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RESEARCH PAPER

A plot-based analysis of the vegetation of the Northern Territory, Australia: a first assessment within the International Vegetation Classification framework

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Abstract

Aims: To develop an interim classification of the vegetation of the Northern Territory at the International Vegetation Classification (IVC) division (level 4) and macrogroup (level 5) levels. These types are produced to assist in the development of an integrated nationwide plot and floristically based classification of Australia allowing integration within a global perspective. **Study Area:** The Northern Territory of Australia covers an area of 1.42 million square kilometres, almost 20% of Australia's land mass. It comprises three distinct climatic zones including tropical, subtropical and arid vegetation types. **Methods:** We used collated vegetation data held by two organisations: the Northern Territory Government, Department of Environment, Parks and Water Security and the Terrestrial Ecosystem Research Network (a total of 45,710 plots used). We applied semi-supervised quantitative classification methods to define vegetation types at the IVC division and macrogroup levels. Analyses used kR-CLUSTER methods on presence/absence data. Macrogroups were characterised by taxa with the highest frequency of occurrence across plots. Additional analyses were conducted (cluster) to elucidate interrelationships between macrogroups and to assist in the assessment of division level typology. **Results:** We propose 21 macrogroups and place these within higher thematic levels of the IVC. **Conclusions:** We found that the IVC hierarchy and associated standard procedures and protocols provide a useful classification tool for Australian ecosystems. The divisions and macrogroups provide a valid framework for subsequent analysis of Northern Territory vegetation types at the detailed levels of the IVC. A consistent typology for the Northern Territory (and hopefully in future, for all of Australia) has numerous benefits, in that they can be used for various applications using a well-structured, systematic and authoritative description and classification that is placed in a continental and global context, readily enabling the one system to be used in studies from the local to global level.

Taxonomic reference: Northern Territory Herbarium (2022).

Abbreviations: DVT = Definitive Vegetation Type; IVC = International Vegetation Classification; nMDS = non-metric multidimensional scaling; NT = Northern Territory; NTVSD = Northern Territory Vegetation Site Database; NVIS = National Vegetation Information System; WA = Western Australia.

Keywords

arid, Australia, Definitive Vegetation Type, International Vegetation Classification, National Vegetation Information System, Northern Territory, semi-arid, sub-tropical, tropical

Introduction

A unified terminology and procedure for classifying vegetation types across jurisdictions and continents is required for clear understandings of their distribution, evolutionary biology, and threats, along with guiding their restoration and rehabilitation (De Cáceres et al. 2015; Gellie et al. 2018; Luxton et al. 2021). The lack of conformity in vegetation survey, classification and description severely limits local, regional, continental, and global understandings. This is a common problem worldwide but has been particularly identified as problematic within Australia (Faber-Langendoen et al. 2014; De Cáceres et al. 2018; Luxton et al. 2021; Muldavin et al. 2021). Many early attempts of vegetation classification within Australia were continental in focus but not plot based (e.g., Beadle 1981; Carnahan 1986; Walker and Hopkins 1990; Specht et al. 1995; Sun et al. 1997). In recent decades Australian vegetation classification has become strongly jurisdictional, with typologies often derived from plotless qualitative methods with no or very limited hierarchical structure (Gellie et al. 2018; Luxton et al. 2021). However, this fragmentation into classifications that are highly dissimilar is an impediment to co-operation at a time when climate change, habitat loss and extinctions are increasing, and cross jurisdictional (national and international) collaboration is a fundamental need (De Cáceres et al. 2018). The single example of a continental floristic based classification of Australia is that of Specht et al. (1995) who used plotless plant species lists in place of plot data, which were then subjectively combined into broad structural types and analysed through TWINSPAN (Hill 1973, 1979). Although plot-based data is still lacking within certain regions of Australia (Gellie et al. 2018), the amount of plot data available is sufficient to allow major vegetation types to be derived at a continental scale using plot-based analysis techniques (e.g., Muldavin et al. 2021).

Australia's vegetation is unique with more than 80% of the vascular flora endemic to the continent (Taxonomy Decadal Plan Working Group 2018), producing at times, distinctive physiognomic vegetation types dissimilar to those of corresponding latitudes elsewhere (Crisp et al. 2009; Hunter et al. 2021), yet botanical species discovery is ongoing (Keith and Tozer 2017; Gellie et al. 2018). The floristic composition is like nowhere else on the planet where vast, relatively intact landscapes (particularly in northern and arid Australia) are dominated by the genera *Eucalyptus*, *Corymbia* and *Acacia*. Over 890 species and subspecies of *Eucalyptus* are currently recognised with the majority endemic to Australia (Chippendale 2020). *Acacia* is the largest genus of vascular plants in Australia with over 1,000 species currently recognised (Maslin 2001). *Acacia* is an ecologically and economically important group prominent in the Australian environment and psyche and is also Australia's floral emblem (Maslin 2001).

Although no continental plot-based vegetation classification currently exists for classifying community types, the Australian National Vegetation Information System (NVIS) is an existing national classification. It is a supervised, largely structural, mapping-based classification with limited floristic data. NVIS was established by the Executive Steering Committee for Australian Vegetation Information (Executive Steering Committee for Australia 2003) to underpin the National Land and Water Resources Audit (NLWRA) assessment of vegetation in Australia (National Land and Water Resources Audit 2001). NVIS is a hierarchical classification scheme that is not floristically derived, but based on dominant growth form, height and cover with limited characteristic flora species (3–5 taxa in each structural layer) (Thackway et al. 2008; NVIS Technical Working Group 2017; Gellie et al. 2018; Lewis et al. 2021a). The NVIS hierarchy recognises six levels ranging from dominant growth form for the dominant stratum at the first level, to detailed descriptions of each substratum and dominant species at the sixth level (NVIS Technical Working Group 2017). NVIS was instrumental in assisting in the compilation of disparate vegetation maps and enabled the first complete vegetation map of the continent (Gellie et al. 2018; Lewis et al. 2021a). However, differences in the spatial and classification resolution of data between jurisdictions transferred into scale issues that are especially evident at state and territory boundaries. For example, where hummock grasslands abruptly turn into mallee woodlands and shrublands at the Western Australia (WA)/South Australia (SA) border, and tussock grasslands turn into eucalypt woodlands at the WA/Northern Territory (NT) border. Although NVIS was developed primarily as a classification scheme for mapping products, it was co-opted as a vegetation classification scheme within the NT (Brocklehurst et al. 2007; Lewis et al. 2008; Lewis et al. 2021a).

The NT is a semi-independent jurisdiction covering 20% of the Australian continent. The mid-1980s saw the introduction of vegetation mapping reliant on plot data to classify vegetation types into mappable units. *Ad hoc* vegetation mapping continues in the NT at varying degrees of attribute detail and spatial scale. No strategic vegetation mapping program for the whole of the NT has been implemented, although scoping documents have been devised to map the NT at 1:100,000 on several occasions (Brocklehurst et al. 2008; Jan and Brocklehurst 2009). During the 1990s two examples of floristic numerical classification were conducted. Russell-Smith (1991) classified the monsoon closed forests in northern Australia, based on a TWINSPAN classification using 1,219 plots with 559 closed forest taxa represented and 16 floristic assemblages described. On an NT-wide scale, Wilson et al. (1990) derived a plot-based vegetation classification for the NT vegetation map at 1:1,000,000 scale based on 2,245 plots using an intuitive appraisal of numerical analytical techniques (TWINSPAN). A total of 112 broad vegetation types were described and delineated based on the dominant woody species, with tussock and hummock grasslands being the only exceptions. The vegetation types were heavily defined by the structural characteristics of the vegetation.

A more recent attempt to classify the vegetation communities of the NT was conducted in 2007 (Brocklehurst and Gibbons 2007). The Definitive Vegetation Type (DVT) concept was developed to provide both a local and nationally recognised systematic taxonomy of vegetation types in the NT. A DVT can be described as a representative or typical example of a vegetation community at the association level (NVIS Level 5) compiled from existing vegetation mapping data. A preliminary list of 367 DVTs was generated from published and unpublished vegetation survey reports (Brocklehurst and Gibbons 2003). Only 285 have been completely built based on NVIS and are aligned with the NVIS Major Vegetation Groups and Sub-groups. This system is not a scientifically robust classification and it can be described as a conglomerate of existing descriptions derived using various numerical, but more often, intuitive analytical techniques.

Although initial plot-based data collection within the NT began in the 1950s, the greatest efforts were placed during the early 2000s; however, no centralised database was available for the collation of early data (Lewis et al. 2021a). Since 2007, the NT government has consistently used plot-based methods to collect vegetation data, including full floristic and structural attributes (Brocklehurst et al. 2007; Lewis et al. 2008; Lewis et al. 2021a). In 2012, the NT Vegetation Site Database (NTVSD) was established and became the centralised repository for all vegetation plot data (Gellie et al. 2018; Lewis et al. 2021a). Thus, there has been a significant increase in available and reasonably well curated plot data in the NT over the last 25 years (Lewis et al. 2021a). With this, the ability to undertake comprehensive floristic ecological analyses based on a hierarchical schema has become feasible. The International Vegetation Classification (IVC) is one such system, and it has already been employed in several published Australian case-studies (Hunter and Addicott 2021; Muldavin et al. 2021).

The IVC is based on the EcoVeg approach (Faber-Langendoen et al. 2014), which preferentially uses floristic plot-based data for primarily analyses and local subregional ecological factors to define lower-levels of the classification hierarchy, floristics, physiognomy, and regional to continental scale ecological factors at mid-levels, and at the highest levels, physiognomy and global ecological drivers are incorporated. This scaling of vegetation and climatic drivers helps guide the data required, with full floristic composition and local site factors required to help drive the classification at the lower levels, which is important for floristic modelling and understanding of rarity of types, whereas physiognomy and regional landscape factors help derive the mid to higher levels, which are applicable to landscape and continental scale mapping.

The IVC has been developed with a rigorous set of standards and principles that seek to characterise the world's vegetation. To date, the IVC has been built to its greatest depth in North America, including national vegetation classifications (NVCs) in both the United States (USNVC) and Canada (Jennings et al. 2009; Faber-Langendoen et al. 2018; Baldwin et al. 2019). The mid and lower levels have been used widely by various classification systems worldwide (Faber-Langendoen et al. 2014) for multiple uses, including vegetation mapping (Franklin et al. 2016; Muldavin et al. 2021). Both approaches shine a light on ways forward for Australian vegetation classification (Luxton et al. 2021). For example, recently, a continental floristic plot-based analysis using IVC protocols was performed within two major vegetation types, *Eucalyptus tetrodonta* Woodland and *Triodia* Hummock Grasslands, both of which have extensive distributions within the NT and across Australian jurisdictions (Muldavin et al. 2021). The use of the IVC structure and methodology has been shown to be useful across a wide range of vegetation types within Australia in recent years and its use promoted as a way forward in cross jurisdictional understanding of vegetation (Hunter and Lechner 2017; Gellie et al. 2018; Hunter 2020; Hunter and Addicott 2021; Hunter and Hunter 2021; Lewis et al. 2021a; Muldavin et al. 2021).

Here we use semi-supervised analyses incorporating plot data from across the NT in order to circumscribe a preliminary series of mid-level (L4 division and L5 macrogroup) IVC natural vegetation types. These types are placed where possible within existing and proposed IVC types, such as those published in Muldavin et al. (2021). This IVC-based classification is not intended to replace existing state and territory-based classification systems, such as the mapping based NVIS, but to compliment, strengthen and expand upon pre-existing systems that are of relevance at a continental and global scale. Aligning structural and floristic types across Australia makes datasets more flexible, and they can be used for an increased number of applications that promote cross continental and global understandings.

Study area

The NT of Australia comprises an area of 1.42 million square kilometres, one-sixth of the total land area of Australia and is sparsely populated (244,800 people; 60% living within the 3,164 square kilometres of the Greater Darwin region (the capital); Australian Bureau of Statistics 2020). It spans a broad climatic and latitudinal gradient, from temperate dry arid deserts in the south (-26 degrees south) to monsoonal tropics in the north -11 degrees north; Fig. 1). The climate range covered is commensurate with a high diversity of native vascular flora (> 4,500 species; Cowie et al. 2017) and endemicity (Crisp et al. 2002; Hunter 2004; Woinarski et al. 2006). Almost 20% of the NTs vascular flora is endemic with regions of high endemism including the Western Arnhem Land Plateau in the Top End, and the West Macdonnell Ranges in Central Australia.

The Interim Biogeographic Regionalisation for Australia (IBRA) provides a division of Australia into units of broadly similar landform, geology and biodiversity akin to ecoregions. These 'bioregions' provide a useful unit for natural resource management and planning (Thackway and Cresswell 1995). There are 12 bioregions wholly within the NT, and another 13 shared with the neighbouring states (Thackway and Cresswell 1995).

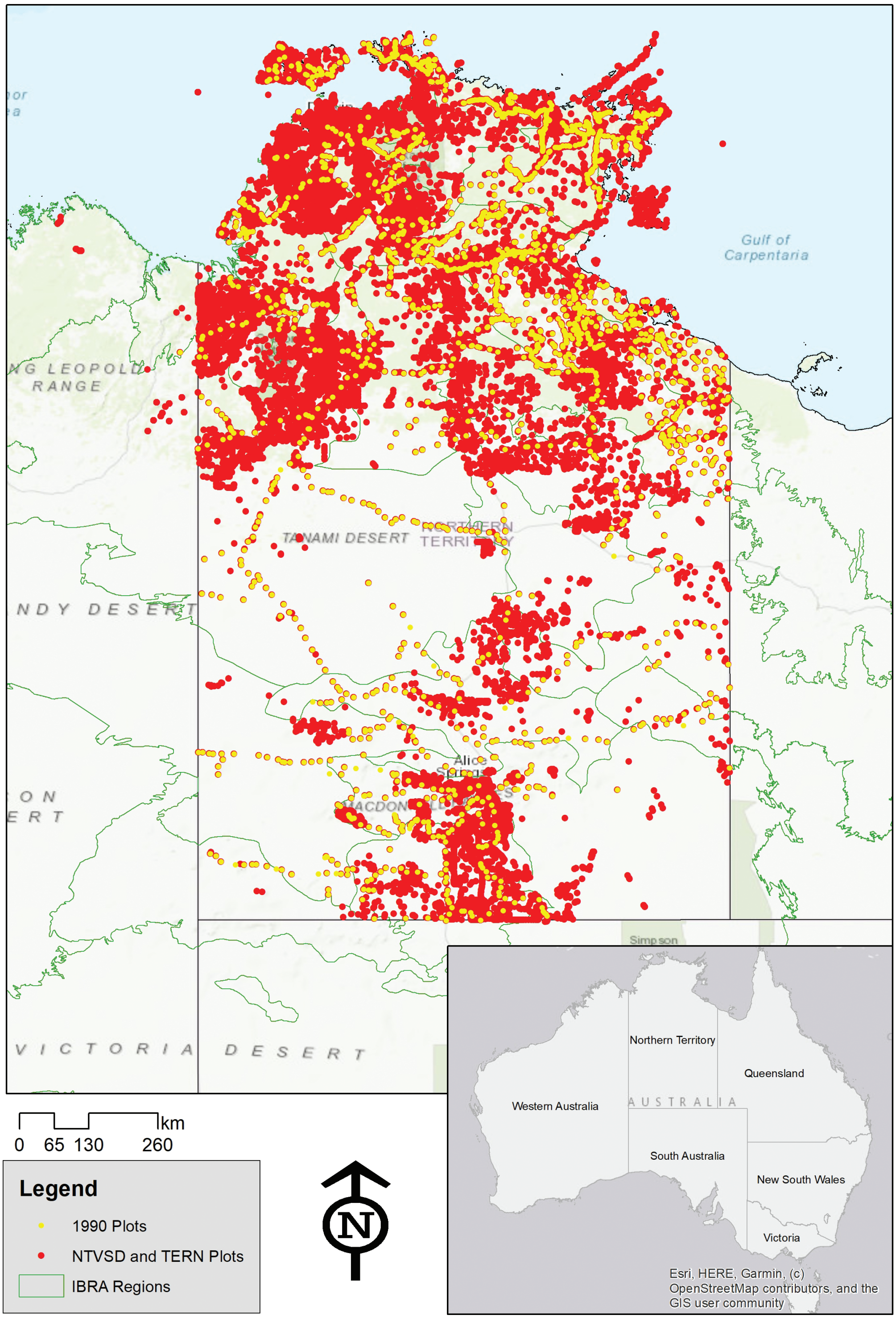

Figure 1. Locality map of Australia's Northern Territory, illustrating the distribution of 2,245 vegetation plots to inform the 1990 1:1 million vegetation map and the additional 45,710 plots sampled in this analysis. Bioregions from interim Biogeographic Regionalisation for Australia (IBRA) version 7 (2012). NTVSD – Northern Territory Vegetation Site Database; TERN – Australian Terrestrial Ecosystem Research Network.

The NT is characterised by tropical and arid zone vegetation types. Tropical savannas are the dominant vegetation type of northern Australia covering about 25% of the continent (Williams et al. 2017) and are comparatively intact ecologically. They consist of a matrix of grasslands and sclerophyllous woodlands dominated by *Eucalyptus* and *Corymbia* species, interspersed with patchy occurrences of monsoon closed forest, sandstone woodland, shrubland, and floodplains (Patykowski et al. 2021). The arid zone is dominated by *Acacia* shrublands and woodlands (Nano et al. 2017), along with *Triodia* hummock grasslands (Wardle and Nano 2017), and like tropical savannas, are also relatively intact.

Methods

Field data

The data extracted from the NTVSD used a common survey protocol. The standard method for vegetation sampling in the NT has been consistently used by government botanists and scientists since the 1970s (Wilson et al. 1990; Brocklehurst et al. 2007; Lewis et al. 2021b). At a minimum, a vegetation sampling plot consists of a 20 m × 20 m quadrat, and larger quadrat sizes in the arid zone (up to 50 m × 50 m) as a result of sparsely vegetated landscapes. In the NT, up to three strata (*sensu* Hnatiuk et al. 2009), including upper strata (tree layer), mid-strata (shrub layer), and ground strata (incorporating tussock grasses, hummock grasses, sedges, forbs, and low shrubs) are recognised. Within the strata, all (or dominant) vascular plant species and cover or abundance are recorded. Cover is generally estimated as canopy cover (crowns treated as opaque) for the upper strata, as projective foliage cover (PFC; vertical projection of foliage only) for the mid-strata, and percentage cover for the ground strata. Mean height (in metres) and range are generally measured for species greater than 2 m tall, and visually estimated for those less than 2 m (for species greater than 1% cover).

The Terrestrial Ecosystem Research Network (TERN) Ecosystem Surveillance monitoring plots of 100 m × 100 m were also used in the analyses. A sampling plot includes the same floristic, structural and environmental attributes as that collected on the NTVSD, however the methods differ and are more rigorous for monitoring purposes as outlined in Sparrow et al. (2020) and White et al. (2012). Samples of vegetation (voucher and genetic) and soils (physical, chemical and biological) are collected and stored for identification and subsequent re-use.

Data access and curation

The full set of more than 77,000 plots were accessed from the NTVSD 2021. The plot data is of varied quality and detail with information including full floristic or dominant species only and data scored on presence/absence or percent cover (Gellie et al. 2018; Lewis et al. 2021a). The plot data were collected for numerous purposes, broadly including land resource and vegetation community mapping, flora surveys, habitat assessment for fauna surveys, rare and threatened species surveys, development assessment and monitoring. Vegetation plot data collected for the TERN Ecosystem Surveillance program were accessed from TERNs Advanced Ecological Knowledge and Observation System (AEKOS; Tokmakoff et al. 2016; Sparrow et al. 2020) which is to be superseded by TERN EcoPlots. In total, 155 NT plots were used in the analyses. TERN employs a suite of standard methods with the aim of standardising data collection in Australian ecological monitoring programs, however this data is also fit for purpose for many other applications such as vegetation classification and mapping (TERN 2021).

Datasets without full floristic information or of plot sizes less than 100 square metres or greater than 25,000 square metres were removed from the NTVSD dataset. Plots where species richness was less than 10 taxa were also removed. It is acknowledged that the removal of plots with less than 10 taxa is likely to remove from the analysis some distinct, but low diversity communities such as coastal samphire, mangrove and some freshwater floodplain vegetation. However, our analysis is not designed to develop a definitive set of all possible types through analysis, but to provide an initial set of types which will be expanded with further analysis both within the NT and across jurisdictional boundaries.

Records that were not identified to species level or better were excluded as they can artificially inflate species richness, as can plots with low frequency taxa. As the remaining dataset was a mixture of plots where taxa were recorded by percentage cover or presence/absence, all scores were reduced to presence/absence only. A total of 45,710 plots were used in subsequent analyses representing 4,566 taxa and 831,149 records. Taxonomic curation was applied to the vascular plants presence data to ensure names to the species-rank were current and in accordance with the Australian Plant Census (APC: Council of Heads of Australasian Herbaria (CHAH)), various dates) and the HOLTZE taxon table, the authoritative vascular plant checklist for the NT as available through Flora NT (Northern Territory Herbarium 2022). Either of these sources may be consulted for the authors of plant names. We did not differentiate taxa to subspecific ranks, apart from those that are distinct in terms of being widely recognised and of use for community recognition. Undescribed species are included in the dataset using informal 'phrase names' (CHAH 2020).

Our analysis utilises a broad concept of Coolabah – *Eucalyptus microtheca*, which here includes a number of segregate taxa recognised by Hill and Johnson (1994), i.e., *E. barklyensis*, *E. cyanoclada* and *E. helenae.* These taxa have been amalgamated into *E. microtheca* by some authorities (Slee et al. 2015) but are currently accepted in the NT (Cowie et al. 2017; Northern Territory Herbarium 2022). However, the site data frequently do not distinguish the segregate taxa for historical and other reasons. Similarly, the broad concept of *Acacia aneura* F.Muell. ex

Benth. used here includes *A. aptaneura*, *A. incurvaneura*, *A. mulganeura* and *A. pteraneura*, as survey data is generally unvouchered and records predating Maslin and Reid's (2012) revision cannot be accurately attributed amongst the segregate taxa now recognised in the NT and WA (Cowie et al. 2017; Council Heads of the Australian Herbaria 2002–2022; Northern Territory Herbarium 2022). *Corymbia opaca* is here treated as distinct from *C. terminalis sensu stricto* following Hill and Johnson (1995) and the APC (CHAH 2002–2022), but this is in contrast to the broad concept of *C. terminalis* (as *E. terminalis*) used by Wilson et al. (1990) in mapping the NT's vegetation.

Growth form data, in accordance with the NVIS growth form definitions and controlled vocabulary, were updated and extracted from HOLTZE for each species (Thackway et al. 2008; NVIS Technical Working Group 2017). This dataset was joined to the final species lists for initially defined types for subsequent analysis of growth form and functional groups. Growth form data was used to assist in vegetation type delineation and circumscription after the floristic classifications were complete, as this information is required to properly place types within the IVC hierarchy at the Macrogroup level. The final delineation of proposed types, while guided initially by the floristic analysis, was informed by expert opinion.

Statistical analysis

Due to size of the final dataset and the computation power required, a limited set of options were available to the authors for initial analyses. Data were transformed into a species by site matrix via the r-package 'tidyr' (v 1.1.3; Wickham 2021). A series of kR-CLUSTER clustering analyses were performed using options from 4 to 20 groups within PAST (ver. 4.06b; Hammer et al. 2001). Expert knowledge of the authors and other relevant experts was used to assess both the validity of circumscribed types, and which types may have warranted further specialist advice or analysis and placement within the IVC hierarchy.

A combination of statistical and intuitive approaches can often produce accurate and stable outcomes particularly at the mid to higher hierarchical levels of a classification (Mucina 1997). Top-down and bottom-up approaches are suggested when allocating vegetation types with expert knowledge and qualitative application of the criteria is often used at upper levels, whereas quantitative analysis of plot-based data is used to distinguish vegetation types at the mid to lower levels (Faber-Langendoen et al. 2014). In order to assist in the placement of types at level 4 (division) within the IVC and to understand the floristic relationships and physiognomic differences between macrogroups, a new dataset was created that contained the most frequent taxa (150) and their frequency within the macrogroup based on the number of plots in which they were found. A cross table of type, species and their frequency score were created. This dataset was analysed using agglomerative hierarchical clustering within Primer-E (ver. 7; Clarke and Gorley 2015) using Bray-Curtis coefficient on square root transformed data. We used agglomerative hierarchical clustering (Flexible Beta), within the CLUSTER routine. This was used as an aid to assess floristic relatedness between types which, along with growth form data, was used to assist in the placement of types within the IVC hierarchy.

Alignment within the IVC hierarchy

An important component of this work was to align our results with the IVC hierarchy. To do this we used the key to IVC formation classes and brief definitions provided by Faber-Langendoen et al. (2016), the criteria of the IVC (Jennings et al. 2009; Faber-Langendoen et al. 2014), environmental data, previous work done by other authors in the Australian context (e.g., Muldavin et al. 2020), and expert knowledge from recognised specialists in the NT flora and the IVC hierarchy (see acknowledgements). We included experts both government and private and with extensive field experience. The expertise called upon including a combined 70 years of field experience for the tropical and semi-arid regions including taxonomy, botanical, ecological, and integrated surveys from monitoring, mapping and modelling. The expertise for the arid zone included experience spanning more than 50 years of field experience. Although explicit environmental analyses were not undertaken within our classification process the intuitive phase of expert opinion took into consideration the combined field knowledge mentioned above of environmental gradients, underlying geology, geomorphology and landscape dynamics.

Results

Four broad types were recognised from initial analysis and can be compartmentalised into the NTs climatic zones (based on Koppen-Geiger: Beck et al. 2018), broadly including tropical (divided into savanna and closed forest), sub-tropical (included as warm temperate in the IVC), and arid. The geographic split of the four types, illustrated in Fig. 2, indicates a strong relationship with bioclimate and geography. This includes a distinct north-south rainfall gradient in the NT that strongly influences species and structural composition. The tropical to semi-arid region extends from -17 degrees latitude, with a 1,000 mm mean annual rainfall isohyet to -20 degrees, with the semi-arid to the arid zone occurring further south (500 mm mean annual rainfall isohyet) (Wilson et al. 1990; Fig. 2). The floristic relationship (Fig. 3) highlights the distinctiveness of the Australian and East Malesian Dry Forests (MG1) and the Northern Australian Tropical Swamp Grass (MG14).

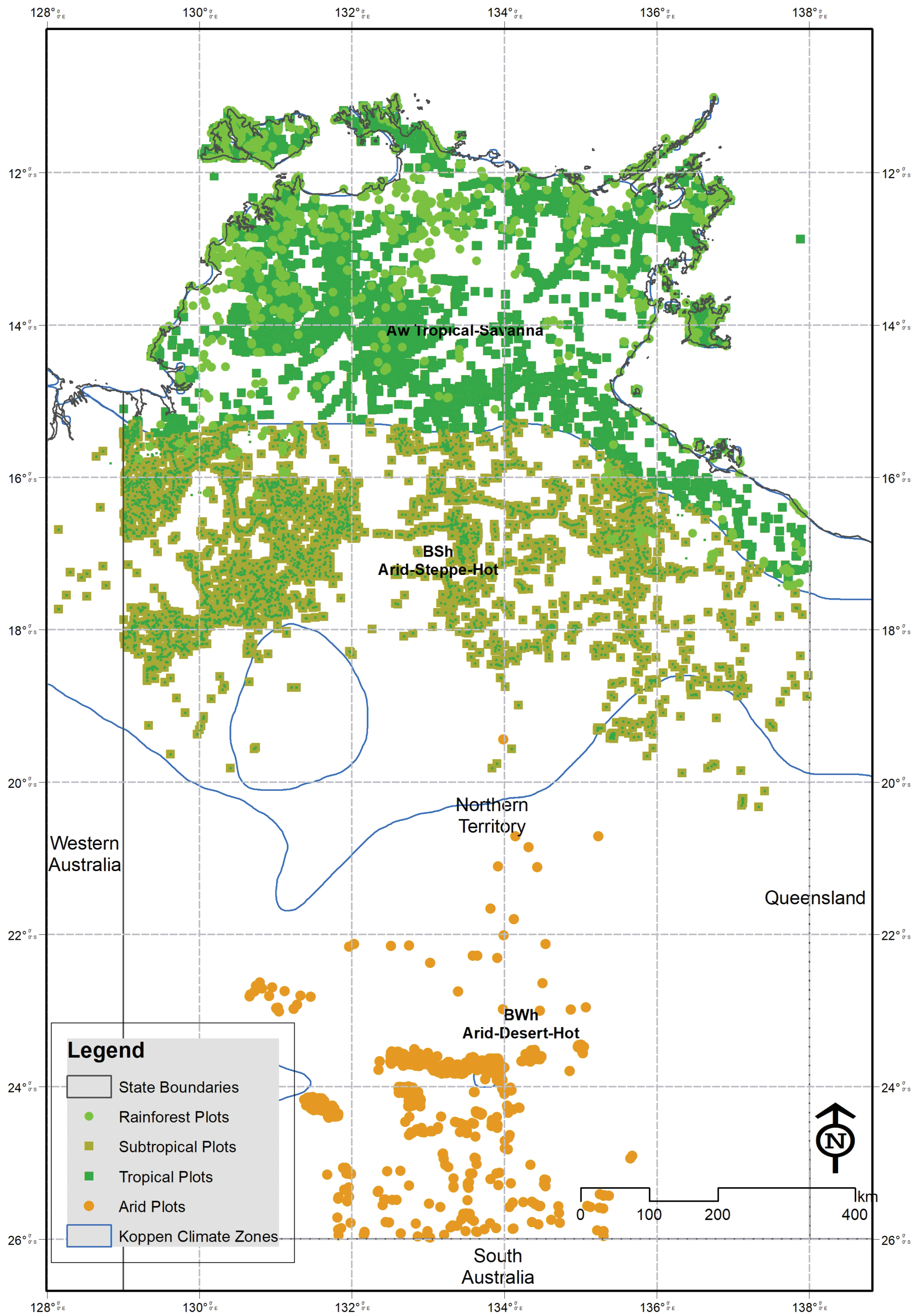

Figure 2. Northern Territory climatic zones (Koppen-Geiger) and geographic distribution of the four broad vegetation types recognised in the initial analysis: a) savanna (tropical), b) rainforest (tropical closed forest), c) warm temperate (subtropical), d) desert / semi-desert (arid).

Alignment with the IVC hierarchy

Due to the necessary inclusion of growth form and climate the final alignment with the IVC hierarchy does not follow the results of the floristic relatedness as indicated in Fig. 3. An interim set of eight divisions and 21 macrogroups were considered robust enough to warrant preliminary definition based on numerical analysis and expert knowledge. Five divisions and 16 macrogroups are considered new for the NT (Table 1). The macrogroups

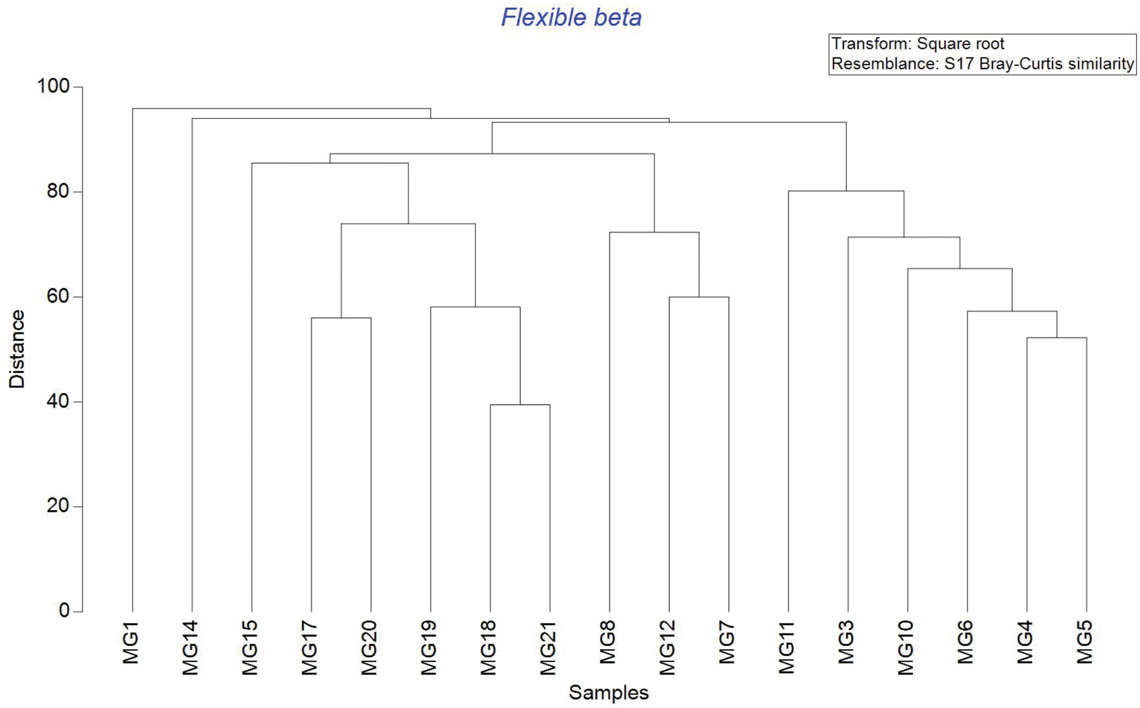

Figure 3. Floristic relatedness of macrogroups based on the 150 most frequent taxa across all plots used to define each type. Only macrogroups defined within this current investigation appear in the analysis. Note this analysis was used as a guide for placement within the upper IVC hierarchy, but due to necessary incorporation of growth form data at the macrogroup and higher levels, these results do not directly relate to the final placement. See Table 1 for full names of macrogroups.

identified are all subcontinental, with regional / meso- climatic differences or geologies, and thus are appropriately categorised at the macrogroup level of the IVC hierarchy. We refrain from adding formal names within the IVC to the new macrogroups and divisions, as we would prefer standardised naming to be provided based on a wider decision-making and peer-review process involving a wider expert panel than the authors alone.

The NT vegetation types were aligned within the three highest levels of the IVC hierarchy, which are global in scope (formation class, formation subclass and formation). At the highest level, the NT vegetation types could be placed into the Formation Classes 1. Forest and Woodland, 2. Shrub & Herb Vegetation, 3. Desert & Semi-Desert and 5. Aquatic Vegetation. The majority of the types (14 of 21) occur in the tropical and subtropical climatic zones, which cover approximately half of the NT. Within these zones, 11 of the 14 types were placed as macrogroups into: formation class 2. Shrub and Herb Vegetation, formation subclass 2.A. Tropical Grassland, Savanna and Shrubland, formation 2.A.1 Tropical Lowland Grassland, Savanna & Shrubland, and into a specific division for Australian tropical savannas: L.4 Australian Tropical Savanna and Scleromorphic Woodland, as defined by Muldavin et al. (2021; Table 1). Although Scleromorphic Woodland may appear to be an initially incongruent placement within the Shrub and Herb Vegetation formation subclass, these woodlands are included as part of the savanna biome under the IVC framework (Faber-Langendoen et al. 2016), the Global Ecosystem Typology (Keith and Williams 2020; Lehmann et al. 2020) and within the Australian context (Williams et al. 2017). These macrogroups span the Top End of the NT, west to the coast of the Kimberley region of WA, and east to east coast of Cape York Peninsula in Queensland (Qld; Suppl. material 1). One type was placed in formation 2.C.3 Tropical Freshwater Marsh, Wet Meadow & Shrubland. It is dominated by tropical grasses and sedges, and consequently a new division in the IVC is proposed for this type: L.4 Australian Tropical Wet Grassland and Sedgeland. This type can also be seasonally inundated with 1–2 m or more of water. Nomenclature for this macrogroup [MG14] could include 'wetland' as it clearly fits Australian definitions.

Analysis group MG1, broadly categorised as 'closed forest', was the only vegetation type placed into the IVC formation class 1. Forest & Woodland, formation subclass 1.A. Tropical Forest & Woodland, and formation 1.A.1. Tropical Dry Forest & Woodland (Table 1). Within this, the macrogroup L.5 (MG1) Australasian & South East Asia Dry Forest is available for placement of the closed forest results. Due to this and Australian closed forests being identified as potentially occurring across Australasia and South East Asia, we propose a new division L.4. Australasian Dry Forest & Woodland and restrict the 'closed forests' macrogroup to L.5 (MG1) Australasian & East Malesian Dry Forest as the application to South East Asia more generally is less certain. Miles et al. (2006) and our results (including expert opinion) would suggest that

Table 1. Alignment of the Northern Territory vegetation types with the International Vegetation Classification hierarchy existing Class, Subclass, Formation, and proposed preliminary Divisions and Macrogroups.

Class	Subclass	Formation	Division	Macrogroup	Analysis Group
1. Forest & Woodland					
	1.A. Tropical Forest & Woodland				
		1.A.1. Tropical Dry Forest & Woodland			
			L.4. Australasian Dry Forest & Woodland **NEW**		
				L.5 (MG1) Australasian & East Malesian Dry Forest **NEW**	[20-18]
		1.A.5 Mangrove			
			1.A.5.Wb Indo-West Pacific Mangrove		
				L.5 (MG2) West Pacific (East Melanesia, Micronesia, Polynesia) Mangrove (M208)	
2. Shrub & Herb Vegetation					
	2.A. Tropical Grassland, Savanna & Shrubland				
		2.A.1. Tropical Lowland Grassland, Savanna & Shrubland			
			L.4 Australian Tropical Savanna and Scleromorphic Woodland (D133; Muldavin et al. 2021)		
				L.5 (MG3) Australian Paperbark Melaleuca viridiflora–Long-fruited Bloodwood Corymbia polycarpa Forest and Woodland **NEW**	[20-2]
				L.5 (MG4) Australian Darwin Stringybark Eucalyptus tetrodonta Scleromorphic Woodland (M530; Muldavin et al. 2021)	[20-6,14,15,19]
				L.5 (MG5) Australian Darwin Box Eucalyptus tectifica Scleromorphic Woodland **NEW**	[20-4]
				L.5 (MG6) Australian Broad-leaved Bloodwood Corymbia foelscheana Scleromorphic Woodland **NEW**	[20-3]
				L.5 (MG7) Australian Lancewood Acacia shirleyi Forest, Woodland and Shrubland **NEW**	[20-5]
				L.5 (MG8) Australian Coolabah Eucalyptus microtheca Tropical Savanna Grassy Woodland and Tussock Grassland **NEW**	[20-7]
				L.5 (MG9) Australian Tropical Triodia bitextura–Triodia microstachya–Triodia bynoei Hummock Grassland and Open Woodland (M531; Muldavin et al. 2021)	
				L.5 (MG10) Australian Small-fruited Bloodwood Corymbia dichromophloia–Curley Spinifex Triodia bitextura Scleromorphic Woodland **NEW**	[20-13]
				L.5 (MG11) Australian Tropical Billy Goat Plum Terminalia carpentariae–Northern Spinifex Triodia microstachya Scleromorphic Woodland and Shrubland complex **NEW**	[20-20]
				L.5 (MG12) Australian Bean Tree Bauhinia cunninghamii Tropical Savanna Tussock Grassy Woodland and Tussock Grassland **NEW**	[20-1,8,16]
				L.5 (MG13) Eremaean Semi-arid Hummock Grassland and Low Open Woodland (M532; Muldavin et al. 2021)	
		2.C.3 Tropical Freshwater Marsh, Wet Meadow & Shrubland			
			L.4 Australian Tropical Grassland and Sedgeland **NEW**		
				L.5 (MG14) Northern Australia Tropical Swamp Grass Pseudoraphis spinescens–Water Chestnut Eleocharis dulcis–Water Lily Nymphaea violacea Grassland and Sedgeland **NEW**	[20-9]
		2.C.4 Temperate to Polar Freshwater Marsh, Wet Meadow & Shrubland			
			L.4 Australian Arid and Semi-arid Grasslands and Sedgelands **NEW**		
				L.5 (MG15) Australian Ephemeral Arid and Semi-arid wetlands **NEW**	Arid Wetlands
3. Desert & Semi-Desert					
	3.A. Warm Desert & Semi-Desert, Scrub & Grassland				
		3.A.2. Warm Desert & Semi-Desert, Scrub & Grassland			
			L.4 Australian semi-desert scrub and grassland (D330; Muldavin et al. 2021)		
				L.5 (MG16) Australian Desert Hummock Grassland (M535; Muldavin et al. 2021)	
				L.5 (MG17) Australian Desert and Semi-arid Mulga Acacia aneura Woodland & Shrubland **NEW**	[10-10]
				L.5 (MG18) Australian Desert and Semi-arid Victoria Wattle Acacia victoriae–Emu Bush Eremophila longifolia–Ironwood Acacia estrophiolata Shrubland **NEW**	[10-1]
				L.5 (MG19) Australian Desert and Semi-arid Witchetty Bush Acacia kempeana Shrubland **NEW**	[10-5]
				L.5 (MG20) Australian Desert and Semi-arid Bloodwood Corymbia opaca Woodland **NEW**	[10-8]
				L.5 (MG21) Australian Desert and Semi-arid Rock Fuchsia Bush Eremophila freelingii–Witchetty Bush Acacia kempeana Shrubland **NEW**	[10-7]
5. Aquatic Vegetation					
	5.B Freshwater Aquatic Vegetation				
		5.B.1 Tropical Freshwater Aquatic Vegetation			
			L.4 Australian Tropical Aquatic Vegetation **NEW**		
			L.4 Australian Desert and Semi-arid Aquatic Vegetation **NEW**		

the Australian and South East Asian dry closed forests are likely to be floristically distinct and that the Australian dry forests have greater affinity with Malesian dry forests.

Further south in the arid zone, six vegetation types were placed into formation class 3. Desert & Semi-Desert, formation subclass 3.A. Warm Desert & Semi-Desert, Scrub & Grassland and formation 3.A.2. Warm Desert & Semi-Desert, Scrub & Grassland. A recent study by Muldavin et al. (2021) identified a new division for Australian arid vegetation and thus proposed L.4 Australian semi-desert scrub and grassland (D330). Arid types, including woodlands, shrublands and grasslands align well with this division. Similar to the tropical and subtropical types, the six arid types identified in this analysis are cross jurisdictional, with all of them crossing the WA, Qld, SA, and New South Wales (NSW) borders. The only Australian jurisdictions that NT types are not represented are in Victoria, Tasmania and the Australian Capital Territory.

Suppl. material 1 provides an interim description of eight divisions and 21 macrogroups within the NT of Australia. Descriptions of the 21 macrogroups include positive diagnostic (based on frequency) categorised by NVIS growth forms and sorted by high frequency taxa, rather than alphabetically. Also included are notes on composition (floristics and structure) and landscape position, and NT and global distribution for each macrogroup. Non-native taxa are indicated by '*'. Suppl. material 2 provides images of a selected number of macrogroups.

Discussion

Here we present the classification of a large vegetation plot dataset (45,710 plots) from the NT, Australia, and align results with the upper levels of the IVC (macrogroup to formation class). Half of the vegetation types (11 of 21 macrogourps) fall into the formation 2.A.1 Tropical Lowland Grassland, Savanna & Shrubland and an Australian specific division – L.4 Australian Tropical Savanna and Scleromorphic Woodland. Closed Forest sites were the only type to align with formation class 1. Forest & Woodland, formation subclass 1.A. Tropical Forest & Woodland, with the potential for a new division L.4. Australasian Dry Forest & Woodland and macrogroup L.5 (MG1) Australasian & East Malesian Dry Forest; that reflects the areas affiliation with the South East Asian flora. Various types covering smaller areas were identified, including one type in formation 2.C.3 Tropical Freshwater Marsh, Wet Meadow & Shrubland, which is dominated by tropical grasses and sedges. Further south, arid types, including woodlands, shrublands and grasslands aligned well with the proposed division L.4 Australian semi-desert scrub and grassland (D330). While NT-derived data underpins this study types within the tropical, subtropical and arid regions cross into WA, Qld, SA, and NSW, highlighting the potential of the IVC as a cross-jurisdictional framework for a nationally consistent vegetation classification in Australia.

One of the strengths of the IVC is that it provides a framework for both existing types and 'place holders' to enable debate on the appropriateness of a type in the hierarchy. For example, the distinctive mangrove vegetation can be aligned with 1. A.5.Wb Indo-West Pacific Mangrove division and the L.5 (MG2) West Pacific (East Melanesia, Micronesia, Polynesia) Mangrove (M208) macrogroup, based on Duke (1992). However, NT botanical experts suggest the terminology 'East Malesia' rather than 'East Melanesia', as most mangrove species in Timor also occur in Australia. This is a very different concept, but without the framework of the IVC, this debate would not be possible. Melanesia is a subregion of Oceania in the southwestern Pacific Ocean. It is a distinct region that designates the three main ethnic and geographical regions forming the Pacific (Melanesia, Micronesia and Polynesia). The term Malesia in comparison, is a biogeographical and floristic region based on a shared tropical flora derived mostly from Asia, but also with numerous elements of the Antarctic flora. Thus, in this context, the term Malesia is more appropriate. Aquatic vegetation types in the NT (both tropical and arid types) provide a similar challenge. While they align with IVC formation class – 5. Aquatic Vegetation, formation subclass – 5.B Freshwater Aquatic Vegetation, 5.B.1 Tropical Freshwater Aquatic Vegetation at the highest levels. However, the NT and much of arid and semi-arid Australia contain wetland types (e.g., Duguid et al. 2005; Hunter and Lechner 2017). Further analyses using plot data for these specialised vegetation types will assist in testing the hypotheses suggested here to create new divisions and macrogroups for wetlands.

The assignment of new types to the IVC was recently demonstrated by Muldavin et al. (2021). They coded the Australian Tropical Savanna and Scleromorphic Woodland (D133) division into the IVC based on numerical analysis of sites from the NT and Qld Tropical savannas. Within an Australian context, these could have been placed in either the Tropical Lowland Grassland, Savanna & Shrubland Formation (TLGSS) or the Tropical Dry Forest and Woodlands Formation (TDFW), as suggested by Keith and Tozer (2017). However, for reasons outlined in Muldavin et al. (2021), Australian tropical savannas are quite unique and structural attributes (such as cover and height) related to these IVC descriptions did not accommodate for them accurately (Hunter et al. 2021). Thus, this study aligned 11 macrogroups into a new Australian tropical savanna division in the IVC, which was straightforward and transparent, despite the unique elements of the Australian flora. This example highlights the inclusiveness and flexibility of the IVC to incorporate the divergent evolutionary history of the Australian flora.

In total, of the eight divisions and 21 macrogroups described across the NT, five new divisions and 16 macrogroups are proposed. The need for these additional groups reflects the high endemicity of the Australian flora (80% of taxa are endemic) and largely northern hemisphere focus of the IVC to date. Of the proposed macrogroups, NT botanical experts suggest that East Malesian (and Australian) *Eucalyptus alba* savanna likely fits under one of the macrogroup L5 categories. However, the ground layer may be too similar to other eucalypt communities for it to be differentiated and its area of occupancy is small. Additionally, there is significant overlap in the East Malesian – north Australian grasses and more plot data would be needed to substantiate these inferences. In addition to the IVC's flexibility, which enables the incorporation of both existing and new types, it provides a numerical, plot-based framework for defining lower-level types in the hierarchy. This is important in the NT, where much historic work has been done, but modern analysis tools have not been widely implemented.

An additional usage for the IVC in the NT is as a framework to bridge historic work with modern vegetation science. Existing classification systems include the 1:1,000,000 vegetation map (Wilson et al. 1990) and community-level DVTs. Both classifications incorporate some plot-based quantitative work with intuitive, expert decision-making; however, they are not aligned hierarchically and neither system explicitly supports the other. Results from the current classification generally support findings from Wilson et al. (1990), including various floristically similar *Eucalyptus tetrodonta* woodlands; however, Wilson et al. (1990) include 11 map units as a result of structural dissimilarities that could be mapped spatially from an image base. Similarly, *Acacia aneura* from the arid interior was represented in eight map units (Wilson et al. 1990). The IVC provides a formal framework for using these results to support lower-level classifications. For example, association and alliance-level types can be built using the same dataset, but at finer detail by incorporating cover percent data, including sites with low species richness (< 10 species), and new decision rules about type groupings. Conversely, quantitative divisions and macrogroups provide placeholders when plot data coverage is insufficient at this scale, and future analysis can more easily incorporate both existing and new data (Tichý et al. 2014).

The IVC provides a means to undertake cross-jurisdictional vegetation analysis in Australia. The NT occupies 20% of the continent and borders most other major states including WA, Qld, NSW, and SA. A number of our vegetation types span political borders, including the tropical savanna biome (Fox et al. 2001), *Acacia* shrublands and woodlands (Nano et al. 2017), and *Triodia* hummock grasslands (Muldavin et al. 2021). However, state and territory (rather than federal) governments lead local and regional scale vegetation work. This had led to alignment issues that spring from different conceptual frameworks and data collection, analysis and storage systems. NVIS provides a national-level structural typology with basic floristic information, but it is 'bottom-up' approach based on mapping products and inherits variation driven by the same issues. The IVC enables classification that is data-driven, with implications for key areas of national-level science and policymaking.

Hunter and Addicott (2021) have highlighted some of the many current issues around different jurisdictional methodologies and how this can significantly affect our understanding of threatened vegetation types. To better comprehend both the true distribution of mid-scale vegetation types and their rarity and threat, we require a unified approach and, even better, is an approach that allows direct global comparisons and understandings. Nationally, a consistent vegetation classification system that includes strong floristic analyses can assist with federal modelling initiatives, for example fuel loads (e.g., Gellie and Hunter 2021), carbon accounting, land condition and to properly underpin national and international accounting. An ecological vegetation approach that includes a strong floristic methodology such as the IVC can strengthen existing systems, such as NVIS, by underpinning it with solid eco-floristic units based on analytical techniques.

Conclusion and future work

This analysis highlights how a rigorous rule-based hierarchical classification system, where the lower schematic levels are based on plot-based vegetation analyses of floristic and ecological data, is best placed to underpin our understanding of Australian vegetation. Such processes allow for a better understanding of distribution, interrelatedness and rarity. Lack of clear guidelines and dissimilar processes applied across state and territory borders only adds further confusion leaving practitioners to rely on intuition and opinion. Using a classification system such as the IVC provides an understanding of vegetation types both at local and regional levels and within a continental and global perspective. Our analysis has shown clearly that the IVC can be applied to a significant proportion of the Australian continent at the macrogroup level.

Data availability

Northern Territory Vegetation Site Database (NTVSD), http://www.ntlis.nt.gov.au/vsd/f?p=113

Natural Resource (NR) Maps data visualisation tool > vegetation > vegetation sites https://nrmaps.nt.gov.au/nrmaps.html

Bookmark NTVSD https://nrmaps.nt.gov.au/nrmaps.html#11569ec5-9ed5-46ce-a084-59bfd049fadc (created December, 2021)

Terrestrial Ecosystem Research Network (TERN) EcoPlots https://ecoplots.tern.org.au

Images of Northern Territory macrogroups https://drive.google.com/drive/folders/1Bl97PYS194XwLZT6c9Kcd-a0HrprJNxH?usp=sharing

Author contributions

Initial data cleaning was provided by DL, subsequent data management and analyses were conducted by JH. JH and DL defined types and their placement within the IVC hierarchy. All authors were involved equally in the assessment of type validity, final circumscription, naming and in the writing of the manuscript.

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References

Australian Bureau of Statistics (2020) Data by region. https://itt.abs.gov.au/itt/r.jsp?databyregion [accessed 8 Sep 2020]

Baldwin K, Chapman K, Meidinger D, Uhlig P, Allen L, Basquill S, Faber-Langendoen D, Flynn N, Kennedy C, … Saucier J-P (2019) The Canadian national vegetation classification: principles, methods and status. Natural Resources Canada, Canadian Forest Service [Report no. GLC-X-23], Sault Sainte Marie, ON, CA.

Beck HE, Zimmermann NE, McVicar TR, Vergopolan N, Berg A, Wood EF (2018) Present and future Köppen-Geiger climate classification maps at 1-km resolution. Scientific Data 5: 180214. https://doi.org/10.1038/sdata.2018.214

Beadle NCW (1981) The vegetation of Australia. Gustav Fisher, Stuttgart, DE. https://doi.org/10.1007/978-94-009-8629-9_23

Brocklehurst P, Gibbons A (2003) The Northern Territory and Commonwealth of Australia information and analysis: NT vegetation site data inventory. Northern Territory Department of Lands Planning and Environment, Darwin, NT, AU.

Brocklehurst P, Gibbons A (2007) Developing a systematic taxonomy for Northern Territory vegetation communities: Part 1. NT vegetation compendium project. Land Assessment Branch, Department of Land Resource Management [Technical Report no. 06/2015D], Darwin, NT, AU.

Brocklehurst P, Lewis D, Napier D, Lynch D (2007) Northern Territory guidelines and field methodology for vegetation survey and mapping. Northern Territory Department of Natural Resources, Environment and the Arts, Darwin, NT, AU.

Brocklehurst P, Sparrow B, Wilson B, Clark M (2008) Scoping paper: a finer scale vegetation map for the Northern Territory. Department of Natural Resources, Environment, the Arts and Sport, Palmerston, NT, AU.

Carnahan JA (1986) Vegetation. In: Jeans DN (Ed.) The Natural Environment. Sydney University Press, Sydney, AU, 260–282.

CHAH (2020) Standardised Informal Names (phrase names). https://www.anbg.gov.au/chah/phrase-names/index.html [accessed 19 Nov 2020]

CHAH (2002–2022) Australian Plant Census. Council of Heads of Australasian Herbaria. https://biodiversity.org.au/nsl/services/search/taxonomy [accessed 10 Jan 2022]

Chippendale GM (2020) Eucalyptus. Flora of Australia. Australian Biological.

Clarke KR, Gorley RN (2015) PRIMER v7. User Manual/Tutorial. PRIMER-E, Plymouth, UK.

Cowie ID, Cuff NJ, Lewis DL, Jobson P (2017) Checklist of the vascular plants of the Northern Territory. Northern Territory Herbarium, Department of Environment and Natural Resources, Palmerston, NT, AU.

Crisp MD, Arroyo MTK, Cook LG, Gondolfo MA, Jordan GJ, McGlone MS, Weston PH, Westoby M, Wilf P, Linder P (2009) Phylogenetic biome conservatism on a global scale. Nature 458: 754–758. https://doi.org/10.1038/nature07764

Crisp MD, Laffan S, Linder HP, Munro A (2002) Endemism in the Australian flora. Journal of Biogeography 28: 183–198. https://doi.org/10.1046/j.1365-2699.2001.00524.x

De Cáceres M, Franklin S, Hunter JT, Landucci F, Dengler J, Roberts D (2018) Global overview of plot-based vegetation classification approaches. Phytocoenologia 48: 101–112. https://doi.org/10.1127/phyto/2018/0256

De Cáceres M, Chytrý M, Agrillo E, Attorre F, Botta-Dukát Z, Capelo J, Czúz B, Dengler J, Ewald J, … Wiser SK (2015) A comparative framework for broad-scale plot-based vegetation classification. Applied Vegetation Science 18: 543–560. https://doi.org/10.1111/avsc.12179

Duguid A, Barnetson J, Clifford B, Pavey C, Albrecht D, Risler J, McNellie M (2005) Wetlands in the arid Northern Territory. A report to the Australian Government Department of the Environment and Heritage on the inventory and significance of wetlands in the arid NT. Northern Territory Government Department of Natural Resources, Environment and the Arts. Alice Springs, AU.

Duke NC (1992) Mangrove floristics and biogeography. In: Robertson AI, Alongi DM (Eds) Tropical Mangrove Ecosystems. American Geophysical Union, Washington, DC, US, 63–100. https://doi.org/10.1029/CE041p0063

Executive Steering Committee for Australia (2003) Australian Vegetation Attribute Manual: National Vegetation Information System, Version 6.0. Executive Steering Committee for Australian Vegetation Information, Canberra, AU.

Faber-Langendoen D, Keeler-Wolf T, Meidinger D, Tart D, Hoagland B, Josse C, Navarro G, Ponomarenko S, Saucier J-P, … Comer P (2014) EcoVeg: a new approach to vegetation description and classification. Ecological Monographs 84: 533–561. https://doi.org/10.1890/13-2334.1

Faber-Langendoen D, Keeler-Wolf T, Meidinger D, Josse C, Weakley A, Tart D, Navarro G, Hoagland B, Ponomarenko S, Fults G (2016) Classification and description of world formation types. US Department of Agriculture, Forest Service, Rocky Mountain Research Station [Gen Tech Rep RMRS-GTR-346], Fort Collins, CO, US, 346 pp. https://doi.org/10.2737/RMRS-GTR-346

Faber-Langendoen D, Baldwin K, Peet RK, Meidinger D, Muldavin E, Keeler-Wolf T, Josse C (2018) The EcoVeg approach in the Americas: U.S., Canadian and international vegetation classifications. Phytocoenologia 48: 215–237. https://doi.org/10.1127/phyto/2017/0165

Flora Of Australia (2021) Resources Study, Department of Agriculture, Water and the Environment: Canberra. https://profiles.ala.org.au/opus/foa/profile/Eucalyptus [accessed 14 Dec 2021]

Fox ID, Neldner VJ, Wilson GW, Bannink PJ, Wilson BA, Brocklehurst PS, Clark MJ, Dickinson KJM, Beard JS, Bean AR (2001) The Vegetation of the Australian Tropical Savannas 1:2,000,000 scale map in 3 sheets. Queensland Herbarium, Environmental Protection Agency, Brisbane and the Cooperative Research Centre for the Sustainable Development of Tropical Savannas, Darwin, NT, AU.

Franklin SB, Hunter JT, De Cáceres M, Dengler J, Landucci F, Krestov P (2016) Introducing the IAVS Vegetation Classification Working Group. Phytocoenologia 46: 5–8. https://doi.org/10.1127/phyto/2016/0116

Gellie NJH, Hunter JT (2021) An alternative broad vegetation hierarchy for eastern New South Wales, with application for environmental planning and management. Australian Journal of Botany 69: 450–467. https://doi.org/10.1071/BT20072

Gellie NJH, Hunter JT, Benson JS, Kirkpatrick JB, Cheal DC, McCreery K, Brocklehurst P (2018) Overview of plot-based vegetation classification approaches within Australia. Phytoceonologia 48: 251–272. https://doi.org/10.1127/phyto/2017/0173

Hammer Ø, Harper DAT, Ryan PD (2001) PAST: Paleontological Statistics Software Package for Education and Data Analysis. Palaeontologia Electronica 4: 1–9.

Hill KD, Johnson LAS (1994) Systematic studies in the eucalypts. 6. A revision of the coolibahs, *Eucalyptus* subgenus *Symphyomyrtus* section *Adnataria* series *Oliganthae* subseries *Microthecosae* (Myrtaceae). Telopea 5: 749–752. https://doi.org/10.7751/telopea19943000

Hill KD, Johnson LAS (1995) Systematic studies in the eucalypts. 7. A revision of the bloodwoods, genus *Corymbia* (Myrtaceae). Telopea 6: 185–504. https://doi.org/10.7751/telopea19953017

Hill MO (1973) Reciprocal averaging: an eigen vector method of ordination. Ecology 61: 237–249. https://doi.org/10.2307/2258931

Hill MO (1979) TWINSPAN: A FORTRAN program for arranging multivariate data in an ordered two-way table by classification of the individuals and attributes. Cornell University, Ithaca, NY, US.

Hnatiuk RJ, Thackway R, Walker J (2009) Explanatory notes for the Vegetation field handbook, version 2. Australian Government, Bureau of Rural Sciences, Canberra, AU.

Hunter JT (2004) Phytogeography, range size and richnesss of Australian endemic *Sauropus* (Euphorbiaceae). Journal of Biogeography 32: 63–73. https://doi.org/10.1111/j.1365-2699.2004.01149.x

Hunter JT (2020) Grasslands on coastal headlands in New South Wales, south eastern Australia. Vegetation Classification and Survey 1: 111–122. https://doi.org/10.3897/VCX/2020/48228

Hunter JT, Addicott E (2021) Poplar box woodlands of Eastern Australia: an assessment of a threatened ecological community within the IVC framework. Vegetation Classification and Survey 2: 241–255. https://doi.org/10.3897/VCS/2021/71216

Hunter JT, Hunter VH (2021) Montane mire vegetation of the New England Tablelands Bioregion of Eastern Australia. Vegetation Classification and Survey 1: 37–51. https://doi.org/10.3897/VCS/2020/48765

Hunter JT, Lechner AM (2017) A multi-scale, hierarchical, ecoregional and floristic classification of arid and semi-arid ephemeral wetlands in New South Wales, Australia. Freshwater and Marine Science 69: 418–431. https://doi.org/10.1071/MF17006

Hunter JT, Franklin S, Luxton S, Loidi J (2021) Terrestrial biomes: a conceptual review. Vegetation Classification and Survey 2: 73–85. https://doi.org/10.3897/VCS/2021/61463

Jan D, Brocklehurst PS (2009) A prospectus for the development of 1:100 000 scale vegetation mapping for the Northern Territory: mapping the future. Northern Territory Department of Natural Resources, Environment, The Arts and Sport, Land and Water Division, Greening Australia (NT), Natural Heritage Trust, Darwin, AU.

Jennings MD, Faber-Langendoen D, Loucks OL, Peet RK, Roberts D (2009) Standards for associations and alliances of the US National Vegetation Classification. Ecological Monographs 79: 173–199. https://doi.org/10.1890/07-1804.1

Keith DA, Tozer M (2017) Girt: a continental synthesis of Australian vegetation. In: Keith D (Ed.) Australian Vegetation. Cambridge University Press. Cornwall, UK, 3–39.

Keith DA, Williams RJ (2020) T4.3 Hummock savannas. In: Keith DA, Ferrer-Paris JR, Nicholson E, Kingsford RT (Eds) The IUCN Global Ecosystem Typology 2.0: Descriptive profiles for biomes and ecosystem functional groups. IUCN, Gland, CH, 58, 170 pp. https://doi.org/10.2305/IUCN.CH.2020.13.en

Lehmann CER, Etter A, Young KR, Keith DA (2020) T4.2 Pyric tussock savannas. In: Keith DA, Ferrer-Paris JR, Nicholson E, Kingsford RT (Eds) The IUCN Global Ecosystem Typology 2.0: Descriptive profiles for biomes and ecosystem functional groups. IUCN, Gland, CH, 57.

Lewis D, Brocklehurst P, Thackway R, Hill J (2008) Adopting vegetation guidelines and the national vegetation information system (NVIS) framework in the Northern Territory. Cunninghamia 10: 557–567.

Lewis D, Patykowski J, Nano C (2021a) Comparing data subsets and transformations for reproducing an expert-based vegetation classification of an Australian tropical savanna. Australian Journal of Botany 69: 423–435. https://doi.org/10.1071/BT20164

Lewis D, Brocklehurst P, Milne D, Cowie ID, Cuff N (2021b) Overview and compatibility of Northern Territory plot-based vegetation data with the National Vegetation Classification System and future vegetation typologies. Australian Journal of Botany 69: 468–477. https://doi.org/10.1071/BT20031

Luxton S, Lewis D, Addicott E, Chalwell S, Hunter JT (2021) Australian advances in vegetation classification and the need for a national, science-based approach. Australian Journal of Botany 69: 329–338. https://doi.org/10.1071/BT21102

Maslin BR (2001) Introduction to *Acacia*. In: Flora of Australia Volume 11A. ABRS/CSIRO Publishing, Melbourne, AU, 3–13.

Maslin BR, Reid JE (2012) A taxonomic revision of mulga (*Acacia aneura* and its close relatives: Fabaceae) in Western Australia. Nuytsia 22: 214–221.

Miles L, Newton AC, DeFries RS, Ravilious C, May I, Blyth S, Kapos V, Gordon JE (2006) A global overview of the conservation status of tropical dry forests. Journal of Biogeography 33: 491–505. https://doi.org/10.1111/j.1365-2699.2005.01424.x

Mucina L (1997) Classification of vegetation: Past, present and future. Journal of Vegetation Science 8: 751–760. https://doi.org/10.2307/3237019

Muldavin EH, Addicott E, Hunter JT, Lewis D, Faber-Langendoen D (2021) Australian vegetation and the International Vegetation Classification framework: an overview with case studies. Australian Journal of Botany 69: 339–356. https://doi.org/10.1071/BT20076

Nano C, Jobson P, Wardle GM (2017) Arid shrublands and open woodlands of inland Australia. In: Keith DA (Ed.) Australian Vegetation. 3rd Edn. Cambridge University Press, Cambridge, UK, 626–650.

National Land and Water Resources Audit (2001) National Land & Water Resources Audit 2001. Theme six report. NLWRA, Canberra, ACT, AU.

Northern Territory Herbarium (2022) FloraNT Northern Territory Flora Online. Department of Environment, Parks and Water Security. http://eflora.nt.gov.au/ [accessed 7 Jan 2022]

NVIS Technical Working Group (2017) Australian Vegetation Attribute Manual: National Vegetation Information System, Version 7.0. Department of the Environment and Energy, Canberra, ACT, AU.

Patykowski J, Cowie I, Cuff N, Chong C, Nano C, Jobson P, Lewis D (2021) Can sampling for vegetation characterisation surrogate for species richness? Case studies from the wet–dry tropics of northern Australia. Australian Journal of Botany 69: 375–385. https://doi.org/10.1071/BT20158

Russell-Smith J (1991) Classification, species richness, and environmental relations of monsoon rain forest in northern Australia. Journal of Vegetation Science 2: 259–278. https://doi.org/10.2307/3235959

Slee AV, Brooker MIH, Duffy SM, West JG (2015) EUCLID Eucalypts of Australia. 4th Edn. Centre for Australian National Biodiversity Research, Canberra, internet based, hosted by the Identic Pty Ltd, Brisbane.

Sparrow BD, Foulkes JN, Wardle GM, Leitch EJ, Caddy-Retalic S, van Leeuwen SJ, Tokmakoff A, Thurgate NY, Guerin GR, Lowe AJ (2020) A vegetation and soil survey method for surveillance monitoring of rangeland environments. Frontiers in Ecology and Evolution 8: 157–174. https://doi.org/10.3389/fevo.2020.00157

Specht RL, Specht A, Whelan MB, Hegarty EE (1995) Conservation Atlas of Plant Communities in Australia. Southern Cross University Press, Lismore, NSW, AU.

Sun D, Hnatiuk R, Neldner V (1997) Review of vegetation classification and mapping systems undertaken by major forested land management agencies in Australia. Australian Journal of Botany 45: 929–948. https://doi.org/10.1071/BT96121

Taxonomy Decadal Plan Working Group (2018) Discovering biodiversity: a decadal plan for taxonomy and biosystematics in Australia and New Zealand 2018–2028. Australian Academy of Science, Canberra, ACT, AU; and Royal Society Te Apārangi. Wellington, NZ.

TERN (2021) Standardising environmental monitoring and data systems for improved decision making. TERN [End stage 3 report. Report to DAWE], Brisbane, AU.

Thackway R, Cresswell I (1995) An interim biogeographic regionalisation for Australia: a framework for setting priorities in the National Reserve System Cooperative Program. Version 4.0. Australian Nature Conservation Agency, Canberra, ACT, AU.

Thackway R, Neldner VJ, Bolton MP (2008) Vegetation. In: McKenzie NJ, Grundy MJ, Webser R, Ringrose-Voase AJ (Eds) Australian Soil and Land Survey Handbook: Guidelines for Surveying Soil and Land Resources. CSIRO Publishing, Melbourne, Vic., AU, 115–142.

Tichý L, Chytrý M, Botta-Dukát Z (2014) Semi-supervised classification of vegetation: preserving the good old units and searching for new ones. Journal of Vegetation Science 25: 1504–1512. https://doi.org/10.1111/jvs.12193

Tokmakoff A, Sparrow B, Turner D, Lowe A (2016) AusPlots Rangelands field data collection and publication: Infrastructure for ecological monitoring. Future Generation Computer Systems 56: 537–549. https://doi.org/10.1016/j.future.2015.08.016

Walker J, Hopkins MS (1990) Vegetation. In: McDonald RC, Isbell RF, Speight JG, Walker J, Hopkins MS (Eds) Australian Soil and Land Survey Field Handbook. 2nd Edn. Inkata Press, Melbourne, Vic., AU, 58–86.

Wardle GM, Nano C (2017) Hummock grasslands: *Triodia*-dominated grasslands in arid Australia. In: Keith DA (Ed.) Australian Vegetation. 3rd Edn. Cambridge University Press, Cambridge, UK, 651–674.

White A, Sparrow B, Leitch E, Foulkes J, Flitton R, Lowe AJ (2012) AUSPLOTS Rangelands Survey Protocols Manual. University of Adelaide Press, Adelaide, SA, AU.

Wickham H (2021) tidyr: Tidy Messy Data. R package version 1.1.3. https://CRAN.R-project.org/package=tidyr [accessed 12 Sep 2021]

Williams RJ, Cook GD, Leidloff AC, Bond WJ (2017) Australia's tropical savannas: vast, ancient and rich landscapes. In: Keith DA (Ed.) Australian Vegetation. 3rd Edn. Cambridge University Press, Cambridge, UK, 368–388.

Wilson BA, Brocklehurst PS, Clark MJ, Dickinson KJM (1990) Vegetation survey of the Northern Territory Australia. Conservation Commission of the Northern Territory [Technical Report no. 49], Darwin, NT, AU.

Woinarski JCZ, Hempel C, Cowie I, Brennan K, Kerrigan R, Leach G, Russell-Smith J (2006) Distributional pattern of plant species endemic to the Northern Territory, Australia. Australian Journal of Botany 54: 627–640. https://doi.org/10.1071/BT05041

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Supplementary material

Supplementary material 1
Classification, diagnostic taxa and notes on the distribution of Northern Territory Macrogroups and synoptic table.
Link: https://doi.org/10.3897/VCS.83045.suppl1

Supplementary material 2
Images of selected macrogroups
Link: https://doi.org/10.3897/VCS.83045.suppl2