Mapping forest cover, Kimberley Region of Western Australia

G. Behn[1], F.H. McKinnell[1], P. Caccetta[2] and T. Vernes[1]

[1]Department of Conservation and Land Management
Locked Bag 104, Bentley Delivery Centre, WA 6983
[2]CSIRO Mathematical and Information Sciences
Private Bag, PO Wembley, WA 6014

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Summary

About half the total forest area of Australia lies north of the Tropic of Capricorn. Improved information about northern forest and woodlands is required for national level statistics, forest policy development, reserve system planning and for ongoing management by relevant State and Territory agencies.

NORFOR, an initiative of National Forest Inventory (NFI), addresses this need. It involves a partnership between Western Australia, Northern Territory and Queensland in the development of a common system for processing of satellite remote sensing data to achieve a consistent product that reliably details the extent of forest cover and broad forest types across northern Australia.

For the purpose of the project three locations across northern Australia were selected to trial the agreed methodology: the Kimberley region of Western Australia, the Daly Basin of Northern Territory and the Einasleigh Uplands of Queensland.

This paper reports on the work in the Kimberley region and describes the methodology used for acquiring ground information, satellite image production and the processing techniques to produce the forest cover map. It also considers issues associated with determination of the forest/savannah boundary and the effect of fire on the reliability of mapping.

Introduction

Forest inventory in Australia is undergoing a marked change as a consequence of the adoption of a definition of forest that is in line with that used internationally. This new definition was first used in the Montreal Process First Approximation Report (Montreal Process 1997) and subsequently in the State of the Forests Report (NFI 1998). Forest is now defined as: ‘Land dominated by trees having a mature codominant height greater than 2 metres and a canopy cover greater than 20 percent.’ In practice the lower limit of 20 percent canopy cover is loosely applied as the cut-off point is often difficult to define on the ground.

The main effect of this change is that the forest estate now includes extensive areas of vegetation in Australia formerly referred to as woodland. As a result, the total area of forest has increased from about 43 million ha (in the high forest zone) to an estimated 156 million ha overall. Much of this additional forest lies in the northern part of the country, where the data for forest cover and forest type are of much poorer quality than in the south.

The National Forest Inventory (NFI) is a cooperative State-Federal initiative aimed at providing improved national level data on forest resources. It funds cooperative projects in States that contribute to the national forest database. One of the issues facing the NFI is the compatibility of forest-related data between adjacent States. NORFOR is a cooperative project between Western Australia, Northern Territory and Queensland that addresses this issue by first developing a common methodology and then applying it across the whole of northern Australia, an area of some 60 million ha of forest.

The existence of reliable data for forest cover for northern Australia will enable completion of the NFI continental forest cover map to an acceptable standard. It will also greatly improve the accuracy of reporting for the Montreal Process criteria and indicators of sustainable forest management, the periodic national State of the Forests Report and carbon storage estimates for greenhouse gas accounting. All these are important contributors to policy formulation.

Satellite remote sensing was considered the only viable approach to mapping an area of such size, given the time constraints of the project, and the need to update the results on a regular basis to detect time trends. The success of remote sensing projects of this magnitude elsewhere within Australia (Woodgate and Black 1988; Ritman 1994; Kuhnell *et al.* 1998) indicated the potential of the technology to provide useful results for this purpose. Landsat Thematic Mapper (TM) imagery was chosen as providing the best balance between accuracy, cost and sensitivity.

TM imagery can provide routine broadscale coverage of an area and is ideal for mapping and monitoring (Pickup *et al.*1993). The ground picture element (pixel) size (30 m) is practical for broad-area surveys and gives results appropriate for resolution with at least several trees and shrubs per pixel and several pixels per homogeneous damage area. Monitoring change also becomes possible with the ability to co-register and analyse imagery from various dates. Landsat TM records measurements in the visible and infrared region of the electromagnetic spectrum and thus observation of ground cover cannot be obtained if cloud is present, and is a factor that needs to be considered.

The nature and distribution of different vegetation associations in the Australian environment create reflectance values and patterns in remotely sensed data that are quite different from those in other parts of the world. The differences are due to the structure of the plant communities, the density of plant foliage, the unique morphological characteristics of the leaves, distribution patterns of vegetation and the spectral characteristics of the soil background (O'Neill *et al.* 1990). Causes of these differences in the Kimberley can be related to seasonal conditions or fire impacts. Due to the predominantly open canopy and sparse vegetation that is generally characteristic of the Kimberley region the thermal band of the TM imagery were not used. Behn and Campbell (1992) found minimal site discrimination by including this information in like vegetation classification procedures.

The primary objectives of the project were to:

- Develop a common remote sensing methodology for reliable mapping of forest cover (current extent), structure and broad forest type, for use across northern Australia, using concurrent pilot projects across each State/Territory.
- Carry out the mapping of forest cover using this methodology in the three jurisdictions, to achieve a seamless coverage of forest and woodland over the north of Australia.

Forest structure in this project meant mapping into NFI height and density classes. The height classes are:

- Low – 2 to 10 m mature codominant height
- Medium – 11 to 30 m
- Tall – greater than 30 m

The density classes are:
- Closed forest – canopy cover greater than 80%
- Open forest – canopy cover 50-80%
- Sparse forest (woodlands) – canopy cover approximately 20-50%

Broad forest types are those defined in the Montreal Process First Approximation Report 1997. The types expected in the Kimberley region were as follows:

- Rainforest vine thickets
- Medium open eucalypt forests
- Low open eucalypt forests
- Medium eucalypt woodlands
- Low eucalypt woodlands
- Acacia forests and woodlands
- Mangrove forests and woodlands
- Unclassified forest

In this paper we address the issue of obtaining structure for extent and density. The NFI unclassified type includes forests that are of a heterogeneous mixed type, of unknown type or comprise a mixture of minor genera.

The Department of Conservation and Land Management is responsible for the project in the Kimberley region, with the Northern Territory being covered by The Department of Lands, Planning and Environment. In Queensland the responsible agency is the Department of Natural Resources in association with the Queensland Herbarium.

Location and extent of NORFOR

The biogeographical boundaries from the Interim Biogeographic Regionalisation of Australia (IBRA) (Thackway and Cresswell 1995) were chosen as the basis for delineation of the area to be covered by the NORFOR project. IBRA divides Australia into bioregions containing recognisably distinct suites of vegetation. Using IBRA maps and the NFI definition of forest, it was possible to define the IBRA regions within the Kimberley in which forest will be found. In this way a southern boundary for the project was established (Fig.1).

Figure 1. The approximate location of the NORFOR project

The approach taken by the partners in NORFOR was to test the Landsat methodology in three trial areas, one in each jurisdiction. The combined IBRAs (327 239 km^2) of the Kimberley region were treated as one such trial area, as it was considerably smaller than the total forest areas in the Northern Territory and Queensland, yet contained a variety of vegetation types. The trial area in the Northern Territory was the Daly River IBRA (20 921 ha) and in Queensland the Einasleigh Uplands IBRA (128 075 ha).

The Kimberley trial area comprises five IBRA regions: Dampier (DAM), North Kimberley (NK), Central Kimberley (CK), Victoria Bonaparte (VB) and Ord-Victoria Plains (OVP) (Fig.2).

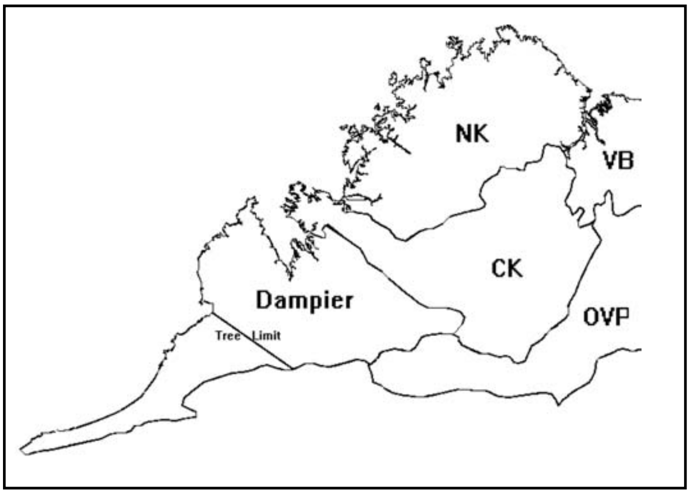

Figure 2. Location of Kimberley IBRA regions

Imagery and site data

Satellite imagery

Imagery acquired in August/September 1994 was chosen to establish the base for the project. This decision was made on the basis that for this period most of the region in question was cloud free, and much of the grass was cured (Duncan *et al.* 1993; Kuhnell *et al.* 1998). A consequence of the latter, however, is that recent fire causes some complications in interpreting subsequent change, and would need to be considered if the exercise was repeated in say, the year 2000.

Thematic Mapper imagery has seven bands - bands one, two and three in the visible parts of the spectrum, band four in the near infrared and bands five and seven in the short-wave infrared portions of the spectrum. The data from these bands can be combined to provide images that reflect particular features of interest on the ground.

Landsat TM data provide broadscale coverage of an area every 16 days, in separate scenes that cover an area about 185 km square or about 3 422 500 ha. The pixel size (30 m) for all channels except the thermal (120 m), is practical for broad-area surveys and gives results with at least several trees and shrubs per pixel and several pixels per homogeneous area.

The choice of which satellite dates to use in 1994 was determined by:

- availability of cloud-free imagery over the area; and
- the need for the grass to be cured to enable separation of the spectral reflectance of trees from grasses.

The dry season in the Kimberley was the obvious choice. However, the major drawback of this choice is the amount and areal extent of annual fire occurrences in the region. Since TM relies on reflectance from vegetation and soil, and recently burnt areas are black, having low, or no, reflectance, they provide little vegetation information to the sensor.

Some twenty-three TM satellite scenes were co-registered against the ground cadastral framework and calibrated (Campbell *et al.* 1994) to form a total mosaic of the Kimberley region shown in Figure 2 . Production of this mosaic is a critical step in establishing a base for subsequent image analysis. Without a mosaic it is not possible to ensure complete coverage of the area, or to ensure that there are no boundary or scale inconsistencies between images.

The data were rectified to latitude/longitude coordinate space with the following parameters;

- datum: WGS84
- projection: Geodetic
- coordinate: EN
- unit: Degrees
- Cell type: Unsigned8BitInteger
- Null cell: 0
- Pixel size : 0.00025 degrees (25 m)

The spatial accuracy has a root mean square (RMS) error of less then 0.0005 degrees to map control (1:100 000 topographic maps).

Calibration was performed by a method described by Furby *et al.* (in press) and includes a linear transformation of a scene to a reference scene. Once calibrated, the digital numbers in one scene are compared to those of another. Calibration attempts to reduce the effects of differences in atmospheric transmittance and sun angle between the target and reference images and allows the whole mosaic to be treated as one seamless image. A minor departure from linearity caused small problems with the calibration of some scenes. Where this occurred a non-linear relationship was used.

Aerial photos

The basic objective of the project was to accurately estimate the variation in projective foliage cover (PFC) across the landscape. A key factor in using satellite imagery for this purpose is to be able to reliably calibrate the satellite image with what we see on the ground. Field validation plots were established across a range of forest types and IBRAs to provide this calibration. Within each Kimberley IBRA region, transects 5-10 km long were located that best represented the variation in forest cover and forest type in the region. These transects were chosen by using expert field staff on the basis of ground and botanical knowledge. Within the transects, 500 m^2 field validation plots were established in areas of homogeneous forest, to gather data on canopy cover, tree crown opaqueness, overstorey and understorey species composition and soils. A total of 180 field validation plots was established across the Kimberley region and marked as permanent plots for future use as monitoring sites.

Canopy cover measurements are difficult to make objectively in field plots, so it was decided to estimate the canopy cover by using aerial photographs that covered the transects. This method increased the speed and amount of site selection, identified canopy variations and forest types, and assisted with the site accessibility for field surveys.

Aerial photography covers the entire Kimberley region at varying scales. From inspection of 1:40 000 or 1:50 000 scale black and white photos it was possible to discriminate between the differing tree cover densities. Photos that covered the identified transect and the field plots were then obtained, digitised and co-registered to the satellite image mosaic. Canopy cover in the field plots was measured on aerial photographs using dot grid templates. The template assumes an opaque crown. To convert the canopy cover to foliage cover (which is what the satellite imagery responds to), ground measurements on a range of sample plots establish the degree of actual crown opaqueness.

Using the digitised aerial photographs, canopy cover templates and crown type diagrams, estimates of PFC were made for each of the field validation plots. These values were then used in the spectral analysis to show the discrimination between layers or classes within the woody category, representing differing forest densities.

The limits to forest cover

Another important issue was to establish the lower limit of canopy cover for what was classified forest. As outlined above, the NFI uses 20% canopy cover as the lower limit, although this figure is interpreted flexibly in the field.

It is important to appreciate that what the Landsat TM image portrays is projective foliage cover, not the canopy cover, which is the attribute used in the NFI definition of forest. Whereas PFC is the projection, on the ground, of the extent of foliage on the tree, a circle describing the extent of the crown gives canopy cover. Here we use the result of McDonald, *et al.* (1990) which estimates that a PFC of 15% is equivalent to a canopy cover of about 20% multiplied by 75% crown openness.

A range of the field validation plots was examined in the field to establish the lower limit of canopy cover for forest, using the NFI definition. Under the conditions encountered in the Kimberley region, a projective foliage cover of 15% was established by a group of experienced observers as the practical boundary between what was plainly vegetation dominated by trees (forest) and what was clearly not dominated by trees (savannah). This figure was used to prescribe the boundary for forest/non-forest for the image analysis in this project. The difference between forest and savannah is illustrated by Figures 3, 4 and 5, photographs from field validation plots, which depict Kimberley forest of <10%, 15% and 20% PFC respectively.

Figure 3. Savannah with a projective foliage cover of less than 10%.

Figure 4. Forest with projective foliage cover of 15%.

Despite the use of an objective definition of the savannah-forest boundary in this way, it is still possible for errors to be made in classifying an area as forest or non-forest. Variations in reflectance values can be due to poor crown condition as a consequence of severe late-season fire or drought. There may be just as many tree stems, of similar size, in two adjacent areas but one may fail to be classified as forest due to previous crown damage that caused it to fall below 15% PFC.

Figure 5. Forest with projective foliage cover of 20%

Site data

One hundred and eighty field sites across the five IBRA regions were considered as candidates for field survey. The number of sites actually ground surveyed was 106, including an additional 21 new sites added during the survey. Time constraints and site accessibility were important factors in limiting the actual number of sites visited. The vegetation was classified using either Specht or Walker and Hopkins (McDonald *et al.* 1990). Line intercept techniques were used to measure frequency and cover of species within the quadrant. Crown covers of the dominant wood layer were measured along a transect and a correction applied (described above) to the data of the emergent and dominant tree layer to compensate for light penetration through the canopy to give the foliage projective cover (PFC). The 21 additional sites were established in vegetation types poorly sampled or to replace inaccessible plots of similar vegetation density. Observational site information was also collected for an additional 64 sites whilst traversing four IBRA regions, to assess the accuracy of the results. Information recorded included location, (%) PFC canopy, (%) PFC ground storey, cover (%) litter, rock and bare ground estimates. These sites were chosen to be large homogeneous areas having values spread between the lower and upper limits of vegetation density.

Image analysis

Spectral information

Reflectance spectra of forest stands are the combination of reflectance spectra of trees, understorey, shadow, debris and the underlying soil. Forest reflectance spectral values depend on the proportions of these different elements in a pixel, and which are visible from above. When the tree crowns are not dense, the effect of underlying soil and vegetation can be dominant and can mask the effect of the trees. The reflectance of a forest canopy can display large differences from leaf reflectance when there is a large contrast between trees and understorey vegetation.

Inspection of preliminary TM images of the Kimberley indicated there were several distinct zones of reasonably uniform appearance. On further examination, it was found that these zones closely coincided with the IBRA regions, probably reflecting the varying geological zones and suites of vegetation on which the IBRA regions are based. It seemed possible, therefore, that the statistical relationship between the spectral image and forest cover could vary between IBRA regions. To test this hypothesis, the imagery was divided so that the five

IBRA regions that cover the Kimberley were processed individually.

The crucial factor in producing spectral maps or enhancements which reliably display areas of greater than 15% PFC is that the spectral separation of the dense from the sparse tree canopy classes is large, compared to the variation within classes. If this can be established, then important band combinations, which provide the discrimination, can be identified and appropriate enhancements produced. A classification mapping approach can also be adopted and pixels allocated with confidence to one or other of the classes (or to none).

Canonical variate (CV) analysis (Anderson 1958) was used to summarise the separation between selected training sites. Associated routines allow the important discriminating spectral bands to be identified (McKay and Campbell; 1982 Campbell 1984). The CV analysis summarises the separation between sites in the multivariate (6 bands = 6 dimensions) spectral space. It discovers successive band combinations (vectors) which maximise the spectral separation of training sites. These vectors are referred to as canonical vectors and associated with each vector is a canonical root, a number that is an index reflecting the overall degree of spectral separation between sites along that vector. The sum of the canonical roots gives a measure of the overall separation in all dimensions. The first CV direction is the single axis having the greatest spectral site separation. Frequently, the site separation in spectral space can be adequately summarised by the first few canonical variates, thus reducing the dimensionality of the training sites while maintaining relevant information on the clustering and separation. Bands that make only a small contribution to the spectral separation of sites can then be eliminated using band reduction routines. The results may be used to identify useful image enhancements, or as input to allocation procedures.

Data for the North Kimberley IBRA region are presented here (Fig. 6) to illustrate the process of developing a relationship between spectral reflectance and PFC and translating the relationship to a map of forest cover. The canonical variate plot shows the separation of dense tree canopy from that of sparse or no canopy. Figure 6 also demonstrates how dark or burnt areas influence the spectral separation of the sites.

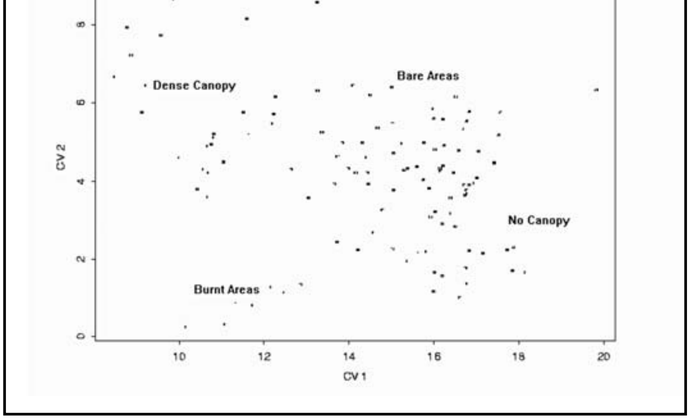

Figure 6. Canonical variate (CV) plot of vectors 1 and 2 of the site data for the North Kimberley IBRA region.

Procedures were directed to contrast those sites which have dense PFC to those with little to no PFC. The results established that satellite TM bands 3, 4 and 5 were most significant in separating the sites and that they provided more than 96% of the separation. The canonical variate analysis was re-run using only these spectral bands; the resultant CV plot (Fig. 6) displays the first and second vectors. Again, sites of high PFC were contrasted against sites of low PFC to establish a smoothed band combination or index for the North Kimberley IBRA, the established index being:

-(3* Band 3) + (3*Band 4) – (Band 5).

For the indices developed (Table 1), it is observed that woody vegetation increases with increasing greenness (a combination of TM satellite bands 3 and 4) and decreasing band 5 values. This result is consistent with those obtained by and Everitt *et al.* 1987. Kuhnell *et al.* 1998.

This band index was then applied to the IBRA region to produce an index image. Mean values for the training sites were extracted from this image. These values were then regressed against the PFC estimates. The resultant linear equation was applied to the index image, creating an expected Projective Foliage Cover image over the IBRA region.

Further analyses established that there were appreciable differences in the relationship between index values and PFC between IBRA regions. Table 1 shows how these indices vary between the five Kimberley IBRAs.

Table 1. Spectral indices for each Kimberley IBRA

	IBRA region				
	Victoria-Bonaparte	North Kimberley	Central Kimberley	Dampier	Ord-Victoria Plains
Spectral index	-(3*Band3)+ (3*Band4) -Band5	-(3*Band3) + (3*Band4) -Band5	-(4*Band3) + (4*Band4) -Band5	-(5*Band3) + (5*Band4) -Band5	-(4*Band3)+ (4*Band4) -Band5

Where:
Band3 = Landsat TM Band 3
Band4 = Landsat TM Band 4
Band5 = Landsat TM Band 5

It can be seen that the five IBRAs can be grouped according to their spectral index. Victoria-Bonaparte and North Kimberley have the same index, Central Kimberley and Ord-Victoria Plains have the same index while Dampier is different from both other groups.

The difference between the regressions for the groups shown in Figure 7 is of practical significance. Therefore it will be necessary to calibrate the index/PFC relationship for each IBRA to ensure accurate mapping of forest cover in this region

Results and discussion

The PFC images obtained by this procedure were combined to map areas of like forest cover density within each of the IBRA regions. Figure 8 below presents the forest cover map for the entire Kimberley area derived in this way.

Observational information from field inspections was used to validate the accuracy of the mapping and confirmed the detection of forest/non-forest boundaries by this methodology. Of the 64 validation sites (Table 2), 43 were located within forests of varying canopy densities and description with the remaining 12 sites located in areas with little to no tree cover.

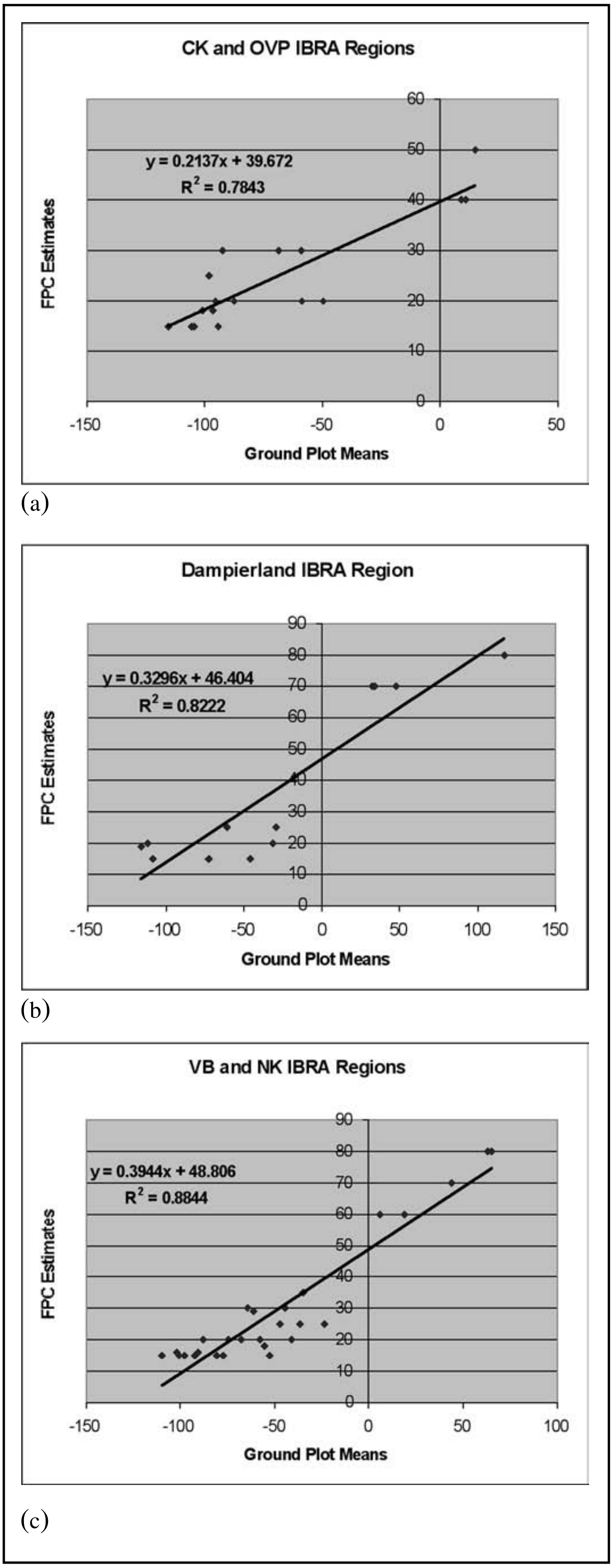

Figure 7. Graphs (a), (b) and (c) show the mean values of the derived index of field plots for each of the IBRA regions regressed against the estimated PFC values. Graphs (b) and (c) tend to suggest further stratification within those IBRAs may be appropriate.

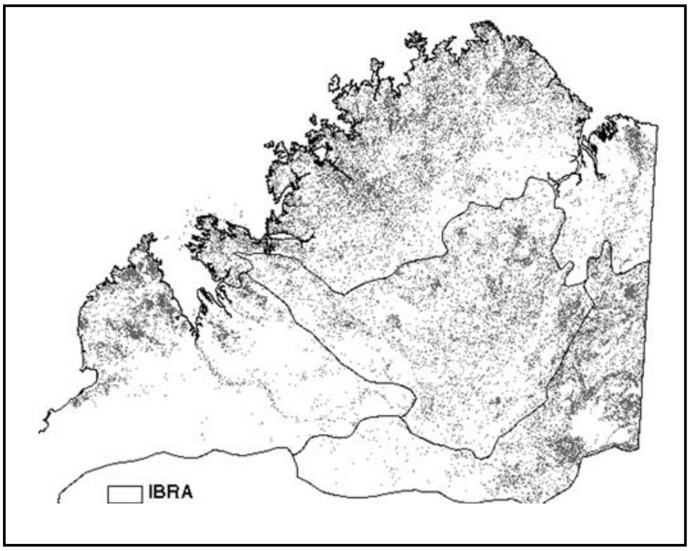

Figure 8. Forest cover map for the Kimberley region

Table 2. Ground accuracy data: the number of sites falling within each category

	Mapped forest	Mapped non-forest
Observed forest	43	6
Observed non-forest	3	12

From Table 2, the overall mapping accuracy (forest/non forest) is 86%. The sites were identified with an accuracy of 93% and 66% for forest and non-forest sites respectively.

Next, we compared the field recorded PFC values with those of the image values. From Figure 9, the linear regression between observed ground PFC measurements and the image estimates has an $R^2 = 0.73$. The larger variances are attributed to two principal causes:

1. Vegetation changes from fire occurrences, both increases and decreases in cover; and 2. Time between image capture (1994) and actual image processing (1998). This is of particular importance when assessing accuracy.

Subtle variations can also be attributed to physiographic regions and their sub-regions, seasonality and plant morphology.

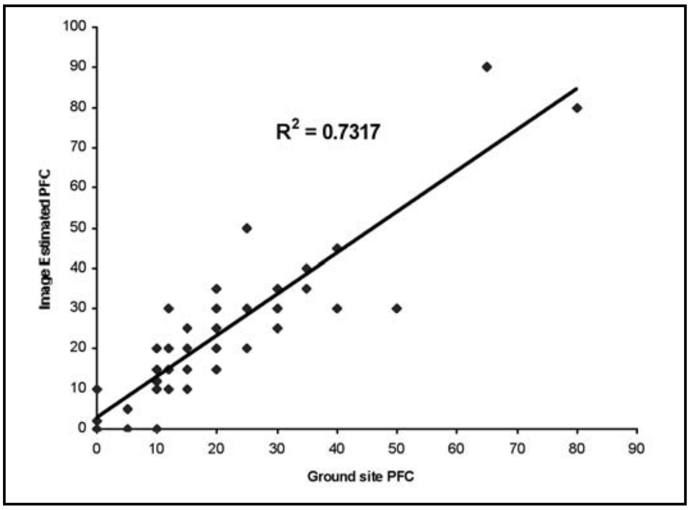

Figure 9. PFC of ground recorded sites against image results

It was not possible to discriminate reliably between different NFI forest types or height classes with Landsat imagery. While the field validation plots did give indications of consistent height or forest type differences on different geological substrates, there was not enough information for reliable mapping. Some forest types, such as mangrove (Danaher 1994) and rainforest vine thickets (Kay *et al.* 1991) can be mapped using satellite imagery. It was not possible, however, to differentiate between other NFI types, such as acacia and eucalypt forests, or between medium (11-30 m) and low (2-10 m) eucalypt forests. Development of an NFI forest type map for the region therefore required a different approach.

The Kimberley region is covered by 1:250 000 scale vegetation maps (Beard 1989) developed from a combination of aerial photography and ground inspection. Vegetation is classified from an ecological standpoint into various species mixtures and structural types. In the absence of a better technique we used this vegetation map for forest type classification. The Beard vegetation types relevant to forests were examined and grouped to conform to the NFI forest types listed earlier in this paper. While this is not ideal, from the viewpoint of management it does give far better data on forest occurrence than before.

The final stage of the project was to use a Geographical Information System to intersect the forest cover data derived from the Landsat imagery with the NFI forest type categories (based on Beard's vegetation mapping) to establish a structure and broad forest type map.

Since the Landsat imagery permits us to classify the forest cover into density classes, we have presented the forest cover data here in four classes, rather than the three classes used by the NFI, to illustrate the flexibility possible in an all-digital environment (Table 3).

Table 3. NFI Forest Type area statement for the Kimberley Region by PFC class (ha)

	Projective foliar cover class (%)				
NFI forest type	15-30	30-50	50-80	80-100	Total
Rainforest	2108	9146	6207	240	17701
Mangrove	15220	23536	70077	14449	123282
Acacia forest	564377	11412	301	13	576102
Low eucalypt forest	173198	21034	7434	306	201972
Medium eucalypt forest	1843266	275382	25857	965	2147471
Unclassified forest	23797	6541	2573	434	33345
Total	2621966	347051	114449	16407	3099873

About half of the 15%-30% PFC class would have been eliminated as forest if we had used a higher cut-off figure of 20% PFC for the image analysis. Whether this figure is generally applicable to inland and northern forest elsewhere in Australia, where satellite imagery is likely to be used to monitor vegetation cover, should be investigated.

A major problem in the image analysis is accounting for the effects of wildfire, a dominant factor influencing forest extent and composition in the Kimberley. Fires cover extensive areas every dry season. Late season fires, in particular, can be very damaging and may kill the overstorey (especially acacia) over large areas, resulting in rapid changes in forest extent at a particular time.

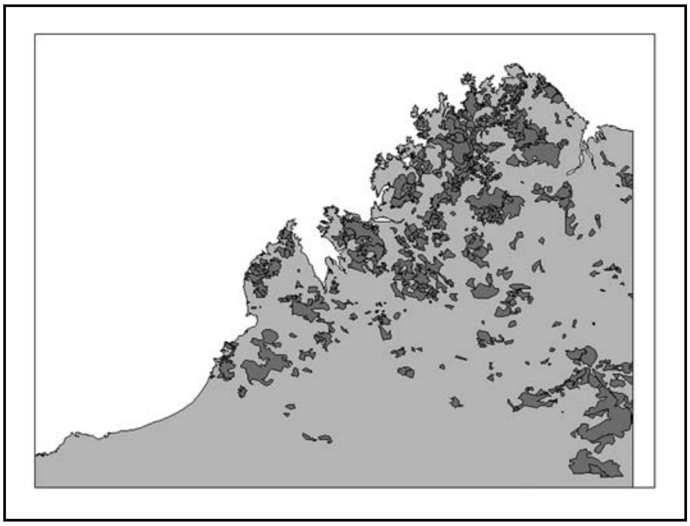

Figure 10. Composite map showing all fires that occurred in the Kimberley region during 1994 (Department of Land Administration, WA)

Figure 10 shows the area burnt during the 1994 fire season across the Kimberley region. The map is based on Advanced Very High Resolution Radiometry (AVHRR) imagery (which has a 1 km resolution) and includes both early and late season fires, so the impact of the fires is not as serious as the map suggests. Nevertheless, the map does demonstrate the significance of fire in this region.

In this project we have concluded that it is too subjective a process to attempt to classify recently burnt forest, and we map it as 'unclassified'. It is quite clear that we are dealing with a totally different situation from southern forests, where forest cover is relatively stable. In the north, forest cover is much more dynamic, the cover on a particular area varying over a relatively short period as a consequence of haphazard fire events.

The methodology described here provides a sound basis for rapid, accurate mapping of forest cover across the more sparsely populated regions of Australia where the use of conventional aerial photography cannot be economically justified. However, our results indicate that the calibration of the PFC/spectral index relationship is needed for each IBRA.

To date, extrapolating (surrogate) ground truth PFC estimates obtained from aerial photo interpretation has derived estimates of the spatial extent of forest cover in the Kimberley. Extrapolation makes use of relationships between PFC and Landsat TM observations. These would be useful avenues to explore in future development.

Aspects of providing PFC estimates not considered in this report but which warrant further investigation include:

1. The use of multitemporal Landsat TM data to improve estimates;
2. Alternative criteria for partitioning the Kimberley into like areas;
3. Different spectral indices and function fitting alternatives (for example spectral unmixing) and;
4. The reliability of density estimates through time, especially in low canopy cover conditions.

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References

Anderson, T. W. (1958) *An Introduction to Multivariate Statistical Analysis*. Wiley, New York.

Beard, J.S. (1979) *Vegetation Survey of Western Australia, Kimberley*. University of Western Australia Press.

Behn, G.A. and Campbell, N.A. (1992) Dieback assessment, using multispectral data, over the Stirling Range National Park. In: Proceedings. 6th Australasian Remote Sensing Conference, Vol. 1 pp. 160-168. Wellington, NZ.

Campbell, N.A. (1984). Some aspects of allocation and discrimination. In: van Vark, G.B. and Howells, W.W. (eds), *Multispectral Statistical Methods in Physical Anthropology.* pp. 177-192, Reidel, Amsterdam.

Campbell, N.A. Furby, S. and Fergusson, B. (1994b) Calibrating images from different dates. Report to LWRRDC. Project CMD1. CSIRO Division of Mathematics and Statistics, Perth.

Duncan, J. D. Stow, D., Franklin, J. and Hope, A. (1993) Assessing the relationship between spectral vegetation indices and shrub cover in the Jornada Basin, New Mexico. *International Journal of Remote Sensing* **14,** 3395-3416.

Danaher, K.F. (1994) Mapping mangrove communities in Cape York Peninsula using Landsat TM data. Proceedings of the 7th Australasian Remote Sensing Conference.

Everitt, J.H., Escobar, D.E., Alaniz, M.A. and Davis, M.R. (1987) Using airborne middle-infrared (1.45-2.0 mm) video imagery for distinguishing plant species and soil conditions. *Remote Sensing of the Environment* **22**, 423-428.

Furby, L.S., Campbell, A.N. and Palmer, J.M., (in press) Calibrating images from different dates to like value digital counts' *Remote Sensing of the Environment.*

Kay, R.J., Hick, P.T. and Houghton, H.J. (1991) Remote sensing of Kimberley rainforests. In: McKenzenie, R.B., Johnston, R.B. and Kendrick, P.G. (eds) *Kimberley Rainforests Australia*, Chapter 4. Surrey Beatty and Sons, NSW.

Kuhnell, C.A., Goulevitch, B.M., Danaher, T.J. and Harris, D.P. (1998) Mapping woody vegetation cover over the State of Queensland using Landsat TM imagery. In: Proceedings, 9th Australasian Remote Sensing and Photogrammetry Conference, July 1998, Sydney, Australia.

McDonald, R.C., Isbell, R.F., Speight, J.G., Walker, J. and Hopkins, M.S. (1990) *Australian Soil and Land Survey Field Handbook.* Second Edition. Inkata Press, Melbourne and Sydney.

NFI (1998) *Australia's State of the Forests Report 1998.* Natural Forest Inventory, Bureau of Rural Sciences, Canberra ACT.

McKay, R.J. and Campbell, N.A. (1982) Variable selection techniques in discriminant analysis. 1. Description. *British Journal Mathematical and Statistical Psychology* **35,** 1-29.

O'Neill, A.L., Hardy, S., Fraser, S.J. and McCloy, K.K. (1990) Leaf morphology and the spectral reflectance of some Australian plant species. In: Procedings. of 5th Australasian Remote Sensing Conference. Perth. pp. 1096-1104.

Pickup, G., Chewing, V.H. and Nelson, D.J. (1993) Estimating changes in vegetation cover over time in arid rangelands using Landsat MSS data. *Remote Sensing of the Environment*. **43**, 243-63.

Ritman, K. (1994) Vegetation mapping for the Murray Darling Basin using Landsat TM. In: Proceedings of the 7th Australasian Remote Sensing Conference, 1-4 March 1994, Melbourne, Australia.

Thackway, R. and Cresswell, I.D. 1995 (eds) *An Interim Biogeographic Regionalisation for Australia: a framework for establishing the national system of reserves, Version 4.0.* Australian Nature Conservation Agency, Canberra.

The Montreal Process (1997) *Australia's First Approximation Report for the Montreal Process.* MIG Secretariat, Forests Branch, Department of Primary Industries and Energy, Canberra, ACT.

Woodgate, P. and Black, P. (1988) *Forest Cover Changes in Victoria.* Department of Conservation, Forests and Lands, Melbourne Victoria.