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A framework for mapping vegetation over broad spatial extents: A technique to aid land management across jurisdictional boundaries

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ABSTRACT

Mismatches in boundaries between natural ecosystems and land governance units often complicate an ecosystem approach to management and conservation. For example, information used to guide management, such as vegetation maps, may not be available or consistent across entire ecosystems. This study was undertaken within a single biogeographic region (the Murray Mallee) spanning three Australian states. Existing vegetation maps could not be used as vegetation classifications differed between states. Our aim was to describe and map 'tree mallee' vegetation consistently across a 104 000 km^2 area of this region. Hierarchical cluster analyses, incorporating floristic data from 713 sites, were employed to identify distinct vegetation types. Neural network classification models were used to map these vegetation types across the region, with additional data from 634 validation sites providing a measure of map accuracy. Four distinct vegetation types were recognised: Triodia Mallee, Heathy Mallee, Chenopod Mallee and Shrubby Mallee. Neural network models predicted the occurrence of three of them with 79% accuracy. Validation results identified that map accuracy was 67% (kappa = 0.42) when using independent data. The framework employed provides a simple approach to describing and mapping vegetation consistently across broad spatial extents. Specific outcomes include: (1) a system of vegetation classification suitable for use across this biogeographic region; (2) a consistent vegetation map to inform land-use planning and biodiversity management at local and regional scales; and (3) a quantification of map accuracy using independent data. This approach is applicable to other regions facing similar challenges associated with integrating vegetation data across jurisdictional boundaries.

1. Introduction

There is widespread recognition of the importance of considering entire ecological systems, or biogeographic regions, when planning for conservation management (Caldwell, 1970). However, the boundaries of natural ecosystems do not always match those of the administrative or political regions within which land management is undertaken (Christensen et al., 1996). Further, natural ecosystems can be transected by human-defined boundaries at many levels of jurisdiction: local, regional and national (Van Eetvelde and Antrop, 2009). Consequently, tools used to inform land management may not be consistent across, or even available for, the entire area in question (Brody et al., 2003).

Patterns of vegetation distribution reflect abiotic characteristics, and have a fundamental influence on ecological processes and the occurrence of biota (Hooper and Vitousek, 1997). Therefore, vegetation maps play a crucial role in asset inventory, land-use planning, conservation management and research development (Cihlar, 2000; Keith and Simpson, 2008). For example, vegetation maps indicate the relative extent of different vegetation types in a region, thus guiding conservation priorities (Crumpacker et al., 1988). They also assist the management of disturbance events, such as fire, that differ in prevalence between vegetation types (Bradstock et al., 2002). For maps to be useful in these applications, it is essential the information they provide is consistent for the entire area of interest (Pressey et al., 2000). Individual vegetation maps can differ considerably in relation to the vegetation types recognised, as well as the method, resolution and currency of both vegetation description and mapping (Hansen and Reed, 2000; Thogmartin et al., 2004). Such variation makes it difficult to integrate the information contained in different maps, even in the

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absence of issues associated with multiple governance boundaries (Keith and Simpson, 2008).

Previous approaches to integrating mapped information include frameworks for evaluating and ranking alternative maps based on attributes such as accuracy, coverage and resolution (Keith and Simpson, 2008), and protocols for translating and harmonising land-cover legends (Herold et al., 2008). For example, an information hierarchy framework was used to combine 67 regional-scale datasets from across Australia into the single National Vegetation Information System (Thackway et al., 2007). Using this approach, detailed vegetation classifications were compiled into broad categories of native, non-native and non-vegetated cover. However, as Van Eetvelde and Antrop (2009) identified when developing a land-cover map for Belgium, differences in the scale and classification of existing data sources may make their integration into a single dataset impossible.

Another consideration in the use of existing mapped information is that of map accuracy. Validation of vegetation maps is uncommon (Özesmi et al., 2006; but see Kozak et al., 2008; Cunningham et al., 2009) despite being a critical step in the process of mapping spatial data (Congalton, 2001). This means that users have no measure of map accuracy, an important consideration when assessing the suitability of contained information for the specified application (Congalton, 2001; Bach et al., 2006).

The use of remotely sensed data to produce maps covering large areas provides another solution to the challenge of describing vegetation across multiple jurisdictions (Fuller et al., 1998). However, the classification detail contained in such maps may be broad (Smith and Wyatt, 2007), and floristic data are less often incorporated (Hobbs et al., 1989). For example, some simply describe the occurrence of a single vegetation class (Pressey et al., 2000; Kozak et al., 2008), while others map the distribution of a few, broad land-cover types (Eva et al., 2004; Huang and Siegert, 2006). Validation of maps produced using remotely sensed data, when undertaken, is often based on satellite imagery or existing maps (Mayaux et al., 2002; Eva et al., 2004). Therefore, such maps may not include field data at any stage in their production or validation.

This study was prompted by difficulties encountered when collating existing vegetation data for our study region: a 104 000 km^2 area of the Murray Mallee in south-eastern Australia. The Murray Mallee lies within a single biogeographic region that comprises three state-level jurisdictions and 16 local government districts (NSW Government, 2008; Government of South Australia, 2009; State Government of Victoria, 2009). While numerous vegetation maps exist for the region (e.g. Fox, 1990; Westbrooke et al., 1998; Val, 2001; White et al., 2003; Department for Environment and Heritage, 2005), none cover all of it. These existing maps were of limited value for region-wide use as they differed in scale, and the number and characteristics of vegetation types recognised. Further, those with the largest coverage (state-level maps) were spatially disjunct, making their integration difficult. In addition, no measure of map accuracy was available for any of them.

Here, we present a framework for classifying vegetation types and producing a validated map of their distribution across a broad spatial extent. We set three objectives: (1) to identify and provide a consistent description of vegetation types common to the whole Murray Mallee region; (2) to map the distribution of these vegetation types across all jurisdictional units comprising the study area; and (3) to validate the map using independent data, thus providing users with an indication of map accuracy. In meeting these objectives, we have employed relatively simple methods to ensure this approach can be applied in other regions facing similar challenges.

2. Methods

2.1. Study area

The study area encompasses 104 000 km^2 of the Murray Mallee and incorporates parts of three Australian states; Victoria, New South Wales and South Australia (Fig. 1). The Murray Mallee is an area of low relief ($\leq$100 m above sea level) and little topographic variation (White et al., 2003). Extensive dune systems characterise the region: linear calcareous dunes follow an east–west orientation while siliceous parabolic/irregular dunes are more variable in form

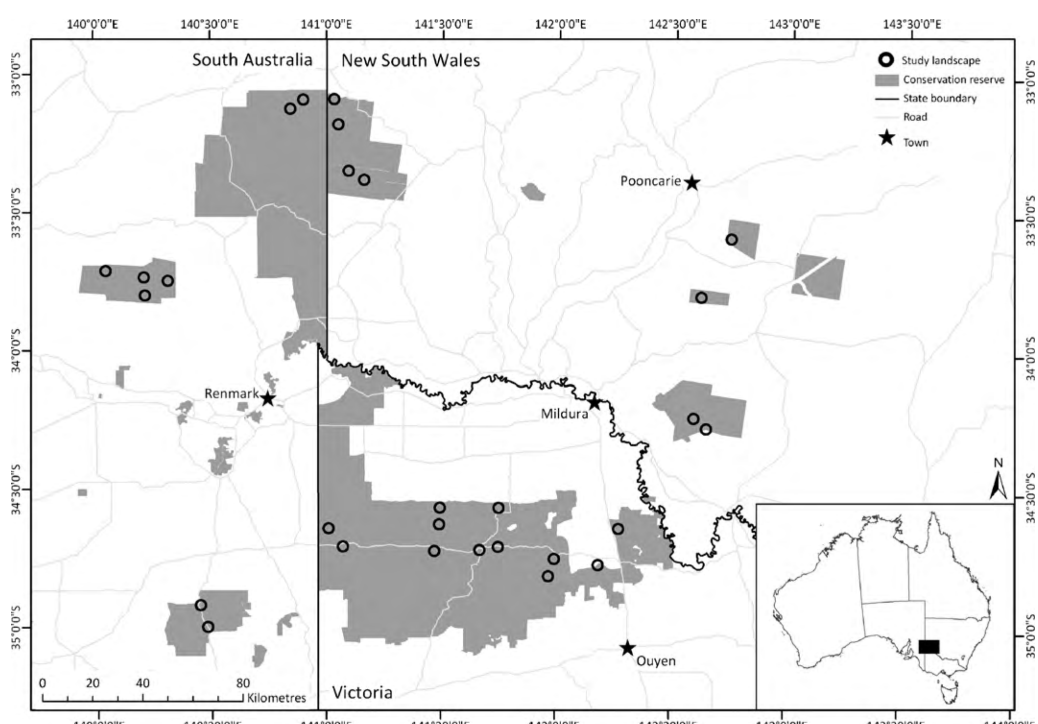

Fig. 1. The Murray Mallee study area in south-eastern Australia, showing the location of 28 study landscapes in Victoria, South Australia and New South Wales. Floristic data were collected at between 29 and 31 sites in each 1256 ha landscape.

(Land Conservation Council, 1987). The climate is semi-arid, with annual rainfall between 220 and 330 mm (raw data supplied by the Australian Bureau of Meteorology). High temperatures are common in summer, with mean daily maxima often exceeding 32 °C, while winter months are mild (mean daily maxima of around 16 °C) (LCC, 1987).

Native vegetation in the region comprises a number of broad types, from semi-arid shrublands and woodlands to treeless plains (LCC, 1987). Since settlement by Europeans in the 1840s, native vegetation has been extensively cleared for agricultural production, primarily cropping and grazing (Harris, 1990). We focus on the most common type of native vegetation in the study area: 'tree mallee'. Tree mallee vegetation is characterised by the occurrence of multi-stemmed ('mallee') eucalypt trees above lower strata of shrubs and perennial and ephemeral grasses (Parkes and Cheal, 1990; Bradstock and Cohn, 2002).

2.2. Study design

This study forms part of a project investigating the response of flora and fauna to different fire mosaics. Site selection was guided by methodological considerations imposed by the whole-of-landscape approach employed in the broader study. Data were collected from 835 sites, grouped in circular study landscapes of 1256 ha spread across the study region. In each study landscape, between 29 and 31 sites were sampled in tree mallee vegetation. Sites were distributed among all fire-age classes, in proportion to their extent in the landscape, and were selected to encompass topographic variation (dune/swale). The latter consideration ensured that sites were representative of tree mallee vegetation types (see LCC, 1987). Study landscapes were separated by a mean distance of 130 km (range: 6.3–217.7 km) and, within individual landscapes, sites were positioned an average of 1.5 km apart. All study landscapes were located in conservation reserves, 8155–631 942 ha in size, composed of stands of relatively continuous native vegetation.

At each site a quadrat of 10 m × 50 m was used for sampling the flora: perennial plant species were identified and their cover-abundance assessed using a modified Braun-Blanquet scale (1 or 2 plants, ≤5% cover, 6–25%, 26–50%, 51–75%, 76–100%). Annual and semi-perennial species were not recorded as their occurrence and abundance varies greatly in response to rainfall events. To avoid potential misclassification, plants were identified to genus level when species-level identification was uncertain. Nomenclature follows relevant state flora texts and census lists (Ross and Walsh, 2003; Barker et al., 2005). Vegetation sampling was undertaken between June and August 2007.

Additional environmental characteristics were compiled for each site. Soil texture was assessed following McDonald et al. (1990). The topographic position of sites was classified using the following categories: dune crest (uppermost dune point), dune slope (any point between dune crest and base), swale (clay/sandy) and flat-plain (terrain with little relief). The fire-age of sites was determined from fire history mapping of the region (Avitabile et al., unpublished data). Fire mapping was based on Landsat imagery recorded on 15 occasions between 1972 and 2007, at intervals of 2–4 years. Time-since-last fire was estimated as the number of years between 2007 (when floristic data were collected) and the midpoint of this 2–4 year interval.

2.3. Identification of mallee vegetation types

Hierarchical cluster analyses were used to identify vegetation types. These analyses were based on Bray Curtis similarity matrices derived from cover-abundance data for perennial species. Species recorded at <10 sites were excluded due to their potential, as 'rare' species, to exert a disproportionate influence on cluster groupings. Sites burnt within the last 10 years were also excluded as their vegetation and appearance on satellite imagery may differ markedly from mature vegetation of the same type. Thus, data for 106 species from 713 sites were included in these analyses (Appendix A).

Floristic differences between distinct clusters of sites were compared by using similarity percentage (SIMPER) analysis. SIMPER results also identified species making a strong contribution to the within-cluster similarity of different groups of sites. A non-metric multidimensional scaling (NMDS) ordination of the similarity matrix was used to further examine variation between different site groupings. Comparison of the soil type and topographic position of sites in different clusters provided additional insights. Cluster, SIMPER and NMDS analyses were undertaken in PRIMER v.6.1.9 (PRIMER-E, 2007).

Results identified a clear split of eight groups of sites that separated at a similarity level of 22%. Three of these groups were retained (n = 65, 231 and 399 sites) and five were discarded due their very small size (all <10 sites). A second cluster analysis examining floristic variation within the two largest groups split the group with 231 sites into two further groups (similarity 27%: n = 52 and 179 sites). Thus, four distinct types of mallee vegetation were identified: Triodia Mallee (TM), Heathy Mallee (HM), Chenopod Mallee (CM), and Shrubby Mallee (SM).

For some sites, vegetation type was assigned independently of the cluster analyses. This was necessary for sites: (a) excluded from analyses (i.e. burnt <10 years ago: n = 122); (b) belonging to small, discarded clusters (n = 18); and (c) identified as outliers, based on the NMDS ordination and soil type/topographic position (n = 21). These sites were allocated to the most appropriate vegetation type based on species cover-abundance data and assessment of site photographs.

The most frequently sampled, and widely distributed vegetation type was Triodia Mallee. Overall, 61% of sites (n = 508) were classified as Triodia Mallee. Chenopod Mallee, the second most common vegetation type (n = 200), was also widely distributed across all three states. Heathy Mallee and Shrubby Mallee were both sampled much less frequently, 66 and 61 sites, respectively, with the former being the most geographically restricted vegetation type.

Vegetation types differed on the basis of canopy dominants, understorey composition, soil characteristics and topographic position. In all cases, canopy species made a strong contribution to within-vegetation type similarity (Table 1). Triodia Mallee was dominated by *Eucalyptus dumosa* and *Eucalyptus socialis*, the latter species also being characteristic of Shrubby Mallee. In contrast, *Eucalyptus oleosa* subsp. *oleosa* and *Eucalyptus gracilis* characterised canopy vegetation in Chenopod Mallee. Heathy Mallee was the only vegetation type in which species other than eucalypts contributed to canopy composition: *Eucalyptus costata* subsp. *murrayana* and *Callitris verrucosa* were both recorded at over 90% of sites in Heathy Mallee.

Triodia scariosa was recorded relatively commonly in all vegetation types (Table 1) but was particularly characteristic of Triodia Mallee, where it was recorded at highest cover abundance. Shrubs such as *Acacia rigens*, *Acacia wilhelmiana* and *Beyeria opaca* were also common at sites in Triodia Mallee, which often supported a high cover of medium to tall shrubs. In Heathy Mallee, ground strata were commonly dominated by a diverse range of small woody shrubs, including heathy species such as *Phebalium bullatum*, *Cryptandra tomentosa* and *Spyridium subochreatum* var. *subochreatum*. Below-canopy vegetation in Chenopod Mallee was characterised by a range of low shrubs occurring at low abundances, including *Olearia* spp., *Zygophyllum* spp. and chenopod species such as *Maireana pentatropis*, *Enchylaena tomentosa* var. *tomentosa* and *Maireana pyramidata*. The understorey of Shrubby Mallee was characterised by relatively low abundances of a range of tall shrubs

Table 1
Perennial species characteristic of four tree mallee vegetation types: Triodia Mallee (TM), Heathy Mallee (HM), Chenopod Mallee (CM) and Shrubby Mallee (SM). The average similarity (%) of sites within each type is shown, as is each species' contribution (%) to within-type similarity[a] (parentheses contain the percentage of sites in each vegetation type at which species were recorded).

Species	Contribution to within-vegetation type similarity (%)			
	TM	HM	CM	SM
Average similarity (%)	35.0	46.6	35.1	35.5
Acacia burkittii				1.7 (34)
Acacia colletioides				7.8 (69)
Acacia rigens	1.6 (25)	2.6 (56)		
Acacia sclerophylla var. *sclerophylla*			1.5 (30)	
Acacia wilhelmiana	2.6 (31)			
Aotus subspinescens		2.6 (61)		
Babingtonia behrii		5.0 (62)		
Baeckea crassifolia		2.0 (55)		
Beyeria opaca	1.6 (26)			4.2 (41)
Callitris verrucosa		14.3 (94)		
Calytrix tetragona		1.5 (45)		
Chenopodium desertorum				2.6 (46)
Cryptandra tomentosa complex		3.4 (68)		
Dodonaea viscosa subsp. *angustissima*				3.5 (46)
Eucalyptus costata subsp. *murrayana*	5.7 (37)	12.7 (91)		
Eucalyptus dumosa	16.9 (72)		7.0 (53)	2.1 (30)
Eucalyptus gracilis			10.9 (59)	5.2 (49)
Eucalyptus leptophylla	6.5 (46)	5.6 (59)	1.1 (21)	
Eucalyptus oleosa subsp. *oleosa*			29.3 (79)	
Eucalyptus socialis	12.8 (68)		2.2 (35)	13.1 (75)
Eucalyptus sp.	7.0 (66)	9.7 (88)	3.2 (53)	
Enchylaena tomentosa var. *tomentosa*				7.5 (72)
Eremophila crassifolia			2.2 (5)	
Eremophila glabra			1.1 (33)	6.4 (69)
Eremophila scoparia				2.2 (36)
Eremophila sturtii				1.5 (33)
Grevillea pterosperma		1.8 (47)		
Hakea leucoptera subsp. *leucoptera*		3.8 (64)		
Hibbertia riparia		3.3 (70)		
Leptospermum coriaceum	1.3 (17)	11.4 (91)		
Maireana pentatropis			2.7 (40)	1.4 (31)
Maireana pyramidata			1.8 (31)	
Maireana sp.			1.1 (30)	
Olearia muelleri			2.1 (40)	1.5 (39)
Olearia pimeleoides subsp. *pimeleoides*			1.1 (31)	
Phebalium bullatum		4.7 (71)		
Sclerolaena diacantha			10.7 (85)	10.5 (75)
Senna artemisioides subsp. *coriacea*				3.3 (46)
Senna artemisioides subsp. *filifolia*			1.5 (30)	3.9 (51)
Senna artemisioides subsp. *petiolaris*				6.9 (61)
Senna artemisioides subsp. *zygophylla*				1.9 (33)
Spyridium subochreatum var. *subochreatum*		3.0 (59)		
Triodia scariosa	35.0 (93)	3.9 (59)	2.1 (28)	2.3 (38)
Westringia rigida			1.2 (29)	
Zygophyllum apiculatum			4.4 (49)	1.6 (34)
Zygophyllum aurantiacum subsp. *aurantiacum*			3.9 (50)	

[a] Species contributing to >90% of the similarity of vegetation types are shown.

including *Acacia colletioides*, *Senna* spp., *Dodonaea viscosa* subsp. *angustissima*, *B. opaca* and *Eremophila sturtii*.

Triodia Mallee occurred predominantly on lighter, sandier soils and on dunes and flat-plains while Heathy Mallee occurred on sandy soils in all topographic positions. Chenopod Mallee was more common on heavier soils with some clay content, and occurred most often on flat-plains and swales. Shrubby Mallee showed a closer association with soils with some loam content than Chenopod Mallee, and occurred most frequently on flat-plains.

2.4. Mapping of mallee vegetation types

Vegetation types identified by the cluster analyses were then mapped across the region. To do this, information on vegetation type, together with a range of additional environmental variables (see below) for the 835 study sites were used to model vegetation type. Neural network classification models (Duda et al., 2001) were used in this process. Neural network models are ideal for modelling complex ecological systems as they incorporate heterogeneous data in a single framework, without needing to explicitly define underlying relationships (Scardi, 1996). Further, this technique is highly effective at modelling non-linear and interacting relationships (Özesmi et al., 2006). Numerous studies have demonstrated the successful use of this approach for modelling a range of vegetation characteristics over broad spatial extents (Foody and Arora, 1997; Linderman et al., 2004; Cunningham et al., 2009).

Ninety-three environmental variables were included in the modelling process, as follows: geographic position ($n=2$ variables); Normalized Difference Vegetation Index, representing vegetation 'greenness' ($n=1$: Tucker, 1979); Landsat imagery, including between four and seven spectral bands for 15 different years (1972–2007: $n=81$); mallee vegetation distribution ($n=3$); radiometric data, representing soil characteristics ($n=2$: Cook et al., 1996); Topographic Wetness Index, representing topographic and hydrologic processes ($n=3$); and altitude ($n=1$). Satellite imagery was acquired from Landsat Multi Spectral Scanner (1972, 1977, 1980, 1985 and 1988), Landsat Thematic Mapper (1989, 1991, 1992, 1995, 1998, 2004, 2005 and 2007) and Landsat Enhanced Thematic Mapper Plus (2000 and 2002). Pre-processing of these images included ortho-correction, radiometric correction, mosaicing of images, and calibration to a common geographic and spectral base (Australian Greenhouse Office year 2000 base: see Furby, 2002).

Environmental variables were extracted from digital maps at the geographic coordinates of all 835 study sites. To counter the possibility of these locations coinciding with sparse vegetation or bare ground, due to the natural openness of tree mallee vegetation, eight additional neighbouring locations were sampled (centre-points of surrounding 150 m pixels). These additional data points were assumed to be of the same vegetation type as the central study site. The benefits of this approach, by ensuring that environmental data for each site were accurate and representative of local conditions, outweighed potential issues associated with spatial autocorrelation in these neighbouring data points. This process resulted in a sample size of 7515 data points.

Exploratory radial bias function (RBF) neural network models (Duda et al., 2001) were used to identify environmental variables that showed a strong relationship with vegetation type, and to remove those showing high intercorrelation. Following this process, the performance of RBF and multi-layer preceptron (MLP) networks (Duda et al., 2001), both with varying numbers of neurons in the hidden layer, were compared. Examination of the error statistics and mapped output for the two best models, as identified by their confusion matrices, indicated both performed very well given the training data. The best model was then used to map vegetation type at a spatial resolution of 25 m (dictated by the resolution of the Landsat imagery).

The resultant vegetation map covered the entire region, including areas not comprising tree mallee vegetation (i.e. cleared land, other vegetation types). Consequently, a second map, describing the distribution of mallee vegetation relative to non-mallee vegetation, was created to restrict this vegetation map to only areas with tree mallee vegetation. Mallee/non-mallee vegetation was modelled using MLP neural network models, with the final model being an average of 15 alternate models. These models included information on vegetation type (mallee, non-mallee), together with a subset of the environmental variables used previously, for 27 627 data points spread across the study region. These data points were remotely identified as locations known to occur in mallee or non-mallee vegetation. All neural network classification models were created in Statistica 6.0 (StatSoft Inc., 2004).

The accuracy of the mallee/non-mallee map was assessed by workers familiar with vegetation in the study area. Based on this assessment, the threshold probability for mapping mallee vegetation relative to non-mallee vegetation was reduced from 50% to 40%. A median filter with a kernel size of five pixels was then applied to reduce speckling and smooth the output image (Gonzalez and Woods, 2002).

The original vegetation map was then clipped by the mallee/non-mallee map, producing a final vegetation map covering only areas of tree mallee vegetation.

2.5. Map validation

Independent data from two sources were used to validate the vegetation map. Vegetation type was assessed in the field, by people involved in the original floristic surveys, at a number of new sites located across all three states. In addition, geographically referenced flora records drawn from a range of sources, and held within the Victorian Flora Information System (FIS), were available for part of the mapped region (Department of Sustainability and Environment, 2004).

Field-assessed validation data were systematically collected in all vegetation types in Victoria and South Australia. Sites were sampled at 500 m intervals along tracks in two originally surveyed reserves located in the southern part of the study region. Site selection was guided by the following protocols: (a) the first and final site on each track was located at least 1 km from the external boundary of tree mallee vegetation; (b) sites were surrounded by ≥100 m of the same vegetation type; and (c) sites were not placed in non-mallee vegetation. Sampling continued until 50 sites had been surveyed in each mapped vegetation type. In addition, a second set of field-assessed sites distributed across New South Wales and Victoria was also available for map validation. Sites located outside the extent of mapping were discarded, resulting in 226 independent field-assessed sites for map validation.

FIS records used to validate the map were limited to those within the geographic extent of the mapping, and those considered likely to be located in tree mallee vegetation (as assessed by species' records). For the 441 sites meeting these criteria, records of all species included in the cluster analyses were extracted from the FIS database. A series of hierarchical rules, based on the SIMPER results and comparisons with floristic characteristics of sites included in the cluster analyses, were used to assign FIS sites to the mapped vegetation types. Firstly, for example, FIS sites were classified as a particular vegetation type when only those species identified by the SIMPER analysis as being particularly characteristic of that vegetation type were recorded. Rules became progressively less restrictive, in terms of the required number of characteristic species from the given vegetation type, relative to those more strongly associated with other vegetation types, until FIS sites could no longer be allocated into particular vegetation types with confidence. Using these rules, 408 FIS sites were assigned a vegetation type.

The use of FIS data for map validation was subject to some limitations, potentially causing map accuracy to be underestimated. First, information to assess the suitability of FIS records was rarely available (e.g. plot size, survey protocols and completeness). Second, information on site characteristics known to influence vegetation composition was lacking (e.g. soil type, topographic position, fire history). Third, vegetation types were identified by complex multivariate analyses, and defined by floristic characteristics specific to the original dataset. Assigning new records, on a case-by-case basis, to these vegetation types was prone to uncertainty. To assess the potential influence of this final limitation on validation results, the performance of rules used to assign FIS sites to vegetation types was investigated. This was done by determining how well the rule set performed when assigning vegetation type to sites of known vegetation type (i.e. those for which vegetation type was identified by the original cluster analyses). The rules were correct in 90% of cases: therefore, assigning FIS sites to vegetation types was considered reasonably accurate, but not without error.

Validation of the vegetation map involved determining the accuracy with which the neural network model predicted vegetation type for all 634 validation sites. Map accuracy was compared between validation datasets and across vegetation types. Kappa coefficients, which range in value between 0 and 1 and provide an estimate of map accuracy accounting for chance agreement between the map and validation data (Congalton, 1991), were also calculated for each dataset.

3. Results

3.1. Mallee vegetation map

The neural network classification models used to create the mallee/non-mallee map showed an average accuracy of 91% when

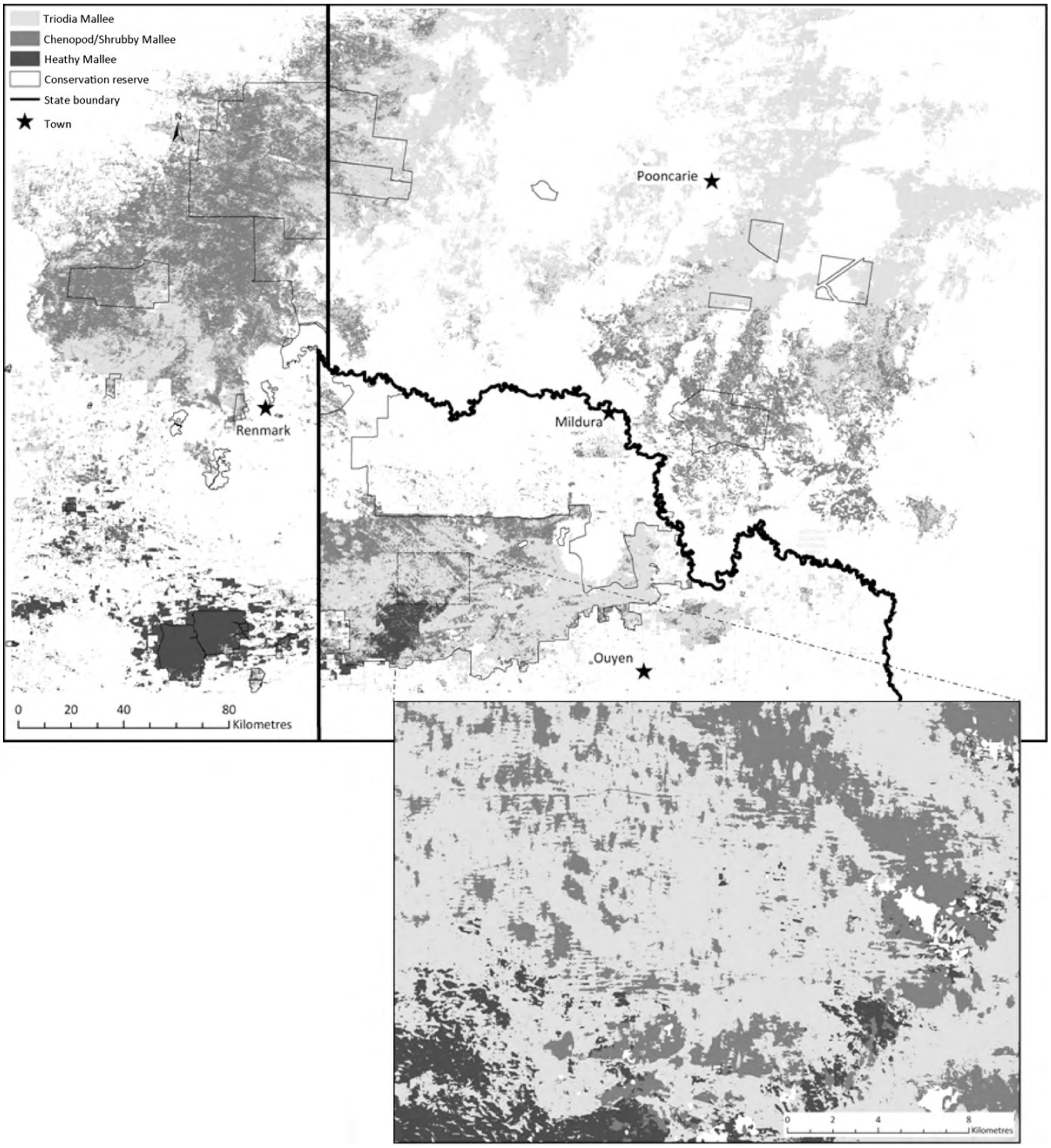

Fig. 2. Distribution of three tree mallee vegetation types across the study region, mapped at a 25 m resolution. Unshaded (white) areas are non-mallee vegetation.

identifying data points known to be located within tree mallee (range of 15 models: 84–97%), and 78% when identifying non-mallee data points (71–82%). Neural network models were also successful in mapping the distribution of three vegetation types, at a resolution of 25 m, across the entire study region (Fig. 2). This approach was unable to consistently distinguish between the two vegetation types showing greatest similarity (as identified by their grouping together in the first cluster analysis): Chenopod Mallee and Shrubby Mallee.

The model used to map vegetation type was an RBF network with 88 neurons in the hidden layer. This model, which included 20 explanatory variables, correctly classified vegetation type for 79% of the 7515 data points. Prediction accuracy varied between vegetation types: 87% of data points in Triodia Mallee, 59% of those in Chenopod/Shrubby Mallee, and 90% of data points in Heathy Mallee were predicted correctly by the model.

Following clipping by the mallee/non-mallee map, the vegetation map covered 3 233 735 ha. Most tree mallee vegetation occurred in New South Wales (1 407 197 ha) and least in Victoria (676 371 ha). Overall, 58% of the mapped area comprised Triodia Mallee, 35% Chenopod/Shrubby Mallee, and 7% Heathy Mallee. Within the same area covered by the vegetation map, 31 different Ecological Vegetation Classes were recognised in Victoria (White et al., 2003), 19 vegetation types were mapped in New South Wales (Val, 2001), and 16 in South Australia (Department for Environment and Heritage, 2005). Comparison of state-level maps with current results identified that the association between individual vegetation types in these different maps was not strong. This indicates that simply combining state-level classifications would not produce equivalent groupings across the entire region.

3.2. Map validation

A priori predictions of expected validation results were made by combining the level of inaccuracy associated with: (a) assigning vegetation type to independent data (FIS sites only: 10%); and

Table 2
Results of validating the vegetation map with independent data from two sources. The number of validation sites assigned to Triodia Mallee (TM), Heathy Mallee (HM) and Chenopod/Shrubby Mallee (CM/SM) by the map (rows) and by expert opinion or rules (columns) are shown for field-assessed and FIS sites, respectively. Measures of user's accuracy (% mapped sites that were correct) and producer's accuracy (% known sites mapped correctly) are included for both datasets.

		'True' vegetation type				User's accuracy
		TM	HM	CM/SM	Total	
Field-assessed sites (kappa coefficient = 0.54)						
Mapped vegetation type	TM	103	13	26	142	73%
	HM	0	29	2	31	94%
	CM/SM	18	0	35	53	66%
	Total	121	42	63	226	74%
Producer's accuracy		85%	69%	56%	74%	
FIS sites (kappa coefficient = 0.31)						
Mapped vegetation type	TM	134	10	96	240	56%
	HM	4	1	4	9	11%
	CM/SM	36	0	123	159	77%
	Total	174	11	223	408	63%
Producer's accuracy		77%	9%	55%	63%	

(b) the model used to produce the vegetation map (21%). The maximum accuracy expected, therefore, for field-assessed validation sites was approximately 80%, while for FIS validation sites it was considered unlikely that results would show >70% accuracy.

The map correctly predicted vegetation type for 425 (67%) of the 634 validation sites. As expected, accuracy differed between validation datasets: 74% of field-assessed sites were mapped correctly, resulting in a kappa coefficient of 0.54, while a lower level of accuracy was identified for FIS sites (63%, kappa coefficient 0.31: Table 2). Of the 59 field-assessed sites that were mapped incorrectly, almost three-quarters ($n = 43$) were within two pixels (<50 m) of the correct vegetation type, with the greatest mapping-error distance being 634 m.

Further examination of FIS results identified that producer's accuracy (% known sites mapped correctly) differed in relation to the rules used to assign new records to vegetation type (range: 50–85%), thus confirming that validation results were influenced by this process. Nevertheless, comparison of validation results with a priori expectations which accounted for inaccuracies associated with the map itself and the classification of FIS sites, confirmed that the vegetation map performed well when validated with independent data.

Validation results also differed between vegetation types (Table 2). Triodia Mallee had higher producer's/user's accuracy than Chenopod/Shrubby Mallee for both validation datasets. The only exception was the user's accuracy (% mapped sites that were correct) of FIS sites: Chenopod/Shrubby Mallee was mapped more accurately than Triodia Mallee for these sites. Validation results from the FIS dataset identified a poor performance for Heathy Mallee. This is likely related to the limited distribution, and therefore limited sampling, of this vegetation type in the study area (see Fuller et al., 1998) and the fact that validation sites were located in only part of the overall distribution of Heathy Mallee (Victoria). Field-assessed validation data revealed a higher mapping accuracy for Heathy Mallee (Table 2).

4. Discussion

Floristic data collected at over 800 sites distributed across three Australian states have enabled the identification and description of four distinct types of tree mallee vegetation common to the study region. Three were mapped across 104 000 km^2 of the broader Murray Mallee bioregion. These vegetation types were characterised by differences in the dominant canopy species, understorey assemblages and soil and topographic associations. Previous work has recognised vegetation types differentiated by similar factors. For example, vegetation types identified by Cheal et al. (1979), Fox (1990) and White et al. (2003) were all distinguished on the basis of similar understorey dominants to those described here: namely *T. scariosa*, tall non-chenopod shrubs, chenopods, and heathy shrub species.

The similarity between vegetation types identified here, and existing vegetation descriptions, verifies current results. Critically, however, while existing vegetation descriptions are broadly similar across the region, the specific communities identified and mapped in each state differ. Variation in mapping classifications can be caused by differing objectives for map production, as perceptions of land-cover types will vary between maps produced for different reasons (Fuller et al., 1998; Van Eetvelde and Antrop, 2009). This study consistently describes and maps vegetation types across all jurisdictions in the Murray Mallee, providing a more complete overview across this biogeographic region than previously available. Vegetation maps for different parts of the region, based on different classification systems, preclude such an understanding but effective conservation management at the scale of entire ecological systems depends on it (Pressey et al., 2000).

Conversely, a disadvantage associated with mapping vegetation over broad geographic extents is the loss of fine-scale differentiation (Smith and Wyatt, 2007). The mapping of fewer vegetation types here than in existing state-level maps exemplifies this unavoidable loss of detail. However, the current map forms a uniform vegetation description that can be supplemented by existing maps if finer classification details are required.

4.1. Map accuracy

When using independent data not subject to internal error (i.e. field-assessed validation sites), a kappa accuracy statistic of 0.54 was achieved for the vegetation map. Other validations of broad-scale maps with independent field data have identified higher levels of map accuracy (between 69% and 88%: Bach et al., 2006; Cunningham et al., 2009), and Bach et al. (2006) similarly found that accuracy differed between mapped classes. To our knowledge, existing vegetation maps for the study region have not been objectively validated with independent data. Assessment of the accuracy of the current map, in comparison to alternative information sources, is therefore difficult.

Large-scale, empirical datasets have been used in both the production and validation of vegetation maps (Fuller et al., 1998; Marvin et al., 2009). Such datasets, like the FIS database used here, provide a valuable and cost-efficient source of independent data for map validation. However, as noted by Fuller et al. (1998), there is potential for subjectivity to affect the classification of these data into mapped classes. In addition, details important for assessing the appropriateness of such data for map validation, such as information on survey techniques, may be lacking. These issues highlight a consideration applicable to map validation more broadly: the validation process necessarily, but not always correctly, assumes that independent or reference data are accurate (Congalton, 1991). If this assumption is invalid, map accuracy may be underestimated. Furthermore, care must be taken when interpreting potential validation datasets, as no single dataset provides a universally appropriate standard against which to assess the accuracy of all maps (Fuller et al., 1998).

4.2. Applications to land-use planning and management

The framework employed here for producing consistent broad-scale vegetation maps has many potential uses for land-use planning and conservation management. The vegetation map provides baseline information against which to assess temporal change to the amount and distribution of tree mallee vegetation. Understanding the rate and pattern of change in vegetation cover is important for future land management and policy development (Başkent and Kadioğullari, 2007). To accurately provide such understanding, maps must be based on data collected at the same time across their full spatial extent (e.g. Bach et al., 2006).

The map describes the extent and type of mallee vegetation outside the reserve system. Such information can be used to guide reservation priorities and ongoing conservation actions (Margules and Pressey, 2000) by identifying key patches of vegetation that connect existing reserves, or areas where connectivity could be enhanced (see Taylor et al., 1993). Establishing monitoring programs to assess vegetation condition, an important characteristic that is infrequently incorporated into mapping, also requires comprehensive baseline information on vegetation cover (Thackway et al., 2007).

In conjunction with an understanding of fire behaviour and flammability in mallee vegetation communities (Bradstock and Cohn, 2002), this map can aid fire management planning. Management of disturbance events, such as fire, that threaten human safety across jurisdictional boundaries is compromised if information used in planning is not consistent across the potential extent of the disturbance.

Lastly, the map provides a basis for investigating patterns in the distribution of fauna. A number of critically endangered, threatened, and vulnerable species, such as the Black-eared Miner *Manorina melanotis*, Malleefowl *Leipoa ocellata*, Common Dunnart *Sminthopsis murina* and Millewa Skink *Hemiergis millewae* (Clarke, 2005; Bennett et al., 2007; Nimmo et al., 2008) occur in the Murray Mallee. Vegetation maps help identify important habitat for these species, and thus guide management for their conservation.

5. Conclusion

The framework developed in this study provides a relatively simple approach to describing and mapping vegetation consistently, and at high resolution, across broad spatial extents. The use of independent validation data has allowed for a measure of map accuracy, and our use of two datasets in this process has provided insight into the relative value of pre-existing data for this purpose. This approach has a range of potential uses in land-use planning and conservation management at both local and regional scales. It is also applicable to other regions facing similar challenges associated with the integration of vegetation data across jurisdictional boundaries.

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Appendix A. Perennial flora species included in the cluster analyses, and the number of sites at which they were recorded

Asteraceae	
Olearia lepidophylla	19
Olearia magniflora	12
Olearia muelleri	143
Olearia passerinoides subsp. *passerinoides*	26
Olearia pimeleoides subsp. *pimeleoides*	125
Boraginaceae	
Halgania cyanea	125
Brassicaceae	
Lepidium leptopetalum	40
Caesalpiniaceae	
Senna artemisioides subsp. *coriacea*	76
Senna artemisioides subsp. *filifolia*	108
Senna artemisioides subsp. *petiolaris*	108
Senna artemisioides subsp. *zygophylla*	59
Casuarinaceae	
Allocasuarina pusilla	12
Chenopodiaceae	
Atriplex stipitata	56
Chenopodiaceae sp.	19
Chenopodium curvispicatum	38
Chenopodium desertorum	177
Chenopodium desertorum subsp. *desertorum*	15
Enchylaena tomentosa var. *tomentosa*	171
Maireana appressa	34
Maireana georgei	33
Maireana pentatropis	129
Maireana pyramidata	97
Maireana radiata	38
Maireana sedifolia	19
Maireana triptera	42
Maireana sp.	116
Rhagodia spinescens	18
Sclerolaena diacantha	330
Sclerolaena obliquicuspis	25
Sclerolaena parviflora	133
Cupressaceae	
Callitris verrucosa	108
Callitris sp.	13

Dilleniaceae	
Hibbertia riparia	50
Hibbertia virgata	73
Epacridaceae	
Astroloma conostephioides	12
Brachyloma ericoides	13
Leucopogon cordifolius	18
Euphorbiaceae	
Bertya tasmanica subsp. *vestita*	33
Beyeria opaca	207
Fabaceae	
Aotus subspinescens	61
Bossiaea walkeri	21
Daviesia benthamii subsp. *acanthoclona*	41
Eutaxia microphylla	33
Pultenaea densifolia	14
Templetonia sulcata	19
Goodeniaceae	
Scaevola spinescens	38
Gyrostemonaceae	
Codonocarpus cotinifolius	27
Lamiaceae	
Prostanthera aspalathoides	13
Prostanthera serpyllifolia subsp. *microphylla*	44
Westringia rigida	148
Leguminosae	
Dillwynia uncinata	18
Mimosaceae	
Acacia acanthoclada subsp. *acanthoclada*	13
Acacia brachybotrya	26
Acacia burkittii	63
Acacia colletioides	150
Acacia ligulata	68
Acacia rigens	172
Acacia sclerophylla var. *sclerophylla*	98
Acacia wilhelmiana	177
Myoporaceae	
Eremophila crassifolia	69
Eremophila glabra	241
Eremophila glabra subsp. *glabra*	19
Eremophila glabra subsp. *murrayana*	25
Eremophila scoparia	56
Eremophila sturtii	28
Myoporum platycarpum	170
Myrtaceae	
Babingtonia behrii	47
Baeckea crassifolia	73
Calytrix tetragona	38
Eucalyptus calycogona	49
Eucalyptus costata subsp. *murrayana*	252
Eucalyptus cyanophylla	18
Eucalyptus dumosa	505
Eucalyptus gracilis	240
Eucalyptus leptophylla	316
Eucalyptus oleosa subsp. *oleosa*	231
Eucalyptus socialis	463
Eucalyptus sp.	514
Leptospermum coriaceum	145
Melaleuca acuminata subsp. *acuminata*	27
Melaleuca lanceolata subsp. *lanceolata*	103
Melaleuca uncinata	33
Pittosporaceae	
Pittosporum angustifolium	21
Poaceae	
Triodia scariosa	591
Proteaceae	
Grevillea huegelii	136
Grevillea ilicifolia subsp. *ilicifolia*	15
Grevillea pterosperma	46
Hakea leucoptera subsp. *leucoptera*	44
Ranunculaceae	
Clematis microphylla	11
Rhamnaceae	
Cryptandra tomentosa	24
Cryptandra tomentosa complex	45
Spyridium subochreatum var. *subochreatum*	40
Stenanthemum leucophractum	13
Rutaceae	
Boronia coerulescens subsp. *coerulescens*	15
Phebalium bullatum	66
Santalaceae	
Exocarpos aphyllus	15
Exocarpos sparteus	28
Sapindaceae	
Alectryon oleifolius subsp. *canescens*	17
Dodonaea bursariifolia	127
Dodonaea viscosa subsp. *angustissima*	127
Violaceae	
Hybanthus floribundus subsp. *floribundus*	14
Xanthorrhoeaceae	
Lomandra leucocephala subsp. *robusta*	78
Lomandra sp.	66
Zygophyllaceae	
Nitraria billardierei	15
Zygophyllum apiculatum	137
Zygophyllum aurantiacum subsp. *aurantiacum*	120

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