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Modelling vegetation structure-based bird habitat resources in Australian temperate woodlands, using multi-sensors

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Abstract

The Great Western Woodlands in S.W. Australia is the largest remaining expanse of temperate woodland on the continent and globally, providing habitat for a significance number of bird species. Conservation planning needs information about bird distributions and habitat resource requirements. Using published information, bird habitat functional groups were identified based upon species that use similar vegetation-based resources. Data from four satellite-borne sensors were analysed to model the distribution of a subset of the key vegetation variables. These results were then used to predict the potential distribution of the functional groups. Field validation suggests ongoing advances in satellite data will enhance the model's accuracy.

Keywords: Vegetation structure, spatial landscape modelling, habitat resources, multi-satellite sensors, temperate woodland.

Introduction

In this paper we use a suite of satellite-born sensors to investigate their application in mapping the landscape wide distribution of vegetation-based habitat resources for woodland birds. Our case study landscape is in the Great Western Woodlands of south-east Western Australia, a bioregion which supports important habitats for native bird species inhabiting the temperate woodland zone [Blakers et al., 1984; Chapman, 2005].

The continued existence of many woodland bird species is threatened with reports of bird populations in serious decline over extensive areas where their habitat has been intensively cleared for agriculture and pastoralism in Australia and degraded by various human activities [Recher and Lim, 1990; Recher, 1999; Birds Australia, 2005]. Systematic conservation planning and management in landscapes that currently support extensive natural vegetation can help maintain important areas of bird habitat [Possingham et al., 2000]. However, the

geographical information needed about the distribution of bird species and their habitat resources is difficult to collect over such landscapes [Major et al., 1999]. The problem is compounded by the diversity of bird species, the different kinds of vegetation-based habitat resources bird species exploit, and the complex land cover mosaic typical of natural and semi-natural vegetation. Furthermore, while remote sensing, particularly with data from satellite-borne sensors, is commonly used in land cover mapping, a more challenging task is using these data sources to map bird habitats.

While there are physical environmental components of bird habitat, at a landscape level what is most important is the vegetation-based habitat used by birds for food, shelter, roosting and nesting. Bird species diversity in both temperate and tropical woodlands has been found to be correlated with attributes of the vertical profile and horizontal patchiness of the vegetation including: canopy cover; canopy height; vegetation layering; vegetation species diversity; foraging height diversity; above-ground vegetation biomass; and vegetation density [MacArthur and MacArthur, 1961; Recher, 1969; James, 1971; Orians, 1971; Emlen, 1977]. Tree hollows are also important in Australia as a habitat resource providing nesting places for about 18% of land birds [Tingay and Tingay, 1984; Ford et al., 2001; Gibbons and Lindenmayer, 2002; Birds Australia, 2005]. However, the specific vegetation-based habitat resources needed by birds are not all directly detectable by satellite-borne sensors. Rather, some may need to be modelled through correlation with detectable vegetation attributes. For example, vegetation attributes such as height [Clawges et al., 2008; Ahmadi et al., 2012], stem thickness [Dobson et al., 1992; Castel et al., 2002] and canopy characteristics [Asrar et al., 1992; Berry et al., 2007] have been found to be amenable to mapping with satellite-borne sensors.

The objectives of this study therefore were to: 1) devise a new functional bird classification scheme based upon information about species preferred habitat resources principally associated with vegetation structure, 2) assess the suitability of a range of satellite-based remotely sensed data for mapping vegetation structural variables associated with key bird habitat resources, and use these to develop a landscape model of vegetation structure, and 3) apply this landscape model to generating spatial predictions of bird habitat functional groups.

Methods

Study site

The extensive temperate woodland complex in south-western Australia is named the Great Western Woodlands (GWW) by Watson et al. [2008]. Woodlands are defined as a vegetation structural formation consisting of trees higher than 10m and with 10 to 30% projective foliage cover [AUSLIG, 1990]. GWW is geographically framed by Kalgoorlie to the north, Esperance to the south, the Nullarbor Plain to the east, and the “rabbit proof fence” next to the Wheatbelt to the west (Fig. 1). It forms a continuous and extensive area (approximately 160,000km²) of mostly intact native vegetation cover much of which is relatively inaccessible being remote from human settlements with few roads and tracks.

While the vegetation cover of GWW is largely intact, it is suffering from habitat degradation. Although only small areas have been subject to land clearing, about half of GWW vegetation has been impacted by human activities to some degree by timber cutting to provide timber, railway lines, fence posts and fuel wood for the mining industry and town development,

starting around 1890. At least eight bird species are known to be threatened in the region with habitat degradation implicated in these assessments and further land cover change impacts predicted for the future [Watson et al., 2008]. Although climate change could be one of the important factors in the habitat's decline, there has only been a modest increase in average temperatures in the region. Rainfall has been decreasing to the west of the region (particularly in the tall wetter forests near the south west coast), but rainfall regimes have not yet shifted significantly in GWW. As documented by Berry et al. [2012], a more likely cause is the impact on vegetation structure from changed fire regimes due to human intervention. Our research focus was vegetation structure at a landscape level and studying climate change impacts was out of scope.

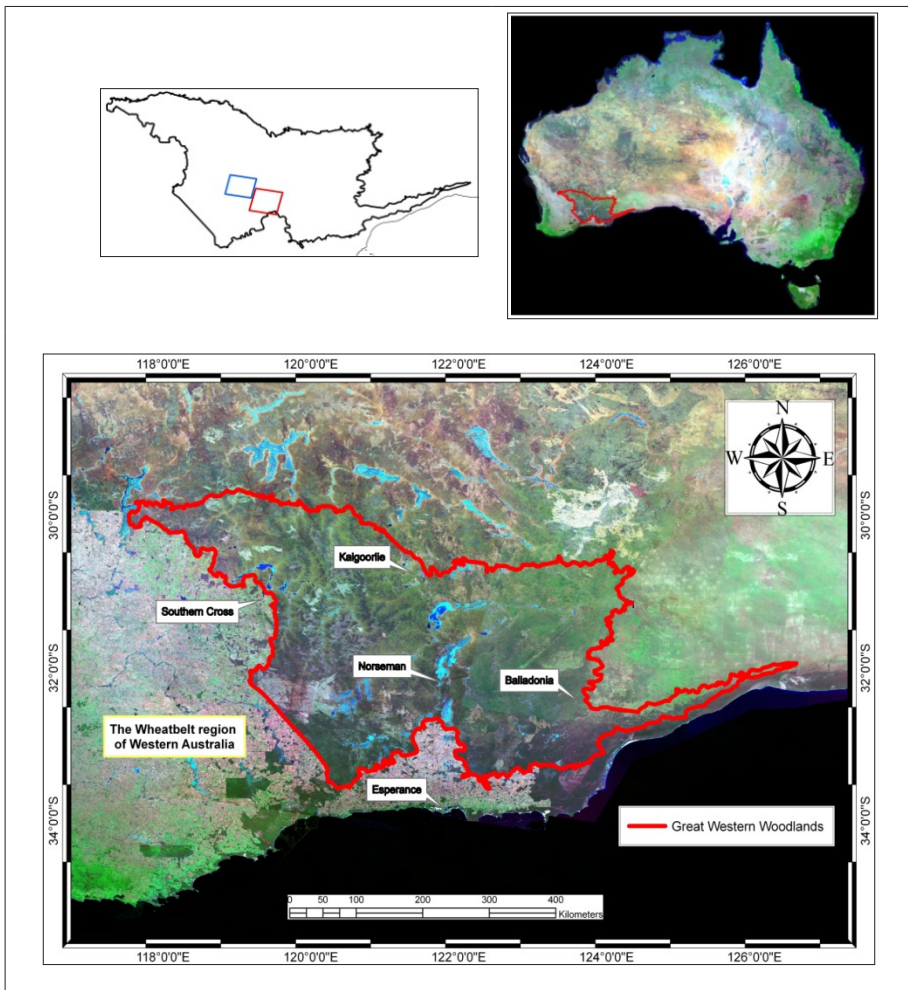


Figure 1 - Location of the Great Western Woodlands (GWW) in Australia. A figure at the right upper corner displays the locations of two main ASTER scenes for this study: ASTER scene 25457 in red; and ASTER scene 30854 in blue.

Within semi-arid GWW temperate woodlands are the main vegetation type covering about 56% of the area with the remainder covered by shrublands (about 20%), mallee shrublands (about 17%) and grasslands (about 2%) [Watson et al., 2008]. Despite precipitation less than $650\text{mm}\cdot\text{yr}^{-1}$ [Bureau of Meteorology, 2010] and poor soils derived from historically prolonged weathering [Beard, 1969], GWW provides critical habitat for both native plants and animals: for instance, 2,571 plant species from the record of the Western Australian Museum [Newby et al., 1984, 1985, 1988, 1992, 1993, 1995], compared to around 19,000 Australian plant species in total [Chapman, 2009]; and various 416 animal species including 215 bird species [Watson et al., 2008]. Since GWW is equivalent only to 2% of the area of the Australian continent, it could therefore be labelled one of the hot spots of biodiversity in Australia.

Bird habitat functional group classification

While each animal species has, to some extent, a unique set of genetically-programmed habitat requirements, groups of species can be identified that share similar kinds of habitat resource requirements referred to here as “functional groups (also commonly called guilds). Using functional groups as the focus of spatial modelling efforts simplifies the modelling challenge when faced with a biologically diverse region such as GWW.

While existing guild schemes are usually focused on traits that mainly related to bird feeding behaviours and/or sources, they generally do not incorporate vegetation structural information. For example, information on the average height at which birds builds nest above the ground [Marchant, 1990] is not typically useful for establishing conventional types of functional groups; rather it is treated as ancillary information. When field studies have revealed relationships between functional groups of bird species and vegetation structure this information has not been used to classify the bird species into functional groups but to address questions concerning guilds; e.g. Rodewald and Smith [1998] compared two timber cutting treatments in American oak-hickory forest on understory and canopy nesting birds. We concluded that none of the existing grouping schemes was explicitly established based upon vegetation structural attributes that relate to species-specific habitat resource use. Therefore, a new functional group classification was needed for this study.

Vegetation habitat resource variables

We developed a new bird classification scheme based upon information about species preferred habitat resources principally associated with vegetation structure. To do so, through reviewing published scientific papers about woodland and/or forest bird species, bird assemblage information related to vegetation structure was collected in association with bird species diversity, richness and abundance (see App. 1). The bird assemblage information, however, is not sufficiently provided by general bird guide books or handbooks, as such books normally present ecological, physiological and morphological information from the bird-centred viewpoint. Fortunately, the Handbook of Australian and New Zealand and Antarctic Birds (HANZAB) [Marchant, 1990] was useful for studying systematic knowledge about vegetation structure-related bird habitat resources. There were two conditions for selecting variables in common between the bird assemblage information and the bird habitat resources: strong links to vegetation structure; and amenability to collection of vegetation structure measurements in the field. According to these rules, a suite of variables were selected. The variables were called Vegetation habitat resource (VHR) variables.

Development of Bird habitat functional group classification

A new classification scheme was developed for creating a compatible system between bird habitat resources information and remotely sensed vegetation structure. The VHR variables selected above were used for assigning GWW bird species into their habitat resources-based functional groups in the numeric classification analysis. To create a numerical data index, each VHR variable had a set of VHR classes that simply and clearly subdivided the structural characteristics of each VHR variable based upon the availability of bird habitat resource information.

Based upon these VHR variables and classes, a numeric dataset was constructed for available GWW bird species. Selected GWW bird species were statistically analysed using a numerical classification method and grouped into functional groups. A data matrix for the selected GWW bird species was produced detailing the VHR class values for each VHR variables shown in Appendix 2. A hierarchical cluster analysis function in the SPSS 16.0 statistical software package (SPSS, Inc., Illinois, USA) was used for analysing the data matrix with the following options. The squared Euclidean distance and the between-groups linkage were selected as the analysis method. The output showed coefficient values of dissimilarity (see App. 3) based upon distance measurements (D) between values for the VHR classes for pairs of the selected bird species. The result from the hierarchical analysis was represented as a dendrogram showing the inter-group similarity. Through this classification analysis, a group of birds which have a common suite of habitat resource preferences was considered a Bird habitat functional group (BHFG), and this process is called a Bird habitat functional group classification (BHFG classification).

Field data

As the dataset collected by the Western Australian Museum since 1975 [WAM field data, unpublished] was not detailed enough, we collected new field data on the GWW vegetation in order to ground-truth, calibrate and validate the satellite-borne data as well as investigate and model vegetation structure-related bird habitat. Three survey methods were designed: Intensive vegetation surveys; ICESat footprint surveys; and Rapid observation surveys. First two methods were developed based upon a Point Centre Quarter (PCQ) [Cottam and Curtis, 1956] method. Major measurements included growth-form, distance to nearest individuals for each growth-form from a centre of a sample plot, canopy height; diameter at breast height (DBH). Sample sites were systematically set to cover all major vegetation types. In total, 21 sites for Intensive vegetation surveys, 41 sites for ICESat footprint surveys and 1,908 sites for Rapid observation surveys were sampled across GWW.

Intensive vegetation surveys were used primarily for analysing MODIS imagery. This was designed by Berry et al. [2010]. Survey sites were located within structurally continuous patches, large enough to avoid edge effects. Each site covered an area of 250×250m corresponding to the pixel size of MODIS data. Within the site, 16 point centres 50m apart each other were regularly distributed. Point centres form the centre of a circular plot with 25m radius. This survey system provided the most detailed information about sample sites in terms of vegetation structure. The second was developed for validating GLAS data that provided information within elliptical samples. Sampling sites were aligned to ICESat footprints by their coordinates. Although the actual sizes of ICESat

footprints vary from the angle of the GLAS sensor, the footprints were assumed to cover circular areas with the minimum footprint size of 25m radius. Average height and coverage for each growth-form per sample were estimated. The third was developed for making a rapid reconnaissance covering an extensive area in a short period. It provided a simple observation of vegetation structure across relatively consistent patches described instantly from a moving vehicle, including growth-form, DBH classes (< 10, 10 to 40, ≥ 40cm) and height classes (< 2, 2 to 4, 4 to 8, ≥ 8m), and density level (0 to 3; according to ground cover between vegetation).

Spatial data layers of Vegetation structure variables

A suite of vegetation structure-related variables were empirically identified by comparing remotely sensed data with field observations. They were Vegetation cover, Foliage density, Shrub layer complexity, Vegetation volume and Vegetation height which were called Vegetation structure (VS) variables. Spatial data layers for each VS variable were generated using ArcGIS 9.3 geographic information system software (ESRI, Inc., California, USA) and the following methods.

Foliage density

To infer vegetation greenness from satellite data, the fraction of photosynthetically active radiation (*f*PAR) was estimated from Moderate Resolution Imaging Spectroradiometer (MODIS) 250m spatial resolution imagery and derived from the Normalised Difference Vegetation Index (NDVI) [Dye and Goward, 1993; Sellers et al., 1994]. *f*PAR-based vegetation greenness could be calculated directly from NDVI:

$$f=1.118 \times \text{NDVI} - 0.168 \quad [1]$$

where $\text{NDVI} \geq 0.15$

$$f=0$$

where $\text{NDVI} < 0.15$

As the *f*PAR reflects not the volume of vegetation but the property of the top surface of vegetation, high *f*PAR does not necessarily mean dense forests. Therefore, *f*PAR was assumed to have a positive relationship with the amount of foliage within the vegetation canopy; and therefore was called Foliage density, one of the VS variables in this research. Foliage density model was applied to GWW, using MODIS data from May 2000 to December 2007 which were processed by a CSIRO research team [Paget and King, 2008] and Dr. Sandra Berry [Berry et al., 2007; Berry et al., 2010]. Foliage density was estimated as a percentage. By investigating the correlation between Foliage density and field measurements, it was concluded that patches with a large amount of foliage, either from tree canopy or shrub crowns, could have high Foliage density. However, due to the vertical alignment of eucalypt leaves, projected foliage cover was not correlated with Foliage density. Volume of trees and shrubs generally associated with foliage production was selected as the field variable to correlate with Foliage density. In this research analysis was designed in binary format due to the limitation of data over GWW. Consequently, Foliage density of 25% was empirically selected as the most suitable threshold for separating high Foliage density groups from low groups based upon the amount of tree volume.

Vegetation cover and Shrub layer complexity

As the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) provided free imagery optically sensed at a resolution of 15 m, it was selected as a reference dataset. Two scenes (ASTER scenes 25457 and 30854) were selected due to cloud-free conditions and coincidence with field survey locations. ASTER imagery was selected for two different purposes. Whereas ASTER band-2 (0.63~0.69 μm) and -3N (0.76~0.86 μm) data for NDVI were used for excluding non-vegetation areas (i.e. Vegetation cover), ASTER band-1 data were used for developing a method for distinguishing the structure of understorey layers (i.e. Shrub layer complexity). Because of topographically and geologically huge variations over GWW, it was necessary to determine threshold on a scene by scene base.

Threshold of Vegetation cover was empirically decided as 0.25 of ASTER NDVI for defining pixels with less than the threshold as non-vegetation areas. To decide threshold of Shrub layer complexity, the ASTER scenes were also used. Compared with field measurements, ASTER band-1 was empirically found to be most sensitive to the changes in understorey vertical layering structure. Two different structural types were distinguished according to the correlation between numbers of understorey layers and ASTER band-1 values: Simple shrub patches having none or one shrub layer; and Multi-shrub patches with equal to or more than two layers. Scene specific thresholds of 98 and 145 for ASTER scenes 25457 and 30854 respectively were selected to generate data layers of Shrub layer complexity. The overall accuracies using a confusion matrix were 69% and 80% for the ASTER scenes 25457 and 30854 respectively.

Vegetation volume

To remotely estimate tree stem volume, or Vegetation volume, data from Phased Array type L-band Synthetic Aperture Radar (PALSAR) were used. PALSAR provides 12.5 m spatial resolution imagery. "L-band" with a long wavelength can penetrate canopy layers, and sensitively responds to branches and stems [Wang et al., 1994] and the water content within vegetation canopy [Jensen, 2000]. So, it was considered useful to analyse sparse vegetation over GWW. Correlation between L-band backscatter and stem volume from field measurements was investigated after applying histogram matching [Richards and Jia, 2006] to selected PALSAR scenes. In general, radar backscatter data are converted to Normalised Radar Cross-Section (NRCS or σ° in decibels (dB)), using the formula [Shimada et al., 2009]: $\sigma^{\circ}=20\log_{10}(\text{DN}) - 83$. However, we developed a new formula which is simpler than the NRCS but fits PALSAR data well. This formula is called a Normalised PALSAR Backscatter Index (NPBI):

$$NPBI(\%) = \frac{DN}{3,000} \times 100 \quad [2]$$

where DN denotes digital numbers of PALSAR backscatter, and 3,000 denotes the image-specific maximum backscatter for vegetation domain.

Vegetation volume derived from the NPBI was compared with stem volume calculated from field measurements. The result showed positively high correlation each other ($r^2 =$

0.80). The regression model was used for generating a binary data layer of Vegetation volume to separate higher stem volume patches from lower patches. The ratio of Vegetation volume to stem volume indicated a saturation point around 50% of the Vegetation volume range. Threshold for this separation was empirically selected as 40% of Vegetation volume, or $6 \text{ kg} \cdot \text{m}^{-2}$.

As PALSAR backscatter can be affected by understorey, shrub volume was treated as part of stem volume. Because of the lack of allometric specialised equations for GWW tree species, the growth-form of GWW trees was regarded as a cylinder. Stem volume was obtained by calculating volume of tree stems using [3] and estimated volume of shrubs using the eucalypt tree species-based allometric equation [5] derived by Berry et al. [2010]:

$$\text{Tree stem volume (m}^3/\text{ha)} = \text{stem density (no./ha)} \times \text{stem basal area (m}^2) \times \text{tree height (m)} \quad [3]$$

where stem basal area was computed as:

$$\text{Stem basal area (m}^2) = \sum \pi (\text{each stem DBH (m)} / 2)^2 \quad [4]$$

Shrub volume was estimated following Berry et al. [2010]:

$$\text{Shrub volume (m}^3/\text{ha)} = 0.0002 \times h^{2.4071} / 0.56 \quad [5]$$

where h denotes shrub height (m).

Vegetation height

The use of a laser sensor of the Geoscience Laser Altimeter System (GLAS) allowed the direct estimation of vegetation canopy height, or Vegetation height over a large area. GLAS provides unique waveform data. The original waveform data were converted to vegetation canopy height using a Centroid-Height model developed by Dr. Peter Scarth at the University of Queensland, Australia [pers. comm., 2nd Nov 2006]. The Centroid-Height model estimates the distance from the centre of the strongest ground pulse as an inferred ground surface height to the centre of the strongest pulse of vegetation canopy areas to model Vegetation height.

Due to significant errors found in Vegetation height compared to field measurements, empirical adjustment of the Centroid-Height model was needed to improve the original fit. To solve this problem, the following rules [Lee, 2011] were applied: 1) detecting and eliminating erroneous and/or uncertain data, 2) setting proper thresholds for some parameters in the GLAS datasets, and 3) relating the values to field data. Consequently, GLAS data predicting incorrect Vegetation height were excluded, and the final product showed a higher r-squared value ($r^2 = 0.74$). The regression equation for predicting Vegetation height was $y = 0.9148 x$. The threshold value for Vegetation height was decided as 8m according to the field survey design. A binary data layer for Vegetation height was generated, which discriminates vegetation patches having tree stems ($\geq 8 \text{ m}$ of Vegetation height) from shrub dominant patches ($< 8 \text{ m}$ of Vegetation height).

Potential bird habitat functional group spatial prediction system

Landscape prediction of vegetation structure variables

A limitation on combining multiple data layers in this study was that the geographic coverage varied with the selected satellite dataset. For this study, ASTER imagery on a fine scale was selected as the geographical reference, and therefore all the data layers prepared above were trimmed to correspond to the geographical boundary of the selected ASTER scenes. Then, a decision tree classifier in ENVI 4.3 image processing software (ITT Industries, Inc., Colorado, USA) was employed for effectively synthesising the data layers. The decision tree classifier is a type of multi-stage classifying tool by using a series of binary decisions for categorising pixel-based data. In this analysis, there were five VS variables used for classifying selected vegetation areas in terms of vegetation structure: Vegetation cover, Foliage density, Shrub layer complexity, Vegetation volume and Vegetation height. All variable-specific data layers were combined into a single spatial model and produced 17 classes of vegetation structure including one class for non-vegetation areas. A resulting comprehensive spatial model was called Landscape prediction of vegetation structure variables (LPVSV).

Potential bird habitat functional group spatial prediction system

BHFGs and LPVSV and were systemically combined using the VS variables as the link. BHFGs and LPVSV were translated in association with the VS variables, respectively. Consequently, they were aligned in a single table in terms of the Vegetation structure variables. The outcome produced vegetation structure-based habitat classification, which was called Vegetation habitat classification (VHC). This entire process was called a Potential bird habitat functional group spatial prediction system (PBHFG-SPS).

A list of the acronyms used in this paper is listed in Appendix 4.

Results

Bird habitat functional group classification

Based upon the Bird habitat resource information related to vegetation structure, VHR variables selected for the BHFG classification were: 1) nest height; 2) nest place; 3) foraging height; 4) foraging place; 5) vegetation type; 6) understorey density; 7) attack method; and 8) food source. The VHR variables selected had a various range of VHR classes (Tab. 1). In the cases of “nest height” and “foraging height”, the classes were based upon the definition of growth-form (i.e. trees ≥ 8 m high and shrubs < 8 m). Due to the lack of data on how foraging and feeding patterns are proportionally distributed, all the classes belonging to some variables could not be thoroughly separated; for example, “gleaning + probing” and “insectivorous + carnivorous food source”. To conduct statistical analysis properly, it was necessary to develop as simple format of the classification scheme as possible by minimising the number of VHR classes. The main reason was there was inconsistent and insufficient information to assign bird species to VHR classes. The categories of nest height and foraging height needed to have a “neutral” class that represented bird species with no preference for those particular categories. The scheme in Table 1 reflected those various requirements and was used for a classification analysis in this research.

The numerical values for the eight VHR variables and VHR classes for each of the 104 bird species used as input into the classification model are listed in Appendix 2. The other 103 species among GWW bird species were excluded because of missing data for some

variables or their water-based habitats.

The resulting classification was represented in a dendrogram format which shows the intergroup similarity. As the analysis clustered the bird species according to the classification scheme (Tab. 1), resulting BHFGs were made up of bird species that are likely to use similar habitat resources in terms of vegetation structure.

Table 1 - Vegetation habitat resource variables and relevant classes developed for classifying Bird habitat functional group.

Variables	Vegetation habitat resource classes		
1 Nest height	(1) Taller than or equals 8 m - Tall vegetation - High biomass	(2) Shorter than 8 m - Low vegetation - Low biomass	(3) No preference*
2 Nest place	(1) Tree cavity, tree high biomass		(2) Others low biomass
3 Foraging height	(1) Taller than or equals 8m - Tall vegetation - High biomass	(2) Shorter than 8m - Low vegetation - Low biomass	(3) No preference*
4 Foraging place	(1) Air (2) Canopy (including crown) (3) Perch	(4) Bark (including stem) (5) Bare-ground (6) Water	
5 Attack method	(1) Glean (including peck, pull, graze) (2) Probe (3) Scratch (including chisel, dig, hammer, drill) (4) Sally (including hawk, hover, strike, screen) (5) Attack in the water		(6) Glean + Probe (7) Glean + Scratch (8) Glean + Sally (9) Probe + Scratch (10) Glean + Probe + Sally
6 Vegetation type	(1) Forest, open forest, woodland, open woodland - Tall vegetation		(2) Shrubland, grassland, wetland - Low vegetation
7 Understorey density	(1) Dense (Usually hard to see bare-ground between shrubs and/or bushes) (2) Sparse (Easy to see bare-ground between shrubs and/or bushes)		
8 Food source	(1) Insectivorous (2) Carnivorous (3) Omnivorous (4) Herbivorous		(5) Aquatic (6) Insectivorous + carnivorous (7) Insectivorous + herbivorous

(*) Both indices were selected.

The optimal number of BHFGs is user-determinant based upon the purpose of the analysis. Therefore, the number of BHFGs can vary from different purposes of research. Nine BHFG model (Fig. 2) was decided as a reference model for this research. The decision was based upon having sufficient differentiation while ensuring there was a reasonable spread of bird species between BHFGs.

Landscape prediction of vegetation structure variables

The outcome of the decision tree classifier classification was 17 vegetation structure-based land-cover classes of LPVSV: 16 classes related to vegetated areas and one class to non-vegetation areas, which are shown in Figure 3. This classification is also able to be spatially mapped in a data layer format.

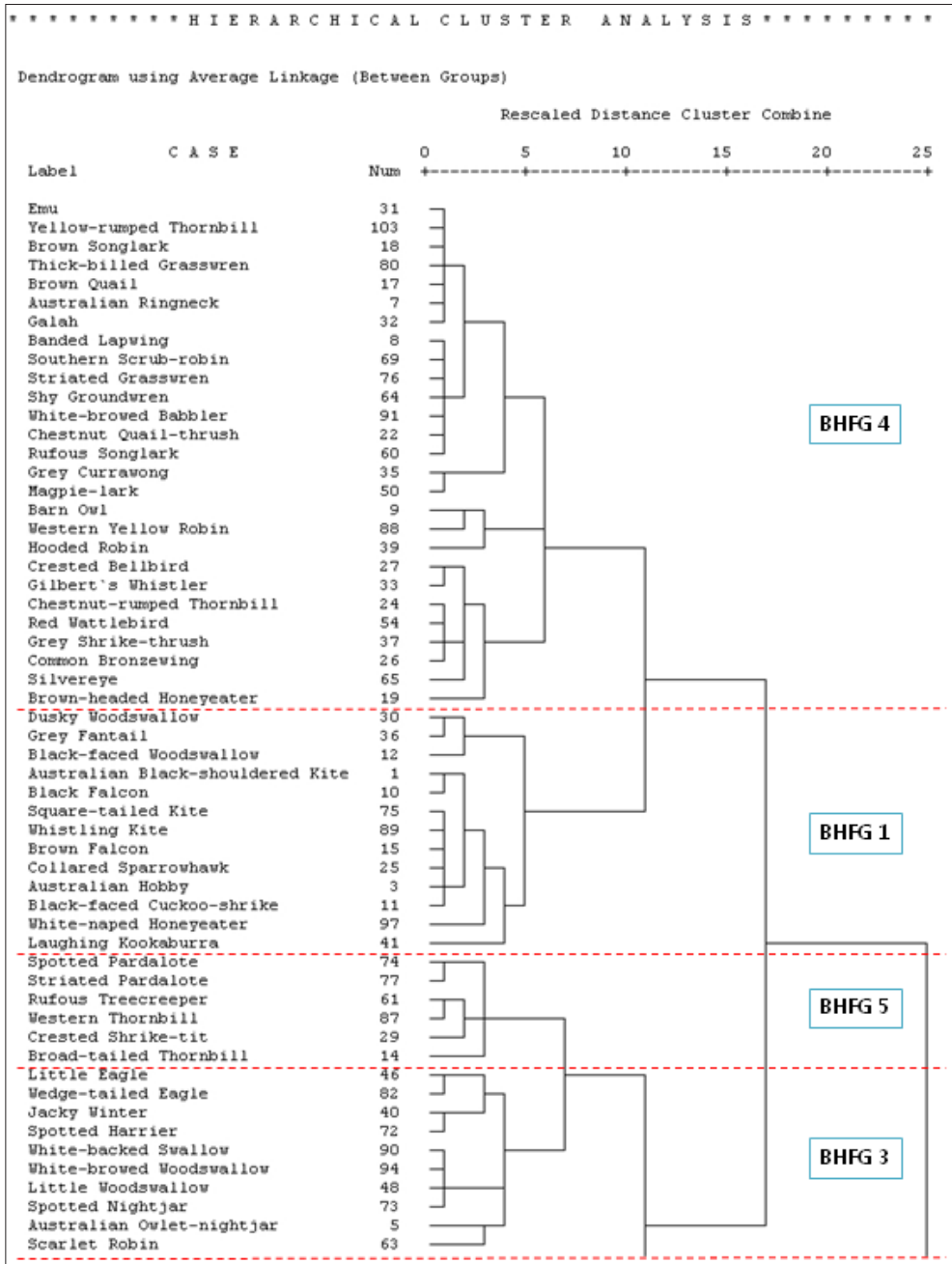


Figure 2 - The output of the Bird habitat functional group (BHFG) classification analysis. In this classification analysis, nine distinct groups are selected as BHFGs based upon the distance between the combinations of habitat resources of GWW species. The nine BHFGs are considered the most suitable model for this study. Dashed lines in red delimit the BHFGs.

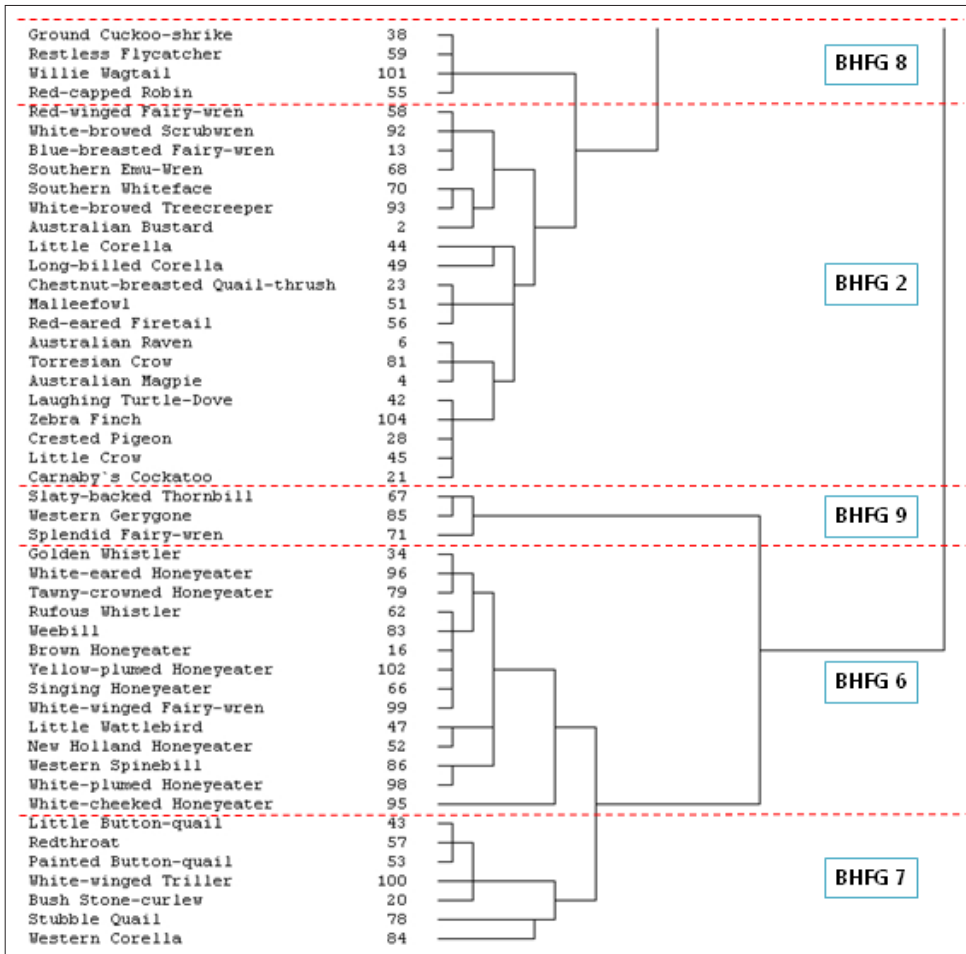


Figure 2 - (Continued) The output of the Bird habitat functional group (BHFG) classification analysis. In this classification analysis, nine distinct groups are selected as BHFGs based upon the distance between the combinations of habitat resources of GWW species. The nine BHFGs are considered the most suitable model for this study. Dashed lines in red delimit the BHFGs.

Potential bird habitat functional group spatial prediction system

In the new system, Potential bird habitat functional group spatial prediction system (PBHFG-SPS), each of nine BHFGs was re-assigned into six classes of VHC (Tab. 2). Following this re-assignment, the resulting six VHC classes could be related to all the VS variables, and then aligned with 17 LPVSV classes. To maintain the binary system, making subjective decisions was inevitable in the case of indicating “no preference” or including multi-tendencies with the analogous proportion within a BHFG. Consequently, BHFGs were connected with relevant LPVSV classes in terms of the VS variables.

Table 2 details the relationship between the BHFGs, the VHC classes and the LPVSV classes. While there is the possibility of 17 LPVSV classes, there exist just six VHC classes. Thus, although there is the potential for 17 LPVSV classes to be classified from the remotely sensed

data, only six types of these LPVSV classes can be linked to the VHC classes. However, this mismatch did not originate from incompleteness of VHC, but is derived from the characteristics of GWW bird species. According to PBHFG-SPS (Tab. 2), seven vegetation structure patterns (i.e. LPVSV Classes 5, 6, 8, 9, 13, 15 and 17) could be considered the major types of GWW vegetation of most relevance to GWW bird habitat resources.

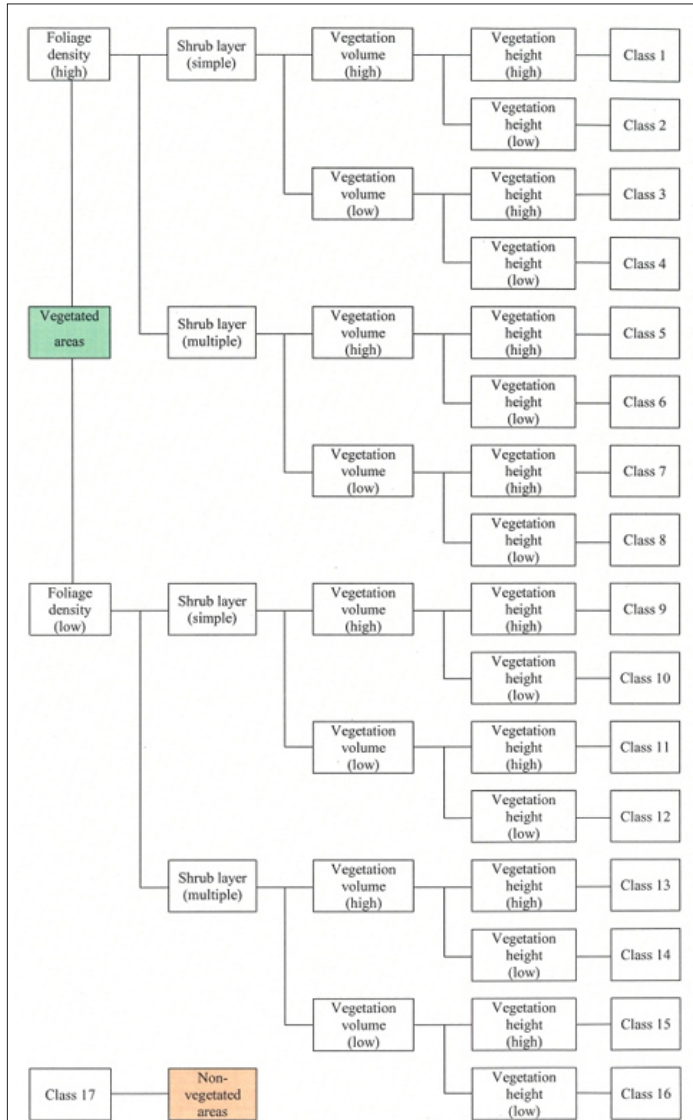


Figure 3 - The 17 Vegetation structure variable (VSV)-derived classes from the decision tree classifier process: 16 classes for vegetated areas, 1 for non-vegetated areas. This classification provides the output of the LPVSV. Vegetation structure variables involved in this analysis are Vegetation cover, Foliage density, Shrub layer complexity, Vegetation volume, and Vegetation height.

Table 2 - Vegetation habitat classification (VHC) in column (f) based upon the relationships between the nine Bird habitat functional groups (BHFGs) and the Vegetation structure (VS) variables. The BHFGs are assigned to six VHC classes according to the combinations of the values for the VS variables. The total number of the VHC classes is smaller than that of the BHFGs. The VHC classes are then related to Landscape prediction of Vegetation structure variable (LPVSV) classes in column (g). Some of the LPVSV classes are not found in this analysis due to the limit of the diversity of BHFGs.

(a)	Vegetation structure variables								(f)	(g)
	(b)		(c)		(d)		(e)			
	High	Low	Simple	Multiple	High	Low	Tree	Shrub		
BHFG ¹	Foliage density		Shrub layer complexity ²		Vegetation volume		Vegetation height ³		VHC classes ⁴	LPVSV classes ⁵
1		✓	✓		✓		✓		1	9
2	✓			✓		✓		✓	2	8
3		✓		✓	✓		✓		3	13
4	✓			✓	✓			✓	4	6
5	✓			✓	✓		✓		5	5
6	✓			✓		✓		✓	2	8
7		✓		✓		✓	✓		6	15
8		✓		✓	✓		✓		3	13
9	✓			✓	✓		✓		5	5
Non-vegetation habitat										17

¹Bird habitat functional groups (BHFGs).
²Decided based upon the BHFG classification as shown in Figure 2 and the bird habitat information from HANZAB (Marchant, 1990).
³Decided as “tree” if the majority of height values of a BHFG is higher than 8m in height, and as “shrub” if the majority is lower than 8m in height.
⁴Classes of the Vegetation habitat classification (VHC). Decided by the differences of the combinations of the Vegetation structure (VS) variables between the nine BHFGs.
⁵Classes of the Landscape prediction of Vegetation structure variables (LPVSV).

Application of PBHFG-SPS

Two spatial predictions from PBHFG-SPS are presented below in Figure 4. Figure 4a shows the distribution of potential BHFGs within the boundary of ASTER scene 25457, and Figure 4b shows the result within ASTER scene 30854. Figures 4a and 4b show the difference in the diversity and distributions of potential BHFGs between two focal sites. This result was attributed to the distinctive land covers within the two sites. Whereas large areas within ASTER scene 30854 affected by a large salt lake located in the middle have an extensively dominant cover of shrubs, the area of ASTER scene 25457 includes diverse growth-forms such as trees, mallee trees and shrubs depending on various natural environments. Some limitations such as unnatural straight boundaries and not entirely classified areas can be seen in these spatial models (Figs. 4a and 4b) due to the incomplete overlaps between input data layers derived from the satellite imagery. In general, however, the distributions of vegetation structure present discernible and plausible spatial patterns in terms of continuity on a landscape scale rather than a collection of randomly scattered fragments. These two

examples show the potential of PBHFG-SPS for analysing vegetation structure and relating the analysis to predicting possible BHFGs within GWW.

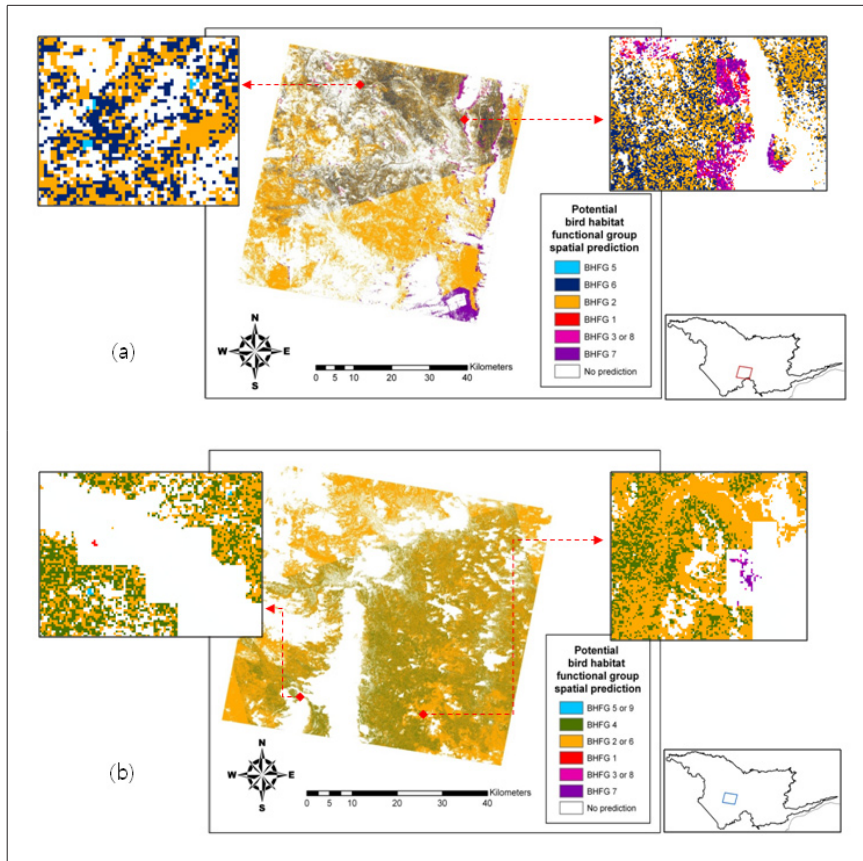


Figure 4 - Spatial predictions of potential bird habitat functional groups within vegetated areas for ASTER scenes 25457 (Fig. 4a) and 30854 (Fig. 4b). “No prediction” includes non-vegetated areas and where there is no combination of VS variables matched with any of the BHFGs. Bird species for each BHFG are shown in Figure 2.

Discussion

Development of BHFGC

For the BHFG classification model, the eight variables were selected on the basis of vegetation structure-related bird habitat resources. Based upon these variables, the BHFG classification model has two implications: 1) there were strong correlations between Bird habitat resources and vegetation structure-related variables, and 2) vegetation structure-related variables could be used for developing a scheme for classifying the GWW bird species. Therefore, the BHFG classification scheme developed here was the complex of bird ecological elements and vegetation structural components. Expect for “attack methods” and “food sources” that are not related to vegetation structure, as the variables are the most

common subjects of bird assemblage studies [Wilson, 1974; Gilmore, 1985; Recher et al., 1985; Antos and Bennett, 2005; Chettri et al., 2005], they are useful as additional information in further distinguishing functional groups that are otherwise close in terms of vegetation structure. Therefore, they were used to generate a more comprehensive classification.

What was developed in this research was a unique system that utilizes vegetation structure-related attributes as classification variables. The reason why vegetation structure variables are important here is that they are a potential link between bird habitat resources information and satellite-borne remotely sensed data. If a strong relationship between the vegetation structure pattern and bird habitat characteristics based upon the vegetation structure is observed, potential bird habitat can be predicted from the relationship. Therefore, the most critical result from this classification analysis was the conversion of bird species-centred data into vegetation structure-based information, which makes it possible to utilise remotely sensed data in predicting bird habitat resources. Unfortunately, due to the inconsistency and incompleteness of the Bird habitat resources information, almost half of the bird species that are reported to occur in GWW could not be used in the BHFG classification analysis. However, future improvements in the quantity and quality of habitat data for these bird species should make it possible to include them in a BHFG classification analysis.

Prediction accuracy of LPVSV

The final product of this research was PBHFG-SPS which was the link between BHFGs and LPVSV classes. It was not possible to independently validate PBHFG-SPS for the following reasons. First, as birds which have their habitats out of entirely vegetated areas were excluded, LPVSV Class 17 and VHC Class 7 were not treated in this analysis. Because they cover a broad range of sites including lakes and bare-ground, more information about these sites needs to be collected. Second, there is a lack of bird data in terms of habitat resource use. To verify this modelling approach, additional validation analysis needs to be undertaken with more comprehensive bird data. Ideally, the bird dataset should include bird census and habitat resource use consisting of observations of bird occupancy and use of vegetation structure based upon field surveys undertaken in GWW.

The potential of LPVSV for modelling landscape patterns of vegetation structure was indirectly evaluated by comparing LPVSV spatial predictions with landscape patterns discernible from two independent datasets, Google Earth imagery and a Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM). The details of these two datasets are described in Table 3.

Table 3 - The characteristics and source information of two datasets used in evaluating a PBHFG-SPS.

	Feature	Source
Google Earth imagery	a. Spatial resolution: 2.5m (SPOT) ~ 15m (Landsat) b. Output: vegetation mapping	Two scenes were downloaded using Google Earth (Google 2009, Google Earth 5.1.3533.1731)
SRTM	a. Spatial resolution: 3arc-seconds b. Wavelength: 5.6cm (C-band) c. Output: 90m DEM	Original DEM data: downloaded from ftp://e0srp01u.ecc.nasa.gov/srtm/version2/SRTM3

From the LPVSV based upon the ASTER 25457, data layers filtered by different window systems were generated and compared with the original data layer and the scene from Google Earth in Figure 5. According to the definition of target vegetation patches, a suitable window size could be differentiated.

Because of the large space between trees or relatively tall vegetation and the high resolution of remotely sensed data, the original classification result (Fig. 5a) looked highly speckled and comprised a large number of small isolated patches and did not enable scaled distinct structural patches to be discerned. While the data layer of Figure 5a was not sufficient to indicate distinct structural patches to be discerned, the one with 7×7 windows (Fig. 5d) showed the most distinguishable patterns of vegetation structure. As a result, the scenes with the largest windows (Fig. 5d) were found to effectively show the kind of vegetation structure patterns that are visibly detectable from Google Earth imagery (Fig. 5e). Comparing these two images suggests that the modelled vegetation structure is consistent with the land-cover patterns apparent in Google Earth imagery and, therefore, the spatial predictions are coherent and provide realistically generalised patterns of vegetation structure in GWW.

A topographic position model derived from SRTM DEM data developed by Gallant and Dowling [2003] provided gridded information of a series of topographic positions over GWW. This complementary approach to indirectly validate LPVSV was undertaken based upon the correlation between topographic positions and vegetation structure patches. As the topographic relief of the GWW landscape is low, positions in a topographic profile are considered more informative rather than elevations of sites per se. The topo-positions derived from the SRTM DEM were compared with LPVSV on the basis that vegetation structure is known to be affected by the physical conditions of its habitat [Tongway and Ludwig, 1990; Knight et al., 1994; Reed et al., 2009]. The conditions influence substrates, temperature and moisture directly or indirectly, and therefore, it is common to find the correlation between vegetation and topographic positions. The 17 LPVSV classes based upon ASTER 25457 were compared with the following seven topo-position classes generated by Mackey et al. [2008] (Fig. 6): ridge top; upper slope; middle slope; lower slope; colluvial valley fill between upland areas; rise in low sloped valley flat; and large area of valley fill.

As there were no apparent significant differences between the three different window sizes, only LPVSV of ASTER 25457 filtered with 7×7 windows was analysed here. In this filtering process, the spatial unit of analysis was a 15m by 15m pixel which is the resolution of the ASTER sensor imagery. This was used because the ASTER imagery provides coverage over the entire GWW. As the classification by Vegetation height was not available to this LPVSV modelling due to lack of the GLAS data on a landscape-wide basis, the LPVSV classes with odd numbers from 1 to 15 were assigned to the next LPVSV classes with even numbers from 2 to 16 (Fig. 6). The area covered by ASTER 25457 mainly comprised top ridge (grey), middle slope (green) and lower slope (blue) areas.

A major finding with LPVSV of ASTER 25457 was that LPVSV Classes 2 to 8 classified into high Foliage density in the LPVSV, had the larger proportion of the “large area of valley fill” position (brown in Fig. 6) and the “rise in low sloped valley flat” position compared to LPVSV Classes 10 to 16 with low Foliage density.

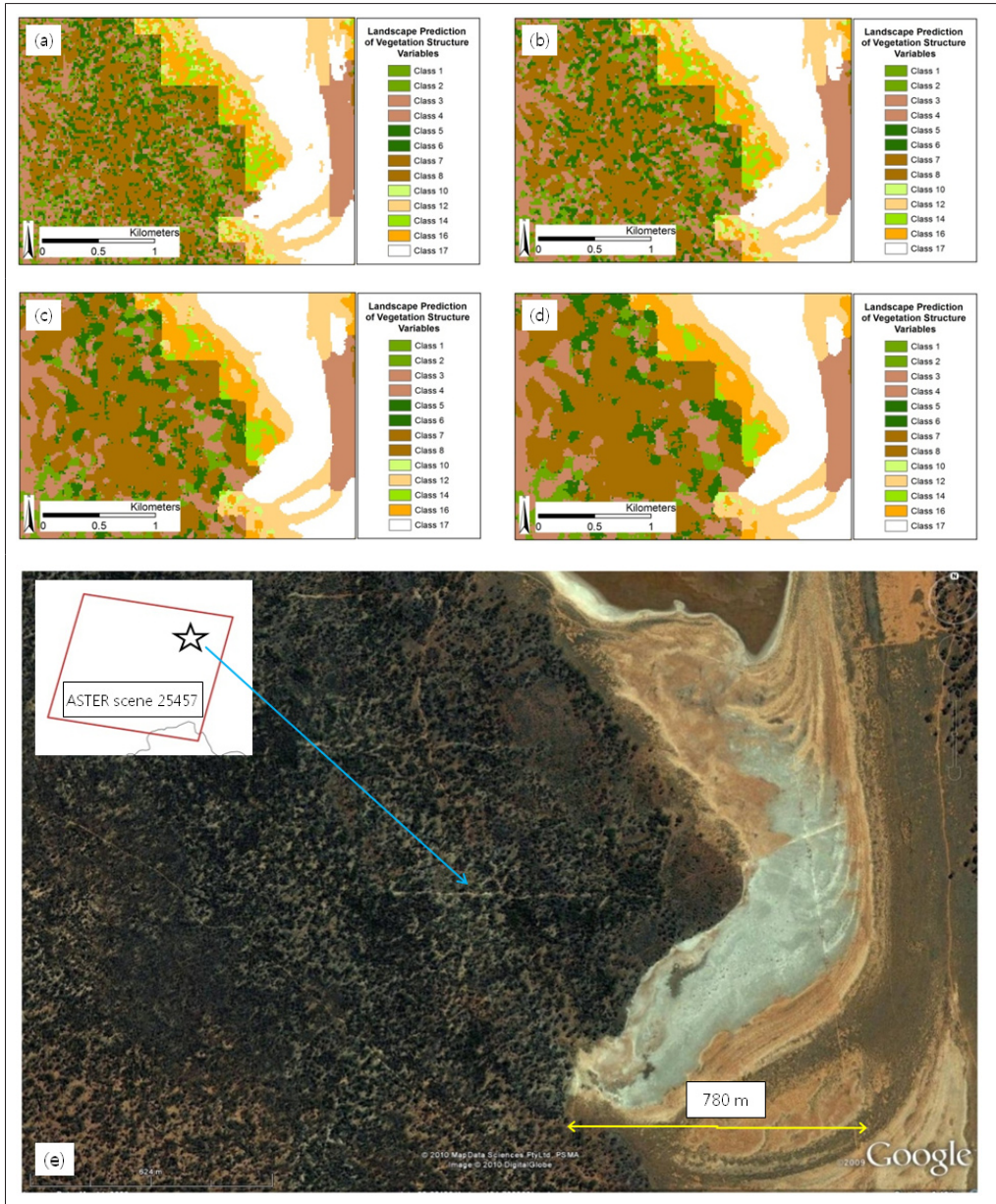


Figure 5 - Comparison of the LPVSV based upon the ASTER scene 25457 with a Google Earth image of the same area e). The spatial unit of analysis for the window filters is a 15 m by 15 m pixel which is the resolution of the ASTER sensor imagery a) the original classification layer; b) the classification filtered by a 3×3 windows; c) the classification filtered by a 5×5 windows; d) the classification filtered by a 7×7 windows; and major patterns of vegetation structure can be identified according to the spatial resolution of the filtering.

At the same time, the classes with low Foliage density were more often found in the “middle slope” position. It was assumed that areas with dense foliage cover were more distributed

at the lower part of topography such as valley due to run-on and greater availability of moisture, the accumulation of deeper alluvial soil, and possibly access to ground water by deeply rooted perennials. This apparent relationship between the vegetation structure and topo-positions is supporting evidence that LPVSV spatial predictions reflect actual landscape patterns and are not simply an artefact of the classification procedure.

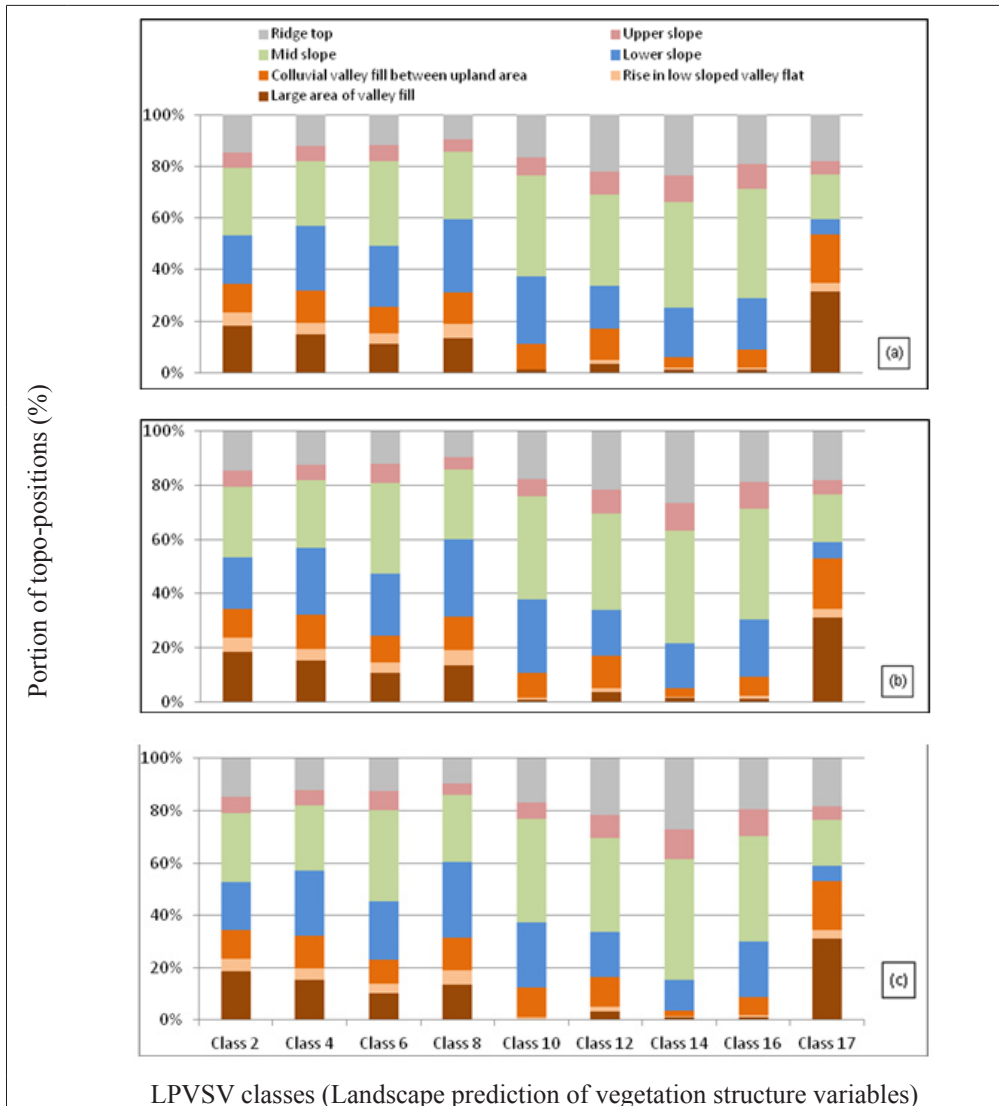


Figure 6 - Proportion of the seven topo-positions for each LPVSV class using an ASTER scene 25457. Each LPVSV class is classified by Foliage density, Shrub layer complexity and Vegetation volume without using Vegetation height: that is, LPVSV Class 2 is combined with LPVSV Class 1; LPVSV Class 4 with LPVSV Class 3; and so on. a) topo-positions compared with the LPVSV with 3×3 windows, b) topo-positions with 5×5 windows, and c) topo-positions with 7×7 windows. This graphs show the relationships between topo-position and vegetation structure for GWW.

Conclusions

The approach developed here is computationally generic and therefore relevant to other extensive remote regions. The four vegetation structural variables we modelled (Foliage density, Shrub layer complexity, Vegetation volume, Vegetation height) provided a useful link between the vegetation-based habitat resources used by birds and the information that can be analysed from satellite-borne remotely sensed data. The sources of remotely sensed data used to model the spatial distribution of the vegetation structure are globally available. Field-based studies in other landscapes have found similar kinds of relationships between birds and vegetation structure. However, the models developed here are empirically based upon and calibrated to local ecological circumstances. Caution should be applied when transferring information about bird-habitat relations between continents and different ecosystem types (e.g., North American spruce forest to Australian eucalypt woodlands), none withstanding the general habitat significance of vegetation structure.

The new BHFG classification used a novel approach based upon numeric classification and life history details gleaned from published information. This method can be applied to any ecosystem types, for which the necessary life history information is available for the bird species, enabling bioregion-specific functional groups to be derived. We were unable to validate the ability of the predicted distribution of BHFG due to a lack of bird data. To do this requires long term in situ observations of bird presence, foraging and nesting behaviours at a network of sites, representative of major vegetation formations.

This study was also limited by the available active and passive remote sensor data sources. As new sources become available, with improvements in spatial and temporal resolutions and geographic coverage, the linking functions developed here can be recalculated and more accurate predictions generated. However, there will always be a gap between the scale at which birds utilise vegetation-based habitat resources and the scale at which satellite-borne sensors capture data about the land cover. This scale mismatch is one reason why approaches are needed that provide knowledge-based links between what sensors “see” about vegetation cover and what birds “see” in terms of their habitat requirements. Building functions that link sensor data, vegetation structure, habitat resources, and bird functional groups, is one approach to filling this gap. However, some level of generalization and loss of information is inevitable. While some of the error terms reported here, particularly with respect to the spatial predictions of vegetation structure at the landscape level are relatively large, the approach has the benefit of being amenable to recalculation with updated biological and sensor data and is in line with the kinds of quantitative information demanded by systematic conservation planning and management.

Acknowledgements

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Appendices

Appendix 1 - Summary of literature on relationship between vegetation structural attributes, bird habitat resources, and influence on bird assemblages. The relationships between the vegetation structural attributes and diversity or richness of bird species are positive without a sign, negative with a sign 'N' and none with a sign 'X'.

Layers ¹	Attributes ²	Habitat types
Multiple layers	Foliage height diversity	A variety of deciduous forests in eastern part of North American continent [MacArthur and MacArthur, 1961]; From dense riverbank vegetation to sparse semi-desert, from fields to tall forests [MacArthur, 1964]; Tropical vegetation including grassland, scrub, savannah and forest [MacArthur et al., 1966]; Wet and dry sclerophyll forest, coastal heath [Recher, 1969]; From no vegetation to structurally mature forest, brush-grasslands and cutover pine forest [Karr and Roth, 1971]; Pasture, grassland, hayfield, shrubland, forest-edge, woodland, bottom- and up-land forest [Wilson, 1974]; Rain forests [Terborgh, 1977]; Eucalypt woodlands [Gilmore, 1985]; Ponderosa pine with white spruce, quaking aspen and paper birch [Clawges et al., 2008]
	No. of canopy layers	From dense riverbank vegetation to sparse semi-desert, from fields to tall forests [MacArthur, 1964]; Tropical vegetation including grassland, scrub, savannah and forest [MacArthur et al., 1966]; From no vegetation to structurally mature forest, brush-grasslands and cutover pine forest [Karr and Roth, 1971]; Pine forest, beech forest, pine-beech mixed forest and grasslands in a Mediterranean mountain [Kati et al., 2009]
	Vegetation cover	From no vegetation to structurally mature forest, brush-grasslands and cutover pine forest [Karr and Roth, 1971]; Pasture, grassland, hayfield, shrubland, forest-edge, woodland, bottom- and up-land forest (X) [Wilson, 1974]
Canopy layer	Canopy cover	Marsh, grassland and forest [James, 1971]; Grassland and woodlands [Ford and Bell, 1981]; A variety of North American forests [James and Wamer, 1982]; Deciduous forest wetlands [Swift et al., 1984]; Eucalypt woodlands [Gilmore, 1985]; Mature oak-hickory forest (N) [Howell et al., 2000]; Mediterranean temperate forests [Gil-Tena et al., 2007]; Deciduous woodlands [Hinsley et al., 2009]
	Tree height	Marsh, grassland and forest [James, 1971]; Rain forests [Terborgh, 1977]; A variety of North American forests [James and Wamer, 1982]; Eucalypt woodlands (Bird species abundance) [Gilmore, 1985]; Broadleaved, conifer and mixed woodlands [Donald et al., 1998]; Boreal forest [Hobson and Bayne, 2000]; Moist evergreen forest [Sekercioglu, 2002]; Second growth deciduous and coniferous-deciduous forests and conifer plantation [Keller et al., 2003]; Two hill forests [Laiolo et al., 2003]; Mediterranean temperate forests [Gil-Tena et al., 2007]; Deciduous woodlands [Hinsley et al., 2009]; Pine forest, beech forest, pine-beech mixed forest and grasslands in a Mediterranean mountain [Kati et al., 2009]
	Vegetation biomass	Tropical forest [Erwin, 1982]; Eucalypt woodlands [Gilmore, 1985]; 7 groups of eucalypt forests [Braithwaite et al., 1989]; Second growth wet forest [Fraga, 1989]; Riparian forest [Pearce, 1996]; Mature oak-hickory forest (N) [Howell et al., 2000]; A transition zone from temperate deciduous forest to boreal coniferous forest (Positive or N) [Hagan and Meehan, 2002]; Temperate forests [Chettri et al., 2005]
¹ Categories for vertically differentiating vegetated areas		
² Vegetation structural attributes that belong to each layering segment		

Appendix 1 - (Continued) Summary of literature on relationship between vegetation structural attributes, bird habitat resources, and influence on bird assemblages. The relationships between the vegetation structural attributes and diversity or richness of bird species are positive without a sign, negative with a sign ‘N’ and none with a sign ‘X’.

Layers ¹	Attributes ²	Habitat types
Canopy layer	Tree species density	A variety of deciduous forests in eastern part of North American continent [MacArthur and MacArthur, 1961]; A variety of North American forests [James and Wamer, 1982]; Rain forest, coastal scrub, spotted gum forest, woolly butt forest, silvertop ash forest, mountain grey gum forest, peppermint forest, early regeneration forest on ridges, advanced regeneration forest on ridges, advanced regeneration forest in gullies [Smith, 1984]; Eucalypt woodlands (X) [Gilmore, 1985]; Mediterranean temperate forests [Gil-Tena et al., 2007]
	Tree species density	A variety of deciduous forests in eastern part of North American continent [MacArthur and MacArthur, 1961]; A variety of North American forests [James and Wamer, 1982]; Rain forest, coastal scrub, spotted gum forest, woolly butt forest, silvertop ash forest, mountain grey gum forest, peppermint forest, early regeneration forest on ridges, advanced regeneration forest on ridges, advanced regeneration forest in gullies [Smith, 1984]; Eucalypt woodlands (X) [Gilmore, 1985]; Mediterranean temperate forests [Gil-Tena et al., 2007]
	Tree hollow	Boreal forest [Hobson and Bayne, 2000]; Second growth deciduous and coniferous-deciduous forests and conifer plantation [Keller et al., 2003]; Broadleaved woodlands [Laiolo, 2002]; Boreal forest [Machtans and Latour, 2003]; Mediterranean oak-pine forests [Díaz, 2006]
	Tree bark type	Eucalypt woodlands [Gilmore, 1985]; Eucalypt riparian forests and swamplands [Pearce et al., 1994]; Riparian forest [Pearce, 1996]
	Vegetation type	Pine plantations and native forests [Gepp, 1976]; Casuarina-Acacia woodland and Eucalypt open forests [Arnold, 1988; Vallecillo et al., 2008]
Understorey layer	Plant density	Deciduous forest wetlands [Swift et al., 1984]; Eucalyptus wandoo open forest, E. accedens open forest and Casuarina-Acacia low open forest [Arnold, 1988]; A transition zone from temperate deciduous forest to boreal coniferous forest (Positive or N) [Hagan and Meehan, 2002]; Temperate forests [Chettri et al., 2005]
	Crown cover	Grassland and woodlands [Ford and Bell, 1981]
Ground layer	Coarse woody debris	Deciduous forest wetlands [Swift et al., 1984]; Eucalypt forests and woodlands [Mac Nally, 1994]; Native pines-hardwoods forests [Shackelford, 1997]; Forests [Hagan and Grove, 1999]; Eucalypt woodlands and open forests [Walters et al., 1999]; A transition zone from temperate deciduous forest to boreal coniferous forest (Positive or N) [Hagan and Meehan, 2002]; Loblolly pine forests [Lohr et al., 2002]; A floodplain forest [Mac Nally et al., 2002]
¹ Categories for vertically differentiating vegetated areas ² Vegetation structural attributes that belong to each layering segment		

Appendix 2 - The values of the Vegetation habitat resource (VHR) variables that characterize the Bird habitat functional groups for the 104 GWW bird species.

No	Common name	VHR variables							
		Nest height	Nest site	Food source	Attack	Forage height	Forage place	Vegetation type	Understorey density
1	Australian Black-shouldered Kite	1	1	6	4	1	3	2	3
2	Australian Bustard	3	2	2	1	3	5	2	3
3	Australian Hobby	1	1	6	4	1	2	1	3
4	Australian Magpie	1	1	3	1	3	5	2	3
5	Australian Owllet-nightjar	3	1	1	4	3	1	1	3
6	Australian Raven	1	1	3	1	3	5	1	3
7	Australian Ringneck	3	1	7	1	3	5	1	3
8	Banded Lapwing	3	2	7	1	3	5	2	1
9	Barn Owl	3	1	6	4	3	5	2	1
10	Black Falcon	1	1	6	4	1	3	1	3
11	Black-faced Cuckoo-shrike	1	1	7	4	1	2	1	3
12	Black-faced Woodswallow	3	2	7	4	1	1	1	3
13	Blue-breasted Fairy-wren	3	2	1	1	3	5	2	1
14	Broad-tailed Thornbill	3	2	1	1	3	2	1	1
15	Brown Falcon	1	1	6	4	1	1	1	3
16	Brown Honeyeater	3	2	7	8	3	2	1	3
17	Brown Quail	3	2	7	1	3	5	2	3
18	Brown Songlark	3	2	7	1	3	5	2	3
19	Brown-headed Honeyeater	3	1	7	1	1	2	1	1
20	Bush Stone-curlew	3	2	7	6	3	5	1	2
21	Carnaby's Cockatoo	3	1	4	1	3	5	1	3
22	Chestnut Quail-thrush	3	2	7	1	3	5	1	1
23	Chestnut-breasted Quail-thrush	3	2	4	1	3	5	2	1
24	Chestnut-rumped Thornbill	3	1	7	1	3	2	1	3
25	Collared Sparrowhawk	1	1	6	4	1	1	1	3
26	Common Bronzewing	3	1	7	1	3	2	1	2
27	Crested Bellbird	3	1	7	1	3	2	2	1
28	Crested Pigeon	3	2	3	1	3	5	1	3
29	Crested Shrike-tit	1	1	1	1	3	2	1	3
30	Dusky Woodswallow	3	1	7	4	3	1	1	3
31	Emu	3	2	7	1	3	5	1	3

Appendix 2 - (Continued) The values of the Vegetation habitat resource (VHR) variables that characterize the Bird habitat functional groups for the 104 GWW bird species.

No	Common name	VHR variables							
		Nest height	Nest site	Food source	Attack	Forage height	Forage place	Vegetation type	Understorey density
32	Galah	3	1	7	1	3	5	2	3
33	Gilbert's Whistler	3	2	7	1	3	2	2	1
34	Golden Whistler	3	2	7	8	3	2	1	1
35	Grey Currawong	1	1	7	2	3	5	1	3
36	Grey Fantail	3	2	7	4	3	1	1	3
37	Grey Shrike-thrush	3	1	6	1	3	2	1	3
38	Ground Cuckoo-shrike	3	1	1	4	3	5	1	2
39	Hooded Robin	3	2	7	4	3	5	1	3
40	Jacky Winter	1	1	1	4	3	1	1	2
41	Laughing Kookaburra	1	1	6	4	3	3	1	2
42	Laughing Turtle-Dove	3	2	3	1	3	5	2	3
43	Little Button-quail	3	2	7	7	3	5	2	3
44	Little Corella	3	1	4	3	3	5	2	3
45	Little Crow	3	1	3	1	3	5	1	3
46	Little Eagle	1	1	2	4	1	1	1	3
47	Little Wattlebird	3	2	7	10	3	2	2	1
48	Little Woodswallow	3	1	1	4	1	1	1	3
49	Long-billed Corella	1	1	4	3	3	5	1	3
50	Magpie-lark	1	1	7	1	3	5	1	3
51	Malleefowl	3	2	4	1	3	5	2	1
52	New Holland Honeyeater	3	2	7	10	3	2	2	1
53	Painted Button-quail	3	2	7	7	3	5	1	3
54	Red Wattlebird	3	1	7	1	3	2	1	3
55	Red-capped Robin	3	2	1	4	3	5	1	3
56	Red-eared Firetail	3	2	4	1	3	5	1	1
57	Redthroat	3	2	7	8	3	5	2	3
58	Red-winged Fairy-wren	3	2	1	1	3	5	1	1
59	Restless Flycatcher	3	1	1	4	3	5	1	2
60	Rufous Songlark	3	2	7	1	3	5	1	2
61	Rufous Treecreeper	3	1	1	1	3	2	1	3
62	Rufous Whistler	3	1	7	8	3	2	1	2
63	Scarlet Robin	3	1	1	4	3	3	1	2
64	Shy Groundwren	3	2	7	1	3	5	1	1
65	Silveryeye	3	2	7	1	3	2	2	3
66	Singing Honeyeater	3	2	7	8	3	2	2	2
67	Slaty-backed Thornbill	3	2	1	8	3	2	1	3
68	Southern Emu-Wren	3	2	1	1	3	5	2	1
69	Southern Scrub-robin	3	2	7	1	3	5	2	1
70	Southern Whiteface	3	1	1	1	3	5	1	3

Appendix 2 - (Continued) The values of the Vegetation habitat resource (VHR) variables that characterize the Bird habitat functional groups for the 104 GWW bird species.

No	Common name	VHR variables							
		Nest height	Nest site	Food source	Attack	Forage height	Forage place	Vegetation type	Understorey density
71	Splendid Fairy-wren	3	2	1	8	3	2	1	1
72	Spotted Harrier	1	1	2	4	3	1	1	3
73	Spotted Nightjar	3	2	1	4	1	1	1	2
74	Spotted Pardalote	3	2	1	1	1	2	1	3
75	Square-tailed Kite	1	1	6	4	1	1	1	3
76	Striated Grasswren	3	2	7	1	3	5	2	2
77	Striated Pardalote	3	1	1	1	1	2	1	3
78	Stubble Quail	3	2	4	7	3	5	2	3
79	Tawny-crowned Honeyeater	3	2	7	8	3	2	2	1
80	Thick-billed Grasswren	3	2	7	1	3	5	2	3
81	Torresian Crow	1	1	3	1	3	5	1	3
82	Wedge-tailed Eagle	1	1	2	4	1	1	1	3
83	Weebill	3	1	7	8	3	2	1	3
84	Western Corella	1	1	4	9	3	5	1	3
85	Western Gerygone	3	1	1	8	3	2	1	3
86	Western Spinebill	3	1	7	10	3	2	2	3
87	Western Thornbill	3	1	1	1	3	2	1	3
88	Western Yellow Robin	3	2	7	4	3	5	1	1
89	Whistling Kite	1	1	6	4	1	1	1	3
90	White-backed Swallow	3	2	1	4	1	1	2	3
91	White-browed Babbler	3	2	7	1	3	5	1	1
92	White-browed Scrubwren	3	2	1	1	3	5	1	1
93	White-browed Treecreeper	3	1	1	1	3	4	2	3
94	White-browed Woodswallow	3	2	1	4	1	1	1	3
95	White-cheeked Honeyeater	3	2	4	8	3	2	2	1
96	White-eared Honeyeater	3	2	7	8	3	2	1	1
97	White-naped Honeyeater	1	1	7	6	1	2	1	3
98	White-plumed Honeyeater	3	2	7	10	3	2	1	3
99	White-winged Fairy-wren	3	2	7	8	3	2	2	3
100	White-winged Triller	3	1	7	8	3	5	1	2
101	Willie Wagtail	3	1	1	4	3	5	2	3
102	Yellow-plumed Honeyeater	3	2	7	8	3	2	1	3
103	Yellow-rumped Thornbill	3	2	7	1	3	5	1	3
104	Zebra Finch	3	2	4	1	3	5	2	3

Appendix 3 - Using SPSS software, the distance coefficients derived from the hierarchical cluster analysis of GWW bird species into Bird habitat functional groups (BHFGs).

Agglomeration Schedule						
Stage	Cluster Combined		Coefficients	Stage Cluster First Appears		Next Stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	31	103	0.000	0	0	39
2	16	102	0.000	0	0	46
3	34	96	0.000	0	0	26
4	58	92	0.000	0	0	30
5	64	91	0.000	0	0	14
6	75	89	0.000	0	0	11
7	61	87	0.000	0	0	66
8	46	82	0.000	0	0	74
9	6	81	0.000	0	0	42
10	18	80	0.000	0	0	200
11	15	75	0.000	0	6	19
12	8	69	0.000	0	0	28
13	13	68	0.000	0	0	30
14	22	64	0.000	0	5	29
15	38	59	0.000	0	0	52
16	24	54	0.000	0	0	35
17	47	52	0.000	0	0	71
18	23	51	0.000	0	0	32
19	15	25	0.000	11	0	40
20	17	18	0.000	0	10	39
21	42	104	1.000	0	0	58
22	66	99	1.000	0	0	46
23	90	94	1.000	0	0	45
24	67	85	1.000	0	0	68
25	62	83	1.000	0	0	56
26	34	79	1.000	3	0	64
27	74	77	1.000	0	0	78
28	8	76	1.000	12	0	44
29	22	60	1.000	14	0	44
30	13	58	1.000	13	4	79
31	43	57	1.000	0	0	47
32	23	56	1.000	18	0	83
33	35	50	1.000	0	0	84
34	28	45	1.000	0	0	48
35	24	37	1.000	16	0	43
36	30	36	1.000	0	0	69

Appendix 3 - (Continued) Using SPSS software, the distance coefficients derived from the hierarchical cluster analysis of GWW bird species into Bird habitat functional groups (BHFGs).

Agglomeration Schedule						
Stage	Cluster Combined		Coefficients	Stage Cluster First Appears		Next Stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
37	27	33	1.000	0	0	70
38	7	32	1.000	0	0	49
39	17	31	1.000	20	1	49
40	3	15	1.000	0	19	51
41	1	10	1.000	0	0	63
42	4	6	1.000	0	9	75
43	24	26	1.333	35	0	59
44	8	22	1.417	28	29	65
45	48	90	1.500	0	23	50
46	16	66	1.500	2	22	56
47	43	53	1.500	31	0	62
48	21	28	1.500	0	34	58
49	7	17	1.500	38	39	65
50	48	73	1.667	45	0	85
51	3	11	1.800	40	0	63
52	38	101	2.000	15	0	57
53	86	98	2.000	0	0	71
54	70	93	2.000	0	0	61
55	40	72	2.000	0	0	74
56	16	62	2.000	46	25	64
57	38	55	2.000	52	0	97
58	21	42	2.167	48	21	75
59	24	65	2.500	43	0	70
60	9	88	3.000	0	0	76
61	2	70	3.000	0	54	79
62	43	100	3.333	47	0	67
63	1	3	3.667	41	51	77
64	16	34	3.778	56	26	80
65	7	8	3.939	49	44	84
66	29	61	4.000	0	7	78
67	20	43	4.000	0	62	95
68	67	71	4.500	24	0	101
69	12	30	4.500	0	36	90
70	24	27	4.900	59	37	82
71	47	86	5.000	17	53	80
72	5	63	5.000	0	0	85

Appendix 3 - (Continued) Using SPSS software, the distance coefficients derived from the hierarchical cluster analysis of GWW bird species into Bird habitat functional groups (BHFgs).

Agglomeration Schedule						
Stage	Cluster Combined		Coefficients	Stage Cluster First Appears		Next Stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
73	44	49	5.000	0	0	88
74	40	46	5.000	55	8	87
75	4	21	5.467	42	58	83
76	9	39	5.500	60	0	92
77	1	97	5.750	63	0	86
78	29	74	5.833	66	27	81
79	2	13	5.833	61	30	91
80	16	47	6.722	64	71	93
81	14	29	7.200	0	78	96
82	19	24	7.286	0	70	94
83	4	23	7.417	75	32	88
84	7	35	7.429	65	33	92
85	5	48	7.500	72	50	87
86	1	41	7.889	77	0	90
87	5	40	8.500	85	74	96
88	4	44	8.682	83	73	91
89	78	84	10.000	0	0	95
90	1	12	10.100	86	69	99
91	2	4	11.275	79	88	97
92	7	9	12.458	84	76	94
93	16	95	13.000	80	0	98
94	7	19	14.388	92	82	99
95	20	78	14.600	67	89	98
96	5	14	15.467	87	81	100
97	2	38	15.675	91	57	100
98	16	20	17.806	93	95	101
99	1	7	26.370	90	94	102
100	2	5	26.391	97	96	102
101	16	67	39.016	98	68	103
102	1	2	40.534	99	100	103
103	1	16	61.680	102	101	0

Appendix 4 - List and definition of acronyms used in this study.

GWW	The Great Western Woodlands
VHR	Vegetation habitat resources
BHFG	Bird habitat functional group
VS variables	Vegetation structure variables
VHC	Vegetation habitat classification
LPVSV	Landscape prediction of Vegetation structure variables
PBHFG-SPS	Potential bird habitat functional group spatial prediction system

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