

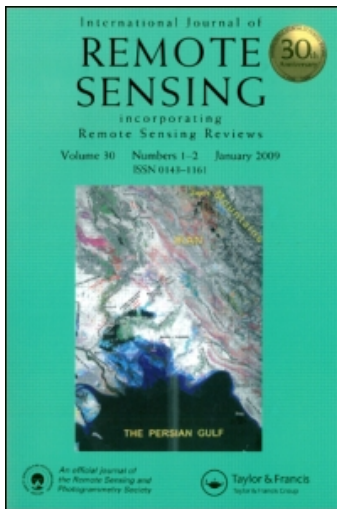
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## Discrimination of dominant forest types for Matschie's tree kangaroo conservation in Papua New Guinea using high-resolution remote sensing data

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Matschie's tree kangaroos (*Dendrolagus matschiei*) are arboreal marsupials endemic to the Huon Peninsula in Papua New Guinea (PNG). Primarily because of an increase in hunting pressure and loss of habitat from agricultural expansion, *D. matschiei* is currently listed as endangered by the International Union for the Conservation of Nature. This paper reports the results of our study to compare the capabilities of Landsat-7 Enhanced Thematic Mapper Plus (ETM+) and Satellite Pour l'Observation de la Terre (SPOT)-4 multispectral image data at discriminating dominant forest types at a remote research location in PNG. Nearest-neighbour vegetation plots were established from July to August 2004 to obtain detailed information about the vegetative communities and guide class assignments. Forests were separated into four distinct habitat types with *Dacrydium nidulum* dominant forests being the most widespread and the most accurately classified. The comparative results indicated that Landsat-7 and Spot-4 had similar classification accuracies but the results were low because of the complex structure and heterogeneity of the forest communities and the limited spatial/spectral resolutions of the satellite data sources. This research provides an improved result compared to past research and provides detailed information towards the future conservation of Matschie's tree kangaroo habitat in PNG.

### 1. Introduction

Tropical forests are recognized for their unique structural, floristic and microclimate characteristics and are some of the richest ecosystems in terms of biodiversity worldwide (Laurance and Laurance 1999, Stibig *et al.* 2003). Although occupying less than 7% of the terrestrial surface on earth, they contain more than half of all plant and animal species (Raven 1988, Myers 1992). The Food and Agriculture Organization (FAO) of the United Nations has estimated that over the past decade (1990–2000), tropical forests are being lost at approximately 12.3 million hectares annually (FAO 2001). Papua New Guinea (PNG), by contrast, is one of a few remaining tropical locations where habitat loss and deforestation have occurred at

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relatively low levels ( $0.1 \text{ km}^2 \text{ year}^{-1}$ ) (McNeely *et al.* 1990). Although preliminary results from an ongoing forest change assessment (1970–2003) conducted by the University of Papua New Guinea (UPNG) show a considerable amount of loss, even in high-altitude montane forests (P. Shearman, personal communication, 2007), PNG is reported to have the largest tracts of mature rainforest remaining in the Asian/Pacific region (McNeely *et al.* 1990). Mainly because of the rugged terrain and high cost of developing infrastructure, over 70% of the country (34 million hectares) is still covered by dense tropical rainforest (Saulei 1990).

PNG, regarded for its rich biodiversity and species endemism (Flannery 1995, 1998, Diamond 1997), is a high priority for conservation (Beehler 1993, Dinerstein and Wikramanayake 1993) not only because of the large proportion of intact rainforest but also because 95% of all land remains in traditional clan-based land ownership (Osborne 1995). Recognizing this potential for conservation, the Tree Kangaroo Conservation Program (TKCP) has been working with local landowners since 1996 to establish a conservation area in the Huon Peninsula. To date, over 85 000 hectares of land have been pledged for conservation.

At the centre of conservation efforts is the Matschie's tree kangaroo (*Dendrolagus matschiei*), an arboreal marsupial endemic to the Huon Peninsula. Primarily because of an increase in hunting pressure and loss of habitat from agricultural expansion, both consequences of rising human population levels (Flannery *et al.* 1996, Flannery 1998, Newell 1999), *D. matschiei* is currently listed as endangered by the International Union for the Conservation of Nature (IUCN 2006). As the largest mammals on the Huon (Flannery 1995), they are an important part of the traditional culture of the people and serve as a focal species for the conservation of large tracts of forest habitat (Pugh 2003). If established, the bioserve will represent the first conservation area ever established under the PNG Conservation Areas Act (enacted in 1998) and will protect tree kangaroos and their habitat, and provide a model for future conservation programmes.

Identifying potential habitat is an essential element to the conservation of any species. In largely inaccessible locations, such as PNG, where travel is restricted to footpaths and light aircraft, remote sensing technology offers the greatest potential for vegetation and land-cover mapping (Conway 1997). Martin *et al.* (1998) suggest that the development of species classification methods using remotely sensed data may be the most effective approach for obtaining assessments of forest cover over large areas and at fine spatial scales. The classification of tropical forests in mountainous areas, however, is not without its challenges because: (1) clouds and/or haze are common and often obscure study areas, restricting image acquisition and adding complexity to image preprocessing, (2) topographic variation adds shadows that can have adverse effects on image classification, and (3) rainforests are composed of a variety of vegetation species at different canopy levels, leading to difficulty in spectral differentiation among species (Trisurat *et al.* 2000).

Landsat satellite imagery has been proven to be useful in mapping vegetation in tropical forest areas (Sader *et al.* 1990, Foody and Hill 1996) because of the two mid-infrared spectral bands (band 5 at  $1.58\text{--}1.75 \mu\text{m}$  and band 7 at  $2.08\text{--}2.35 \mu\text{m}$ ) that are less sensitive to atmospheric perturbations and high spatial resolution (15 m) of the panchromatic band (Trichon *et al.* 1999). Past research conducted by the TKCP used Landsat-7 Enhanced Thematic Mapper Plus (ETM+) data and provided a regional assessment of land cover throughout the entire study area (Pugh 2003), vastly improving available vegetation maps that were based on circa 1970

aerial photographs. Pugh (2003) also combined these data with information collected in the field into a Geographic Information System (GIS) and provided a regional habitat quality assessment of the species. This assessment, however, made no differentiation between the habitat quality of different forest types, essentially classifying all montane forests located between 1000 and 3000 m in elevation and away from village communities (subject to low hunting pressure) as 'Good' habitat. To prioritize areas for conservation, more detailed information was required about the species and about the land cover throughout the area.

This paper reports the results of our research to compare the capabilities of two high-resolution satellite sources, Landsat-7 ETM+ and Satellite Pour l'Observation de la Terre (SPOT)-4, at discriminating dominant forest types throughout a subset of the TKCP study area, thus providing a necessary base layer to correlate with individual animal locations. Both satellite sources have similar spatial resolutions and near-identical temporal characteristics. While past research also used Landsat-7 ETM+ satellite imagery and provided a broad assessment of land cover throughout the area, our results provide finer detail by increasing the amount of information known about the forest communities through extensive field sampling.

## 2. Methodology

### 2.1 Study area

Research was focused in TKCP's Wasaunon Field Research Area (WASU), Morobe Province, PNG. The area is located between latitude 6°3' and 6°10' S and longitude 146°51' and 146°58' W on the northeastern side of the Huon Peninsula in the Sarawaged mountain range (figure 1). The WASU represents approximately 4000 ha of land that has been pledged for conservation by clan landowners in the local villages of Yawan, Towet and Worin. The area is covered extensively (98%) by upper montane tropical rainforest (Pugh 2003) with an elevation range from 2122 to 3067 m and slopes in excess of 60°. Mean annual precipitation is estimated to be 2717 mm and the mean annual air temperature is 13.4°C (Hijmans *et al.* 2004).

### 2.2 Data sources

In addition to the two satellite sources being compared, a digital elevation model (DEM) was created from Shuttle Radar Topography Mission (SRTM) data, and *in situ* data were collected to improve the classification results. ERDAS Imagine 8.7 software (Leica Geosystems, Heerbrugg, Switzerland) was used for all analyses, unless noted otherwise.

**2.2.1 Landsat-7 ETM+ satellite imagery.** Landsat-7 ETM+ satellite imagery (path 96, row 64) was downloaded from the Global Land Cover Facility (GLCF; [www.landcover.org](http://www.landcover.org)). The scene, acquired on 8 September 2000, depicts a 185 km × 185 km area and contains six multispectral bands at 28.5-m resolution and one panchromatic band at 14.25-m resolution. The thermal band was not used in this study because of its coarse spatial resolution (60 m). The scene is a GeoCover product and was received orthorectified and registered to UTM zone 55 S, WGS 84 spheroid with a root mean square error (RMSE) of less than 50 m (Tucker *et al.* 2004). A resolution merge of the six multispectral bands and the single panchromatic band was performed using cubic convolution resampling. The new dataset possesses six multispectral bands and 14.25-m spatial resolution.

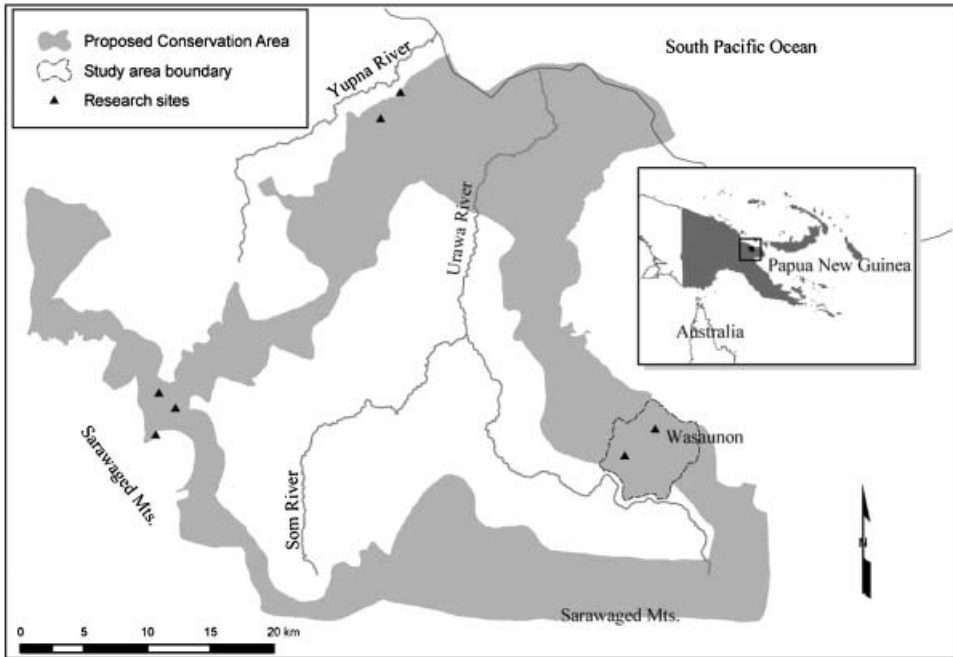


Figure 1. Map of the Tree Kangaroo Conservation Program research area.

**2.2.2 Spot-4 satellite imagery.** Spot-4 satellite imagery was provided by UPNG from their ongoing forest change assessment (P. Shearman, personal communication, 2004). The image has four multispectral bands with 20-m spatial resolution and depicts a 60 km × 60 km area. Two near-vertical ‘stripes’ run throughout the length of the scene; these are errors in the sensor and are localized to the mid-infrared band (band 4). The scene was collected on 7 October 2002 and was received commercially orthorectified to a 90-m DEM created by UPNG with an RMSE of less than 20-m (P. Shearman, unpublished data, 2004). The image was registered to UTM zone 55 S, Australian National spheroid and reprojected to the WGS 84 spheroid.

**2.2.3 DEM.** The DEM used to improve the classification of land-cover categories was created from SRTM data. Data for PNG are distributed in 3 arc-sec or 90-m spatial resolution (USGS 2004). Data voids in the SRTM terrain model were filled with an ancillary data source (PNG 90-m DEM). The PNG 90-m DEM was created from the digitized 1 : 250 000 Joint Operations Graphic (JOG) charts of PNG and the 1 : 100 000 Royal Australian Survey Corps (RASC) series. The PNG 90-m DEM and also the final SRTM DEM were created using ER Mapper software at UPNG (P. Shearman, unpublished data, 2004).

**2.2.4 In situ data collection of ground truth data.** To assist in the vegetation classification, a series of ground reference points (GRPs) were collected from 1 July 2004 to 12 August 2004. These included (1) nearest-neighbour vegetation plots and (2) field survey points. A total of 168 GRPs were collected.

(1) Seventeen nearest-neighbour vegetation plots were conducted within the WASU. Plots were placed in what was best delineated on the ground as distinct and homogeneous because no aerial photographs were available to aid the process. Modified from Webb *et al.* (1976), the plots were based on a set number of stems

from the canopy species of the vegetation type being described rather than a set area (Goosem 1992, Stanton and Fell 2005).

In each of the approximate 0.18 ha plots (ranging from 0.06 to 0.30 ha), a centre tree was identified at random, and the plot separated into four quadrats that coincided with the four cardinal directions (north, east, south, west). The eight nearest canopy species to the centre tree location were marked with flagging tape in each quadrat, for a total of 33 canopy species per plot. Plots were conducted in this fashion for three main reasons: (i) to investigate floristic trends or anomalies that could be used to extrapolate the identified vegetation types outside the surveyed areas, (ii) to provide a dataset that could be used statistically by hierarchical clustering to support or refute the satellite image interpretation, and (iii) to provide baseline information for the vegetation type descriptions.

A voucher specimen from each tree was collected and given a name or hispid name (if unknown) and the specimens kept for identification and lodgment at the National Herbarium in Lae, PNG, with a duplicate set for the Queensland Herbarium (BRI) in Brisbane, Australia. The plant specimens were initially identified at the National Herbarium in Lae, the named species being matched to existing specimens with assistance from the herbarium staff. Forty-two of the 48 canopy species were identified to species level and the remaining six were identified to genus and given a hispid. The authority used for plant names and families was *The International Plant Name Index* (IPNI 2004). Hoft (1992), Henderson (1997) and Mabberly (1997) were also used as references in the herbaria to standardize names. Consequently, only one species identified to species level could not be matched with an IPNI authority. The forest type descriptions were based on those of Webb *et al.* (1976) and Tracey (1987). Coordinates (UTM zone 55S, WGS 84 spheroid) of each plot were collected using a Garmin 12XL GPS unit (Garmin International, Olathe, KS, USA), so that the location and area of each plot could be determined.

Tree height,  $H$ , was calculated using a simple trigonometric formula ( $H = \tan \theta \times x$ ). The distance  $x$  away from the tree was measured using a laser rangefinder (Bushnell Yardage Pro, Bushnell Corporation, Overland Park, KS, USA) and the angle  $\theta$  to the top (and bottom, if not level with the tree base) using a Suunto clinometer (PM-5/360PC, Vantaa, Finland). A distance from each tree of at least 10 m was maintained for accuracy in angle collection. Canopy cover was measured with a concave spherical densitometer (model C, Robert E. Lemmon, Forest Densimeters, Bartlesville, OK, USA). A series of five measurements were made, one from each of the four cardinal points and one from the plot centre. The five measurements were averaged to get a more reliable measure of overall canopy cover throughout the plot. The plot data were tabulated in a matrix of species versus plot, analysed by hierarchical cluster analysis, and grouped into discreet forest types.

(2) Field survey points consisted of visually discernable patches of homogeneous land cover (i.e. grassland, 4 points) and the precise tree species of radio-tracked *D. matschiei* locations (147 points). In April 2004, three sexually mature female *D. matschiei* were fitted with Televilt GPS-PosRec<sup>™</sup> GPS collars (model C200) for a related study investigating the habitat use and movement patterns of the animal (Dabek, unpublished field report, 2004; Porolak and Dabek, unpublished data, 2005; Stabach 2005). Devices, designed as 'store-on-board' GPS dataloggers, also emit a VHF/UHF signal that allowed for animals to be tracked manually on a daily basis using traditional radio-telemetry devices (3-element Yagi and/or RX-98H

antenna). Once located, a Trimble Geo3c receiver with an external antenna (Trimble Navigation Ltd, Sunnyvale, CA, USA) was used to mark the position of each animal. Vegetation information collected included the identification of trees from tracked locations to species level, canopy closure, and the height and diameter at breast height (DBH) of each tree (Stabach 2005). For this study, the radio-tracking data provided the exact location of 147 dominant canopy trees.

A series of at least four digital photographs were taken at each field survey point and dynamically linked by their respective time stamps to provide a Virtual Field Reference Database (VFRDB), guiding class assignments. Geographic coordinates were based on a minimum of 10 positions recorded at 1-s intervals and were post-processed with differential correction from the Cape Ferguson, Australia base station data (1454 km distance). A firmware-imposed positional dilution of precision (PDOP) mask of 8.0 and a signal-to-noise ratio (SNR) threshold of 4 were used. However, the PDOP was changed to as high as 20.0 on select occasions to accommodate difficulty in signal acquisition. Points were converted from decimal degrees to UTM zone 55 S (WGS 84 spheroid), and entered into a GIS as a point coverage.

### 2.3 Image classification

A multistep, hybrid classification approach was used to separate the upper montane forest into three distinct forest classes identified by the nearest-neighbour vegetation plots conducted during the 2004 field survey. These three distinct forest types are referred to as *Dacrydium nidulum* dominant, *Caldehuvia nymanii* dominant and *Nothofagus starkerborghiorum* dominant, named according to the dominant tree species identified within vegetation plots. An additional 'Other' forest class was also distinguished based on both visual interpretation and the examination of spectral statistics, but *in situ* data were not collected for verification. Each image was subset to the boundary of the WASU after imposing a 500-m buffer using Arc/Info Workstation 9.0 (Environmental Systems Research Institute, Redlands, CA, USA). The procedure described here was applied individually to both images.

Persistent cloud cover is a common problem with optical remote sensing applications in tropical areas (Trisurat *et al.* 2000). Removing these areas prior to image classification was a necessary preliminary step. Area of Interest (AOI) polygons were created to minimize misclassification throughout the image and a 50-class unsupervised classification using the Iterative Self-Organizing Data Analysis Technique (ISODATA) was recoded to two classes to separate the AOIs into cloud and non-cloud areas. ISODATA requires minimal input from the analyst and is the process whereby pixels are grouped together based on their similarity in spectral properties (Jensen 1996). A majority analysis based on a  $3 \times 3$  pixel window was used to reduce variability and the raster-fill tool was used to manually correct remaining misclassified pixels. The resultant classification was used as a mask to produce a cloud-free image and used for all subsequent stages of the vegetation classification.

Grassland areas were easily visually discernable and were separated from the image using the same procedure as described above for removing the areas of cloud from the image. This step served to provide the greatest amount of separability between the targeted forest classes. Attempts at spectral separation of grassland areas into two separate classes, alpine and anthropogenic, were unsuccessful and the DEM was used in a rule-based model to separate them. Areas above 2750 m in elevation were recoded as alpine and all other areas remained anthropogenic. This

elevation gradient was specific to the WASU, but was based on the fact that alpine gardens were found at lower elevations throughout the area and grasslands found above 2750 m would be located too far away from any local village to serve anthropogenic purposes.

A 50-class unsupervised classification (ISODATA) was conducted on the remaining upper montane forest areas, recoded into four separate forest classes: *Dacrydium nidulum* dominant, *Caldcluvia nymanii* dominant, *Nothofagus starkenborghiorum* dominant, and 'Other'. A supervised classification using these spectral signatures was performed using the maximum likelihood parametric decision rule with equal prior probabilities for each class. This rule makes use of statistics, such as the mean and covariance of each class, to assign pixels to classes that they are most similar to (Jensen 1996). Histograms were examined throughout the classification process to ensure that classes were normally distributed. Additional spectral signatures where land cover was known from GRPs were added to improve the classification results. Both grassland areas were re-added to the final classification result using a raster math calculation for a total of six land-cover classes: *Dacrydium nidulum* dominant forest, *Caldcluvia nymanii* dominant forest, *Nothofagus starkenborghiorum* dominant forest, 'Other' forest, Alpine grassland, and Anthropogenic grassland (table 1). Class variability was reduced by a GIS analysis to eliminate 'island' polygons below a 2-pixel minimum. Because the elevation gradient of each

Table 1. Descriptions of land-cover classes derived for Landsat-7 ETM+ and Spot-4 satellite image classifications. Dominant forest species derived from nearest-neighbour vegetation plots conducted by TKCP field botanist (R. Jensen, unpublished data, 2005). Elevation ranges summarize data from vegetation plots and provide detail to the cut-off ranges used to separate grassland areas.

Land-cover class	Description
<i>Dacrydium nidulum</i> dominant forest	Dominant forest type composed of 24 canopy species. Tree species <i>Quintinia ledermanii</i> , <i>Decaspermum forbesii</i> , <i>Dacrydium nidulum</i> and <i>Saurauia capitulata</i> represent 56.3% of total trees surveyed Elevation range: 2850–3100 m
<i>Caldcluvia nymanii</i> dominant forest	Dominant forest type composed of 35 canopy species. Tree species <i>Caldcluvia nymanii</i> , <i>Schizomeria serrata</i> , <i>Astronia atroviridis</i> , <i>Dryadodaphne crassa</i> , <i>Macaranga trichanthera</i> and <i>Prunus glomerata</i> represent 53.3% of total trees surveyed Elevation range: 2400–2600 m
<i>Nothofagus starkenborghiorum</i> dominant forest	Dominant forest type composed of six canopy species. Tree species <i>Nothofagus starkenborghiorum</i> represent 87.9% of total trees surveyed Elevation range: 2800–2850 m
'Other' forest	Dominant forest type not defined by vegetation plots. Classification based on a difference in spectral reflectance identified visually Elevation range: unknown
Alpine grassland	Grassland Elevation range: $\geq 2750$ m
Anthropogenic grassland	Grassland, including fallow and agricultural land Elevation range: $\leq 2749$ m

of the dominant forest types identified from the vegetation plots was not known at that time, further separation using the DEM was not possible. To assist future land-cover classifications, however, a 200-m contour interval was created and overlaid for visual purposes.

#### 2.4 Accuracy assessment

The accuracy of each of the satellite image classifications was evaluated using quantitative procedures to compare the 'true' land cover with the land-cover class as determined through image classification. Four hundred random sampling points were generated automatically throughout the study area, stratified by land-cover class, with a minimum of 50 points per class, following guidelines suggested by Congalton (1991), Jensen (1996) and Congalton and Green (1999), and added to GRPs collected during the field survey for a total of 568 sampling points. Two GRPs, however, fell within cloud areas that had been removed in the Spot-4 image classification and were therefore excluded from the accuracy assessment of this image. Because the 'true' land cover of the additional randomly generated sampling points was not known, the assessment of accuracy using these points was based on our knowledge of the study areas and of the satellite imagery. Standard accuracy measures such as commission errors (user's accuracy), omission errors (producer's accuracy), overall accuracy, and Kappa statistics were generated to create an evaluation of error. To test for significant differences between the two classifications, a test Z-statistic was used to make a pairwise comparison of the error matrices at the 95% confidence level (Congalton and Green 1999).

It should be noted that ground truth data were not collected for the entire WASU study area and GRPs were also used for training purposes. The biased validation caused by using the same areas for training and accuracy assessment was unavoidable because of the small number of data points collected in the field. However, because the random sampling goes beyond the areas in which GRPs were collected, bias is minimized.

### 3. Results

Nearest-neighbour vegetation plots provided an essential aspect of categorizing the broad vegetation types throughout the study area. Cluster analysis clumped the forest types into three distinct forest types (*Dacrydium nidulum* dominant forest, *Nothofagus starkenborghiorum* dominant forest, and *Caldcluvia nymanii* dominant forest). In total, 49 different canopy species were recorded: 24 species for the *Dacrydium nidulum* dominant forest, six species for the *Nothofagus starkenborghiorum* dominant forest, and 35 species for the *Caldcluvia nymanii* dominant forest. A complete list of all canopy species recorded is summarized in table 2.

*Dacrydium nidulum* dominant forests (14.3% *D. nidulum*) were found on the upper slopes and ridges, up to an elevation of 3100 m (the upper extent of the WASU). The canopy was moderately dense (84.1%), but open enough to support a separate stratum that often reached 3 to 4 m in height. *Nothofagus starkenborghiorum* dominant forests (87.9% *N. starkenborghiorum*; 2.0% *D. nidulum*) were found on or near the ridge crest but at a slightly lower elevation. The canopy was mid-dense to sparse, averaging 82.1%, and supported a dense separate layer 3 to 5 m in height. The third, or *Caldcluvia nymanii* dominant forest type, was dominated by four species (*C. nymanii*, *Schizomeria serrata*, *Astronia atroviridis* and *Dryadodaphne crassa*) that collectively

Table 2. Scientific name, family name, and percentage abundance of all canopy species identified in nearest-neighbour vegetation plots. Information separated into dominant forest types with species listed in order of decreasing abundance. Plant names and families derived from the *International Plant Name Index* (IPNI 2004). Authors provided (if known) according to the International Code of Botanical Nomenclature. Henderson (1997), Mabberly (1997) and Hoft (1992) were used as references for standardization.

Scientific name	Family name	% Abundance
<i>Dacrydium nidulum</i> dominant forest		
<i>Quintinia ledermannii</i> Schltr.	Saxifragaceae	15.2
<i>Decaspermum forbesii</i> Baker f.	Myrtaceae	14.7
<i>Dacrydium nidulum</i> de Laub.	Podocarpaceae	14.3
<i>Saurauia capitulata</i> A.C. Sm.	Actinidiaceae	12.1
<i>Libocedrus papuana</i> F.Muell.	Cupressaceae	7.8
<i>Podocarpus crassigemmis</i> de Laub.	Podocarpaceae	6.1
<i>Syzygium alatum</i> Diels	Myrtaceae	4.8
<i>Eurya tigan</i> K.Schum. & Lauterb.	Theaceae	3.0
<i>Levieria squarrosa</i> Perkins	Monimiaceae	3.0
<i>Prunus grisea</i> (Blume ex C.Muell.) Kalkman	Rosaceae	2.6
<i>Sphenostemon papuanum</i> (Lauterb.) Steenis & Erdtm.	Aquifoliaceae	2.6
<i>Symplocos cochinchinensis</i> S.Moore subsp. <i>leptophylla</i> (Brand) Noot.	Symplocaceae	2.6
<i>Acronychia murina</i> Ridl.	Rutaceae	2.2
<i>Timonius longitubus</i> Merr. & L.M.Perry	Rubiaceae	1.7
<i>Dryadodaphne crassa</i> Schodde ex Philipson	Monimiaceae	<1
<i>Elaeocarpus polydactylus</i> (Schltr.)	Elaeocarpaceae	<1
<i>Endiandra fragrans</i> (C.K.Allen) Kosterm.	Lauraceae	<1
<i>Helicia odorata</i> Diels	Proteaceae	<1
<i>Polyosma forbesii</i> Valetton ex Lauterb.	Escalloniaceae	<1
<i>Prunus glomerata</i> (Koehne) Kalkman	Rosaceae	<1
<i>Rapanea</i> sp.	Myrsinaceae	<1
<i>Schuurmansia elegans</i> Blume	Ochnaceae	<1
<i>Zanthoxylum conspersipunctatum</i> Merr. & L.M.Perry	Rutaceae	<1
<i>Nothofagus starkenborghiorum</i> dominant forest		
<i>Nothofagus starkenborghiorum</i> Steenis	Fagaceae	87.9
<i>Elaeocarpus altigenus</i> Schltr.	Elaeocarpaceae	5.1
<i>Podocarpus crassigemmis</i> de Laub.	Podocarpaceae	3.0
<i>Dacrydium nidulum</i> de Laub.	Podocarpaceae	2.0
<i>Prunus grisea</i> (Blume ex C.Muell.) Kalkman	Rosaceae	1.0
<i>Quintinia ledermannii</i> Schltr.	Saxifragaceae	1.0
<i>Caldcluvia nymanii</i> dominant forest		
<i>Caldcluvia nymanii</i> (K.Schum.) Hoogland	Cunoniaceae	14.3
<i>Schizomeria serrata</i> Hochr.	Cunoniaceae	9.5
<i>Astronia atro-viridis</i> Mansfeld	Melastomataceae	8.2
<i>Dryadodaphne crassa</i> Schodde ex Philipson	Monimiaceae	7.4
<i>Macaranga trichanthera</i> Perry	Euphorbiaceae	7.4
<i>Prunus glomerata</i> (Koehne) Kalkman	Rosaceae	6.5
<i>Timonius longitubus</i> Merr. & L.M.Perry	Rubiaceae	4.8
<i>Turpinia pentandra</i> (Schltr.) van der Linden	Staphyleaceae	4.3
<i>Sphenostemon papuanum</i> (Lauterb.) Steenis & Erdtm.	Aquifoliaceae	3.9
<i>Litsea</i> sp.	Lauraceae	3.5
<i>Alstonia glabriflora</i> Markgr.	Apocynaceae	3.0
<i>Dacrydium nidulum</i> de Laub.	Podocarpaceae	3.0
<i>Zanthoxylum conspersipunctatum</i> Merr. & L.M. Perry	Rutaceae	3.0
<i>Ascarina philippinensis</i> C.B. Rob.	Chloranthaceae	2.6
<i>Saurauia capitulata</i> A.C. Sm.	Actinidiaceae	2.6

Table 2. (Continued.)

Scientific name	Family name	% Abundance
<i>Macaranga inermis</i> Pax & K. Hoffm.	Euphorbiaceae	2.2
<i>Acronychia pullei</i> Lauterb.	Rutaceae	1.7
<i>Podocarpus crassigemmis</i> de Laub.	Podocarpaceae	1.7
<i>Bubbia calothyrsa</i> (Diels) A.C.Sm.	Winteraceae	<1
<i>Casearia grewiifolia</i> Vent.	Flacourtiaceae	<1
<i>Cinnamomum ledermannii</i> Schewe	Lauraceae	<1
<i>Cryptocarya xylophylla</i> Kosterm.	Lauraceae	<1
<i>Cyathea</i> sp.	Cyatheaceae	<1
<i>Dendrocnide</i> sp.	Urticaceae	<1
<i>Elaeocarpus</i> sp.	Elaeocarpaceae	<1
<i>Endospermum medullosum</i> L.S.Sm.	Euphorbiaceae	<1
<i>Ilex archboldiana</i> Merr. & L.M. Perry	Aquifoliaceae	<1
<i>Ilex</i> sp.	Aquifoliaceae	<1
<i>Levieria squarrosa</i> Perkins	Monimiaceae	<1
<i>Polyosma cestroides</i> Schltr.	Escalloniaceae	<1
<i>Polyosma forbesii</i> Valetton ex Lauterb.	Escalloniaceae	<1
<i>Quintinia ledermannii</i> Schltr.	Saxifragaceae	<1
<i>Sericolea pullei</i> Schltr.	Tiliaceae	<1
<i>Symplocos cochinchinensis</i> S.Moore subsp. <i>leptophylla</i> (Brand) Noot.	Symplocaceae	<1

accounted for 39.4% of the canopy. Again, the occasional *D. nidulum* was present (3.0%). The canopy ranged from moderate to dense, averaging 85.7%, with ground cover that ranged from absent to uniform or dense (table 2 and table 3).

The results of the image classifications (figures 2 and 3) indicate that the area was covered extensively by *Dacrydium nidulum* dominant forest (39.3% for Landsat-7 and 45.0% for Spot-4), followed by *Caldcluvia nymanii* dominant and/or 'Other' dominant forest (depending on satellite source). Areas of no data (i.e. clouds) accounted for 3.9% and 2.7% (Landsat-7 and Spot-4, respectively) of the total study area (table 4).

The overall Kappa coefficients for the Landsat-7 and Spot-4 data were 59.4% and 62.7%, respectively. The highest Kappa values for the Landsat-7 data were achieved for Anthropogenic grassland (91.6%), Alpine grassland (83.9%), *Dacrydium nidulum*

Table 3. Average physiognomic attributes calculated from nearest-neighbour vegetation plots throughout the Tree Kangaroo Conservation Program's Wasaunon Field Research Area, Huon Peninsula, Papua New Guinea.

	No. of plots	Total species	<i>n</i>	Physiognomic attributes		
				DBH (cm)	Height (m)	Canopy cover (%)
<i>Dacrydium nidulum</i> dominant forest	7	24	231	40.8 (9–131)	19.3 (13–39)	84.1 (67–93)
<i>Nothofagus</i> <i>starkenborghiorum</i> dominant forest	3	6	99	73.4 (12–128)	38.0 (13–53)	82.1 (66–94)
<i>Caldcluvia nymanii</i> dominant forest	7	35	231	51.6 (11–130)	24.1 (11–39)	85.7 (60–95)

DBH, diameter at breast height.

Ranges are included in parentheses.

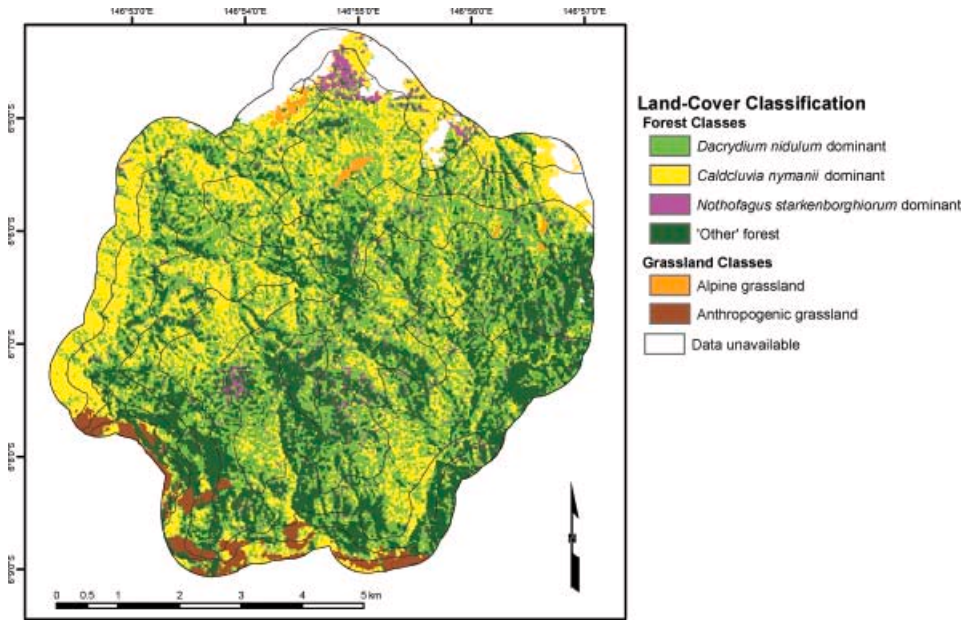


Figure 2. Land-cover classification results of Landsat-7 ETM+ satellite imagery. Contour lines are provided for future reference (200-m interval).

dominant forest (79.0%), and *Nothofagus starkenborghiorum* dominant forest (59.7%). The four highest Kappa values for the Spot-4 data included the same four land-cover categories: Alpine grassland (91.7%), Anthropogenic grassland (89.5%), *Dacrydium nidulum* dominant forest (73.9%), and *Nothofagus*

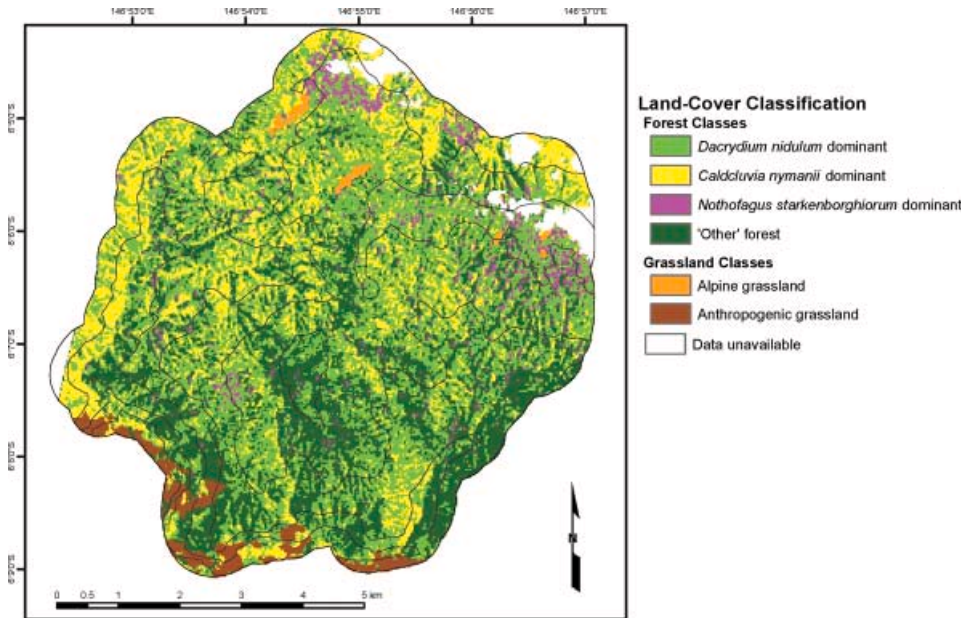


Figure 3. Land-cover classification results of Spot-4 satellite imagery. Contour lines are provided for future reference (200-m interval).

Table 4. Summary statistics of land-cover classification.\*

Land-cover class	Landsat-7 ETM+ (14.25-m)			Spot-4 (20-m)		
	Pixels	Hectares	% of landscape	Pixels	Hectares	% of landscape
<i>Dacrydium nidulum</i> dominant forest	104 717	2126.4	39.3	60 827	2433.1	45.0
<i>Caldcluvia nymanii</i> dominant forest	69 423	1409.7	26.0	25 750	1030.0	19.1
<i>Nothofagus</i> <i>starkenborghiorum</i> dominant forest	7364	149.5	2.8	4921	196.8	3.6
'Other' forest	66 692	1354.3	25.0	35 623	1424.9	26.4
Alpine grassland	1253	25.4	0.5	716	28.6	0.5
Anthropogenic grassland	6782	137.7	2.5	3662	146.5	2.7
No data (clouds)	10 480	212.8	3.9	3640	145.6	2.7
Total	266 711	5415.9	100.0	135 139	5405.6	100.0

\*Statistics include 500-m buffer.

*starkenborghiorum* dominant forest (55.0%). Confusion matrices and accuracy totals are presented in tables 5 and 6.

Confusion occurred between each of the four forest classes, as evidenced by high classification omission and commission errors (tables 5 and 6). This was expected because of the complexity of each of the forest types and the limited spatial and spectral resolutions of the remote sensing data available for this project. The highest classification accuracy for each of the forest classes was the *Dacrydium nidulum* dominant forest type (90.0% for Landsat-7 and 87.8% for Spot-4). Overall classification for the Landsat-7 and Spot-4 satellite images was 69.0% and 72.4%, respectively (tables 5 and 6). While Kappa analyses and overall classification accuracies for Spot-4 were slightly better than Landsat-7, the *Z*-score comparing the Kappa values of the two error matrices equalled 0.71, which is smaller than  $Z_{0.05}=1.96$ , indicating no significant difference between the two classifications.

#### 4. Discussion

This research demonstrates that Landsat-7 ETM+ and Spot-4 satellite imagery have similar capabilities at discriminating dominant forest types within a heterogeneous tropical rainforest. However, the low classification accuracies and Kappa coefficients indicate that pixel-based classifications alone may be unreliable because of the complex structure of the vegetative communities. Spot-4 and Landsat-7 had similar classification results, even though Landsat-7 had superior spatial and spectral resolution. These results indicate that the finer detail provided from high-resolution satellite sources (spatially and spectrally) may not necessarily lead to improved classification accuracies.

Nearest-neighbour vegetation plots were fundamental to the classification efforts and highlight the heterogeneity between dominant forest types. *Dacrydium nidulum* and *Caldcluvia nymanii* dominant forest types were the most heterogeneous and many of the tree species identified were common to both forest types (table 2), albeit in different proportions, explaining the high degree of error between classes. *Nothofagus starkenborghiorum* dominant forests were the most homogeneous and

Table 5. Confusion matrix and summary statistics for Landsat-7 ETM+ satellite imagery.

	Classified results						Total	Omission errors (%)	Classification accuracy (%)	Kappa coefficient (%)
	Dacrydium	Caldcluvia	Nothofagus	'Other' forest	Alpine grassland	Anthropogenic grassland				
Dacrydium	<b>162</b>	7	1	9		1	180	10.0	90.0	79.0
Caldcluvia	86	<b>57</b>		2			145	60.7	39.3	30.9
Nothofagus	11		<b>35</b>	10			56	37.5	62.5	59.7
'Other' forest	31	1	3	<b>44</b>		2	81	45.7	54.3	48.4
Alpine grassland	8				<b>46</b>		54	14.8	85.2	83.9
Anthropogenic grassland		4				<b>48</b>	52	7.7	92.3	91.6
Total	298	69	39	65	46	51	568	31.0		
Commission errors (%)	45.6	17.4	10.3	32.3	0.0	5.9				
	Mean classification accuracy=70.6%									
	Overall classification accuracy=69.0%									
	Overall Kappa coefficient=59.4%									
	Percentage unclassified pixels=0.0%									
	Variance of Kappa=0.001047155									

Mean classification accuracy refers to the average of all class accuracies.  
 Overall classification accuracy refers to the total correctly classified pixels.

Table 6. Confusion matrix and summary statistics for Spot-4 satellite imagery.

	Classified results							Omission errors (%)	Classification accuracy (%)	Kappa coefficient (%)
	Dacrydium	Caldcluvia	Nothofagus	'Other' forest	Alpine grassland	Anthropogenic grassland	Total			
Dacrydium	<b>187</b>	11	2	12	1		213	12.2	87.8	73.9
Caldcluvia	47	<b>49</b>					96	49.0	51.0	44.7
Nothofagus	14	2	<b>33</b>	8			57	42.1	57.9	55.0
'Other' forest	47		1	<b>45</b>		2	95	52.6	47.4	40.5
Alpine grassland	4				<b>49</b>		53	7.5	92.5	91.7
Anthropogenic grassland	2	3				<b>47</b>	52	9.6	90.4	89.5
Total	301	65	36	65	50	49	566	27.6		
Commission errors (%)	37.9	24.6	8.3	30.8	2.0	4.1				
	Mean classification accuracy=71.2%									
	Overall classification accuracy=72.4%									
	Overall Kappa coefficient=62.7%									
	Percentage unclassified pixels=0.0%									
	Variance of Kappa=0.001034658									

Mean classification accuracy refers to the average of all class accuracies.  
 Overall classification accuracy refers to the total correctly classified pixels.

were also the easiest to visually separate, due in part to the difference in physiognomic features between forest types (table 3, mean tree height=38.0 m). However, the overall classification accuracy of this forest type was very low, possibly because of the limited number of vegetation plots established throughout the entire study area (17 in total) and the shadow effects created from the mountain topography. *Dacrydium nidulum* dominant forest had the highest overall classification accuracy, but was also the dominant forest type identified throughout the study area and was where the majority of GRPs (155 of 168) were collected.

Radio-tracked animals were primarily observed throughout the *Dacrydium nidulum* dominant forest (Porolak and Dabek, unpublished data, 2005; Stabach 2005), thus highlighting the importance of accurately classifying this forest type. However, as only three animals were radio-tracked and within a relatively small area (500 ha), it is unclear how the animals use each forest type and therefore the habitat quality of each dominant forest type cannot be assessed at this time. In 2005 the TKCP completed a second radio-tracking season, with two of the main goals being to increase the sample size and the area being surveyed (Dabek, unpublished field report, 2006). However, the results from this research are not yet available. Future goals of the TKCP are to perform an analysis of habitat utilization versus availability (Neu *et al.* 1974, Johnson 1980, Aebischer *et al.* 1993, Manly *et al.* 2002), so that areas of utilization can be prioritized/targeted for conservation. For now, the vegetation map provides a starting point to assess each of the habitats throughout the area.

The methodology used for image classification represents a simple and replicable technique that may be useful for other studies. Application over large study areas, however, may be impractical because of the manual steps used to remove misclassified pixels, and may be labour intensive if multiple grassland or cloud areas exist. The use of unsupervised classifications proved to be an effective way to separate areas of cloud cover from the image and was a logical choice to provide an initial assessment of land cover as so few reference points were collected. Cloud and grassland areas were removed prior to the image classification because of the improved separability that resulted between the targeted, forest classes. Signatures for the supervised classification were derived to improve upon the unsupervised classification, but only in areas where reference information existed. Additional field sampling would clearly be beneficial to improve classification results and would be especially advantageous to clarify the 'Other' forest class visually identified.

The classification results could have also been further improved by a more extensive use of the DEM. Although the DEM was used to separate the Anthropogenic and Alpine grassland classes, none of the forest classes were improved based on the SRTM data. To make use of this crucial piece of information, more research is necessary to understand the elevation ranges of each of the dominant forest classes identified. For instance, data collected from vegetation plots suggest that *Dacrydium nidulum* dominant forests occupy the upper slopes and ridges of the study area but the lower range of their distribution is still largely unknown. Understanding the upper and lower ranges of each of the forest types would allow for the incorporation of the DEM into a rule-based model to reduce misclassified pixels between forest classes.

Field research alone, however, is unlikely to provide detailed information about the extents of each of the dominant forest types if the spatial patterns cannot be first identified in the remotely sensed data. High-resolution satellite imagery proved to be too coarse to visually identify the extent of the *Dacrydium nidulum* and *Caldechuvia*

*nymanii* dominant forests, possibly because of the heterogeneity of each of these forest classes, explaining why the classification accuracies and Kappa coefficients were so low. The use of hyperspatial resolution satellite imagery (such as Quickbird-2 with its 2.5-m multispectral resolution and/or Ikonos with its 4.0-m multispectral resolution) may provide finer detail that may be useful for further separation of each of these vegetative communities. Although the results of our research show that Landsat-7, with its higher spatial and spectral resolution, did not have a better overall accuracy than the Spot-4 satellite imagery, it is conceivable that hyperspatial resolution satellite imagery would improve the detail of the vegetation map and provide a more accurate result when combined with object-based techniques (i.e. image segmentation).

Image texture was also not used in this research and may be useful to further separate the largely homogeneous *Nothofagus starkenborghiorum* dominant forests as these forests were easily identified visually in the imagery. Franklin *et al.* (2000) reported improved classification accuracies when using image texture, especially when combined with hyperspatial resolution imagery. Further and more accurate separation of the two heterogeneous forest classes (*Dacrydium nidulum* and *Caldcluvia nymanii* dominant forests) may only be accomplished by the use of hyperspectral resolution satellite sources (such as AVIRIS or Hyperion) because these data separate the electromagnetic spectrum into a vast number of discrete spectral bands (Turner *et al.* 2003, Clark *et al.* 2005). The complexity of each of the forest communities will complicate their classification but it seems logical that these techniques could only enhance classifications and potentially reveal detailed species–habitat relationships (Gottshalk *et al.* 2005, Wallace and Marsh 2005).

In conclusion, this research provides detailed information about the capabilities of two high-resolution satellite sources to discriminate dominant forest types in a dense tropical rainforest. Although the classification accuracies are low, our results provide valuable information for future research and for the future conservation of Matschie's tree kangaroos in PNG. Vegetation plots proved to be essential aspects in the classification as they provided detailed information about the broad vegetation types in the area. Additional vegetation sampling should improve upon the classifications but it seems likely that the detailed mapping at the level of species and forest type is unreliable when using high-resolution satellite sources.

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