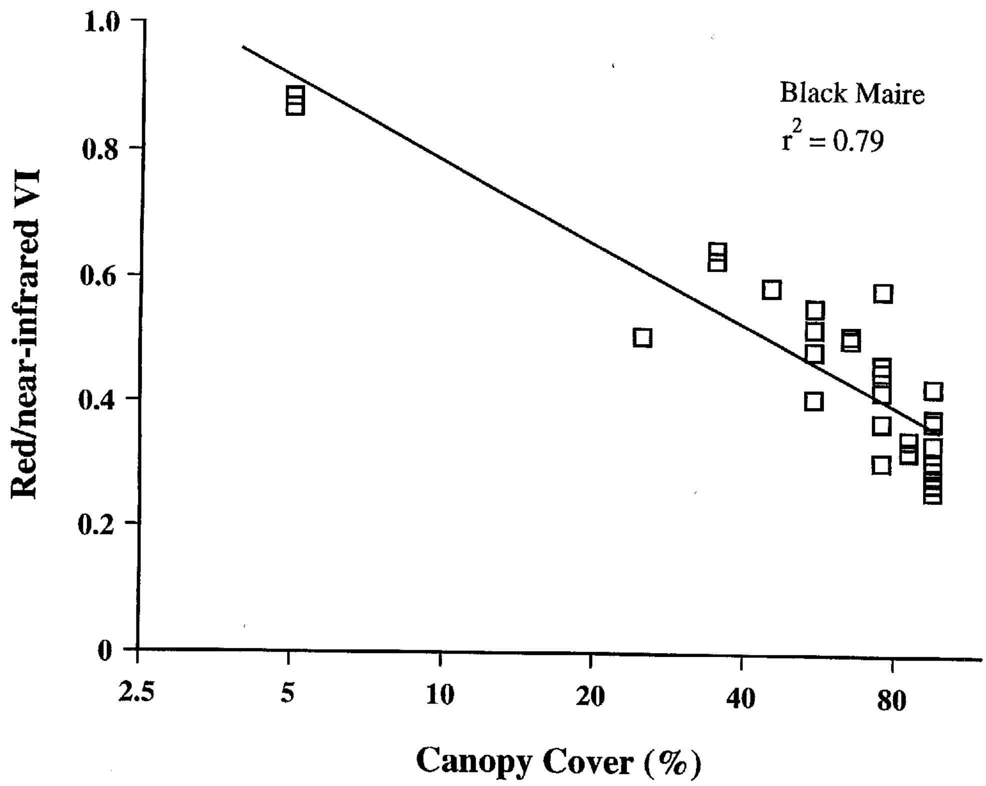


Figure 9. Linear (top) and log-linear (bottom) relationships between the red/near-infrared simple VI and percentage canopy cover, for individual black maire trees.

5.2 VEGETATION INDICES OF CONIFER/ BROADLEAVED FOREST SPECIES

The linear relationships between percentage canopy cover (i.e., canopy defoliation level) and vegetation indices will only be useful for routine surveys over large areas if the relationships are relatively independent of tree species. (This assumes that adequate directional reflectance and topographic correction methods are also available.) However, data obtained during the Horopito study indicated that some tree species possessed quite different defoliation/VI relationships to those for kamahi and black maire. Rimu, for example, was found to exhibit a very low near-infrared reflectance, which causes even healthy trees to have a vegetation index similar to 90% defoliated kamahi or maire. Fortunately, rimu can be readily identified on the basis of this anomalous infrared reflectance, and assigned a high percentage canopy cover rating since it is not browsed by possums. However, it is probable that other species might show spectral responses that are not sufficiently anomalous to allow identification, yet still possess a defoliation/VI relationship which is quite different to that of kamahi and maire.

The dead vegetation of any species has a similar vegetation index. To get consistency between species, either the vegetation indices of all undamaged trees need to be similar or the indices of these trees need to be adjusted to a similar value using some independent source of information. To examine the variation in the VI values of undamaged trees, reflectance data were obtained for a range of species at both the Horopito and Hihitahi sites. Undamaged trees were identified from visual interpretation of 1:10 000 CIR photos where it was known that the species were unpalatable. For palatable species, trees that showed no visible defoliation on 1:1000 scale natural colour photos were selected for study, and re-located on the CIR photos.

TABLE 6. AVERAGE RED/NEAR-INFRARED AND RED/GREEN VEGETATION INDICES FOR UNDAMAGED (AND DEAD, FOR COMPARISON) TREES IN CONIFER-BROADLEAVED FOREST. STANDARD DEVIATIONS ARE GIVEN IN BRACKETS.

SPECIES*	NO. SAMPLES	AVERAGE $VI_{R/IR}$	AVERAGE $VI_{R/G}$
Beech, red	10	0.35 (0.03)	0.18 (0.06)
Kamahi	20	0.35 (0.03)	0.37 (0.08)
Maire, black	8	0.33 (0.03)	0.33 (0.08)
Miro	3	0.34 (0.02)	0.37 (0.08)
Coprosma, small leaved	10	0.67 (0.05)	0.52 (0.05)
Horopito	10	0.63 (0.07)	0.43 (0.05)
Kaikawaka	15	0.63 (0.07)	0.45 (0.07)
Hall's totara	12	0.67 (0.05)	0.42 (0.02)
Rimu	13	0.75 (0.13)	0.48 (0.07)
Wineberry	10	0.50 (0.02)	0.52 (0.03)
Dead trees	10	1.11 (0.12)	0.84 (0.07)

* Forest species are (in order of presentation in the table): *Nothofagus fusca, Weinmannia racemosa, Nestegis cunninghamii, Prumnopitys ferruginea, Coprosma propinqua, Pseudowintera colorata, Libocedrus bidwillii, Podocarpus cunninghamii, Dacrydium cupressinum, Aristotelia serrata*.

The results of the study are summarised in Table 6, and show that there is a wide range in the vegetation indices recorded for undamaged examples of different tree species (some of which are spectrally indistinct). To place these data in context, the simple red/infrared and green/red VIs for the various tree species are plotted in Fig. 10, together with the individual tree data obtained for kamahi. It is apparent from Fig. 10 that the green/red VI performs better than the red/infrared VI in depicting the state of these undamaged tree species, but still has significant limitations. It also illustrates that a red/green VI shows significant promise for providing accurate data on the area of dead canopy, even in the presence of a range of species (unlike a red/infrared VI). However, the results show clearly that simply interpreting vegetation indices as species-independent measures of defoliation will generally lead to gross errors, especially at low to intermediate defoliation levels. An approach based on species stratification will probably be essential to achieve accurate results. There is also a need to investigate regions of the spectrum that are not accessible to CIR photography, but have proved useful for defoliation studies in conifer forest (e.g., the mid-infrared region of the spectrum).

5.3 ASSESSING CANOPY CONDITION IN MIXED SPECIES FORESTS

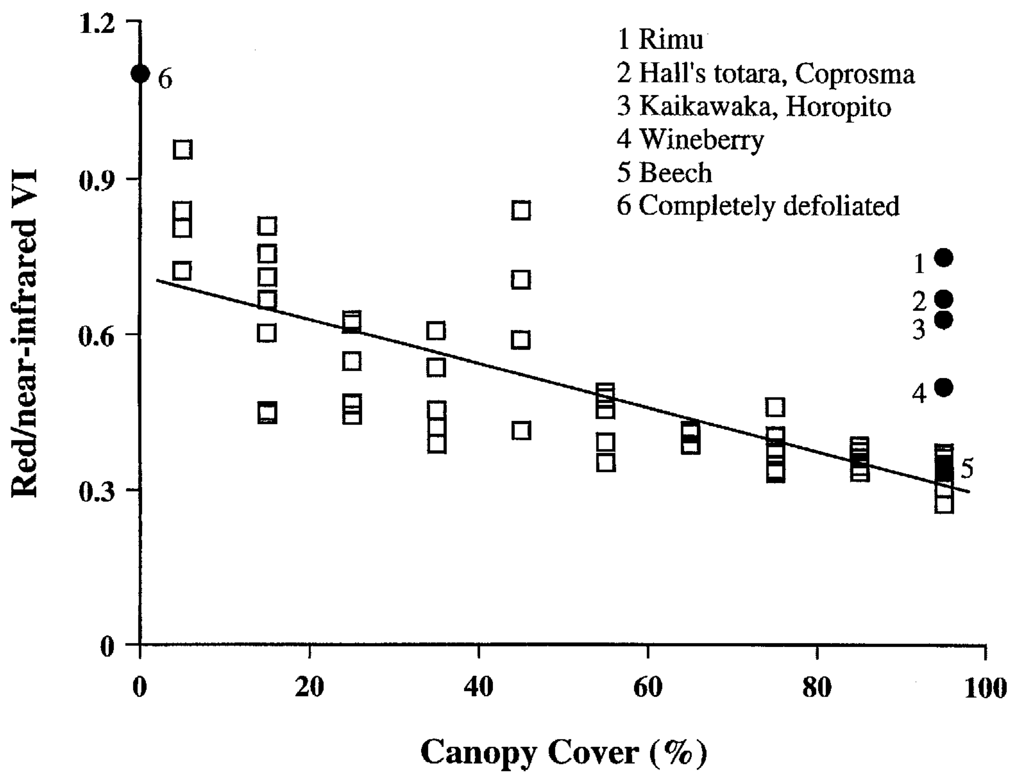
Because vegetation indices are not unique predictors of defoliation across tree species, remotely sensed images need to be segmented by species type. In some cases, a range of species may be treated as a group, if they possess common spectral features. This should allow unique defoliation/vegetation-index relationships to be applied on a per-species (or per-group) basis. A full examination of the feasibility of using such an approach to defoliation rating is beyond the scope of this study. However, data collected to date provide a positive indication that such an approach might be possible (see Table 6).

Table 6 lists vegetation indices for a set of undamaged forest species found in broadleaved-conifer forests. The red/infrared vegetation indices fall essentially into two groups: those with values of about 0.35, and the rest with values above 0.5. Except for coprosma, a minor canopy species, this latter group has anomalous near-infrared responses: either very low (kaikawaka, rimu, totara), or very high (horopito, wineberry). Those with a very high infrared reflectance are not very palatable to possums, and can be assumed to be undamaged. Those with a low infrared reflectance are conifers, which (apart from miro) have a fairly uniform red/infrared response and could be considered as having a uniform VI/defoliation relationship (see Fig. 10). Although this relationship has yet to be properly established for conifers, the defoliation rating scheme below may provide accurate rating of broadleaved-conifer forest:

Step 1. Mask all pixels affected by shadows.

Step 2. Classify all material with $\leq$5% canopy cover as dead (using direct classification of greyness/blueness, or a green/red index).

Step 3. Identify unpalatable horopito and wineberry by their high infrared reflectance, and assign them to the undamaged class.



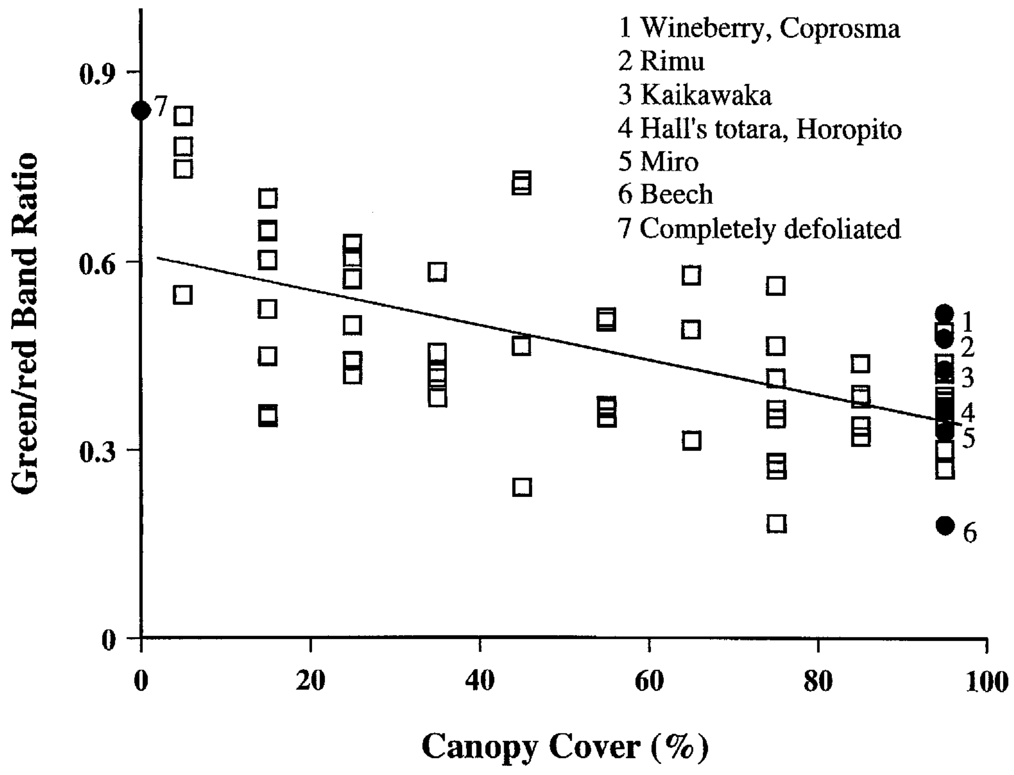


Figure 10. Red/near-infrared and red/green simple VI data (open squares) for individual kamahi trees, plotted together with the same VIs obtained for a range of undamaged tree types found in conifer/broadleaved forest. The VI of undamaged canopy varies considerably with tree type. The red/green VI performs best In terms of narrowing the range of VI values for undamaged canopy between tree species.

Step 4. Identify rimu, kaikawaka, or Hall's totara by their low infrared reflectance, and assign defoliation ratings based on a "conifer-calibrated" red/infrared index.

Step 5. Assign defoliation ratings to the remainder of the image based on a "broadleaf-calibrated" red/infrared index.

The question of whether similar hierarchical schemes can be devised to cope with the full range of canopy species appearing in mixed forests requires further research.

6. Summary and conclusions

6.1 REMOTE SENSING FOR MONITORING CANOPY DEFOLIATION: A SUMMARY

The major conclusions of this investigation are given below in **bold**, together with supporting information:

1. **A red/green index shows significant promise for determining areas with canopy defoliation levels greater than 95% in mixed species forests, with errors expected to be less than ±5% when using radiometrically calibrated airborne data.**

The study has shown that areas of dead canopy (i.e., defoliation greater than 95%) should be accurately measured using a red/green index, with errors of less than ±5% for single tree species. More importantly, a red/green index shows an encouraging species independence, and suggests this accuracy is likely to be maintained even in mixed-species forests. In addition, a red/green index has advantages in terms of reducing directional reflectance, illumination and topographic effects. The percentage of dead canopy is used already in semi-quantitative, visually based assessment of forest decline for some common forest types. Remote sensing of canopy deadness offers the advantages of comprehensive spatial coverage at low cost, more accurate assessment of the total area of damage, and improved detection of change.

2. **Conifer density is readily quantifiable, and colour-infrared data from airborne sensors should allow accuracies of better than ±10% to be obtained.**

Conifer density appears to be another potentially useful parameter that can be quantified by remote sensing. Although a formal test of the accuracy of conifer density accuracy is beyond the scope of this investigation, the spectral signature of conifer species is sufficiently distinct (apart from miro) that accuracies of better than ±10% are expected. It is estimated that the cost of acquiring and analysing colour-infrared data for canopy deadness and conifer density would be less than the present cost of aerial photography alone, provided that data were acquired using a digital camera.

3. **Spatially detailed remotely sensed data with pixel sizes in the two to three metre range are required if the severity of canopy damage is to be assessed accurately, due to the patchy nature of canopy damage in**

forest ecosystems. Currently, therefore, airborne rather than satellite remotely sensed data must be used for defoliation rating.

The patchy nature of defoliation damage typically encountered in our indigenous forest means that the small pixels available in airborne remotely sensed data are more appropriate for defoliation surveys than the larger pixels in satellite data. Although satellite data have significant advantages in terms of cost and ease of acquisition, they will tend not to show the extremes of defoliation damage, and will be rather insensitive for detecting change. For example, complete defoliation of a 10 m diameter tree will be registered as only a minor change in the percentage defoliation calculated for an entire Landsa t TM pixel, if that is the only tree undergoing change within the 30 m square pixel area (which may frequently be the case). Future satellites with smaller pixel sizes may alleviate this problem. Satellites acquiring colour-infrared data with 10 m pixels will be launched over the next few years. However, data from even these satellites may be of limited use, depending upon the extent to which hill-country is illuminated at the time of satellite over-pass (typically 10:30 am).

4. If left uncorrected, the effects of directional reflectance, illumination, and topography can cause errors in excess of 50% in canopy defoliation levels derived from data from wide-angle airborne sensors.

Data from airborne sensors have the correct spatial scale for defoliation monitoring. However, a range of factors relating to viewing and illumination conditions must be taken into consideration, and minimised, if vegetation indices are to be calculated accurately from imagery acquired with airborne sensors. These factors are listed in Table 7, together with methods to minimise

TABLE 7. RESIDUAL ERRORS ASSOCIATED WITH AIRBORNE DATA AFTER STEPS ARE TAKEN TO CORRECT OR LIMIT THE INFLUENCE OF DIRECTIONAL REFLECTANCE, ILLUMINATION AND TOPOGRAPHY. TOTAL ERRORS WOULD SELDOM EXCEED 20% IF ALL CONDITIONS ARE MET.

LIMITATIONS OF AIRBORNE DATA		METHOD TO MAXIMISE ACCURACY
1.	Film exposure/ processing/printing variations	Use a fully calibrated digital cameral (including calibration of lens fall-off) under controlled temperature conditions. Record incoming light levels for exposure normalisation. Residual error in reflectance recorded under these conditions: <2%.
2.	Effects due to directional scattering of light (changes in view angle, sun elevation, and sun direction)	Limit view angles to within ±20°, and sun elevations to more than 40°. Use a simple empirical directional reflectance function to minimise remaining effects. Confine analysis to well-lit canopy only. Report results on an area averaged basis to avoid any effects associated with removing differing shadowed areas from the scene at different sun elevations or positions. Residual error in reflectance recorded under these conditions: <5%.
3.	Changes in geometry of viewed target with view angle	Limit view angles to within ±20°, restrict analysis to well-lit canopy only, and report results on an area-averaged basis. Residual error in reflectance recorded under these conditions: <5%.
4.	Topographic effects	Limit view-angles to within ±20°, and sun elevations to at least 20° more than the steepest slope. Confine analysis to well-lit canopy only. Residual error due to topographic effects: <10%.

their effect on the accuracy of vegetation indices. If these effects remain uncorrected, this and other studies indicate that **for a given vegetation type,** errors in excess of 50% may occur in the defoliation levels derived from wide view-angle, low sun elevation, remotely sensed data. However, by placing relatively simple restrictions on the conditions under which airborne data are acquired (Table 7), **absolute** levels of defoliation should be measurable to within 20%, for a given tree species. **Changes** in defoliation levels of 15% should be detectable irrespective of tree species. The level of accuracy of **absolute** defoliation ratings could be further improved with a simple topographic correction, but the complexity of data processing associated with this would make it an expensive task. The topographic effect will not significantly limit the detection of **change** in defoliation levels over time, provided repeated surveys are performed at similar sun elevations and positions, with photos/images recorded at similar geographic co-ordinates.

5. **Absolute levels of canopy defoliation will be accurate to better than 20%, for a given tree species, under the following conditions: data acquisition by a calibrated digital camera at high sun angles and narrow view angles, correction of directional scattering of light from the canopy with an empirical model, and restriction of data analysis to areas of well-lit canopy.**

6. **Changes in the level of canopy defoliation of 15% are expected to be detectable, irrespective of tree species. Data for change detection will need to be acquired under the same conditions as in the last point above. In addition, the sun position must be similar for repeated surveys, and photos/images must be recorded at similar geographic co-ordinates.**

Achieving even the levels of accuracy stated in points (5) and (6) above will only be possible when analysis is restricted to fully sunlit canopy, and when data are reported as summary statistics for reasonably sized areas (≥1 ha). This is because the vegetation-index/defoliation relationships are not robust enough to permit accurate predictions at the pixel or individual tree levels. Reporting summary statistics on an area basis also means that some variation in the amount and location of sunlit canopy elements can be tolerated. That is, minor changes in sun position, sun elevation and photo/image co-ordinates should not influence area-averaged results significantly. This is an important consideration when determining change in canopy defoliation over time, as having to restrict repeated aerial surveys to identical sun and image positions would impose too restricted a set of conditions on flying times to be practical.

7. **In the absence of directional reflectance, illumination, and topographic effects, canopy defoliation levels in kamahi and black maire are well-related in a linear manner to vegetation indices calculated from airborne data that include the near-infrared band (r^2 between 0.49 and 0.83, depending on the band combination and data transform).**

In the absence of variations in directional reflectance, illumination and topography, there is a good relationship between vegetation indices and the percentage canopy cover determined from ground surveys, for kamahi and black maire. As expected, ratios of red and near-infrared reflectance are most strongly related to the percentage canopy cover, although green/infrared ratios also perform well. The green/red ratio also shows some promise as a measure of percentage canopy cover, although its predictive accuracy is not as good as ratios that include infrared reflectance. In linear regression, values of r^2 varied between 0.49 and 0.83, depending both on the particular wavelength combination used and on whether the vegetation index data (as the dependent variable) were log transformed. The relationship between percentage canopy cover and the simple red/infrared or green/infrared VIs was the same for the kamahi and black maire datasets.

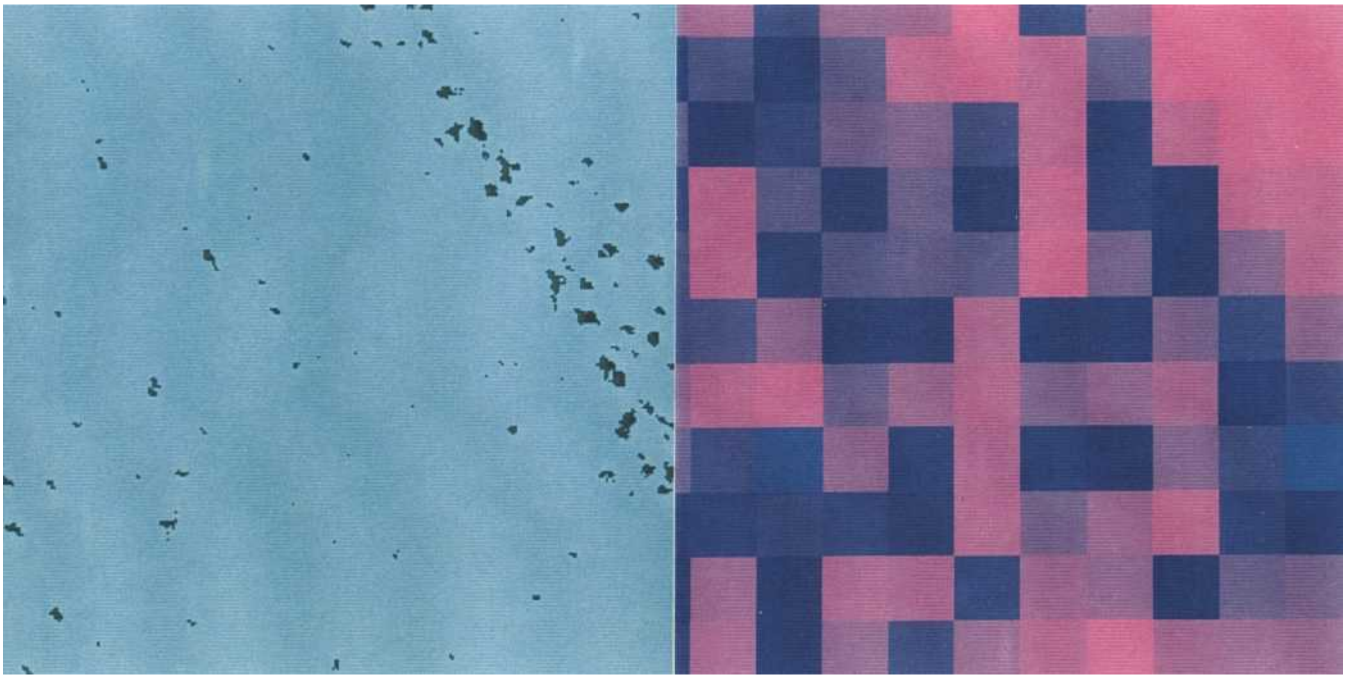
8. **Variation in the defoliation/vegetation-index relationship between species remains the major impediment to using remote sensing for rating forest defoliation levels over wide areas. Development of forms of the relationship that are species-specific (or specific to a group of species) appears to have potential if such groups can be identified by some independent means. Simple stratification of forest types based on their near-infrared reflectance may offer an independent way of sorting species into groups with a similar defoliation/vegetation-index response. Further research is required to confirm this.**

The greatest challenge identified by this study to the use of remote sensing for acquiring data on canopy defoliation over wide areas is variation in the defoliation/vegetation-index relationships between tree species. For example, conifers exhibit a very low near-infrared reflectance. This results in undamaged specimens having red/infrared vegetation indices that are representative of maire and kamahi trees that are largely defoliated. Other species, such as horopito and wineberry, have high reflectance at both red and near-infrared wavelengths, a combination that again results in vegetation indices for undamaged trees that are associated with high defoliation levels in maire or kamahi. The only option for dealing with this problem is to develop forms of the defoliation/vegetation-index relationship that are species-specific (or specific to a group of species with common spectral features). For the limited range of species in conifer-broadleaved forest that have been studied to date, segregation of forest species on the basis of their near-infrared reflectance has provided an independent way of forming groups which have common defoliation/spectral-index responses. Whether this method will continue to be valid when extended to a wider range of species can only be determined through further research.

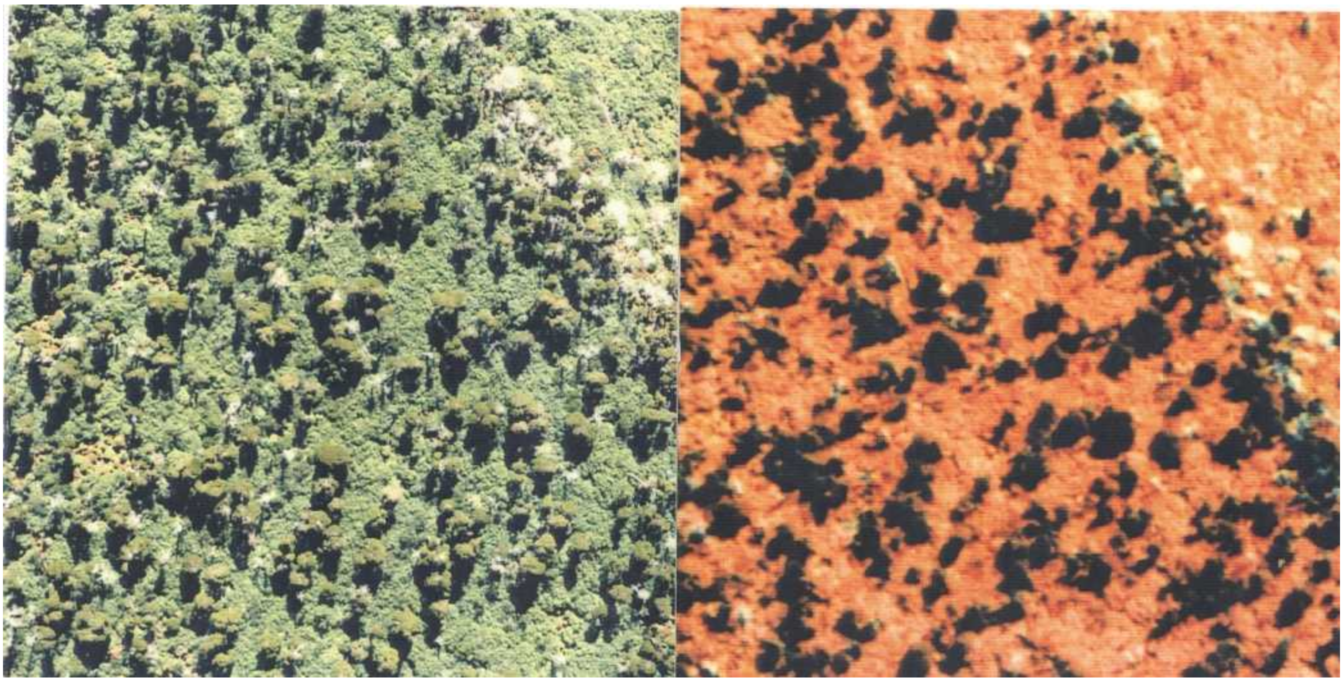
6.2 RECOMMENDATIONS

Future studies be used to:

1. Resolve the sources of variation that exist between ground-measured and vegetation-index-estimated defoliation levels. This will involve rating defoliation levels in a large sample of trees, with multiple ground-based observers, and noting such things as epiphyte presence/absence that might confuse the remotely-sensed rating.
2. Investigate regions of the spectrum that are not accessible to CIR photography, but have proved useful for defoliation studies in conifer forest



A B



C D

Figure 11. Examples of quantitative products from remote sensing. A-distribution of dead canopy; B-conifer density shown in five steps (magenta to light blue, lowest to highest density respectively) and averaged on a 20 m grid; C-a 1:1000 scale natural colour photo of the same area; and D-an extract of the 1:10 000 colour-infrared photo from which the quantitative data is derived.

(e.g., the mid-infrared region of the spectrum), to establish whether the species sensitivity of defoliation/vegetation-index relationships can be reduced.

6.3 EXAMPLES OF INFORMATION PRODUCTS FROM REMOTE SENSING

We provide here a series of image products that illustrate the mapping of defoliation levels, and also give an example of a conifer density map. The need for considerable caution when interpreting vegetation indices as species-independent measures of defoliation is clearly demonstrated by these products (see Fig. 13). In addition, the impact of the spatial-smoothing that occurs at large pixel sizes is illustrated by comparing vegetation indices derived from airborne and Landsat TM data, at two sites (Fig. 11, 12). In the example images that follow, the sun elevation is at least 20° larger than the steepest slope angle, and only subsets of photos which fall within the recommended view angle range of $\pm$20° have been used.

Figure 11 shows data for the Hihitahi site, illustrating the two products than can currently be determined to a high level of accuracy from airborne remotely sensed data: areas with defoliation levels greater than 95%, and conifer density. An extract of a 1:1000 scale natural colour photo is included to provide a good level of visual detail against which to compare the data derived from the 1:10 000 scale colour-infrared photography. Conifers at this site are kaikawaka and Hall's totara, and appear as olive green tones in the colour-infrared photo. Because of their low infrared reflectance, conifers contrast much more with the background of horopito and wineberry in the colour-infrared photo than in the natural colour.

Figure 12 contrasts airborne and satellite colour-infrared data for the Horopito site. The satellite and airborne data were matched to produce equivalent data across the two image types. The conifers present at this site are all rimu. They appear as olive-green tones in the colour-infrared photo, while dead kamahi appear as blue-grey tones. Figures 12e and 12f show red/infrared vegetation index data interpreted as percentage canopy defoliation, using the defoliation/vegetation-index relationship derived earlier, in section 5.1. The red/infrared vegetation index over-represents the area of completely defoliated forest, and results in all rimu being rated as dead trees (Fig. 12e). Grasses and tussocks within the forest, shown as very pale red tones in the colour-infrared photo, are also rated as either completely or highly defoliated, which may be acceptable.

The effect of spatial smoothing in satellite data can be seen in Fig. 12c, where a semi-isolated area containing many dead trees in a matrix of still living vegetation can be seen. Comparing the photo- and satellite-derived vegetation index data for this area (Fig. 12e and 12f) shows that the satellite data contains a smaller proportion of pixels with the highest defoliation severity rating. This is a result of practically all satellite data including both non-defoliated and fully-defoliated areas within the area covered by a given pixel.

Figure 13 shows the airborne data only for the Horopito site, and contrasts the levels of defoliation depicted by red/near-infrared, and red/green, vegetation

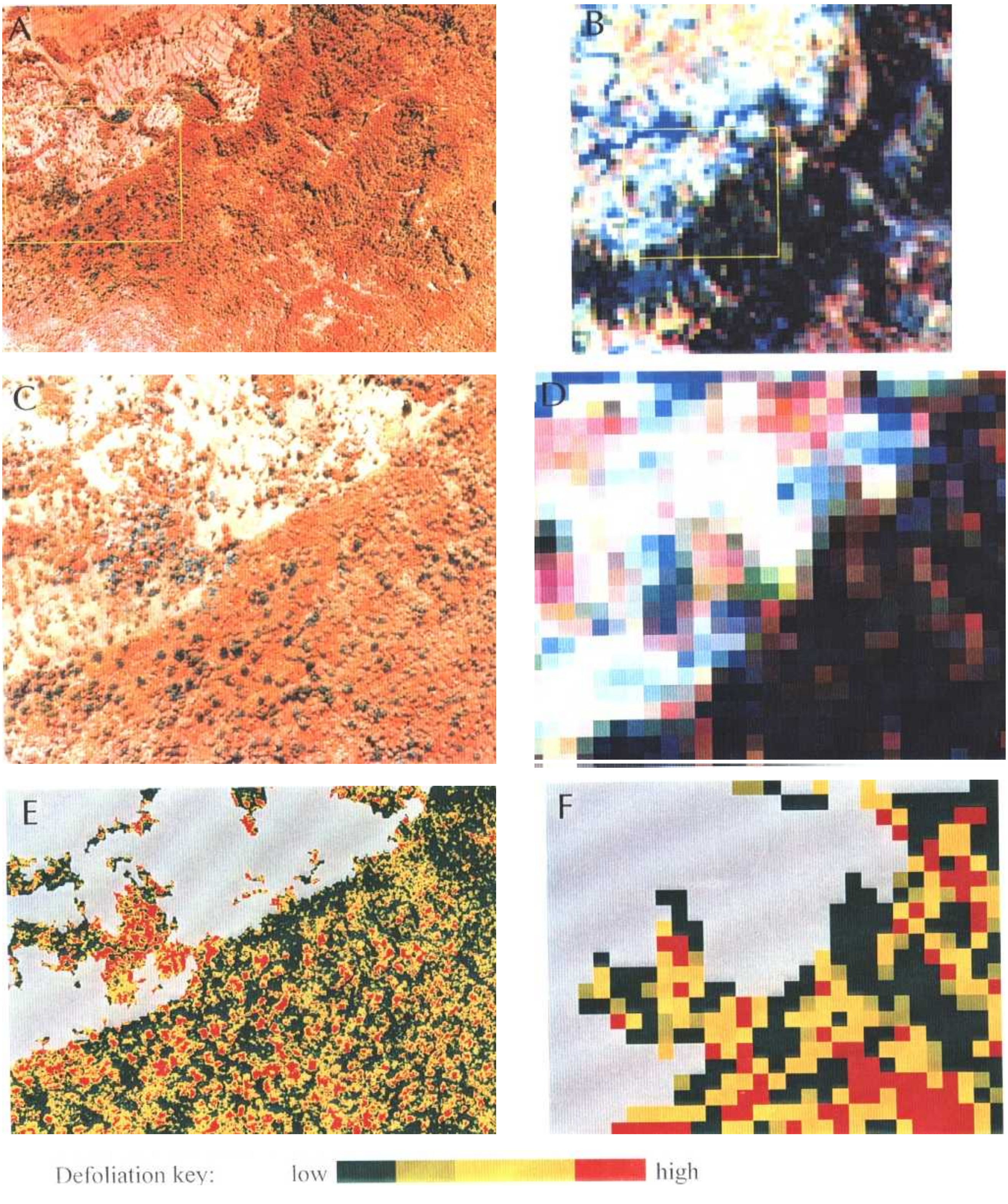


Figure 12. Comparison of data for the Horopito site, derived from an aerial photograph and a satellite image. The location of the site is outlined in yellow on A-an extract of a colour-infrared photo, and I3-a Landsat TM image. The Horopito railway viaduct is immediately below the bottom left corner of the photo extract. The area covered approximately by the site only is shown in extracts C and D, which illustrate the spatially coarse nature of the satellite data (30 m pixels) in comparison with the scale of variation within the forest. Canopy defoliation data derived from a red/near-infrared VI, according to the relationship between defoliation and the VI developed for kamahi, are shown in extracts E and F. (Defoliation is rated in five equal steps of 20% canopy cover: red is <20% cover, and dark green is more than 80% cover.)

indices. Inspection of the data derived from the red/green index reveals that rimu are no longer rated as defoliated, although areas of grasses/tussocks continue to show as completely or highly defoliated. This difference in representation of the defoliation state of the forest by the two vegetation indices is as expected from the earlier results obtained for individual trees (see Fig. 10).

Figures 14 and 15 present data for Hihitahi. The steeper topography at this site makes it more difficult to match the airborne and satellite data because of differences in the extent of shadowing and in the topographic effect. These arise because the sun elevation and position were significantly different at the times of acquisition of the two image types. This did not lead to significant problems at the Horopito site, because it is relatively flat. The satellite- and airborne-derived data for the Hihitahi site are therefore only approximately equivalent. Figure 14 contrasts the colour-infrared data from airborne and satellite sensors, and again illustrates the effect of spatial averaging inherent in satellite data. It also shows that the red/infrared vegetation index grossly over-estimates the amount of defoliation present at this site, by including undamaged conifers, horopito, and wineberry, in either the completely or highly defoliated classes (Fig. 14e). In contrast, the defoliation levels predicted by a green/red vegetation index are more realistic (Fig. 15c), although they are still of limited absolute accuracy. These results are consistent with earlier results obtained for individual trees (see Fig. 10).

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