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Ecological niche modeling of customary medicinal plant species used by Australian Aborigines to identify species-rich and culturally valuable areas for conservation

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ABSTRACT

Customary medicinal plant species used by Australian Aborigines are disappearing rapidly with its associated knowledge, due to the loss of habitats. Conservation and protection of these species is important as they represent sources of novel therapeutic phytochemical compounds and are culturally valuable. Information on the spatial distribution and use of customary medicinal plants is often inadequate and fragmented, posing limitations on the identification and conservation of species-rich areas and culturally valuable habitats.

In this study, the habitat suitability modeling program, MaxEnt, was used to predict the potential ecological niches of 431 customary medicinal plant species, based on bioclimatic variables. Specimen locality records were obtained from the Global Biodiversity Information Facility (GBIF) data portal and from Australia's Virtual Herbarium (AVH).

Ecological niche models of 414 predicted species, which had 30 or more occurrence points, were used to produce maps indicating areas that were ecologically suitable for multiple species (concordance of high predicted ecological suitability) and having cultural values. For the concordance map, individual species niche models were thresholded and summed. To derive a map of culturally valuable areas, customary medicinal uses from Customary Medicinal Knowledgebase (CMKb) (www.biolinfo.org/cmkb) were used to weight individual species models, resulting in a value within each grid cell reflecting its cultural worth.

Even though the available information is scarce and fragmented, our approach provides an opportunity to infer areas predicted to be suitable for multiple species (i.e. concordance hotspots) and to estimate the cultural value of a particular geographical area. Our results also indicate that to conserve bio-cultural diversity, comprehensive information and active participation of Aboriginal communities is indispensable.

1. Introduction

Australia is one of the 17 megadiverse countries in the world with an estimated total of 290,000 floral species (including plants and fungi) (Williams et al., 2001). The long isolated continent supports an estimated 21,000 vascular plant species, of which 85 percent are endemic (Mummery and Hardy, 1994). For more than 40,000 years, Australian Aborigines have lived on this continent (Roberts-Thomson et al., 1996) and currently an estimated 2.5% of the total Australian population self-identifies as Aboriginal (ABS, 2006). Indigenous Australians have extensive knowledge of the biological resources available to them, including the use of medicinal plants for healthcare and general well-being (Barr et al., 1988).

Aborigines lived as hunter-gatherers and were known to be healthier than contemporary indigenous Australians (O'Dea et al., 1991). Occasionally, they required medications to treat ailments including cuts, wounds, coughs, snake-bites, digestive problems, cold, fever and headaches. For remedies, the Aborigines depended on a large number of commonly occurring medicinal plants, having multiple therapeutic uses, such as *Corymbia terminalis* and *Eremophila freelingii* (Low, 1990; Hiddins, 1999; Lassak and McCarthy, 2001). If the preferred medicinal plant was unavailable, a local substitute was used instead. The preference for a large number of medicinal plants with multiple uses avoided exploitation of any particular species as well as reliance on a single species, which might be rendered ineffective due to unfavorable environmental

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conditions. Culturally valuable medicinal plant knowledge, such as the optimal season, the time and place for collection and the correct preparation methods and use, is passed from generation to generation, in the form of songs, dance and stories (Barr et al., 1988). At present, many medicinal plants used by contemporary Aborigines are native to Australia, while some are exotic species, such as *Chamaesyce hirta* and *Opuntia stricta*, introduced by the early European settlers (Low, 1990; Lassak and McCarthy, 2001).

The interrelationship between indigenous communities and medicinal plant biodiversity is widely acknowledged, due to its significant contribution to health and conservation of natural habitats (Hamilton, 2004). Globally, 80% of plant-based medicines have arisen from traditional knowledge systems (Fabricant and Farnsworth, 2001). Australia's medicinal plant diversity, distributed across varied ecosystems, constitutes a significant source of novel phytochemical compounds and drugs (Harvey, 2000; Wickens and Pennacchio, 2002; Barlow et al., 2005; Newman and Cragg, 2007). Customary medicinal plant knowledge, comprising traditional and contemporary use by the Australian Aboriginal communities, is an important source of wisdom for accelerating the process of biodiscoveries. The benefits reaped from the potential biodiscovery endeavors may help to significantly improve the socioeconomic status of Aboriginal communities and increase opportunities to engage with mainstream Australia.

Unfortunately, highly diverse and species-rich ecosystems supporting customary medicinal plants are disappearing due to the degradation of habitats and unsustainable resource exploitation (Williams et al., 2001; Barlow et al., 2005). In addition, cultural diversity with its wealth of knowledge, beliefs, healing practices and values interlinked with these species-rich habitats, is also being lost at alarming rates. In recent years, it is recognized that the interactions between the biological and cultural diversities contribute to the resilience of ecosystems and thus require protection and conservation of these bio-cultural hotspots (McIvor et al., 2008). However, studies to delineate and prioritize bio-cultural hotspots in Australia for conservation are hampered due to the vastness of the continent and limited access to large tracts of land. Further limitations include the expense of conservation and management difficulties that occur due to the lack of constructive collaborations between scientific and Aboriginal communities. The available documented information on customary medicinal plants is in heterogeneous forms, geographically biased, often limited and fragmented. Given these difficulties and limitations, innovative and efficient methods are needed to identify and prioritize areas for conservation.

In this study, we take advantage of statistical modeling methods that are commonly used to predict the spatial distribution patterns of species (Guisan et al., 1998; Godown and Peterson, 2000; Chen and Townsend Peterson, 2002; Sánchez-Cordero et al., 2005; Li and Hilbert, 2008; Ortega-Huerta and Peterson, 2008). These tools have broad uses, including identifying biological hotspots and setting conservation priorities (Godown and Peterson, 2000; Chen and Townsend Peterson, 2002; Store and Jokimäki, 2003; Sánchez-Cordero et al., 2005; Parviainen et al., 2009; Trotta-Moreu and Lobo, 2010). The aim of our study is to (1) identify the potential spatial distribution of species-rich hotspots of bio-culturally significant, customary medicinal plant species used by Australian Aboriginal, using the species habitat suitability modeling program, MaxEnt (Phillips et al., 2006) and (2) map areas of high cultural value (hotspots), where the known customary medicinal uses confers a value to the location, using the schema shown in Fig. 1.

2. Material and methods

2.1. Species for modeling

For this study, species were selected from the Customary Medicinal Knowledgebase (CMKb), available online at http://www.biolinfo.org/cmkb (Gaikwad et al., 2008). The database contains baseline information on 456 customary medicinal plant species such as family and scientific names, parts of the plant used, preparation and application methods, medicinal uses, biogeographical distribution and information on phytochemicals and biological activities. The data is collated from various open access ethnobotanical publications on Australian medicinal plants, including some primary information from Aboriginal communities. Scientific names from CMKb were checked for any taxonomic discrepancies and resolved using the Australian Plant Name Index (http://www.cpbr.gov.au/apni/), the International Plant Name Index (www.ipni.org), the Global Biodiversity Information Facility (GBIF) (http://www.gbif.org/) and the Angiosperm Phylogeny Website (http://www.mobot.org/mobot/research/apweb/). From a total

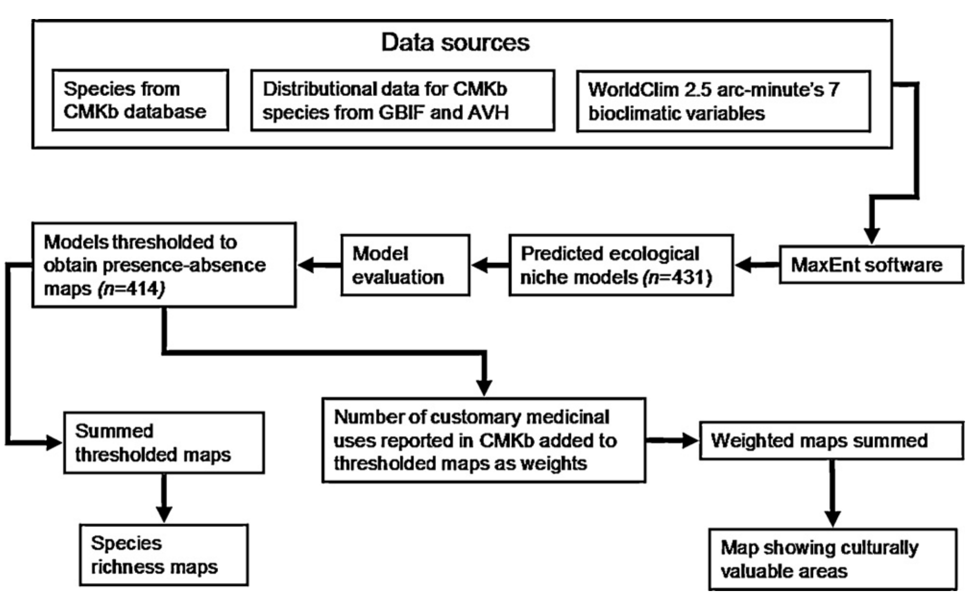

Fig. 1. Schematic representation of the methodology showing steps involved to generate the summed species richness and culturally valuable habitat maps.

of 456 species from CMKb, 25 species were discarded, as the correct scientific name could not be confirmed. The remaining 431 customary medicinal plant species were selected for ecological niche modeling. The selected species occur in a broad array of vegetation types including tropical rainforests and savannas, temperate alpine and sub-alpine, arid and semi-arid deserts, and littoral rainforest and mangrove forests.

2.2. Distributional data

The occurrence data for the selected species was primarily obtained from Australia's Virtual Herbarium (AVH) (http://www.ersa.edu.au/avh/). AVH is a dynamic online resource, providing access to plant specimen data and its associated occurrence records, held by participating herbaria across Australia. Among the selected species, many have a geographic distribution ranges extending outside Australia while some have sparse distributional data. Thus, to ensure full representation of the environmental conditions associated with each species (Pearson and Dawson, 2003; Broennimann and Guisan, 2008; Beaumont et al., 2009) and to counter any sampling bias, global scale occurrence data was obtained from the GBIF data portal (http://data.gbif.org). All occurrence data from GBIF and AVH were compiled and records with obvious geocoding errors such as zero coordinates, points outside land boundaries and textual locality references without coordinates were discarded.

2.3. Bioclimatic data

Raster-based bioclimatic variables, derived from the WorldClim dataset (Hijmans et al., 2005) were used to model the climate component of the realized ecological niche of each species. The WorldClim dataset provides baseline climate averages of monthly temperature and precipitation data for the period from 1960 to 1999. These data have been interpolated onto GIS grids and we chose to use data with a spatial resolution of 2.5 arc-min because this provided a compromise between fine spatial resolution of ecological niche models and the presumed accuracy and precision of the coordinates for the species occurrences. The WorldClim dataset also provides grids of the 19 bioclimatic variables defined by Nix (1986) and Busby (1991), which are widely used to model the ecological niches of species. However, these bioclimatic variables include many that are highly correlated. To minimize the impact of multicollinearity and over-fitting on the stability and quality of models, we selected seven minimally correlated variables (i.e. correlation coefficient < 0.75) (Table 1). We did this by calculating the correlation matrix for the 19 bioclimatic variables and selecting representative variables from highly correlated clusters. The final set of selected variables were checked for correlations low enough (less than 0.75) to avoid problem of multicollinearity or over-fitting. The selected minimally correlated environmental variables reflect ecologically important annual totals (e.g. annual precipitation), seasonality effects (e.g. precipitation seasonality) and extreme environmental factors (e.g. maximum temperature of the warmest period). These bioclimatic variables are the best descriptors available for large geographical regions such as Australia, despite the uncertainty and error associated with the values (Hijmans et al., 2005).

Table 1
List of global bioclimatic variables from WorldClim dataset used for predicting ecological niches.

No.	Bioclimatic variables at 2.5 arc-min resolution
1	Annual precipitation (mm)
2	Maximum temperature of warmest period (°C)
3	Minimum temperature of coldest period (°C)
4	Precipitation of driest period (mm)
5	Precipitation of wettest period (mm)
6	Precipitation seasonality (coefficient of variation) (mm)
7	Temperature seasonality (coefficient of variation) (°C)

2.4. Ecological niche modeling (ENM)

In 1957, Hutchinson defined the fundamental ecological niche as a multi-dimensional range of environmental conditions within which a species can survive and grow (Pearson and Dawson, 2003). However, observed occurrences of species can only provide an approximation of the realized niche of a species (i.e., the range of environmental conditions). Several methods have been used to approximate the realized niche as a statistical model between occurrence and observed environmental variables at occurrence locations (Guisan and Zimmermann, 2000; Austin, 2002; Elith and Leathwick, 2009).

In recent studies, models based on only bioclimatic envelope have been questioned for validity and criticized due to the exclusion of biotic interactions and the process of dispersal (Davis et al., 1998; Lawton, 2000). However, these models have been shown to play an important role in providing a first approximation for assessing the potential distributions of the species, when the information is limited and the spatial extent associated with the study is of macro-scale (Guisan and Zimmermann, 2000; Pearson and Dawson, 2003; Beaumont et al., 2005).

We chose MaxEnt software (Phillips et al., 2006) to model potential ecological niches of Australian customary medicinal plants using a species' bioclimatic envelope (Fig. 1). MaxEnt, based on a statistical mechanics approach called maximum entropy, estimates the probability distribution when only presence data is available for analysis (Elith et al., 2011). It calculates a probability distribution for species occurrences by finding the distribution of maximum entropy (i.e., closest to uniform), subject to restrictions defined by the environmental features being analyzed. MaxEnt software was selected because it is user friendly, amenable to batch processing and requires presence-only data. In recent studies, MaxEnt performed well in comparison to the other algorithms and has better predictive power across varied sample sizes (Elith et al., 2006; Hernandez et al., 2006; Ortega-Huerta and Peterson, 2008; Wisz et al., 2008).

Ecological niche models were generated using MaxEnt v3.3.2, available online at http://www.cs.princeton.edu/~schapire/MaxEnt/. Following Phillips and Dudík (2008), default values were selected for the maximum number of iterations (500), the convergence threshold (0.00001), the replicated run type (10 cross-validations with the default 90% training and 10% test split), the selection of feature classes (autofeature), background points (10,000) and regularization values (1), and the default setting to reject duplicated occurrence records in the cells of the environmental variable grid.

The importance of individual environmental variables in model development was assessed using the in-built jackknife technique. During the process, models were trained on the global-scale environmental layers and then projected onto the Australian geographic region. Finally, we interpreted the fitted model for a species as representing the bioclimatic suitability of each grid cell and not predicted probability of occurrences. This is because the strict conditions required for ecological niche models to be interpreted as species distribution models cannot be met by the presence-only data we used (Guisan and Thuiller, 2005).

2.5. Species richness and cultural valuation

Often, species-rich areas or 'hotspots' are directly identified by modeling species richness data (Zaniewski et al., 2002). However, recent studies have derived similar results by summing individual projected species distribution models based on occurrence data (Guisan and Theurillat, 2000; Lehmann et al., 2002; Parviainen et al., 2009). Using this approach, in the first phase, a composite map was derived by summing up the predicted bioclimatic suitability models for individual species. With a total of *N* species models, the combined suitability, *CS* in the *k*th grid cell was calculated as shown in Eq. (1):

$$CS_k = \sum_{i=1}^{N} s_{ik} \tag{1}$$

where s_{ik} is the MaxEnt suitability score for the *i*th species in grid cell *k*. This represents a simple additive model of potential co-occurrence and assumes the independent association of species. Our source data did enable us to model the influence of positive or negative interactions between species. Before overlaying all species models, the continuous predicted suitability values were converted to binary predictions of presence-absence across Australia. Averaged maximum test sensitivity plus specificity logistic threshold values generated by the MaxEnt were selected for the conversion and the threshold was applied to the mean suitability map for each species using a script in the statistical program R (version 2.11.1). The map was interpreted as showing the degree of correspondence or concordance of environmental suitability across 414 models and provided an indication of the spatial distribution of suitability hotspots. But, it does not provide an estimate of the cultural worth of a predicted area. An approach was presented by Root et al. (2003), where the ecological value of a site was estimated by assigning species-specific extinction risks as weights to the predicted habitat suitability models. Based on this approach, in the second phase, individual ecological niche models were scaled by the numbers of species-specific singular (non-redundant) records of customary medicinal uses as weights, obtained from the CMKb database. The number of unique customary medicinal plant uses from CMKb, ranging from 1 to 15, reflects the cultural value of the species and thus, the largest value reflects high cultural significance (Appendix 1). Finally, the weighted ecological niche models were overlaid to derive a composite map of suitable environments with cultural values. Here, the weighted combined suitability value, *WCS*, in each grid cell was computed as follows (Eq. (2)), reflecting the constraint imposed by the data of stationarity in weights:

$$WCS_k = \sum_{i=1}^{N} w_i s_{ik} \tag{2}$$

where $w_i s_{ik}$ is the weighted MaxEnt suitability score for the *i*th species in grid cell *k*.

3. Results

3.1. Species ecological niche distributions

Initially, ecological niche models were projected for 431 species, based on a combined total of 254,812 occurrence points and 7 bioclimatic variables. The average contribution of each bioclimatic variable towards model development is represented by the overall mean percentage contribution across 431 MaxEnt models (Fig. 2). On an average, bioclimatic variables such as temperature seasonality contributed the most whereas precipitation seasonality contributed the lowest information to the overall predicted ecological niche models. The predicted models showed diverse patterns ranging from broad to narrow distribution. For example, broad potential distribution was projected for some of the species, such as *Corymbia terminalis*, *Hakea lorea*, *Cleome viscose*, and *Ricinus communis*. Conversely, *Capparis lanceolaris*, *Tamarindus indica*, *Zieria smithi*, *Rorippa islandica*, *Syzygium suborbiculare*, and some species of *Eremophila* and *Acacia* were projected to have restricted potential distribution range in Australia. Sample sizes used for projecting ecological niches ranged from one (*Lepidium oleraceum*) to 12,567 occurrence points (*Lythrum salicaria*).

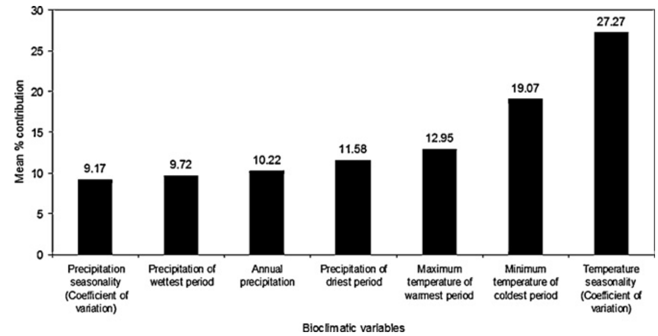

Fig. 2. Graphical presentation of the overall mean percentage contribution of bioclimatic variables towards the development of 431 MaxEnt models.

We evaluated the quality of all models using the average across 10 cross-validation runs of the area under the receiver operating characteristic curve (AUC) and the number of occurrence points (sample size) used by MaxEnt for modeling. AUC is considered a valid measure of relative model performance, with values typically ranging from 0.5 for random to 1.0 for precise distinction (Hernandez et al., 2006; Phillips and Dudík, 2008). It is possible that models developed using occurrence data with small sample sizes can potentially result in poor models. However, comparative studies have shown that MaxEnt performs well even with small sample sizes ($n < 30$) to produce good results (Hernandez et al., 2006). On the other hand, there is evidence indicating that no algorithm consistently performs well with sample sizes less than 30 (Wisz et al., 2008). Hence, we restricted our further analyses to 414 species with more than 30 occurrence points and whose projected distributions had AUC values greater than 0.850 (Appendix 1).

3.2. Species hotspots and cultural valuation

The resulting map illustrated in Fig. 3 illustrates areas that potentially have the greatest species richness (i.e. contain suitable climate/niche for a large number of species). The hotspot values across Australia ranges from seven to 199 (mean = 103.7). Grid cells with high value represent locations favorable for greatest number of species (Fig. 4).

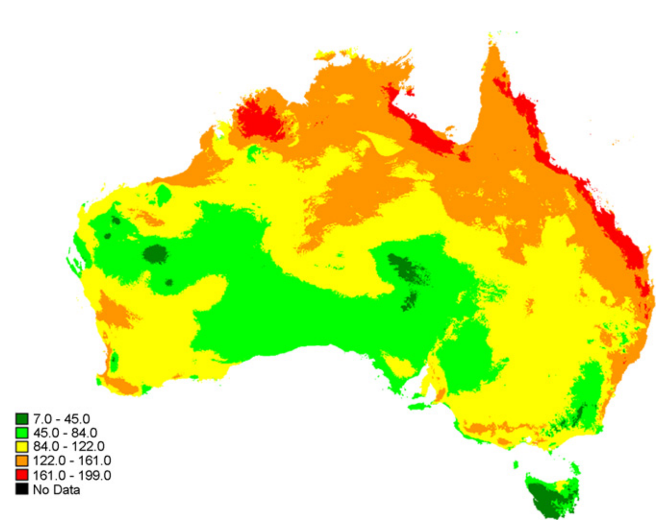

Fig. 3. Summed map showing customary medicinal plant concordance hotspots.

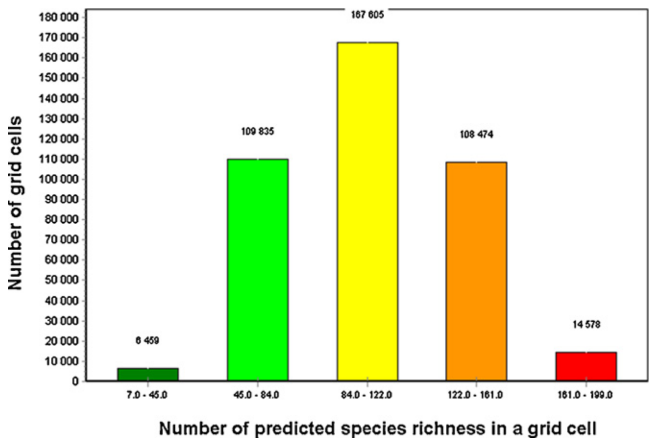

Fig. 4. Graphical presentation of the number of grid cells representing predicted species richness.

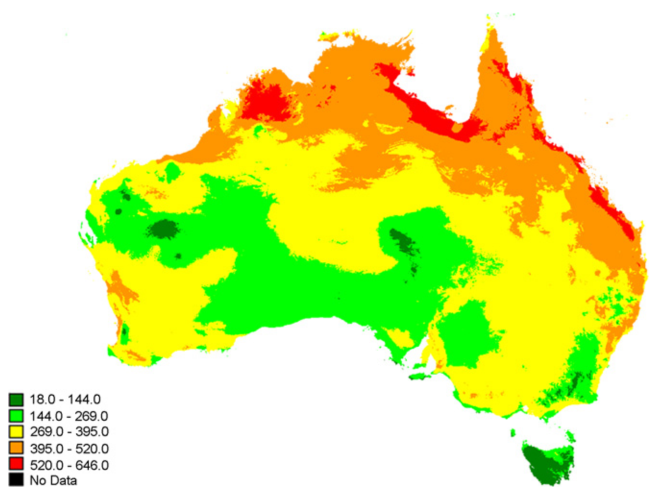

Fig. 5. Weighted summed map using customary medicinal uses as cultural values shows areas with cultural worth.

The summed weighted map represented in Fig. 5 reveals culturally valuable habitats scattered across Australia. Depending upon the number of customary medicinal uses assigned as weights, the cultural value of the habitats ranged from 18 to 646 (mean = 334.1) with higher grid value indicating highest cultural value (Fig. 6). To statistically compare the composite weighted and non-weighted distribution maps we used the paired-t test method as suggested by Levine et al. (2009), indicating differences (t-value = 363.58, p-value < 2.2e-16, df = 408,466).

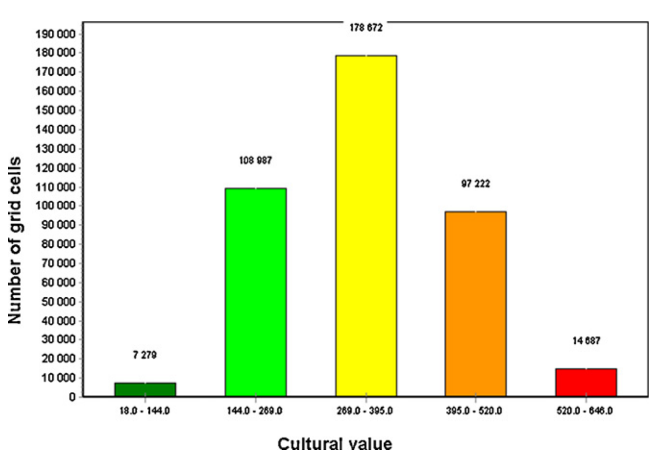

Fig. 6. Graphical presentation of the number of grid cells representing predicted areas having cultural values.

4. Discussion

The results of this study demonstrate the potential of combining ethnobotany with GIS and ecological niche modeling to explore the complex relationship between customary knowledge and spatial distribution. MaxEnt was used to project the potential distributions of 414 species with high statistical significance (Appendix 1). Ecological niche models and derived composite maps provide a useful means for identifying customary medicinal plant species hotspots and culturally valuable habitats for prioritizing conservation. The major advantage of this method is its ability to use scarce and biased information available on customary medicinal plants to identify critical locations for conservation. Another advantage of this method is its flexibility to incorporate different scales of measurements to assess quantitative value of a predicted area. For example, different measures such as conservation status, risk factors, economic values, expert opinion and measure of species preference by the communities can be used as weights to evaluate the worth of a given habitat for conservation and sustainable management. However, since the results are based on relatively limited data, interpretation of the summed richness and culturally valuable habitat maps should be made with caution.

The accuracy of ecological niche models can be influenced by a range of issues including sampling bias, selection of environmental variables, accuracy of the occurrence data (Araújo and Guisan, 2006; Guisan et al., 2006; Heikkinen et al., 2006; Araújo and New, 2007) and limited access to the documented customary medicinal plant knowledge. Although, all the projected models are statistically significant, due to the lack of comprehensive customary knowledge and consultation with Australian Aboriginal communities, the results could not be validated in the field. Most of the available ethnobotanical information in CMKb is collated from the published literatures which are product from specific localities such as Northern territory and northern parts of Western Australia and Queensland. Similarly, the information related to the customary medicinal uses of the plants is not comprehensive. Predominantly for many species only single customary use is present in CMKb (n = 176). These data deficiencies are reflected in the maps of predicted species richness and culturally valuable habitat maps in the form of biased presentation. It is likely that the overall pattern of the composite maps would change with the inclusion of more comprehensive data on customary medicinal plants.

Today, many medicinal plant species, which are now part of contemporary Aboriginal pharmacopeia, were introduced to Australia by European settlers and have become invasive. Although non-native, these species outside Australia in different traditional medicinal systems such as Ayurveda are valued for their therapeutic uses. The introduced species now have become an integral part of contemporary Aboriginal culture. Therefore management and conservation of these species has become a challenging task for policy makers and park managers. The major task is to maintain the balance between Aboriginal communities inclination towards the persistence of an invasive plant species with broader societal expectations of the control (and potential elimination) of invasive species. In such scenarios, the methodology used in this study can easily integrate customary knowledge, planning options and other species attributes to quantify the worth of potentially important areas for management and conservation.

5. Conclusions

Customary medicinal plants and their habitats are of immense cultural value to Aboriginal communities and are a potential source of novel phytochemicals having beneficial therapeutic values. Ecosystems and biogeographic regions containing high medicinal plant diversity areas warrant conservation and protection due to their cultural and socio-economic significance. The identification of these areas is difficult, requiring comprehensive information on medicinal, cultural and socio-economic values of the species as well as their known occurrences. Given the scarcity of data, an alternative method like this, can efficiently utilize available information to infer optimal species-rich hotspots and to estimate the cultural value of a particular habitat. The approach presented in this study is flexible and can be used more effectively to identify and prioritize areas for conservation by integrating feedback from domain experts. This study is a step towards establishing collaborative relationships with Aboriginal communities to identify likely medicinal plant species-rich areas and involve the communities in the management and protection of culturally-valuable regions. It will also form the basis to understand the effect of future climate change scenarios on the distribution of the species and the cultural worth of their habitats.

Australian customary medicinal plant knowledge and habitats are being rapidly lost due to the diminishing culture and unsustainable resource management. Conservation and protection of bio-cultural diversity, before it disappears, is important as it contribute to the resilience of the ecosystems and human well-being.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2011.07.005.

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