Digitisation and analysis of customary medicinal plant knowledge using biodiversity informatics

by

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A thesis submitted in fulfillment of the requirements for the degree of

Doctor of Philosophy

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Macquarie University

Sydney, Australia

February 2011

DEDICATED TO

MY PARENTS

LATE MR. ASHOK GAIKWAD AND MRS. SULBHA GAIKWAD

MY TEACHERS

LATE DR. JAGANNATH SONTHATE AND LATE MRS. MEGHANA SANT

AND

ABORIGINAL AUSTRALIA

DECLARATION

This thesis contains original work, which was performed by me. Several aspects of this work have been carried out with collaborating research groups; these people have been acknowledged and their contributions recognised in the section in which their assistance was received. This thesis contains no material that has been accepted for the award of any higher degree or diploma at any University or Institution, and to the best of my knowledge, contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

Jitendra Ashok Gaikwad

February 2011

ACKNOWLEDGEMENTS

Early in the process of completing this project, it became quite clear to me that a researcher cannot complete a PhD thesis alone. Although the list of individuals I wish to thank extends beyond the limits of this format, I would like to thank the following persons for their encouragement, prayers, and support:

❖ My mentor Dr. Vishwas Chavan, for introducing me to the field of Biodiversity informatics. He has constantly supported and inspired me, to grow as a good human-being and researcher with a passion for biodiversity informatics. Thanks are also due, for encouraging me to take this important step in my life as a PhD researcher.

❖ My supervisor Professor Shoba Ranganathan- her understanding, encouraging and personal guidance have provided a good basis for the present thesis. I thank her for taking trouble to bring me to Australia from India as a Project Coordinator and later as a PhD student.

❖ My co-supervisors- A/Prof. Jim Kohen, A/Prof. Joanne Jamie, A/Prof. Subramanyam Vemulpad and Ms. Karen Wilson for their support throughout my PhD tenure. My special thanks to Ms Karen Wilson for providing me access to Royal Botanic Gardens, identification of voucher specimens and for many valuable suggestions and constructive advice.

❖ Elders from Yaegl Aboriginal communities, Northern New South Wales for permitting me to conduct my fieldwork with them. Without the willingness of these Elders to share knowledge on customary medicinal plants this research would not have been possible.

❖ Macquarie University, for the award of MQRES research scholarship for pursuing PhD degree and PGRF funding for attending international biodiversity informatics conference in London.

❖ Mr. David Harrington, for introducing me to the Australian Aboriginal culture and biodiversity. He is my first Australian "mate" who helped me experience Aussie culture and taught to speak characteristically “Aussie” lingual. I am also indebted to him, for making our life in Australia comfortable and enjoyable.

- ❖ Ms. Joanne Packer, for good company and support during the long field trips.

- ❖ Dr Peter Wilson, for taking intense academic interest in my work, many ideas, useful suggestions and for helping me to carry out habitat suitability modelling.

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- ❖ Dr Linda Beaumont, for her valuable suggestions and instruction which helped to improve the quality of this study.

- ❖ Past and current lab colleagues- Dr. Shivshankar Nagaraj, Dr. D. Bollina, Mr. Gaurav Kumar, Mr. Gagan Garg, Mr. Varun Khanna, Mr. Javed Khan, Mrs. Ranjeeta Menon, Mrs. Elsa Chacko, and Mr. Mohammad Islam. Particular thanks to Mr. Gaurav Kumar for helping me to integrate Google Maps with CMKb.

- ❖ Ms. Catherine Wong, Ms. Maria Hyland, Ms. Jane Yang, Dr. Chris McRae, Mr. Michael Baxter, and Mr. Doan Lee, for administrative and IT support.

- ❖ My heartiest thanks to Mr. Nandakumar Dahibhate, Dr. S.Krishnan and my parents-in-laws, Mr and Mrs. Khade, for their kindness and affection.

- ❖ My special appreciation goes to my mother Mrs Sulbha Gaikwad and younger sister Ms. Yogita Gaikwad, who always kept me away from family responsibilities and encouraged me to concentrate on my study.

- ❖ Finally, I would like to express special thanks to my wife Preetam for her love and patience. She helped me to concentrate on completing this dissertation and supported mentally during the course of this work. Without her help and encouragement, this study would not have been completed.

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ABBREVIATIONS

ABCD	Access to Biological Collection Data
ALA	Atlas of Living Australia
APNI	Australian Plant Name Index
AVH	Australia's Virtual Herbarium
BHL	Biodiversity Heritage Library
BI	Biodiversity informatics
BOLD	Barcode Of Life Database
CBIC	Canadian Biodiversity Informatics Consortium
CBOL	Consortium for the Barcode of Life
CMKb	Customary Medicinal Knowledgebase
COL	Catalogue of Life
CSIRO	Commonwealth Scientific and Industrial Research Organization
DNA	Deoxyribonucleic acid
EFG	Electronic Field Guide
EIMP	Encyclopedia of Indian Medicinal Plants
EOL	Encyclopedia of Life
EwE	Ecopath with Ecosim
GBIF	Global Biodiversity Information Facility
GISD	Global Invasive Species Database
GSIS	Global Species Information System
GUID	Globally Unique Identifiers
HISPID	Herbarium Information Standards and Protocols for Interchange of Data
HTTP	Hypertext Transfer Protocol
IPNI	International Plant Name Index
ITIS	Integrated Taxonomic Information System
NCBI	National Center for Biotechnology Information
NSW	New South Wales
OBIS	Ocean Biogeographic Information System
REST	Representational State Transfer
SOAP	Simple Object Access Protocol
TAPIR	TDWG Access Protocol for Information Retrieval
TDWG	Taxonomic Database Working Group
ToL	Tree of Life
uBio	Universal Biological Indexer and Organizer
UN	United Nations
WHO	World Health Organization
XML	Extensible Markup Language

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LIST OF PUBLICATIONS INCLUDED IN THIS THESIS

The following publications are presented in their published form in this thesis and are referred to from this point onwards as listed in respective sections of the thesis.

1. **J. Gaikwad**, V. Khanna, S. Vemulpad, J. Jamie, J. Kohen, S. Ranganathan (2008) CMKb: a web-based prototype for integrating Australian Aboriginal customary medicinal plant knowledge. *BMC Bioinformatics* 9 Suppl 12:S25.
2. **J. Gaikwad**, K. Wilson, J. Kohen, S. Vemulpad, J. Jamie, S. Ranganathan (2011): Combining Ethnobotany and Informatics to Discover Knowledge from Data, in *Ethnomedicinal Plants: Revitalization of Traditional Knowledge of Herbs*, eds. M. Rai, D. Acharya and J.L. Rios, Science Publishers, USA, pp.444-457. *Invited book chapter.*
3. J. Packer*, **J. Gaikwad***, D. Harrington, S. Ranganathan, S. Vemulpad, J. Jamie (2011): Medicinal Plants of New South Wales, in *Genetic Resources, Chromosome Engineering and Crop Improvement Series: Medicinal Crops,* eds. R.J. Singh, CRC Press, Taylor & Francis Group, USA. *Invited book chapter, in press.* (*joint first authors)
4. **J. Gaikwad**, P. Wilson, S. Ranganathan: Modeling potential distribution of customary medicinal plant species used by Australian Aborigines to identify species-rich areas and culturally valuable habitats for conservation. *Under review.*
5. **J. Gaikwad**, P. Wilson, S. Ranganathan: Climate change: another impending threat to customary medicinal plant species used by Australian Aborigines. *Under review.*

ABSTRACT

The overall aims of this thesis are to design and implement customary medicinal plant species information management system and to analyse the collated data using biodiversity informatics tools and resources.

Australian customary medicinal plants comprise a major part of the biodiversity and form an inextricable link between biological and cultural diversity. Unfortunately, indigenous medicinal plant knowledge linked with these species is declining due to the loss of biodiversity, habitat destruction and acculturation. For developing effective conservation and adaptive strategies, easy access to relevant information is essential. However, the information on customary medicinal plants is geographically scattered among different indigenous communities, institutions and research organisations in heterogeneous format, rendering it difficult to access and limiting usability.

Customary Medicinal Knowledgebase, accessible at http://www.biolinfo.org/cmkb is developed in collaboration with Aboriginal communities for collating, integrating, visualising, disseminating and analysing public domain data and first-hand information on customary medicinal plants. To acknowledge and protect the intellectual rights of the Aboriginal communities, access to sensitive first-hand information is password protected, accessible only by authorised community members and approved researchers. Further, CMKb is also compliant with current international biodiversity informatics standards, specifically Economic Botany Data Standards, Darwin Core and Dublin Core for easy integration with national and global biodiversity informatics initiatives.

Culturally valuable customary medicinal plant species-rich habitats are distributed across Australia and conservation of these habitats is important. However, studies to identify and conserve such areas are hampered due to the vastness of the continent and lack of adequate data on the spatial distribution of customary medicinal plants species-rich habitats.

Models were developed to identify culturally significant species-rich hotspots using habitat suitability modelling tool Maxent and bioclimatic variables. Further, the predicted models were weighted using customary medicinal uses from CMKb to evaluate the cultural worth of the predicted hotspots.

In recent times, similar to global trends, profound impacts of human-induced climate change are observed on Australian biodiversity. To devise adaptive strategies for conservation it is important to understand the impact of current and future climate change on the spatial distribution of the customary medicinal plant species.

Using Maxent and a bioclimatic envelope, models for twelve multi-therapeutic and culturally important customary medicinal plant species were developed for current and future (decade 2020, 2050 and 2080) climate scenarios using four General Circulation Models (GCMs). The results from this study will help us to further understand the implications of these changing scenarios on customary medicinal plant species and its consequences on Aboriginal customary knowledge.

Chapter 1: Introduction

1.1 Overview

Over a period of four billion years, evolution has resulted in a complex biodiversity on earth [1] and has remained the fundamental force for the development of diverse life forms across the globe. It is estimated that of the total number of organisms ranging from 7-20 million, only 1.8 million species are scientifically named [2, 3]. Predominantly, the world's biodiversity is concentrated in tropical developing countries, referred to as "biodiversity storehouses" with unique taxa and species diversity [4, 5]. Climate change and human activities have resulted in an unprecedented loss of biodiversity, with an estimated 100-1000 fold acceleration in the extinction rate of floral and faunal species compared to their natural rate [6]. Unfortunately, conservationists are faced with a paucity of data as only 1% of all identified species [7] has been studied beyond basic nomenclature.

Historically, humans have relied on biodiversity as a primary source of food, shelter and medicines and for spiritual and mental well-being. Medicinal plants comprise a significant part of the biodiversity and form an inextricable link between biological and cultural diversity. Their co-evolution has produced local traditional medicinal plant knowledge and practices [8]. This broad knowledgebase is passed on from generation to generation orally in the form of dance, stories and songs [9] and forms the basis for the sustainable exploitation and conservation of biodiversity. According to the World Health Organization (WHO), 80% of the population from developing countries depends on traditionally used medicinal plants as a source for their primary health care [10]. It is estimated that there are 300,000 plants in the world [11] of which 75,000 plant species are used as traditional medicine [12]. However, continuing habitat destruction and human-induced environmental changes have led to the loss of important medicinal plants used traditionally by indigenous communities. Furthermore, along with the loss of biodiversity, cultural diversity associated with valuable medicinal knowledge is also disappearing at an alarming rate, due to acculturation and urbanisation. Consequently, researchers and policy makers are recognizing that the solution for the conservation of biodiversity lies in a multi-disciplinary and integrated approach along with the essential involvement of indigenous communities. Additionally, there is also a global consensus that easy and efficient access to information on traditional medicinal plant knowledge and practices is essential for efficient conservation strategies and the sustainable use of biodiversity. Organisations including the

United Nations (UN) are currently searching for ways to safeguard traditional knowledge and use it for the benefit of both indigenous and non-indigenous people [13].

The growing realisation and recognition of the above facts has resulted in the conception of this large collaborative project between researchers from Macquarie University's Indigenous Bioresources Research Group (IBRG) and Indigenous communities from Northern New South Wales, Australia.

The project entails two-way exchange of knowledge, skills and benefits between the Aboriginal communities and the University researchers. It follows the ethical guidelines of UNESCO and NH&MRC for conduct of research with indigenous people and is, and will continue to be, conducted with the explicit consent of the appropriate Aboriginal authorising body and with the prior informed consent of all individuals. Cultural and intellectual rights of the communities are protected by a process of negotiation with the appropriate local Aboriginal representative body (Land Council, Elders Group, or Traditional Owners group).

For all elders and communities currently involved, Human Ethics approval is already in place. The research group respects the cultural values and contemporary needs of have established an iterative negotiation process to allow for equality in engagement between the researchers and the relevant communities and enhancement of capacity building. The research steps are guided by the UNESCO Participatory Action Research (PAR) methodology, which involves the community members as an integral part of each stage of the project. We have made this stepwise PAR process a necessary part of our Human Ethics Approval to ensure best ethical practices are in place, including the need to provide benefits back to the communities, recognition of ownership of the customary knowledge by the communities, and co-authorship of any published materials.

A biodiversity informatics approach was used to digitise and analyse valuable customary medicinal plant knowledge, comprising contemporary and traditional uses, possessed by the Aboriginal communities. This thesis demonstrates the development of a multi-disciplinary information infrastructure to archive Aboriginal medicinal plant knowledge. It also shows the potential of such an information infrastructure to visualise data, identify information gaps and to facilitate analytical processes, such as species distribution modelling, to address conservation issues.

1.2 Biodiversity Informatics

Biological diversity or biodiversity is the variety exhibited by all living organisms, at the genetic, species and ecosystem levels (Fig. 1.1).

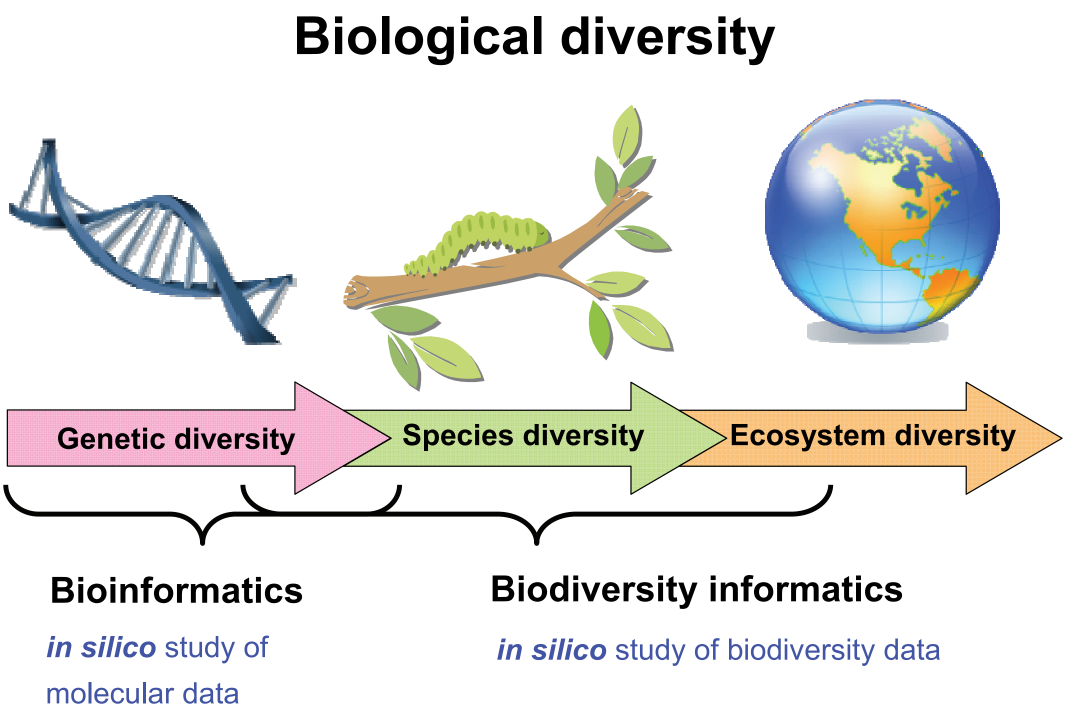

Figure 1.1: Biodiversity Informatics forming links across biological diversity to organise and study species level information.

Biological data is diverse and varied, arising from different domains including ecology, taxonomy, genetics, pharmacology, ethnobiology, molecular biology, structural biology and physiology, presented in different formats such as text, images, audio and video [14]. Biodiversity informatics (BI) is the application of information technology for storing, managing, disseminating and analysing species level information, using the scientific name of each species as the linking theme [15]. This term was coined by John Whiting in 1992 during the formation of the Canadian Biodiversity Informatics Consortium (CBIC) [16]. Today, biodiversity informatics, a part of biological informatics, aims to form a link between molecular informatics (or bioinformatics) and environmental informatics, with the objective of providing a robust informatics infrastructure to mobilise primary biodiversity data for diverse analytical research tasks [17].

1.3 Biodiversity informatics data resources and tools

Biodiversity informatics is emerging as a discipline focusing on the collection, digitisation, collation, dissemination and analysis of species-level data. To facilitate the exchange of information between diverse users, significant information management systems are required. Biodiversity researchers also need intelligent tools to collate, retrieve and analyse the immense wealth of biodiversity data available currently [18]. Moreover, for efficient data access and management, protocols and standards are required [19, 20].

1.3.1 Identification tools

The first step towards the effective management and mobilisation of biodiversity data is species identification and digitisation of specimens and culture collections which are housed across the world in different museums, herbaria and academic institutions. Interactive software programs, available either as standalone applications or web services, are commonly used for species identification. A selection of such systems is listed in Table 1.1, which is categorized based on their availability and implementation. Field guides are handy tools for taxonomists on exploratory field expeditions for studying species and facilitate the rapid identification of the species based on diagnostic characters (referred to as "identification keys").

Table 1.1: Selected species identification systems

Software	Input data	Category*	URL
EDIT's Cybertaxonomy platform	Flora, fauna	W, F	http://wp5.e-taxonomy.eu/
Electronic field guide (EFG)	Flora, fauna	W, S, F	http://wiki.cs.umb.edu/
FreeDELTA	Flora, fauna	S, F	http://freedelta.sourceforge.net/
IDnature guides	Flora, fauna	W, F	http://www.discoverlife.org/mp/20q
LucID	Flora, fauna	S, C	http://www.lucidcentral.com
Medical Fungi Identification Website	Fungal	W, F	http://www.cbs.knaw.nl/medical/ DefaultPage.aspx
Meka	Flora	S, F	http://ucjeps.berkeley.edu/keys/ downloads/Meka31.exe

Software	Input data	Category*	URL
Open Identification API	Flora, fauna	S, F	http://wwbota.free.fr/Identification/
OpenKey	Flora	S, F	http://www3.isrl.uiuc.edu/~TeleNature/projects/openkey.html
PANKEY	Flora, fauna	S, C	http://www.exetersoftware.com/cat/pankey/pankey.html
PHPKey	Flora	W, F	http://www.borealis.nu/exjobb/Index_en.html
PollyClave	Flora, fauna	W, S, F	http://prod.library.utoronto.ca:8090/polyclave/
Rachis	Flora, fauna	S, F	http://rachis.sourceforge.net/
Scratchpads	Flora, fauna	W, F	http://editwebrevisions.info/scratchpads
Stinger's Lightweight Interactive Key Software (SLIKS)	Flora	W, S, F	http://www.stingersplace.com/SLIKS/
Taxy	Fungi	S, F	http://www.collectivesource.com/taxy/taxy.html
TeleNature	Flora	W, F	http://www3.isrl.uiuc.edu/~TeleNature/projects/telenature.html
X:ID	Flora, fauna	W, S, F	http://uio.mbl.edu/services/key.html
Xper^2	Flora	S, F	http://lis-upmc.snv.jussieu.fr/lis/?q=en/resources/software/xper2

*W = Web-based application, S= Standalone application software, F= Free, C= Commercial

1.3.2 Digitisation tools

Digitisation of natural history collections is essential for making primary biodiversity data available for global access and analysis [21]. Digitisation systems are used to collate information on each specimen such as the nomenclature (scientific name, synonyms, common names, and biogeographic details), images and collection and curator details, and have been developed independently, based on locally defined specifications. A selection of such systems is listed in Table 1.2.

Table 1.2: Selected specimen digitisation systems

Software	Input data	Category*	URL
Bauble	Flora	S, F	http://bauble.belizebotanic.org/
Bibmaster	Flora, fauna	S, F	http://www.gbif.es/bibmaster/bibmaster_Inphp
Biota	Flora, fauna	S, F	http://viceroy.eeb.uconn.edu/biota
Biotica	Flora, fauna	S, F	http://www.conabio.gob.mx/biotica/cms /index.php
BRAHMS	Flora	S, F	http://dps.plants.ox.ac.uk/bol/BRAHMS/Home /Index
Herbar	Flora	S, F	http://www.gbif.es/herbar/herbar_Inphp
KE Emu-Electronic museusm	Flora, fauna	S, C	http://www.kesoftware.com/emu-home.html
Pandora	Flora	S, F	http://www.ibiblio.org/pub/academic/biology /ecology+evolution/software/pandora/
Specify 6	Flora, fauna	S, F	http://specifysoftware.org/
Zoorbar	Flora, fauna	S, F	http://www.gbif.es/zoorbar/zoorbar_Inphp

*W = Web-based application, S= Standalone application software, F= Free, C= Commercial

1.3.3 Biodiversity databases

Globally, there are 100 million species and so far approximately 1.8 million species are studied and described or named by taxonomist. To conduct fundamental biodiversity research, access to quality information, related to these known species such as taxonomy, molecular data, ecology and distributions in a standardised electronic format is important. Similar to data aggregators in mainstream bioinformatics such as National Center for Biotechnology Information (NCBI) [www.ncbi.nlm.nih.gov] and ENSEMBL [www.ensembl.org], unified data repositories for biodiversity studies, are essential. There are growing efforts such as Species2000, ITIS, Antbase and Fishbase to develop electronic catalogues of known species (ECAT) that varies in taxonomic and geographic scope.

Further, there are other initiatives such as Barcode of Life Database (BOLD) and Biodiversity Heritage Library (BHL), for making information related to diverse aspects of these known organisms available to foster research in biodiversity. A large number of initiatives with varied scope are available on the internet. Representative databases dedicated to biodiversity are listed in Table 1.3, grouped according to their taxonomic content, followed by a brief description of the more comprehensive of these.

Table 1.3: Selected biodiversity databases

Database name	**Taxonomic content**	**URL**
Biodiversity Heritage Library (BHL)	All kingdoms	www.biodiversitylibrary.org
Integrated Taxonomic Information System (ITIS)	All kingdoms	http://www.itis.gov/
Species2000	All kingdoms	http://www.sp2000.org/
Tree of Life	All kingdoms	http://tolweb.org/tree/phylogeny.html
TreeBASE	All kingdoms	http://www.treebase.org/treebase-web/home.html
Barcode of life database (BOLD)	Protists, fungi, flora, fauna	http://www.barcodinglife.org/views /logInphp
Global invasive species database (GISD)	Microbes, Flora, fauna	http://www.issg.org/database/welcome/
Invasive and Exotic species	Microbes, flora, fauna	http://www.invasive.org/
Invasive species in Canada	Microbes, flora, fauna	http://www.invasivespecies.gc.ca/english/view.asp?x=1
Biodiversity of Mexico-VN	Flora, fauna	http://www.vivanatura.org/About%20VN.html
Natural History Museum (UK)	Flora, fauna	http://www.nhm.ac.uk/nature-online/life/index.html

Database name	**Taxonomic content**	**URL**
South African National Biodiversity Institute Databases	Flora, fauna	http://www.sanbi.org/frames/infofram.htm
Amphibian Species of the World	Fauna	http://research.amnh.org/herpetology/ amphibia/index.php
Antbase	Fauna	http://antbase.org/
Australian Biological Resources Study Fauna Online	Fauna	http://www.environment.gov.au/ biodiversity/abrs/online-resources/fauna/index.html
Biosystematic Database of World Diptera	Fauna	http://www.sel.barc.usda.gov/Diptera/
Butterflies and Moths of the world	Fauna	http://www.nhm.ac.uk/research-curation/projects/butmoth/
CephBase	Fauna	http://www.cephbase.utmb.edu/
Fishbase	Fauna	http://www.fishbase.org/home.htm
Mammal Species of the World	Fauna	http://vertebrates.si.edu/mammals/msw/
The Reptile Database	Fauna	http://www.reptile-database.org/
Universal Chalcidoidea Database	Fauna	http://www.nhm.ac.uk/research-curation/projects/chalcidoids/index.html
Zoology: Extinct and Endangered database	Fauna	http://www.oum.ox.ac.uk/database/zoology /extinct.htm
AlgaeBase	Flora	http://www.algaebase.org/
Australian Biological Resources Study Flora Online	Flora	http://www.environment.gov.au/ biodiversity/abrs/online-resources/flora/index.html
DiaMedBase	Flora	http://www.progenebio.in/DMP/DMP.htm
Encyclopedia of Indian Medicinal Plants	Flora	http://envis.frlht.org.in/indian-medicinal-plants-database.php

Database name	**Taxonomic content**	**URL**
Plants for a future (Edible and medicinal plants)	Flora	http://www.pfaf.org/user/plantsearch.aspx
Royal Botanic Garden Edinburgh	Flora	http://www.rbge.org.uk/databases
USDA Plant Database	Flora	http://plants.usda.gov/
Fungal Records Database of Britain and Ireland	Fungi	http://www.fieldmycology.net/
Index Fungorum	Fungi	http://www.indexfungorum.org/Names/Names.asp
MycoBank	Fungi	http://www.mycobank.org/
USDA Fungal database	Fungi	http://nt.ars-grIngov/fungaldatabases/

(i) ***Species2000 ITIS Catalogue of Life (CoL)***

Species2000 aims to create an exhaustive list of all known flora, fauna, fungi and microbes for studying global biodiversity. The Integrated Taxonomic Information System (ITIS) is a complementary initiative for cataloguing known biota, especially from North American ecosystems. Since 2001, Species2000 and ITIS have collaborated to create the Catalogue of Life (COL), which as on October 2010 contains 1,257,735 species from 77 contributing databases across the globe in its 2010 release.

(ii) ***Barcode of life database (BOLD)***

The DNA barcode is a short unique genetic sequence of 648 bps in the cytochrome c oxidase 1 (COI) gene, a conserved part of a genome used for many animal species identification, other than plants, where COI evolves slowly. This barcode has been developed as a signature for species identification as well as to capture the link between the genome and the morphologically observed characteristics, referred to as the “genome-phenome” link. DNA barcode records are stored in BOLD by the International Consortium for the Barcode of Life (CBOL) [http://barcoding.si.edu/]. BOLD is an integrated platform which provides support from specimen collection to a validated barcode library [22], with

78,033 species formally described with barcode data. BOLD houses 997,836 barcode records and is linked to different external molecular data resources, such as GenBank and the Canadian Centre to serve as a reference library for species identification [http://barcoding.si.edu/whatis.html].

(iii) ***Tree of Life (ToL)***

The Tree of life is a web-based database dedicated to compiling information on biodiversity and evolutionary relationship between organisms. There are more than 10,000 web pages providing information on diversity of organisms and their evolutionary history. Each page contains information about a particular group of organisms which are linked to one another in the form of the evolutionary "tree of life". The ToL illustrates the genetic connections between living organisms, starting from the root of life on earth to diverging branches of individual species.

(iv) ***Global invasive species database (GISD)***

Invasive species are a major threat to local biodiversity and ecosystems. GISD is an online database to spread awareness about invasive alien species, with information on 681 species pertaining to their ecology, distribution, management information, impact and references. GISD covers species from all ecosystems such as micro-organisms, plants and animals.

(v) ***Encyclopedia of Indian Medicinal Plants (EIMP)***

As a part of biodiversity studies, medicinal plants have been of great importance due to their economic value and health benefits. For the sustainable use and conservation of medicinal plants, the Foundation for Revitalisation of Local Health and Traditions (FRLHT) has developed the Encyclopedia of Indian Medicinal Plants (EIMP), a web-based information system that documents multi-faceted information on Indian medicinal plants. The EIMP database houses information on 6,198 medicinal plants species and 798 plant images along with information on various aspects such as geographical distribution, vernacular names, pharmacology, pharmacognosy, seed storage, trade and propagation. Currently, the database provides species names in 12 different languages including English.

(vi) ***Biodiversity Heritage Library (BHL)***

Recognising the importance of detailed legacy literature related to biodiversity, 12 libraries, representing museums, herbaria and research institutions, in the main from the

US and UK, have come together to form the Biodiversity Heritage Library consortium. Under this project, published literature on biodiversity housed by these participating libraries are digitised and made freely accessible to researchers, policy makers, students and to a global audience on the World Wide Web. The information available through this initiative helps biodiversity researchers to study organism more elaborately with regard to its systematics and conservation status. These libraries are in possession of over 2 million volumes of biodiversity literature, spanning two centuries. As of October 2010, BHL has digitised 31,397,395 pages from 83,616 volumes, from 43,140 titles.

1.3.4 Federated data portals

As the databases described above are independent of each other, the challenge of data analysis in this realm has led to the hosting of federated data portals, to provide a one-stop access point to data and in some cases, to associated analysis tools. These federated portals serve as facilitators, where the digital data, housed by the participating data providing agencies, is presented virtually to the user. Some of these initiatives such as the Global Biodiversity Information Facility (GBIF), the Global Species Information System (GSIS) [23] leading to SpeciesBase, and iSpecies are listed in Table 1.4, along with a brief description of select mature portals.

(i) *Global Biodiversity Information Facility*

The Global Biodiversity Information Facility (GBIF) was established to facilitate the development of standards, digitisation and dissemination of global biodiversity primary data. GBIF is a digital data warehouse, linked to data provided by global, regional and national contributing organisations and to genome information (*via* the NCBI Taxonomy database). GBIF's current one-stop data portal is effectively mobilising the shared biodiversity data, through efficient search engines. Through this portal, as of October 2010, users have access to 216,970,036 occurrence records, from 11,607 datasets, shared by 321 data publishers.

(ii) *Ocean Biogeographic Information System (OBIS)*

The Ocean Biogeographic Information System is the information component of the Census of Marine Life (CoML), developed to document the ocean's diversity, distribution and abundance of life, in partnership with various organisations such as GBIF, CBOL and TDWG.. OBIS is also a web-based federated information system that collates data from distributed and heterogeneous databases. OBIS provide access to nearly 27.7 million records of 126,000 species from 849 databases.

Table 1.4: Selected biodiversity federated portals

Portal name	Country/ Region	URL
Atlas of living Australia (ALA)	Australia	http://www.anbg.gov.au/cpbr/program/hb/index.html
Australian Virtual herbarium (AVH)	Australia	http://www.ersa.edu.au/avh/index.jsp
Encyclopedia of Life (EOL)	USA	http://www.eol.org/home.html
Global Biodiversity Information Facility (GBIF)	Europe	http://www.gbif.org
iSpecies	Europe	http://darwInzoology.gla.ac.uk/~rpage/ispecies/index.php
LifeWatch	Europe	http://www.lifewatch.eu/index.php?id=411
Ocean Biogeographic Information System (OBIS)	USA	http://v2.iobis.org
SpeciesBase	Europe	http://www.speciesbase.org/
uBio	USA	http://www.ubio.org

(iii) ***Universal Biological Indexer and Organizer (uBio)***

uBio is a significant effort to synthesise data from different data resources and present it to the user in a meaningful way, using SOAP and XML REST web services. It is made up of a species name thesaurus, known as the Taxonomic Name Server, which is divided into two interconnected services viz; NameBank (11,106,374 records) and ClassificationBank (90 classifications). NameBank serves as a repository for recorded biological names and ClassificationBank, for multiple classification and taxonomic concepts. uBio also provides different tools and algorithms which can be used by experts for information management and analysis.

(iv) ***Australian Virtual herbarium (AVH)***

The Australian Virtual Herbarium is a common gateway to provide botanical information on 6M specimens housed in Australian herbaria, along with the biogeographical distribution of each species. A query to AVH is passed to all the herbarium specimen databases across Australia and the consolidated results are displayed, thereby reducing access time in information gathering.

1.3.5 Standards and Protocols

The highly heterogeneous nature of biodiversity data, presented in varied formats and logical structures across the globe, have posed serious problems for data integration and analysis. Schema, standards and protocols have been proposed to overcome these impediments. Different protocols such as the DarwinCore [http://wiki.tdwg.org/ twiki/bin/view/DarwinCore/WebHome], the Access to Biological Collection Data (ABCD) Schema [http://www.bgbm.org/TDWG/CODATA/Schema/], the Biological collection access service for Europe (BioCASE) Protocol [http://www.biocase.org/] and the Herbarium Information Standards and Protocols for Interchange of data (HISPID) [http://www.tdwg.org/standards/110/] from Australia, have been developed to address the requirements of the specific region and data domaIn The Taxonomic Database Working Group (TDWG) [http://www.tdwg.org/], now known as Biodiversity Information Standards, has been working towards a unified globally accepted system for data interoperability since 1994. TDWG is responsible for developing the TDWG Access Protocol for Information Retrieval (TAPIR) and at present are examining the use of Global Unique Identifiers (GUIDs) in the form of Life Science Identifiers (LSIDs) as potential unique identifiers (similar to unique sequence identifiers in bioinformatics). TAPIR specifies a standardised, stateless, HTTP transmittable, XML-based request and response protocol for accessing structured data that may be stored on any number of distributed databases of varied physical and logical structures, and interfaced to current standardized databases in bioinformatics and other domains. Similarly, GUID technology provides a mechanism to identify and access data objects on the web from distributed biodiversity data sources stored in different formats, providing a nomenclature standard for easy data integration and cross-linking. Current initiatives actively using this technology are BioMOBY, Index Fungorum, Taxonomic search engine, Global Compositae Checklist, Universal Biological Indexer and Organizer (uBio) and New Zealand Plants.

1.3.6 Analytical tools

Today, biodiversity informatics is developing as a field, overlapping with diverse disciplines including forensic, ecoinformatics, chemoinformatics, molecular biology and statistics. Overall, due to the advent of information technologies, many multidisciplinary datasets are being made available through the internet. However, to use this information to better understand and address issues related to biodiversity and ecology, efficient analytical tools are required. Select software tools, used for addressing complex questions including evolution and phylogeny, ecological forecasting, niche modelling, morphometry, paleontology, genetics and statistics are listed in Table 1.5.

Table 1.5: Selected software tools for biodiversity data analysis

Software	Use	Category*	URL
ADE4	Ecological analysis	S, F	http://cran.r-project.org/src/contrib/Descriptions/ade4.html
ADAPTS	Palaeobiological analysis	S, F	http://www.paleodb.org/paleosource/code.php?stage=download&project_no=4
APE	Phylogenetic and diversification analyses	S, F	http://pbil.univ-lyon1.fr/R/ape/
CODA	Nature conservation planning	S, F	http://members.ozemail.com.au/~mbedward/coda/coda.html
DIVA-GIS	Mapping and Ecological modelling	S, F	www.diva-gis.org/
Ecopath with Ecosim (EwE)	Ecological modelling (marine environment including effects of fishing)	S, F	http://www.ecopath.org/index.php?name=About
GARP	Ecological modelling (species distribution)	S, F	http://nhm.ku.edu/desktopgarp/
GRASS GIS	GIS used for geospatial data management and	S, F	http://grass.itc.it/

	analysis		
Software	**Use**	**Category***	**URL**
LAMARC	Population studies	S, F	http://evolution.genetics.washington .edu/lamarc.html
MAXENT	Ecological modelling (species distribution)	S, F	http://www.cs.princeton.edu/~schapi re/maxent/
MEGA	Phylogenetic analysis	S, F	http://www.megasoftware.net/
Mesquite	Evolutionary analysis	S, F	http://mesquiteproject.org/mesquite/ mesquite.html
Molphy	Phylogenetic analysis	W, F	http://bioweb.pasteur.fr/seqanal/ interfaces/prot_nucml.html
MrBayes	Phylogenetic analysis	S, F	http://mrbayes.csit.fsu.edu/index. php
PAST (PAlaeontol ogical STatistics)	Palaeontological statistics	S, F	http://folk.uio.no/ohammer/past/
PATN	Pattern analysis	S,C	http://www.patn.com.au/
PopTools	Population dynamics and ecological model analysis	S, F	http://www.cse.csiro.au/poptools/
PAUP	Phylogenetic analysis	S, C	http://paup.csit.fsu.edu/
PHYLIP	Phylogenetic analysis	S, F	http://evolution.genetics.washington .edu/phylip.html
Rarefaction calculator	Diversity estimation and indices	W, F	http://www2.biology.ualberta.ca /jbrzusto/rarefact.php
TNT	Phylogenetic analysis	S, F	http://www.cladistics.com/aboutTN T.html
TreeAlign	Phylogenetic analysis	W, F	http://bioweb.pasteur.fr/seqanal/ interfaces/treealign-simple.html
TreeView X	Phylogenetic tree visualization	S, F	http://darwInzoology.gla.ac.uk /~rpage/treeviewx/

* W = Web-based application,   S= Standalone application software, F= Free, C= Commercial

1.4 Australian biodiversity

Australia is one of the 17 megadiverse countries in the world, with an estimated total of 290,000 floral species (plants and fungi) [24], and supports almost 10% of the global biological diversity [25]. This ancient continent is the world's most arid and low-nutrient landmass with the oldest soils and rocks [26]. The described Australian biodiversity comprises of over 20,000 vascular and 14,000 non-vascular plants; 250,000 species of fungi and over 3,000 lichens. Further, an estimated of 85% of all vascular plant species are endemic to the continent, including nine plant families [27].

The characteristically, "Australian" floral diversity is due to the isolation of the island continent, following the break-up of the Gondwanan supercontinent in the early Cretaceous period. This geographic isolation has resulted in speciation across Australia's large latitudinal and climatic range [28]. The present day vegetation varies enormously, ranging from alpine regions to semi-arid and arid areas of inland, tropical rainforest, and scrub [29].

The Australian flora is adapted to arid conditions, nutrient poor soils and fire, by developing suitable physiological traits, which include scleromorphy (*Acacia*), lignotuber (*Eucalyptus*), epicormic buds (*Banksia*), and serotiny (*Hakea*) [30]. Much of the flora, particularly the Myrtaceae, Proteaceae, Scrophulariaceae and Rutaceae, are high in essential oils, tannins and alkaloids [31, 32]. The adaptation and development of this immense diversity, contributes to the incredible potential range of novel compounds to be found in Australian plant species [33, 34].

1.5 Aboriginal Australians and customary medicinal plant knowledge

Australia has been inhabited for at least 40 to 50 thousand years [35, 36] and the Aborigines of Australia hold the record for the longest continuous heritage of human culture [37, 38]. Currently, approximately 2.5% of the total Australian population are considered Aboriginal [39]. It is postulated that before the European settlement, Aboriginal population could have been around 750,000. Unfortunately, most of the population declined due to various factors including new introduced infectious diseases, and social and cultural repression [40].

Given the lengthy period of continuous human habitation in Australia, the Aboriginal people have adapted to every possible habitat, from the arid central deserts to coastal and alpine areas. This adaptation to their locality has resulted in the sustainable exploitation of natural resources for food and medicine, specifically from medicinal plants. Although, traditionally Australian Aborigines led a nomadic hunter-gatherer lifestyle, they were known to be healthier than contemporary Indigenous Australians [41]. At times, they required medicinal plants for treating ailments such as cuts, wounds, coughs, snake-bites, digestive problems, cold, fever and headaches. The Aborigines derived their medications from a variety of commonly occurring native medicinal plants, with multiple therapeutic applications, such as *Corymbia terminalis* and *Eremophila freelingii* [42-44], with local substitutes used if the preferred plant was not available. Rather than over-exploit a single species, their preference was for an array of medicinal plants with several therapeutic uses, as an insurance against species depletion. Lacking a written script to record culturally valuable medicinal plant knowledge, such as the optimal season, the time and place for collection and the correct preparation methods and use, the Aborigines resorted to oral transmission of knowledge, in the form of songs, dance and stories [9]. This tradition has survived till today, with contemporary Aboriginal societies referring to species from over 100 plant genera [37, 38] as medicine.

The history of ethnobotanical studies in Australia dates back to the late eighteenth century when the European settlers came in contact with the local indigenous population. The early explorers and settlers gathered ethnobotanical information, as they had to depend occasionally on local biological resources for food during the shortage of supplies and for potential future economic benefits. At the same time, knowledge related to exotic plants used by the settlers as tonics and medicine, such as sow thistle (*Sonchus oleraceus*) and camphor laurel (*Cinnamomum camphora*), was adopted by Australian Aborigines in their daily lives [42, 45, 46].

The arrival of the European settlers and their knowledge related to the use of exotic medicinal plants, technologies and practices immensely influenced Aboriginal traditional knowledge. Before the arrival of the European settlers, Aboriginal traditional medicinal plant knowledge was evolving in close interaction with the local natural environment, containing native flora. Today, the contemporary Aboriginal pharmacopeia is an amalgamation of knowledge related to the use of native and introduced medicinal plant species. In this thesis, the amalgamated contemporary Aboriginal medicinal plant knowledge is referred as “customary medicinal plant knowledge”.

In the 19th century, the first chemical and pharmacological study was conducted of an Australian Aboriginal plant by the physician Joseph Bancroft, who analysed properties of narcotic pituri (*Duboisia hopwoodii*), used by the Aboriginal people, which contained nicotine alkaloids [45]. Later during the 1970s, with the change in ethical standards, collaborative projects between Aboriginal communities and researchers developed such as “The Bush Medicine Project” which resulted in the publication of pharmacopeia from the Northern Territory [9].

1.6 Major research issues

A limited number of systematic ethnobotanical studies have been undertaken. Documented Australian medicinal plant knowledge is in the main, fragmented, restricted to specific locales and of limited applicability, usually to pharmacology or phytochemistry. The available information in published literature is species-specific, scattered and in different formats, making data integration challenging.

Most studies have been restricted to the Northern Territory, where medicinal plant use has been documented, along with limited data on chemical components and pharmacological assay work [47, 48]. In the Kimberley region, a few ethnobotanical studies have been undertaken with individual Aboriginal communities [49], but these studies have focused on the customary use of plants as food. A major database of plants [50] used as bush foods and medicines by the New South Wales Aboriginal communities contains information largely obtained from published sources or early manuscripts, with little direct input from Aboriginal communities. Moreover, it represents only a fraction of the plant species that have been used medicinally by New South Wales communities and does not include chemical or pharmacological data. A database of published information on Australian medicinal plants has been established by the CSIRO [51] but was last updated in 2000. There has since been an explosion in ethnopharmacology and phytochemistry studies of medicinal plants. Neither of these databases covers first-hand and public domain ethnobotanical information, along with chemical and biological data of the medicinal plants and related species. Thus, there is no single comprehensive inventory of Aboriginal medicinal plants available.

1.7 Objectives

Customary medicinal plant knowledge, comprising traditional and contemporary use by Australian Aboriginal communities, is regarded as a significant medicinal resource. This medicinal plant knowledge, evolved over 40,000 years, is dwindling due to the loss of biodiversity, habitat destruction, acculturation and the demise of knowledge custodians 'without being able to pass on their knowledge to interested younger Aborigines' [52]. Further, the increased interest in customary medicinal knowledge has resulted in cases where indigenous knowledge has been treated as a resource to be exploited by bioprospecting industries [52]. To combat the loss of bio-cultural diversity and protect against misappropriation, it has become essential to document, digitise and conserve the customary knowledge. Further, for holistic understanding, conservation and sustainable use of biodiversity, a comprehensive informatics infrastructure is needed to provide easy and effective access to this knowledge.

This thesis deals with the application of biodiversity informatics tools and resources to develop and provide multi-disciplinary informatics infrastructure to conserve and protect Aboriginal customary medicinal plant knowledge. The thesis also demonstrates the potential of such an information infrastructure to visualise data, identify information gaps and to facilitate analytical processes, such as habitat suitability modelling, to address conservation issues.

The scaffold for the objectives of the research presented here was defined based on the above mentioned considerations. Specifically two main research objectives were defined for this PhD research project. Firstly, in collaboration with Aboriginal communities, to develop a web-based multidisciplinary information management system for digitising and archiving Australian Aboriginal medicinal plant knowledge; and secondly, to use biodiversity informatics analytical tools to analyse the digitised information.

The above objectives were sub-divided into specific aims, described in the following sections and addressed in detail in five publications presented in this thesis:

1. Review the current status of ethnobotanical data and the potential application of information technology for efficient data integration and use (Publication 1).

2. Based on the review and in collaboration with Aboriginal communities, develop web-based multi-disciplinary information management system (Customary Medicinal Knowledgebase, CMKb; http://www.biolinfo.org/cmkb) as a unique Australian resource (Publication 2 and Appendices 1 and 2).

3. Using CMKb as an initial information resource, review literature and consolidate information on customary medicinal plant species that grow in NSW (Publication 3).

4. Apply GIS and species distribution modelling techniques to identify customary medicinal plant species-rich areas and evaluate the cultural value of the predicted habitats (Publication 4).

5. Analyse the likely impact of future climate change on the spatial distributions of suitable bioclimatic envelope of the customary medicinal plant species with the highest cultural values (Publication 5).

Finally, the overall conclusions and future research directions are presented in the concluding chapter.

Chapter 2: Methods and Applications

Methods and applications that were developed and used in this study are summarised in Table 2.1. The ensuing publications have also been listed and included in the relevant chapter.

Table 2.1: Methods, applications and publications

Methods/Applications	Chapter	Refer to Publication
Combining ethnobotany and informatics to discover knowledge from data	3	1
CMKb: a web-based prototype for integrating Australian Aboriginal customary medicinal plant knowledge	4	2
Medicinal plants of NSW, Australia	5	3
Modeling potential distribution of customary medicinal plant species used by Australian Aborigines to identify species-rich areas and culturally valuable habitats for conservation	6	4
Climate change: another impending threat to the customary medicinal plant species used by Australian Aborigines	7	5

Chapter 3: Combining ethnobotany and informatics to discover knowledge from data

3.1 Summary

There has been an exponential growth in the availability of primary biodiversity data through different web portals, some of which are discussed in Chapter 1. However, it is important to ensure interlinking and integration of disparate digital data resources spanning across the biological spectrum with primary biodiversity data to understand complex biodiversity processes and to promote improved decision-making [14].

Ethnobotanical information shared by indigenous communities is a significant contributor to scientific research and development in pharmaceuticals, cosmetics, food, agricultural products, biodiversity and ecology. This information is scattered in diverse formats, geographically restricted and with a limited scope of application. Access to vast amounts of ethnobotanical data is crucial not only for conserving culture, knowledge and biodiversity, but also to policy makers for making informed decisions. In the recent past, researchers have begun harnessing the power of information technology for digitisation, collation, analysis and dissemination of ethnobotanical information. However, the increasing volume of digital ethnobotanical data in varying quality, formats and physical distribution makes it difficult to access pertinent information. This paper discusses the importance and potential application of informatics for efficient ethnobotanical information management and the challenges faced in implementing it. Key components for data integration strategies are identified for ethnobotanical data management, global access, sustainable use and conservation.

Pages 23-36 of this thesis have been removed as they contain published material. Please refer to the following citation for details of the article contained in these pages.

Gaikwad, J., Wilson, K., Kohen, J., Vemulpad, S., Jamie, J., & Ranganathan, S. (2011). Combining ethnobotany and informatics to discover knowledge from data. In M. Rai, D. Acharya, & J. L. Ríos (Eds.), *Ethnomedicinal plants: revitalization of traditional knowledge of herbs* (1st ed., pp. 444-457). Enfield, NH: Science Publishers.

3.2 Conclusions

An enormous amount of ethnobotanical data is scattered among different indigenous communities, institutions and research organisations across the globe in digital and non-digital format However, despite the growth in the availability of ethnobotanical data on the internet, the lack of interoperable informatics infrastructure is making it difficult to access and use the available information for developing conservation and adaptive strategies (Chapters 6 and 7). The development of well-organised informatics tools and infrastructure will enable users to access vast quantities of biodiversity and its related ethnobotanical data facilitating to produce new knowledge wealth and socio-economic benefits, particularly in the developing world [4], using strategies proposed to link biodiversity storehouses in the United States and Europe [5]. It is very important that the design and establishment of such an informatics infrastructure should be done in collaboration with indigenous knowledge custodians (Chapter 4). Moreover, while aiming to make ethnobotanical information easily accessible, mutually agreed codes of conduct needs to be set to protect the intellectual property rights of the indigenous communities.

Chapter 4: CMKb: a web-based prototype for integrating Australian Aboriginal customary medicinal plant knowledge

4.1 Summary

A plethora of customary medicinal plant knowledge, which comprises traditional and contemporary medicinal uses by Australian Aborigines, is scattered in different literature resources and among Indigenous communities in diverse formats. The customary knowledge possessed by the Aboriginal communities is declining due to the acculturation and loss of biodiversity. The efforts to document and digitise this significant knowledge are fragmented and restricted to specific locales. Further, digitally available Australian ethnobotanical information is minuscule, isolated and with limited usability. Moreover, what is lacking in Australia is the availability of integrated multi-disciplinary interoperable web-based data management systems through which ethnobotanical information is easily and quickly available. Additionally, it should also facilitate the archiving and conservation of the diminishing knowledge without compromising the intellectual property rights of the Aboriginal communities. It is very important therefore, that the design and establishment of such an informatics infrastructure should be done in collaboration with indigenous knowledge custodians, to encourage two-way exchange of skills, knowledge and benefits. One of the main aims of this thesis was to develop this infrastructure to collate information as much as possible on customary medicinal plants, validate it in accordance with the current taxonomic nomenclature and disseminate the data for further research endeavours.

In collaboration with Indigenous communities the Customary Medicinal Knowledgebase (CMKb, http://www.biolinfo.org/cmkb) was designed and developed to archive and conserve medicinal plant knowledge. The important aspects and steps involved in the design and implementation of CMKb are shown in Figure 4.1. The steps illustrated are the result of iterative discussions between the Aboriginal communities and the research group at Macquarie University. Generally, data organisation can also precede content building: a data schema can be in place, before adding in the actual data. But in this context, to aggregate the views and opinions of data providers and based on the nature of the data, precedence was given to content building.

CMKb is a web-enabled species-centric knowledgebase collating first-hand medicinal plant information from Aboriginal communities and secondary data from published

scientific literature. Any sensitive Aboriginal community information is password protected, with access only to authorised researchers and community members, while secondary data is freely available. The communites are involved throughout CMKb development, determining the nature of data collection, content management and presentation, thus helping to reinforce a sense of ownership among the Aboriginal communities. The species occurrence data from the Australia's Virtual Herbarium is incorporated to visualise biogeographical distribution across Australia. CMKb also complies with Darwin Core and Dublin Core schemata enabling easy integration with national and international initiatives such as the Atlas of living Australia (ALA) and the Global Biodiversity Information Facility (GBIF).

In this paper we describe the development and deployment of web-based CMKb to archive and conserve Australian Aboriginal customary medicinal plant knowledge.

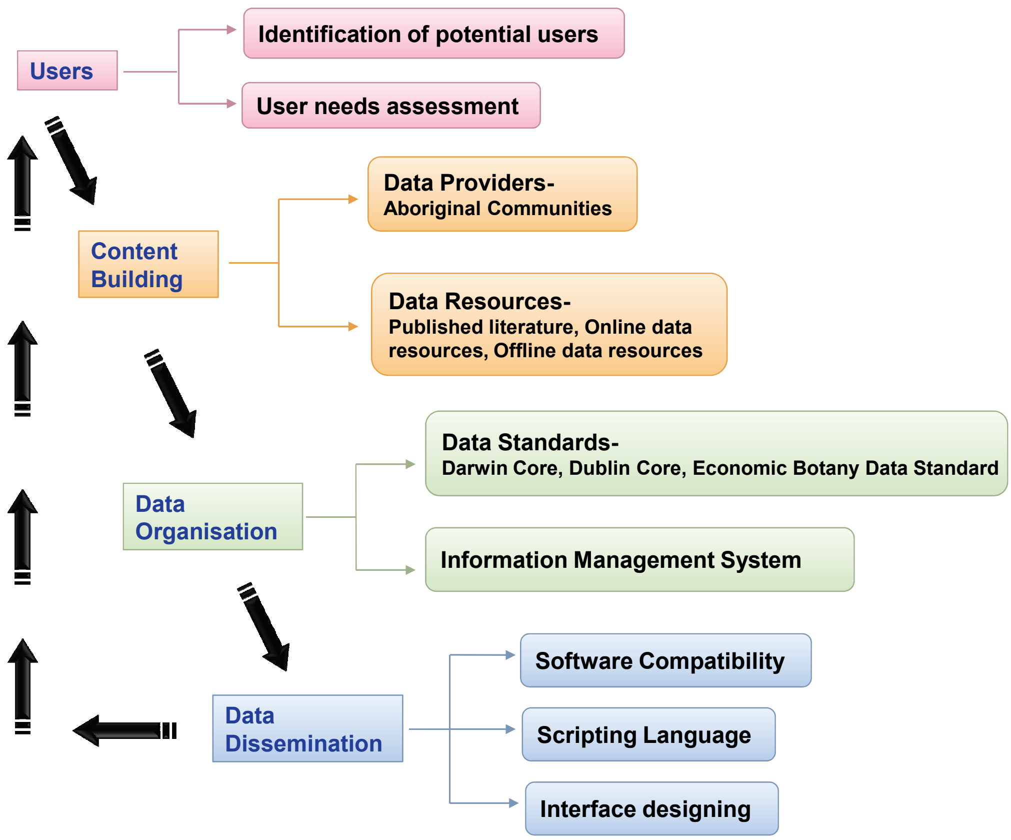

Figure 4.1: Steps involved during the design and implementation of the Customary Medicinal Knowledgebase

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Research

CMKb: a web-based prototype for integrating Australian Aboriginal customary medicinal plant knowledge

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from Asia Pacific Bioinformatics Network (APBioNet) Seventh International Conference on Bioinformatics (InCoB2008)
Taipei, Taiwan. 20–23 October 2008

Published: 12 December 2008

BMC Bioinformatics 2008, **9**(Suppl 12):S25 doi:10.1186/1471-2105-9-S12-S25

This article is available from: http://www.biomedcentral.com/1471-2105/9/S12/S25

Abstract

Background: The customary medicinal plant knowledge possessed by the Australian Aboriginal people is a significant resource. Published information on it is scattered throughout the literature, in heterogeneous data formats, and is scattered among various Aboriginal communities across Australia, due to a multiplicity of languages. This ancient knowledge is at risk due to loss of biodiversity, cultural impact and the demise of many of its custodians. We have developed the Customary Medicinal Knowledgebase (CMKb), an integrated multidisciplinary resource, to document, conserve and disseminate this knowledge.

Description: CMKb is an online relational database for collating, disseminating, visualising and analysing initially public domain data on customary medicinal plants. The database stores information related to taxonomy, phytochemistry, biogeography, biological activities of customary medicinal plant species as well as images of individual species. The database can be accessed at http://biolinfo.org/cmkb. Known bioactive molecules are characterized within the chemoinformatics module of CMKb, with functions available for molecular editing and visualization.

Conclusion: CMKb has been developed as a prototype data resource for documenting, integrating, disseminating, analysing multidisciplinary customary medicinal plant data from Australia and to facilitate user-defined complex querying. Each species in CMKb is linked to online resources such as the Integrated Taxonomic Information System (ITIS), NCBI Taxonomy, Australia's SpeciesLinks-Integrated Botanical Information System (IBIS) and Google images. The bioactive compounds are linked to the PubChem database. Overall, CMKb serves as a single knowledgebase

Gaikwad, J., Khanna, V., Vemulpad, S. et al. CMKb: a web-based prototype for integrating Australian Aboriginal customary medicinal plant knowledge. BMC Bioinformatics 9, S25 (2008). https://doi.org/10.1186/1471-2105-9-S12-S25

for holistic plant-derived therapeutics and can be used as an information resource for biodiversity conservation, to lead discovery and conservation of customary medicinal knowledge.

Background

Australia is among the 34 biodiversity hotspot countries in the world [1] endowed with unique endemic plant diversity. It is estimated that 85 percent of over 21,000 vascular plant species are endemic to Australia [2]. More than 40,000 years of Aboriginal inhabitation [3] has led to the use of medicinal plants from this vast bioresource for maintaining and treating health-related problems [4]. Aboriginal remedies vary between clans and in different parts of the country, with no single set of aboriginal medicines and remedies [5]. The indigenous knowledge has been passed on from one generation to the next orally through traditional songs, stories, poetry and legends [6]. Unfortunately, Aboriginal customary medicinal knowledge is poorly documented and is on the verge of being lost due to dislocation and the westernisation of the communities [7,8].

Documented Australian medicinal plant knowledge is in the main, fragmented, restricted to specific locales and of limited applicability, usually to pharmacology or phytochemistry. Several studies have focussed on the Northern Territory, where the use of medicinal plants has been documented, with limited data on chemical components and pharmacological assay work [9,10]. A database of plants used as bush foods and medicines by New South Wales Aboriginal communities comprises information largely obtained from published sources or early manuscripts [11], but does not include chemical or pharmacological data. The CSIRO Australian phytochemical database comprises a compendium of published work, searchable by plant and chemical names alone [12]. Thus, there is no single comprehensive inventory of Aboriginal medicinal plants available similar to initiatives such as Native American Ethnobotany database [13] and Prelude Medicinal Plants Database from Africa [14]. The available information in published literature is species-specific, scattered and in different formats, making data integration challenging.

Customary knowledge of medicinal plants and practices is a significant contributor to scientific research and development in pharmaceuticals, cosmetics, foodstuffs, agricultural products and a wide range of other biologically based products and processes [15]. Access to public domain information on Australian customary medicinal plants will advance research in bioinformatics, ethnobotany, taxonomy, biogeography and phytochemistry. Here, we report the development of a comprehensive knowledgebase for Australian customary medicinal plants, CMKb. To the best of our knowledge, this is the first such knowledgebase of its kind.

Construction and content

System architecture

The goal was to design a database which could be flexible and could accommodate heterogeneous data from published literature or bibliographic search. CMKb is developed using MySQL 5 relational database [16] for systematic and efficient content management. The user-friendly interface, consisting of dynamic web pages, is developed using PHP 5 [17] for data visualisation and data management. The chemoinformatics module incorporates Jmol, a Java based applet program [18] for visualization and Marvin Sketch [19] for drawing and editing of chemical structures. The data is served using Apache webserver [20] (Figure 1).

Construction method

Before developing the database schema, end user and data resource availability assessment was carried out. The assessment results showed that the potential end users range from members of Aboriginal communities to scientists with interests in ethnobotany, phytochemistry, biology and microbiology. The major data resource is the information collated from an exhaustive literature survey.

We have created a novel schema for integrating multidisciplinary information on medicinal plant species, such as taxonomy, habit and habitat, phytochemistry, bioactivity, biogeography, data sources, medicinal preparation methods and usage, community information, and images into CMKb. Since the species name is the fundamental biological descriptor [21], all the information is linked to the scientific name. Thus, the species information table is central to our schema, and is connected to the other tables (Figure 2). CMKb is designed with the possibility of future expansion including scaling to accommodate very large datasets, and the addition of other multidisciplinary components, described later.

Content of the database

Information related to medicinal plant species is stored in seven major tables (Figure 2) which are briefly described below. Mandatory information comprises the species name, the published reference and the medicinal use.

1. Species information

Information related to customary medicinal plant species such as kingdom, family, scientific name, synonym, com-

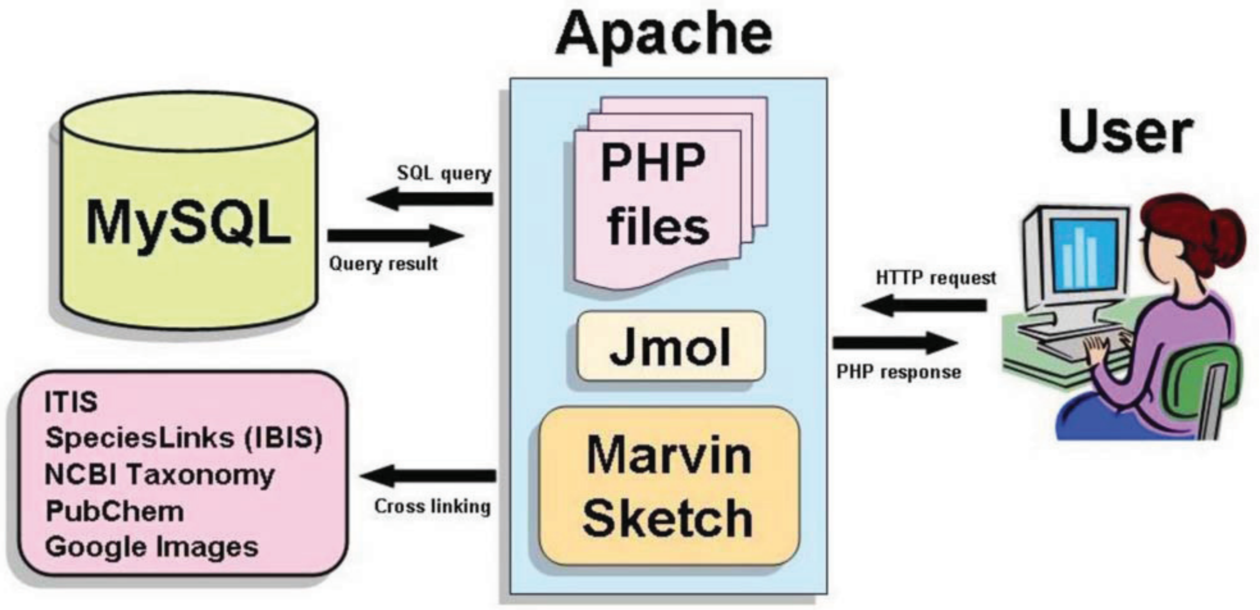


Figure 1
Schematic presentation of system architecture of CMKb.

mon name, native language name, habit and habitat as well as author citation, is stored in this table. This table is the hub to which all other tables are connected. The scientific name from this table is also used for cross-linking to external data portals, such as IBIS, ITIS and NCBI Taxonomy.

2. Data Source Number (DSN)
Each published article in the literature used to collate and populate the database, is assigned a unique DSN identifier. The DSN table contains fields such as the title of the article, reference type (such as thesis, journal or book), names of authors and citation details.

3. Medicinal information
Species-specific customary medicinal information such as the parts of the plant used, preparation method, taste, odour, colour, application and storage method, is collated in this table.

4. Biological activity information
This table records the biological activity associated with the medicinal plant. The type of assay used to identify biological activity (such as antifungal, antiviral, antibacterial), the specific assay used, assay targets (such as cell line, enzyme and organism name) are recorded in this table.

5. Chemical information
This table is used to store the chemical information and structure of bioactives derived from the medicinal plants such as IUPAC name, CAS number, PubChem [20] identifier, common chemical name, chemical structures in SMILES and MOL formats, biological activity related to that chemical compound, spectral data and other physical properties. The chemical structures are created locally using Marvin Sketch and are displayed using Jmol, a freely available Java applet. PubChem identifier stored in this table is used to link to PubChem database [22] from CMKb (Figure 3).

6. Biogeography information
The biogeography table collates observational data of the species from the published literature such as locality name, latitude and longitude in decimal units, district/town, state and country.

7. Multimedia information
CMKb will also accept data in multimedia formats. This table is used to store multimedia information for each species, in the form of videos, drawings and photographs. Multimedia file formats such as jpeg, mpeg and avi can be uploaded to the database, with detailed text description.

Utility and discussion

CMKb provides a user friendly web interface for accessing and managing the customary medicinal plant data. The

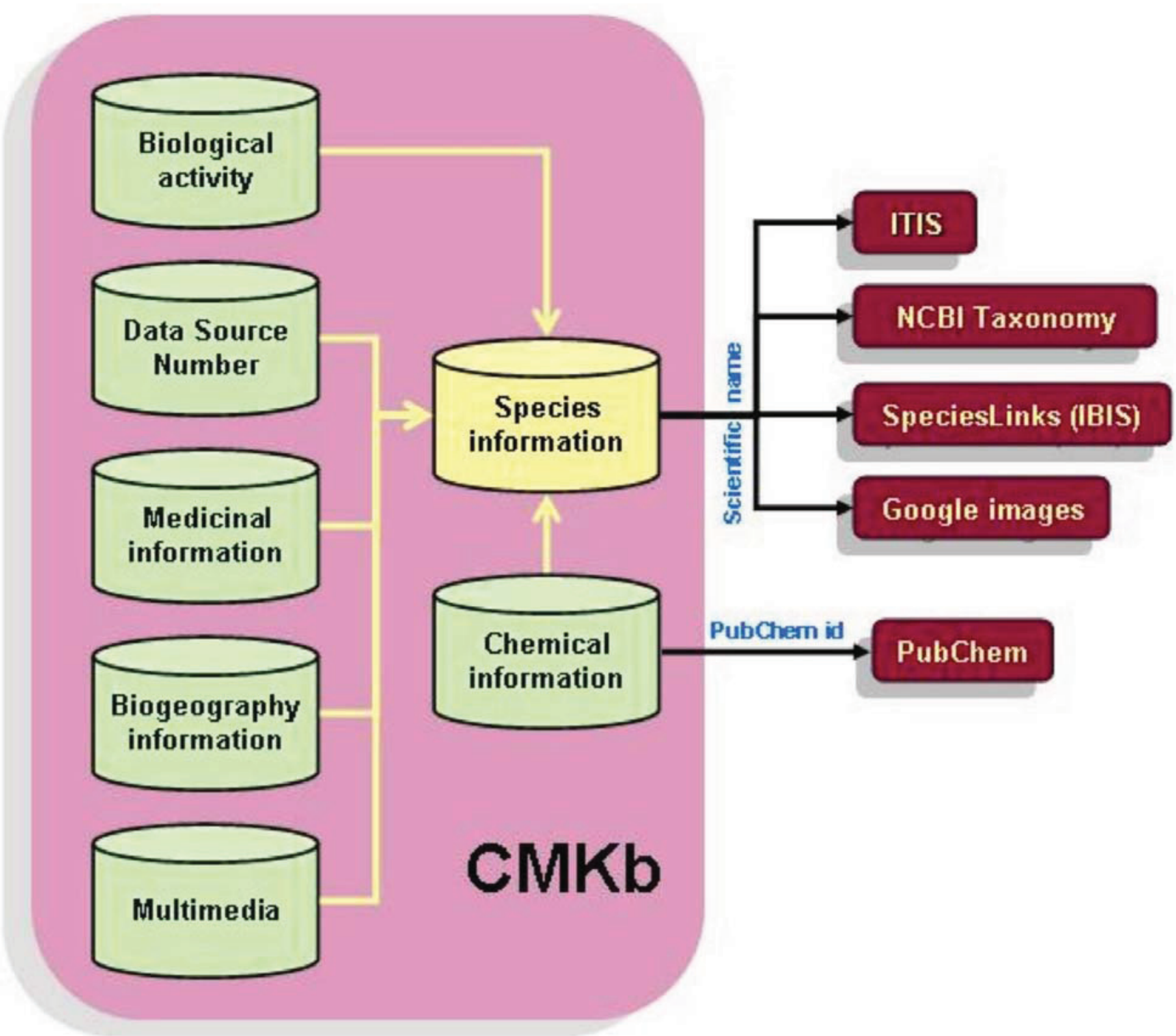


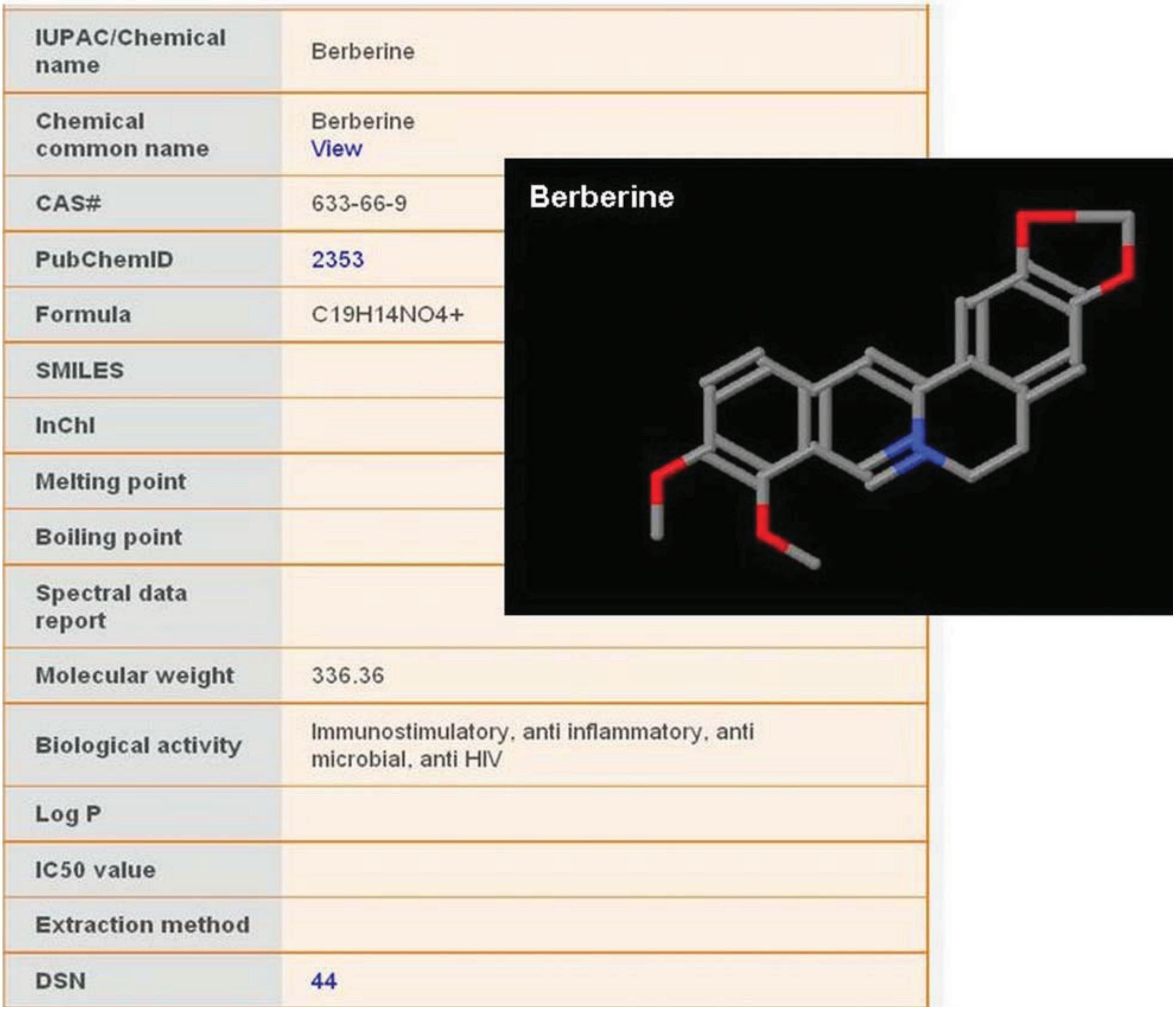
Figure 2
Dataflow in CMKb, showing external links.

database consists of three main modules: ***Browse, Search*** and ***Data Management***. Links to these modules are provided as a menu on the LHS of the CMKb website, as "Browse," "Search" and "Login," respectively. A brief description of each module is given below.

• Browse module

The database contents can be browsed (Figure 4a) using the alphabetical listing of scientific names and these are hyperlinked to a species list (Figure 4b), each of which is linked to a detailed information page.

Since CMKb is a web-based application, we have provided external links to other relevant global databases and data portals. Linking with other databases providing taxonomic, geospatial and molecular information, and search engines for images will help in data mining and facilitate the exploration of questions that, at present, cannot readily be answered [23] and would provide additional value to the information. Using the scientific name from CMKb we have provided external links to public domain data portals such as Integrated Botanical Information System (IBIS) [24] which provides links to a range of Australian data portals, Integrated Taxonomy Information System



IUPAC/Chemical name	Berberine
Chemical common name	Berberine View
CAS#	633-66-9
PubChemID	2353
Formula	C19H14NO4+
SMILES	
InChI	
Melting point	
Boiling point	
Spectral data report	
Molecular weight	336.36
Biological activity	Immunostimulatory, anti inflammatory, anti microbial, anti HIV
Log P	
IC50 value	
Extraction method	
DSN	44

Figure 3
Chemical information page with structure visualization.

(ITIS) [25], NCBI Taxonomy [26,27] and Google images [28] for species images.

• Search module

The database can be searched using its comprehensive search engine. The "Quick Search" option provides users with the facility to query the database by scientific name, species common name, native name, locality or chemical name using different logical parameters such as "contains", "begins with", "ends with" and "is" (Figure 5a).

For more complex queries, the "Advanced Search" option can be used, where the user can combine different search fields, using AND as the logical parameter (Figure 5b)

• Data management module

Efficient online content management is coordinated by CMKb's data management module, accessible to authorized users via the Login link. The data management module is provided with ADD, EDIT and DELETE functionality for managing data present in different tables.

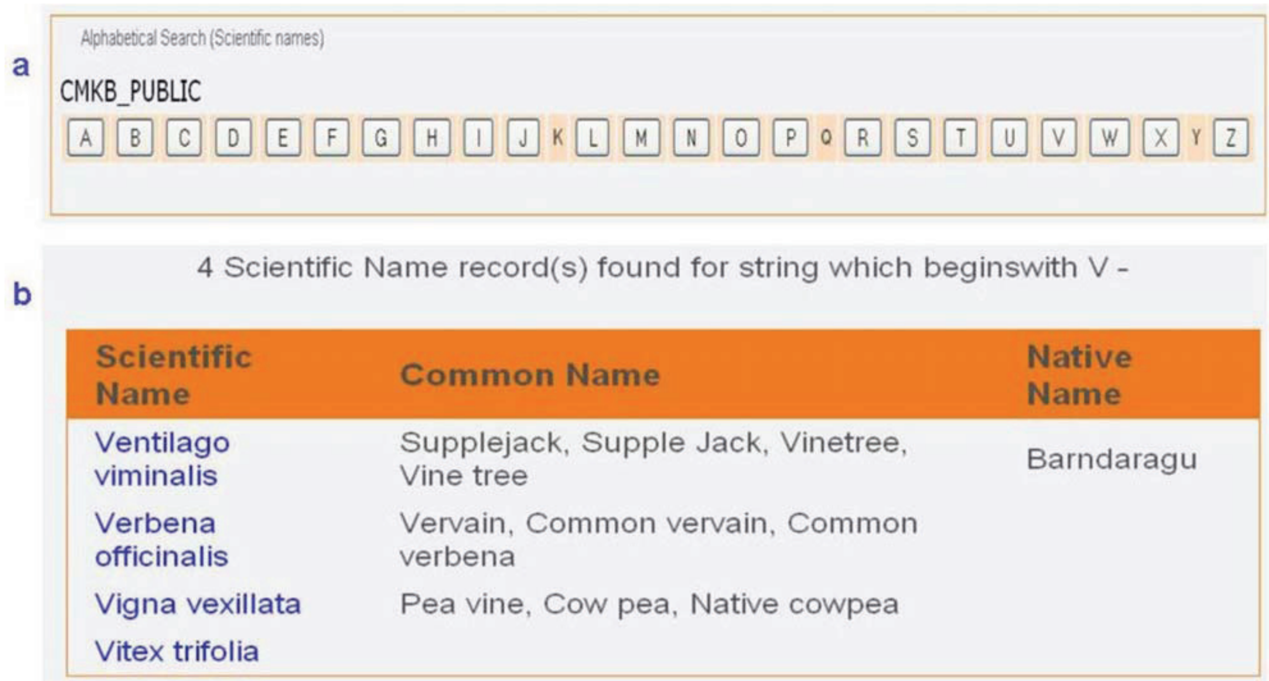


Figure 4
Browsing the CMKb database. a. Alphabetical listing of species in the Browse module, and b. a list of species starting with "V".

The overall contents of the database can be accessed from the "Content Summary" link.

Conclusion

Customary Medicinal Knowledgebase (CMKb) is a prototype for collating, integrating, visualising, disseminating and analysing multidisciplinary public domain data on customary medicinal plants. It is a holistic knowledgebase with data on taxonomy, biogeography, ethnobotany, phytochemistry, and bioactivity of the customary medicinal plants used by the Australian Aboriginals. The goal of CMKb is to collate information from scientific publications which are peer reviewed along with documenting and conserving the dwindling customary medicinal plant knowledge. The data will be constantly scrutinised by the experts and will be updated accordingly. Overall, CMKb is developed as a single knowledgebase for holistic plant-derived therapeutic substances and can be used as an integrated resource by researchers, policy makers, students and Aboriginal communities. As the database grows CMKb can be used for research in areas such as Geographical Information System (GIS) studies, chemoinformatics and biodiversity informatics. Further, the goal is to help address global and national priorities of biodiversity conservation, better human health, and smart use of information using information technology.

Availability and requirements

CMKb is freely available online at http://biolinfo.org/cmkb/

List of abbreviations used

CAS: Chemical Abstracts Service; **CMKb**: Customary Medicinal Knowledgebase; **CSIRO**: Commonwealth Scientific and Industrial Research Organisation; **DSN**: Data Source Number; **FDSN**: Field Data Source Number; **GIS**: Geographical Information System; **IBIS**: Integrated Botanical Information System; **ITIS**: Integrated Taxonomic Information System; **IUPAC**: International Union of Pure and Applied Chemistry; **JRE**: Java Runtime Environment; **LHS**: Left Hand Side; **NCBI**: National Center for Biotechnology Information; **SMILES**: Simplified Molecular Input Line Entry Specification

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

SR, JK, JJ and SV conceived the database concept. JG developed and constructed the database. VK contributed to the web interface and developed the Chemical information module. JG and SR wrote the paper. All authors approved the manuscript and declare that there is no conflict of interest.

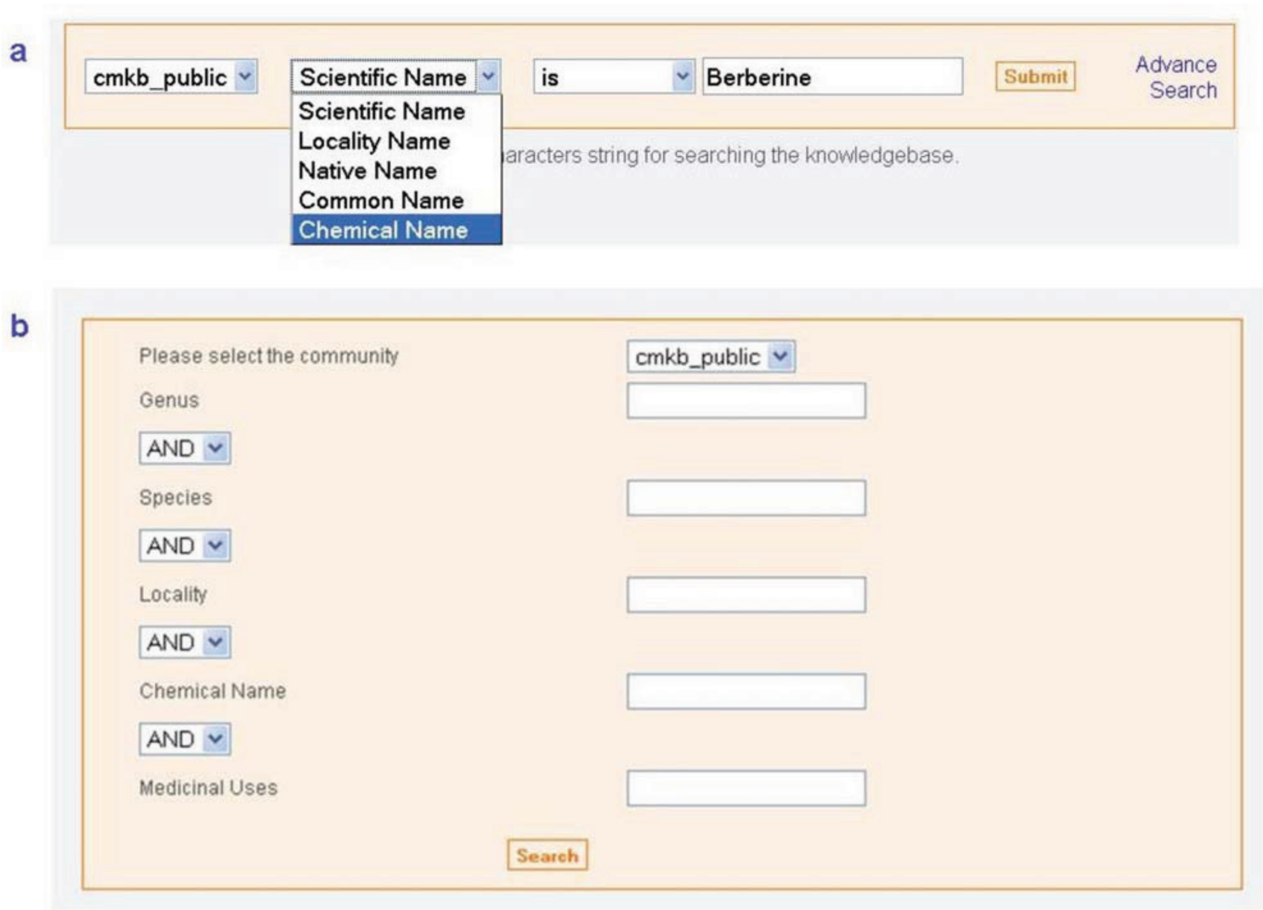


Figure 5
User-defined querying facilities. a. Quick search and b. Advanced searching for expert users.

Acknowledgements

JG and VK are grateful to Macquarie University for the award of MQRES PhD scholarships. We thank Doan Le, Moa Ek, David Harrington and Elsa Chacko (Macquarie University); Karen Wilson (Royal Botanic Gardens, Sydney, Australia); Vishwas Chavan (Global Biodiversity Information Facility, Denmark) and Greg Whitbread (Australian Centre for Plant Biodiversity Research) for their assistance and suggestions. This work was initially supported by a Macquarie University grant (MURDG A006661). Funding to pay the Open Access publication charges for this article was provided by Macquarie University.

This article has been published as part of *BMC Bioinformatics* Volume 9 Supplement 12, 2008: Asia Pacific Bioinformatics Network (APBioNet) Seventh International Conference on Bioinformatics (InCoB2008). The full contents of the supplement are available online at http://www.biomedcentral.com/1471-2105/9?issue=S12.

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4.2 Conclusions

As of November 2010, the knowledgebase has been accessed from more than 22 countries and the visitors are predominately from Australia, United States of America and India. It is also used as a good information resource by students, researchers and Aboriginal communities.

Statistical summary of the records, collated in CMKb from publicly available ethnobotanical resources, are shown in Figure 4.2. CMKb contains public domain information on 456 species belonging to 101 families (Table 4.1) collated from 45 heterogeneous data resources. Species belonging to families such as Scrophulariaceae (24), Myrtaceae (38), Fabaceae (46) and Euphorbiaceae (29) are well represented in the database. Scientific names in CMKb are checked for taxonomic discrepancies and are resolved using biodiversity informatics resources such as Australian Plant Name Index (APNI) and International Plant Name Index (IPNI).

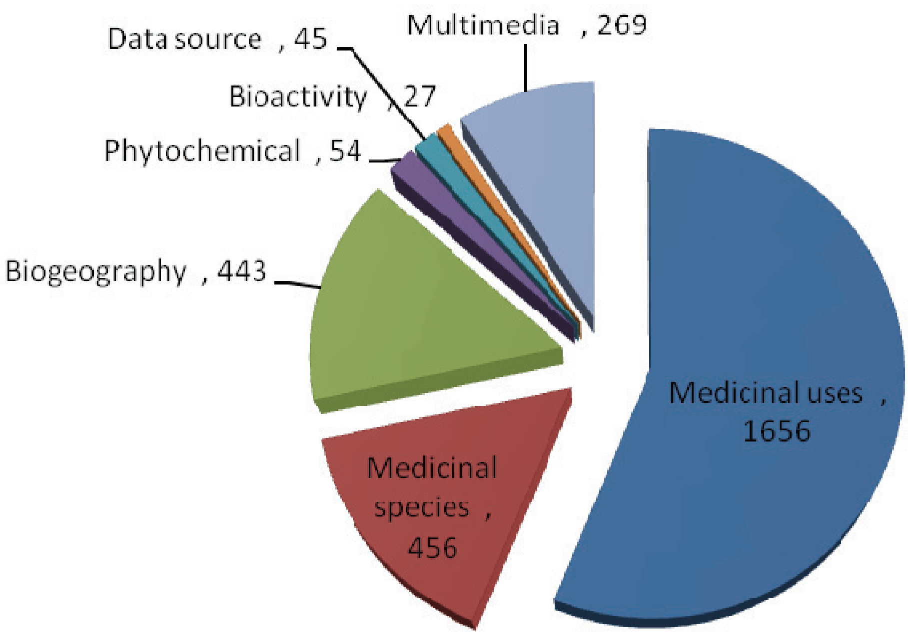

Figure 4.2: Summary of records related to Australian customary medicinal plants, collated from the publicly available ethnobotanical resources, in Customary Medicinal Knowledgebase

Currently, we are having collaborative partnerships with the Yaegl Aboriginal community from northern New South Wales, Australia and the Chungtia Indigenous community from Nagaland; north East state of India. Along with the public domain data on customary medicinal plants, CMKb also stores digitised first-hand information on medicinal plants, owned by the Yaegl and Chungtia communities. The archived information is password protected and accessibility is only to authorised users, to protect the sensitive information from misappropriation.

CMKb is a step towards institutionalising 'data disseminating framework' that facilitates documentation, conservation and dissemination of customary medicinal plant knowledge. Although developed in an Australian context, this model is applicable universally to global indigenous medicinal knowledge conservation.

Table 4.1: A list of unique families present in CMKb (public), along with the corresponding number of species.

Family	**No. of species**	**Family**	**No. of species**
Acanthaceae	1	Casuarinaceae	2
Aizoaceae	2	Celastraceae	2
Amaranthaceae	5	Cleomaceae	1
Amaryllidaceae	3	Clusiaceae	1
Anacardiaceae	2	Combretaceae	2
Apiaceae	2	Commelinaceae	1
Apocynaceae	19	Convolvulaceae	5
Araceae	3	Cucurbitaceae	3
Araucariaceae	1	Cunoniaceae	1
Arecaceae	9	Cupressaceae	2
Aristolochiaceae	1	Cyatheaceae	1
Asparagaceae	2	Cycadaceae	2
Asteraceae	17	Cyperaceae	4
Atherospermataceae	4	Dennstaedtiaceae	1
Bixaceae	1	Dilleniaceae	1
Boraginaceae	3	Dioscoreaceae	2
Brassicaceae	4	Euphorbiaceae	29
Burseraceae	2	Fabaceae	46
Cabombaceae	1	Flagellariaceae	1
Cactaceae	1	Gentianaceae	3
Campanulaceae	2	Goodeniaceae	5
Capparaceae	6	Gyrostemonaceae	1

Family	No. of species	Family	No. of species
Haemodoraceae	2	Portulacaceae	1
Hernandiaceae	2	Primulaceae	2
Lamiaceae	19	Proteaceae	11
Lauraceae	5	Psilotaceae	1
Lecythidaceae	4	Ranunculaceae	2
Loganiaceae	1	Rhamnaceae	3
Loranthaceae	4	Rhizophoraceae	2
Lycopodiaceae	1	Ripogonaceae	1
Lythraceae	2	Rosaceae	4
Malvaceae	11	Rubiaceae	9
Meliaceae	4	Rutaceae	6
Menispermaceae	2	Santalaceae	8
Moraceae	5	Sapindaceae	3
Musaceae	2	Sapotaceae	2
Myristicaceae	1	Scrophulariaceae	24
Myrtaceae	38	Simaroubaceae	2
Nelumbonaceae	1	Smilacaceae	2
Nyctaginaceae	1	Solanaceae	9
Nymphaeaceae	2	Thymelaeaceae	2
Orchidaceae	5	Typhaceae	2
Oxalidaceae	1	Unknown	2
Pandanaceae	2	Urticaceae	4
Passifloraceae	1	Verbenaceae	2
Phytolaccaceae	1	Violaceae	1
Piperaceae	1	Vitaceae	3
Pittosporaceae	2	Winteraceae	1
Plumbaginaceae	1	Xanthorrhoeaceae	2
Poaceae	12	Zingiberaceae	1
Polygonaceae	3	Zygophyllaceae	1

Chapter 5: Medicinal plants of New South Wales, Australia

5.1 Summary

In this paper, we reviewed the multi-disciplinary information available in the literature on customary medicinal plants from New South Wales (NSW), Australia. The review focused on different aspects of customary medicinal plants such as habitat distribution, phytochemistry and biological activities. For this review, baseline information such as species distribution and customary uses was obtained from CMKb. The baseline information was enhanced by using relevant additional information, available online, on customary uses, habitat distribution, phytochemistry and biological activities. Additionally, the review also emphasises the value of having a multi-disciplinary informatics infrastructure such as CMKb for knowledge conservation and the need to follow best ethical practices while working with Aboriginal communities.

Pages 52-95 of this thesis have been removed as they contain published material. Please refer to the following citation for details of the article contained in these pages.

J. Packer, J. Gaikwad, D. Harrington, S. Ranganathan, J. Jamie, S. Vemulpad (2012). Medicinal Plants of New South Wales, Australia. In R. J. Singh (Eds.), *Genetic Resources, Chromosome Engineering and Crop Improvement Series: Medicinal Crops* (pp. 259-296) CRC Press, Taylor & Francis Group, USA.

5.2 Results and Discussion

Information on 128 customary medicinal plants from NSW were collated and it was noted that for many of the plants, the biological activities and phytochemistry are aligned with their ethnomedicinal use; e.g. tea tree (*Melaleuca alternifolia)* oil used customarily for the treatment of minor cuts, abrasions and sores, has established antibacterial and anti-inflammatory properties, which are specially attributed to terpenes and terpenoids.

With the increase in the availability of multi-disciplinary information over the internet, scientists and researchers are now able to identify crucial information gaps. Through this review potential gaps and limitations in the available information have been identified.

5.3 Conclusions

Although there is an increase in the scientific publications related to medicinal plant studies, not all of the information is easily accessible or available in digital format. Thus, to close the knowledge gaps and to better understand human-plant interactions, access to more detailed information on distribution, customary uses, phytochemistry and biological activities is essential.

Chapter 6: Modeling potential distribution of customary medicinal plant species used by Australian Aborigines to identify species-rich areas and culturally valuable habitats for conservation

6.1 Summary

Predictive species distribution modelling is a valuable tool required for many aspects of biodiversity conservation. In this research article, predictive models of 414 customary medicinal plant species used by Australian Aborigines were developed using Maxent. The developed models were integrated within a GIS environment to identify and visualise potential species-rich areas. In this study, we have also estimated the cultural value of the predicted habitats by assigning the customary medicinal uses as weights. For this study, the list of species and customary uses as weights were obtained from CMKb, while its associated distribution data was acquired from the Australia's Virtual Herbarium (AVH) and the Global Biodiversity Information Facility (GBIF).

Modeling potential distribution of customary medicinal plant species used by Australian Aborigines to identify species-rich areas and culturally valuable habitats 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 limitation to the identification and conservation of species-rich areas and culturally valuable habitats.
In this study, the habitat suitability model, Maxent, was used to predict the potential current spatial distribution of 431 customary medicinal plant species, based on their climatic niche. Specimen locality records were obtained from the Global Biodiversity Information Facility (GBIF) data portal and from Australia's Virtual Herbarium (AVH).
414 predicted species models developed using occurrence points >30, were used to produce composite maps to indicate customary medicinal plant species rich areas and habitats having cultural values. For species richness, individual species presence/absence models were summed. To derive a map of culturally valuable habitats, unique customary medicinal uses were used to weigh the individual predicted species model, resulting in a value of a particular habitat, reflecting its cultural worth.

Even though the available information is scarce and fragmented, our approach provides an opportunity to infer optimal species-rich hotspots and to estimate the cultural value of a particular habitat. Our results also indicate that to conserve bio-cultural diversity, comprehensive information and active participation of Aboriginal communities is essential.

Keywords:
Maxent; Customary medicinal plants; Australian Aborigines; Spatial distribution; Species distribution modeling; Cultural value; Species-richness; Medicinal use

1. Introduction

Australia is one of the 17 megadiverse countries in the world with an estimated total of 290,000 floral (plant and fungal) species (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 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 that can use the available information 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 prioritizes (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) project the potential spatial distribution of a large number of bio-culturally significant, customary medicinal plant species used by Australian Aboriginal, using the habitat suitability model, Maxent (Phillips et al., 2006) and (2) map areas of high cultural value (hotspots), i.e. locations where the composition of medicinal plant species confers a broad variety of medicinal uses.

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 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 modeling potential species distribution. 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 for predicting potential species distribution areas. The WorldClim is a dataset of global scale climate grids at a spatial resolution of a square kilometer. From WorldClim, 19 bioclimatic variables are derived, of which seven uncorrelated variables with a spatial resolution of 2.5 arc-minutes were chosen for modeling (Table 1). The selected environmental variables reflect annual trends (e.g. annual precipitation), seasonality (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).

2.4 Species Distribution Modeling (SDM)

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). Several methods have been used to predict this fundamental ecological niche of species. We chose Maxent (Phillips et al., 2006) to model potential geographic distributions of Australian customary medicinal plants. Maxent, based on a statistical mechanics approach called maximum entropy, estimates the probability distribution when only presence data is available for analysis. 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 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 (Hernandez et al., 2006; Wisz et al., 2008). Distribution models were generated using Maxent v3.3.2, available online at http://www.cs.princeton.edu/~schapire/maxent/. Following Phillips and Dudík (Phillips and Dudík, 2008), default values were selected for the maximum number of iterations (500), the convergence threshold (0.00001), the replicated run type (crossvalidate), the selection of feature classes (autofeature), background points (10,000) and regularization values.

Maxent selects background points to which it can compare the characteristics of occurrence data. To reduce the potential for biases to occur due to the random selection of background points, we generated 10 replicate models for each species. Also, 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 on Australian geographic region. For projecting the trained models, environmental layers restricted to Australian geographic regions were used as projection layers.

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 species-richness map was derived by summing up the predicted species distribution models for individual species. The predicted species richness map show the probable suitable habitats for the species to occur based on occurrence data and environmental variables. But, it does not provide an estimate of the cultural worth of a predicted area. An approach was presented by Root et al., where the ecological value of a site was estimated by assigning species-specific extinction risks as weights to the predicted habitat suitability models (Root et al., 2003). Based on this approach, in the second phase, individual distribution models were scaled by the numbers of species-specific unique customary medicinal uses as weights, obtained from the CMKb database. The number of unique customary medicinal plant uses, 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 distribution models were overlaid to derive a composite map of habitats with cultural values.

3. Results

3.1 Species Distribution

Initially global scale species distribution models were projected for 431 species, based on a combined total of 254,812 occurrence points and 7 bioclimatic variables. On the whole, bioclimatic variables such as temperature seasonality contributed the most whereas annual precipitation contributed the lowest information to the overall predicted models (Table 1). 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 *Datura stramonium*, *Cleome viscose*, *Tamarindus indica, Ricinus communis,* and *Ipomoea pes-caprae*. Conversely, *Zieria smithi, Rorippa islandica, Corymbia terminalis, Syzygium suborbiculare,* and species of *Eremophila* and *Acacia* were projected to have potential distribution range restricted to Australia. Sample sizes used for projecting distribution models ranged from one (*Lepidium oleraceum*) to 12,567 occurrence points (*Lythrum salicaria*).

Table 1 here

We evaluated all models for their predictive ability, based on the average value 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 perform 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

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. The resulting map (Fig 1) identifies areas that potentially have the greatest species richness (i.e. contain suitable climate 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. 2).

Figures 1 and 2 here

The summed weighted map represented in Fig 3 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 values indicating highest cultural value (Fig. 4). Both composite maps shows nearly similar patterns in the distribution of customary medicinal plant species rich hotspots and culturally valuable sites around the northern parts of Western Australia, Northern Territory, Queensland and northern-east parts of Queensland and New South Wales in Australia. The visual and statistical evaluation between the composite weighted and non-weighted map shows very significant correlation (Pearson correlation coefficient, $r = 0.9893$).

Figure 3 and 4 here.

4. Discussion

The results of this study demonstrate the potential of combining ethnobotany with GIS and habitat suitability 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). Habitat suitability 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 habitat suitability models can be influenced by a range of issues including sampling bias, selection of environmental variables, accuracy of the occurrence data 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 projected species richness and culturally valuable habitat maps in the form of biased presentation. The highly correlated composite maps indicate that the customary medicinal uses as weights have not contributed significantly to the identification of areas having cultural worth.

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 indigenous customary knowledge, planning options and other species attributes for targeting 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. 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 relationship with the 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 future climate change scenarios on the distribution of the species and their customary uses.

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.

Acknowledgement

JG is grateful to Macquarie University for the award of MQRES PhD scholarships. We thank Mick Ashcroft and John Tann (Australian Museum, Sydney), Samy Gaiji, Vishwas Chavan (Global Biodiversity Information Facility, Denmark), and Lesley Hughes (Macquarie

University) for their assistance and suggestions. We also thank Linda Beaumont (Macquarie University) for discussions and useful comments regarding this manuscript.

Appendix

Appendix 1. List of species used for analysis and number of point occurrences used by Maxent for developing prediction models, with AUC, Standard deviation and uses count as weights

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Legends

Figures

Figure 1. Summed map showing customary medicinal plant species-rich hotspots.

Figure 2. Number of grid cells representing predicted species richness.

Figure 3. Weighted summed map using customary medicinal uses as cultural values shows areas with cultural worth.

Figure 4. Number of grid cells representing predicted areas having cultural values.

Tables

Table 1. List of global bioclimatic variables from WorldClim dataset used for predicting species distribution.

Appendix

Appendix 1. List of species used for analysis and number of point occurrences used by Maxent for developing prediction models, with AUC, Standard deviation and uses count as weights.

Tables

Table 1. List of global bioclimatic variables from WorldClim dataset used for predicting species distribution.

No	Bioclimatic variables (2.5 arc-minutes resolution)	Mean (range)
1	Annual precipitation (^{O}C)	10.221 (0.008-54.051)
2	Maximum temperature of warmest period (^{O}C)	12.951 (0.111-57.878)
3	Minimum temperature of coldest period (^{O}C)	19.070 (0.431-62.521)
4	Precipitation of driest period (mm)	11.582 (0.058-46.951)
5	Precipitation of wettest period (mm)	9.727 (0.004-88.127)
6	Precipitation seasonality (Coefficient of variation) (mm)	9.179 (0.140-43.828)
7	Temperature seasonality (Coefficient of variation) (^{O}C)	27.270 (0.903-60.790)

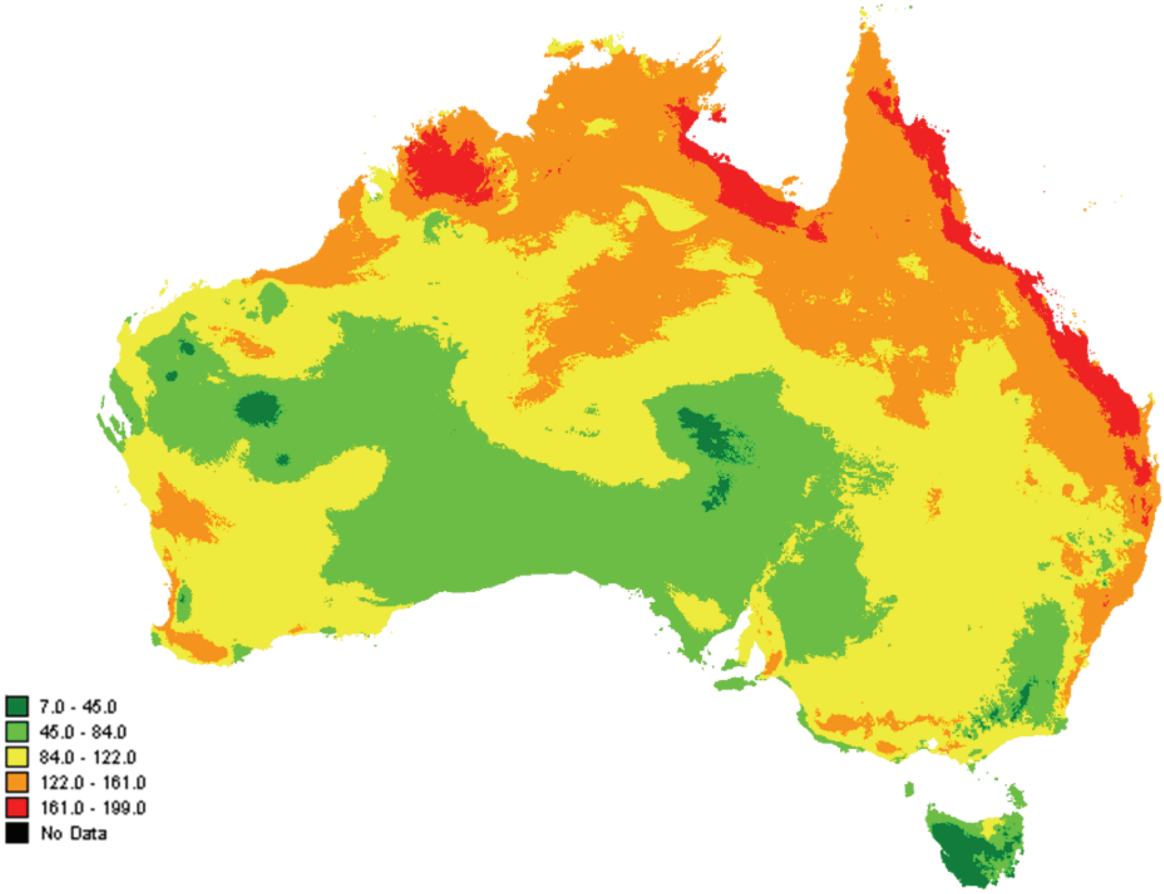

Figure 1. Summed map showing customary medicinal plant species-rich hotspots.

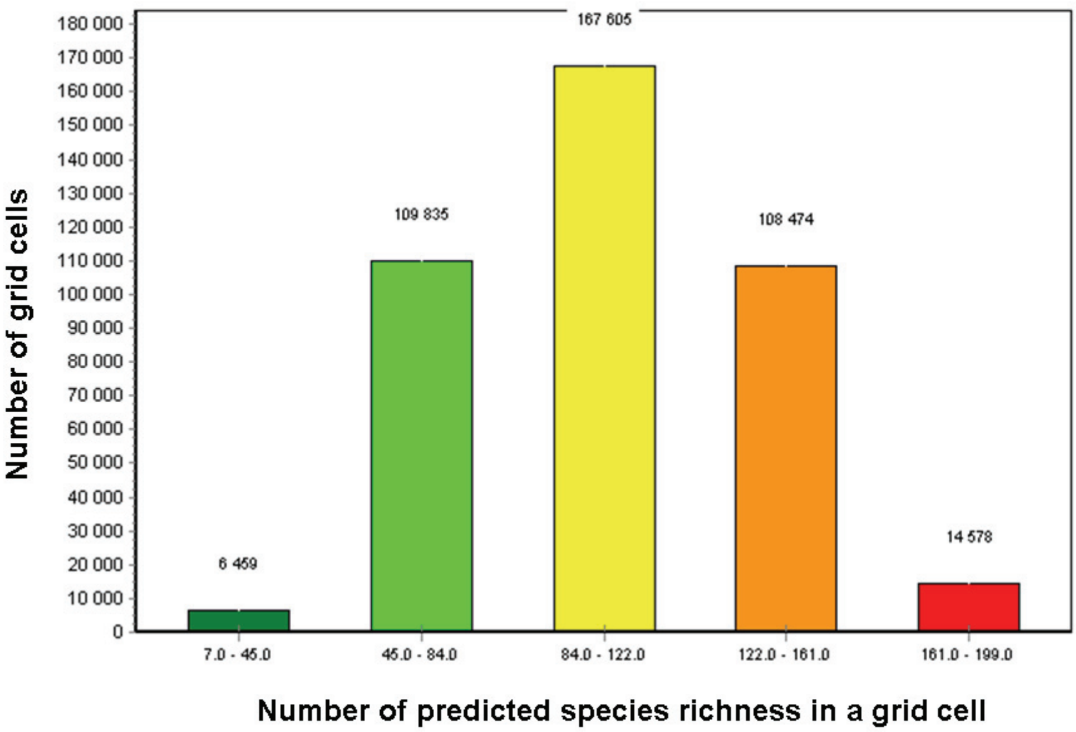

Figure 2. Number of grid cells representing predicted species richness

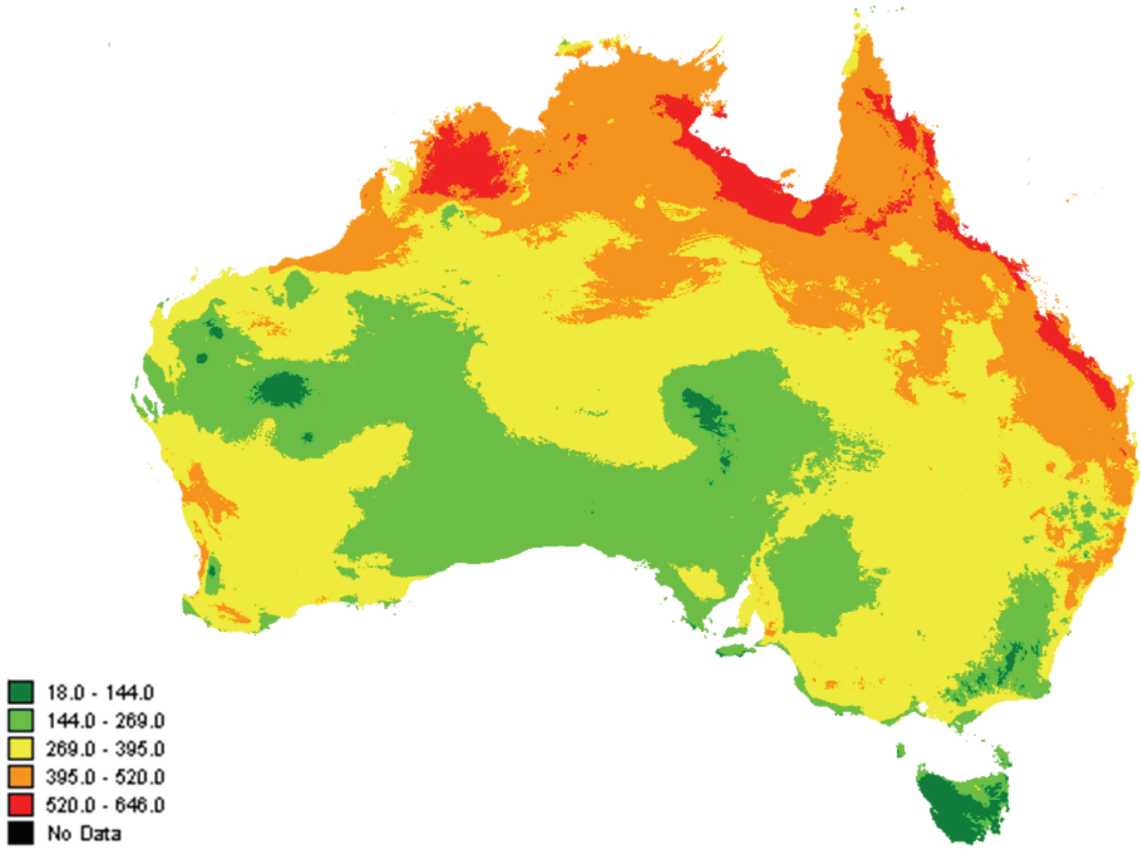

Figure 3. Weighted summed map using customary medicinal uses as cultural values shows areas with cultural worth.

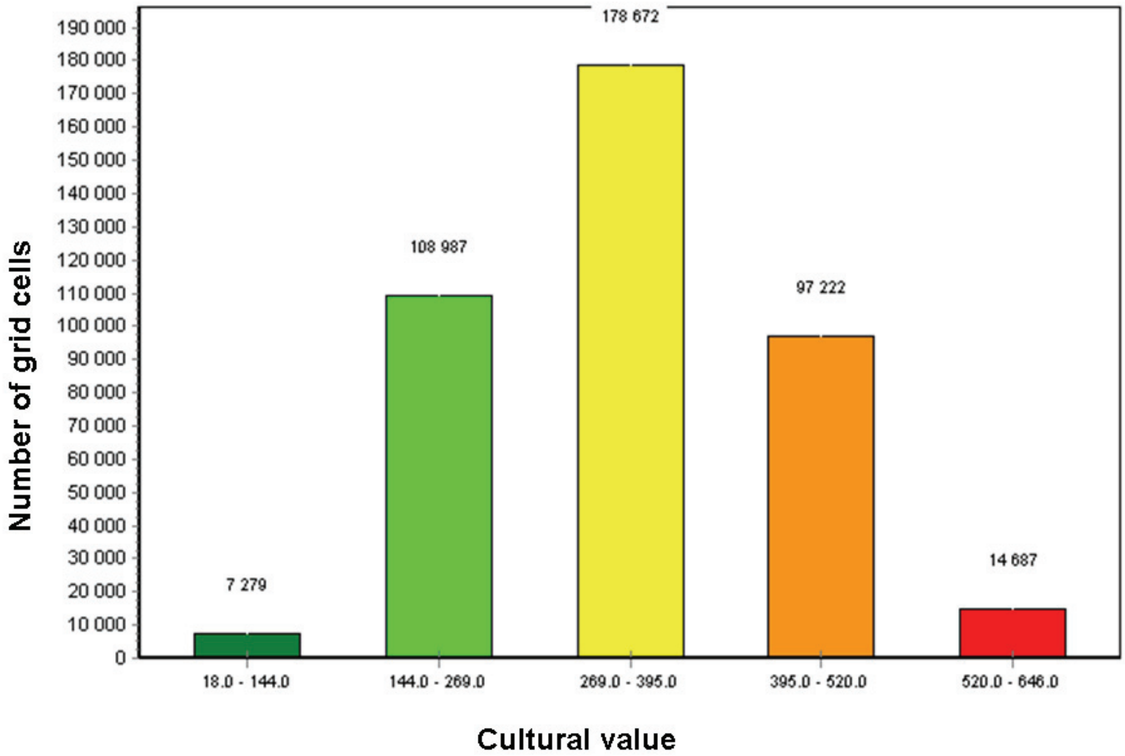

Figure 4. Number of grid cells representing predicted areas having cultural values

Modeling potential distribution of customary medicinal plant species used by Australian Aborigines to identify species-rich areas and culturally valuable habitats for conservation

Jitendra Gaikwad, Peter D. Wilson, Shoba Ranganathan

Appendix 1

Table S1. List of species used for analysis and number of point occurrences used by Maxent for developing prediction models, with AUC, Standard deviation and uses count as weights.

Scientific name	AUC	Standard Deviation	Points used	Uses count / Weights
Acacia adsurgens	0.9760	0.0020	390	1
Acacia ancistrocarpa	0.9640	0.0020	679	5
Acacia auriculiformis	0.9750	0.0050	431	1
Acacia beauverdiana	0.9910	0.0050	128	1
Acacia bivenosa	0.9700	0.0030	565	2
Acacia cuthbertsonii	0.9800	0.0020	330	2
Acacia decurrens	0.9750	0.0070	405	1
Acacia dictyophleba	0.9750	0.0020	393	1
Acacia estrophiolata	0.9890	0.0020	193	1
Acacia falcata	0.9790	0.0030	414	1
Acacia farnesiana	0.9000	0.0050	1055	1
Acacia holosericea	0.9510	0.0020	914	3
Acacia implexa	0.9640	0.0020	783	1
Acacia inaequilatera	0.9860	0.0020	218	1
Acacia kempeana	0.9600	0.0020	788	3
Acacia leptocarpa	0.9710	0.0040	476	1
Acacia lysiphloia	0.9660	0.0030	646	1
Acacia melanoxylon	0.9420	0.0040	1286	1
Acacia monticola	0.9640	0.0030	657	2
Acacia orthocarpa	0.9790	0.0030	341	1
Acacia pruinocarpa	0.9810	0.0040	307	1
Acacia pyrifolia	0.9820	0.0030	330	1
Acacia tetragonophylla	0.9490	0.0040	1012	5
Acacia trachycarpa	0.9890	0.0020	185	4
Acacia translucens	0.9830	0.0030	279	2
Acacia wickhamii	0.9800	0.0030	338	2
Acalypha wilkesiana	0.9460	0.0330	51	2
Acmella grandiflora	0.9745	0.0070	218	1
Aegiceras corniculatum	0.9690	0.0040	434	1
Ageratum conyzoides	0.9200	0.0100	884	1
Ageratum houstonianum	0.9470	0.0090	420	1
Ailanthus triphysa	0.9900	0.0040	82	1
Ajuga australis	0.9530	0.0030	951	5
Aleurites moluccana	0.9830	0.0100	75	4

Scientific name	AUC	Standard Deviation	Points used	Uses count / Weights
Allocasuarina decaisneana	0.9890	0.0010	203	2
Alocasia macrorrhizos	0.9330	0.0280	42	3
Alphitonia excelsa	0.9430	0.0030	1037	8
Alphitonia petriei	0.9920	0.0020	126	1
Alstonia actinophylla	0.9840	0.0090	145	2
Alstonia constricta	0.9750	0.0030	432	10
Alstonia scholaris	0.9750	0.0120	102	5
Alyxia buxifolia	0.9670	0.0030	688	1
Alyxia spicata	0.9790	0.0050	318	2
Ampelocissus acetosa	0.9860	0.0020	228	2
Amyema maidenii	0.9720	0.0040	419	1
Amyema quandang	0.9570	0.0030	733	1
Anagallis arvensis	0.8760	0.0020	11355	2
Angophora costata	0.9830	0.0030	328	1
Antidesma bunius	0.9382	0.0357	39	1
Apophyllum anomalum	0.9820	0.0040	281	1
Araucaria cunninghamii	0.9760	0.0090	222	2
Aristida contorta	0.9370	0.0020	1206	1
Asparagus racemosus	0.9750	0.0160	102	1
Atherosperma moschatum	0.9880	0.0020	219	9
Atriplex nummularia	0.9540	0.0020	900	3
Avicennia marina	0.9650	0.0070	484	4
Barringtonia asiatica	0.9870	0.0070	40	1
Barringtonia calyptrata	0.9900	0.0100	42	2
Barringtonia racemosa	0.9820	0.0160	81	4
Basilicum polystachyon	0.9600	0.0060	375	2
Bauhinia cunninghamii	0.9764	0.0070	362	1
Bauhinia hookeri	0.9940	0.0020	53	1
Beyeria leschenaultii	0.9920	0.0010	130	2
Boerhavia diffusa	0.9160	0.0250	230	1
Brasenia schreberi	0.9380	0.0050	849	2
Breynia cernua	0.9470	0.0050	650	1
Brucea javanica	0.9800	0.0050	153	1
Buchanania arborescens	0.9800	0.0040	297	3
Buchanania obovata	0.9820	0.0090	288	5
Calamus australis	0.9930	0.0030	45	2
Callicarpa longifolia	0.9770	0.0100	129	1
Callitris glaucophylla	0.9370	0.0030	1379	5
Callitris intratropica	0.9820	0.0020	314	6
Calophyllum inophyllum	0.9780	0.0070	132	2
Calostemma purpureum	0.9889	0.0020	153	2
Calytrix brownii	0.9760	0.0040	442	2
Calytrix exstipulata	0.9560	0.0050	930	2
Canarium australianum	0.9760	0.0030	410	2
Canavalia rosea	0.9475	0.0080	641	6
Capparis lanceolaris	0.9850	0.0050	40	2
Capparis lasiantha	0.9590	0.0020	607	6
Capparis mitchellii	0.9840	0.0090	129	2

Scientific name	**AUC**	**Standard Deviation**	**Points used**	**Uses count / Weights**
Capparis umbonata	0.9730	0.0030	338	1
Carallia brachiata	0.9650	0.0070	485	2
Carissa spinarum	0.9441	0.0060	759	4
Carpobrotus glaucescens	0.9945	0.0020	80	6
Cassytha filiformis	0.9210	0.0050	909	6
Cassytha glabella	0.9670	0.0030	624	2
Casuarina equisetifolia	0.9520	0.0090	327	4
Cayratia trifolia	0.9760	0.0060	307	1
Centaurium spicatum	0.9460	0.0060	760	9
Centella asiatica	0.9480	0.0050	479	12
Centipeda cunninghamii	0.9670	0.0030	525	7
Centipeda minima	0.9380	0.0070	743	4
Centipeda thespidioides	0.9760	0.0070	358	5
Cerbera manghas	0.9760	0.0080	201	2
Chamaesyce alsiniflora	0.9785	0.0080	150	2
Chamaesyce australis	0.9577	0.0040	649	4
Chamaesyce coghlanii	0.9703	0.0040	348	3
Chamaesyce drummondii	0.9450	0.0040	851	3
Chamaesyce hirta	0.8772	0.0030	1536	7
Chamaesyce mitchelliana	0.9735	0.0040	335	1
Chamaesyce wheeleri	0.9846	0.0110	133	1
Chenopodium cristatum	0.9790	0.0030	312	4
Chrysocephalum apiculatum	0.9050	0.0030	2145	1
Chrysopogon benthamianus	0.9470	0.0040	794	1
Cinnamomum oliveri	0.9940	0.0010	105	2
Cissampelos pareira	0.9310	0.0060	947	3
Cissus hypoglauca	0.9820	0.0100	313	1
Citrullus colocynthis	0.9460	0.0140	270	1
Citrus glauca	0.9849	0.0020	226	1
Clematis glycinoides	0.9750	0.0030	489	4
Clematis microphylla	0.9580	0.0020	925	1
Cleome viscosa	0.9210	0.0090	1098	13
Clerodendrum floribundum	0.9380	0.0050	947	3
Clerodendrum inerme	0.9770	0.0050	228	3
Cochlospermum fraseri	0.9850	0.0040	222	2
Codonocarpus cotinifolius	0.9660	0.0030	526	5
Commelina ensifolia	0.9630	0.0090	273	1
Convolvulus erubescens	0.9890	0.0040	101	3
Cordyline fruticosa	0.9596	0.0180	131	1
Corymbia dichromophloia	0.9773	0.0040	430	9
Corymbia gummifera	0.9892	0.0060	147	4
Corymbia maculata	0.9851	0.0020	301	7
Corymbia papuana	0.9791	0.0060	206	6
Corymbia polycarpa	0.9681	0.0060	551	2
Corymbia ptychocarpa	0.9838	0.0040	238	1
Corymbia terminalis	0.9449	0.0030	1057	12
Corymbia tessellaris	0.9850	0.0060	148	1
Crotalaria cunninghamii	0.9810	0.0100	129	5

Scientific name	AUC	Standard Deviation	Points used	Uses count / Weights
Crotalaria eremaea	0.9850	0.0040	203	1
Croton arnhemicus	0.9842	0.0040	146	5
Croton insularis	0.9860	0.0030	213	4
Croton tomentellus	0.9940	0.0030	58	1
Curcuma australasica	0.9800	0.0210	55	1
Cyathea australis	0.9850	0.0040	244	1
Cycas armstrongii	0.9920	0.0090	100	1
Cycas media	0.9870	0.0040	199	2
Cymbidium canaliculatum	0.9744	0.0040	351	4
Cymbidium madidum	0.9924	0.0040	100	2
Cymbonotus lawsonianus	0.9859	0.0070	203	1
Cymbopogon ambiguus	0.9415	0.0040	953	7
Cymbopogon bombycinus	0.9621	0.0050	591	3
Cymbopogon obtectus	0.9575	0.0030	647	3
Cymbopogon procerus	0.9743	0.0060	353	5
Cymbopogon refractus	0.9621	0.0060	562	1
Cynanchum floribundum	0.9723	0.0100	280	1
Cyperus bifax	0.9573	0.0050	475	1
Daphnandra micrantha	0.9930	0.0090	57	2
Datura stramonium	0.9010	0.0070	3018	1
Daviesia latifolia	0.9670	0.0040	721	3
Decaisnina brittenii	0.9850	0.0180	104	2
Dendrobium affine	0.9960	0.0010	66	2
Dendrobium canaliculatum	0.9860	0.0140	91	2
Dendrobium teretifolium	0.9860	0.0090	157	2
Dendrocnide excelsa	0.9930	0.0040	98	4
Denhamia obscura	0.9830	0.0060	239	1
Dianella ensifolia	0.9720	0.0160	113	1
Dillenia alata	0.9910	0.0050	115	1
Dioscorea bulbifera	0.9430	0.0120	326	2
Dioscorea transversa	0.9740	0.0040	429	1
Diplatia grandibractea	0.9767	0.0060	177	2
Dodonaea lanceolata	0.9640	0.0050	471	2
Dodonaea triquetra	0.978	0.003	382	3
Dodonaea viscosa	0.8920	0.0040	3646	8
Doryphora aromatica	0.9950	0.0030	91	1
Doryphora sassafras	0.9870	0.0020	268	1
Duboisia hopwoodii	0.9870	0.0030	154	1
Duboisia myoporoides	0.9770	0.0070	429	1
Dysphania kalpari	0.9790	0.0030	281	1
Dysphania rhadinostachya	0.9700	0.0030	462	2
Ehretia saligna	0.9800	0.0040	214	2
Eleocharis dulcis	0.9700	0.0070	256	2
Emilia sonchifolia	0.9520	0.0090	339	3
Enchylaena tomentosa	0.9280	0.0030	1427	1
Enneapogon purpurascens	0.9770	0.0040	352	2
Entada phaseoloides	0.9770	0.0160	70	1
Epipremnum pinnatum	0.9630	0.0150	138	2

Scientific name	AUC	Standard Deviation	Points used	Uses count / Weights
Eragrostis eriopoda	0.9450	0.0020	1068	1
Eremophila alternifolia	0.9760	0.0020	444	1
Eremophila bignoniiflora	0.9720	0.0050	345	2
Eremophila cuneifolia	0.9910	0.0020	151	1
Eremophila debilis	0.9812	0.0040	300	1
Eremophila duttonii	0.9640	0.0020	716	1
Eremophila fraseri	0.9910	0.0010	151	3
Eremophila freelingii	0.9780	0.0030	401	11
Eremophila gilesii	0.9700	0.0020	548	2
Eremophila latrobei	0.9340	0.0040	1410	2
Eremophila longifolia	0.9100	0.0020	2003	8
Eremophila maculata	0.9500	0.0030	833	1
Eremophila mitchellii	0.9710	0.0020	542	1
Eremophila sturtii	0.9740	0.0030	508	6
Erythrophleum chlorostachys	0.9800	0.0020	315	9
Eucalyptus brevifolia	0.9810	0.0040	332	4
Eucalyptus camaldulensis	0.8900	0.0050	2295	9
Eucalyptus crebra	0.9258	0.0050	1777	1
Eucalyptus haemastoma	0.9940	0.0010	143	4
Eucalyptus mannifera	0.9700	0.0020	678	1
Eucalyptus microtheca	0.9730	0.0030	431	7
Eucalyptus miniata	0.9740	0.0030	509	2
Eucalyptus pilularis	0.9830	0.0020	338	1
Eucalyptus piperita	0.9830	0.0010	371	2
Eucalyptus pruinosa	0.9680	0.0030	623	2
Eucalyptus racemosa	0.9860	0.0030	310	1
Eucalyptus resinifera	0.9830	0.0020	322	2
Eucalyptus tetrodonta	0.9720	0.0020	551	9
Eucalyptus viminalis	0.934	0.002	1605	3
Eucryphia lucida	0.9900	0.0020	207	1
Euphorbia atoto	0.9770	0.0200	57	1
Euphorbia peplus	0.8690	0.0030	6399	1
Euphorbia tannensis	0.9264	0.0040	1344	1
Evolvulus alsinoides	0.8807	0.0050	1858	2
Excoecaria agallocha	0.9726	0.0120	197	5
Excoecaria dallachyana	0.9925	0.0020	120	2
Excoecaria parvifolia	0.9924	0.0030	67	2
Exocarpos aphyllus	0.9569	0.0030	879	4
Exocarpos cupressiformis	0.9649	0.0020	692	2
Exocarpos latifolius	0.9636	0.0040	511	2
Ficus coronata	0.9890	0.0060	142	2
Ficus opposita	0.9570	0.0070	573	6
Ficus racemosa	0.9710	0.0050	317	6
Ficus watkinsiana	0.9930	0.0040	77	2
Flagellaria indica	0.9640	0.0040	468	7
Flindersia maculosa	0.9850	0.0020	263	3
Flueggea virosa	0.9540	0.0080	586	13
Gardenia megasperma	0.9890	0.0020	187	1

Scientific name	AUC	Standard Deviation	Points used	Uses count / Weights
Gardenia vilhelmii	0.9960	0.0020	69	1
Geijera parviflora	0.9670	0.0020	688	3
Gmelina fasciculiflora	0.9980	0.0020	34	2
Goodenia ovata	0.9710	0.0030	607	2
Goodenia scaevolina	0.9870	0.0030	160	1
Goodenia varia	0.9900	0.0020	165	1
Gratiola pedunculata	0.9860	0.0040	201	3
Gratiola peruviana	0.9780	0.0030	391	2
Grevillea pyramidalis	0.9740	0.0090	374	3
Grevillea striata	0.9660	0.0030	450	1
Grewia latifolia	0.9860	0.0100	143	1
Grewia retusifolia	0.9630	0.0050	624	7
Gymnanthera oblonga	0.9738	0.0060	148	1
Gyrocarpus americanus	0.9610	0.0050	476	4
Haemodorum corymbosum	0.9880	0.0100	64	1
Haemodorum spicatum	0.9920	0.0020	148	1
Hakea divaricata	0.9900	0.0040	162	1
Hakea eyreana	0.9900	0.0030	90	1
Hakea lorea	0.9480	0.0030	878	2
Hakea macrocarpa	0.9820	0.0030	268	2
Helichrysum luteoalbum	0.9480	0.0050	915	1
Heliotropium ovalifolium	0.9620	0.0060	341	1
Hernandia nymphaeifolia	0.9929	0.0040	69	2
Heteropogon contortus	0.8960	0.0060	1318	2
Hibiscus diversifolius	0.9690	0.0180	170	1
Hibiscus heterophyllus	0.9810	0.0040	366	1
Hibiscus splendens	0.9900	0.0050	129	1
Hibiscus tiliaceus	0.9580	0.0090	423	2
Hibiscus vitifolius	0.9650	0.0190	95	1
Hybanthus enneaspermus	0.9460	0.0070	625	4
Ipomoea mauritiana	0.9650	0.0060	104	1
Ipomoea pes-caprae	0.9460	0.0120	390	15
Isopogon ceratophyllus	0.9910	0.0020	151	1
Isotoma petraea	0.9660	0.0040	626	3
Jacksonia dilatata	0.9810	0.0060	316	1
Lawrencia spicata	0.9900	0.0050	95	1
Leptomeria acida	0.9870	0.0010	255	1
Litsea glutinosa	0.9790	0.0080	223	8
Livistona australis	0.9820	0.0410	32	1
Livistona decora	0.9944	0.0090	31	1
Livistona humilis	0.9927	0.0020	107	2
Livistona muelleri	0.9862	0.0230	36	1
Lycopodium phlegmaria	0.9810	0.0180	34	1
Lysiphyllum carronii	0.9910	0.0040	76	1
Lythrum salicaria	0.8700	0.0020	12567	5
Macaranga tanarius	0.9730	0.0070	279	1
Mallotus mollissimus	0.9810	0.0070	133	1
Malva preissiana	0.9658	0.0040	610	4

Scientific name	AUC	Standard Deviation	Points used	Uses count / Weights
Marrubium vulgare	0.9010	0.0060	2799	5
Marsdenia australis	0.9693	0.0040	346	1
Melaleuca alternifolia	0.9930	0.0010	150	7
Melaleuca cajuputi	0.9770	0.0050	304	13
Melaleuca hypericifolia	0.9920	0.0020	139	1
Melaleuca leucadendra	0.9595	0.0040	665	4
Melaleuca nervosa	0.9500	0.0040	922	1
Melaleuca quinquenervia	0.9690	0.0070	517	8
Melaleuca uncinata	0.9600	0.0030	803	2
Melicope vitiflora	0.9925	0.0050	50	2
Mentha australis	0.9770	0.0030	241	8
Mentha diemenica	0.9720	0.0040	534	6
Mentha satureioides	0.9850	0.0030	270	14
Mimulus gracilis	0.9720	0.0070	286	1
Morinda citrifolia	0.9610	0.0090	265	8
Morinda reticulata	0.9960	0.0010	73	1
Mukia maderaspatana	0.9310	0.0100	502	2
Musa banksii	0.9840	0.0370	35	1
Myoporum acuminatum	0.9640	0.0060	438	1
Myoporum platycarpum	0.9560	0.0020	973	1
Myristica insipida	0.9830	0.0050	210	1
Nauclea orientalis	0.9700	0.0050	282	8
Nelumbo nucifera	0.9440	0.0160	169	1
Nicotiana benthamiana	0.9820	0.0030	187	1
Nicotiana cavicola	0.9920	0.0080	72	1
Nicotiana excelsior	0.9970	0.0020	47	1
Nicotiana gossei	0.9920	0.0040	105	1
Nymphaea gigantea	0.9800	0.0090	117	1
Ochrosia elliptica	0.9910	0.0080	36	1
Ocimum tenuiflorum	0.9700	0.0110	152	4
Oldenlandia auricularia	0.9708	0.0050	330	1
Oldenlandia galioides	0.9670	0.0080	395	1
Omalanthus populifolius	0.9920	0.0080	46	1
Opuntia stricta	0.9750	0.0110	143	1
Owenia acidula	0.9740	0.0060	313	2
Owenia reticulata	0.9870	0.0040	112	5
Owenia vernicosa	0.9847	0.0050	215	5
Oxalis corniculata	0.9670	0.0090	278	1
Pandanus spiralis	0.9890	0.0020	151	9
Passiflora foetida	0.8700	0.0080	1702	1
Pemphis acidula	0.9837	0.0090	141	1
Persicaria barbata	0.9619	0.0170	125	3
Persoonia falcata	0.9690	0.0040	484	3
Petalostigma pubescens	0.9490	0.0050	910	9
Petalostigma quadriloculare	0.9790	0.0040	363	8
Philotheca brucei	0.9904	0.0030	121	1
Phytolacca octandra	0.9690	0.0060	395	1
Pimelea microcephala	0.9600	0.0030	724	5

Scientific name	AUC	Standard Deviation	Points used	Uses count / Weights
Piper hederaceum	0.9892	0.0030	181	3
Pittosporum angustifolium	0.9315	0.0050	1494	9
Pittosporum venulosum	0.9970	0.0010	51	1
Pityrodia jamesii	0.9970	0.0010	50	4
Planchonia careya	0.9770	0.0040	313	12
Plectranthus congestus	0.9800	0.0180	70	1
Plectranthus parviflorus	0.9720	0.0020	494	1
Plumbago zeylanica	0.9340	0.0080	519	1
Polygonum hydropiper	0.8720	0.0040	6117	4
Portulaca oleracea	0.8540	0.0060	5132	3
Pouteria pohlmaniana	0.9863	0.0020	153	2
Pouteria richardii	0.9800	0.0230	41	1
Pratia purpurascens	0.9900	0.0030	178	1
Prostanthera rotundifolia	0.9860	0.0030	252	1
Prostanthera striatiflora	0.9740	0.0030	493	3
Prunella vulgaris	0.8710	0.0030	8550	6
Psilotum nudum	0.9333	0.0110	655	1
Pteridium esculentum	0.9526	0.0020	920	5
Pterocaulon serrulatum	0.9656	0.0050	410	7
Pterocaulon sphacelatum	0.9402	0.0020	981	3
Rhaphidophora australasica	0.9960	0.0030	48	2
Rhizophora mucronata	0.9810	0.0170	60	1
Rhyncharrhena linearis	0.9780	0.0040	228	1
Ricinus communis	0.8850	0.0090	939	3
Ripogonum album	0.990	0.002	139	1
Rorippa islandica	0.9320	0.0030	2806	1
Rorippa palustris	0.8690	0.0030	8397	1
Rubus fruticosus	0.8820	0.0030	6066	2
Rubus moluccanus	0.9729	0.0050	305	1
Rubus parvifolius	0.9798	0.0030	344	1
Rubus rosifolius	0.9909	0.0020	142	5
Santalum acuminatum	0.9400	0.0040	1283	6
Santalum lanceolatum	0.9310	0.0050	1109	12
Santalum obtusifolium	0.9900	0.0020	160	3
Santalum spicatum	0.9790	0.0020	322	4
Sarcostemma australe	0.9640	0.0250	37	11
Sarcostemma viminale	0.9480	0.0050	517	1
Scaevola spinescens	0.9510	0.0010	891	8
Scaevola taccada	0.9728	0.0070	266	4
Scleria polycarpa	0.9770	0.0120	131	1
Scoparia dulcis	0.9140	0.0080	1003	4
Sebaea ovata	0.9810	0.0020	325	2
Secamone elliptica	0.9720	0.0040	271	2
Senna barronfieldii	0.990	0.004	119	1
Senna pleurocarpa	0.9653	0.0030	585	1
Sida rhombifolia	0.8900	0.0050	1510	2
Silybum marianum	0.9080	0.0050	2014	2
Siphonodon pendulus	0.9950	0.0020	44	3

Scientific name	AUC	Standard Deviation	Points used	Uses count / Weights
Smilax australis	0.9690	0.0040	573	2
Smilax glyciphylla	0.9860	0.0020	242	5
Solanum lasiophyllum	0.9660	0.0030	606	1
Sophora tomentosa	0.9680	0.0210	162	1
Spartothamnella juncea	0.9870	0.0030	208	3
Spinifex longifolius	0.9850	0.0150	114	3
Stemodia grossa	0.9890	0.0040	88	3
Stemodia lythrifolia	0.9870	0.0030	155	1
Stemodia viscosa	0.9780	0.0060	220	7
Sterculia quadrifida	0.9820	0.0120	184	4
Streptoglossa bubakii	0.9850	0.0040	140	4
Streptoglossa odora	0.9770	0.0030	239	4
Striga curviflora	0.9790	0.0070	184	2
Strychnos lucida	0.9830	0.0060	251	1
Swainsona galegifolia	0.9690	0.0030	626	2
Swainsona pterostylis	0.9910	0.0030	141	2
Syzygium suborbiculare	0.9890	0.0060	129	5
Tabernaemontana orientalis	0.9799	0.0110	170	2
Tabernaemontana pandacaqui	0.9796	0.0110	170	3
Tamarindus indica	0.9470	0.0110	280	1
Taraxacum officinale	0.8730	0.0030	3811	1
Tasmannia lanceolata	0.9830	0.0020	345	2
Tephrosia varians	0.9780	0.0150	64	1
Terminalia catappa	0.9550	0.0090	205	2
Terminalia ferdinandiana	0.9934	0.0020	90	3
Tetragonia implexicoma	0.9900	0.0020	190	1
Timonius timon	0.9630	0.0070	414	4
Tinospora smilacina	0.9730	0.0070	302	9
Toona ciliata	0.9772	0.0110	190	2
Trachymene didiscoides	0.9880	0.0070	112	3
Tribulus cistoides	0.9510	0.0090	262	1
Trichodesma zeylanicum	0.9360	0.0040	966	1
Trigonella suavissima	0.9750	0.0030	433	1
Tylophora erecta	0.9840	0.0100	76	1
Typha domingensis	0.8630	0.0120	1281	2
Typha orientalis	0.9650	0.0060	426	2
Urtica incisa	0.9560	0.0030	953	4
Urtica urens	0.9010	0.0030	4144	1
Ventilago viminalis	0.9660	0.0040	457	6
Verbena officinalis	0.8780	0.0030	6002	8
Vigna vexillata	0.9250	0.0080	556	2
Xenostegia tridentata	0.9619	0.0050	464	1
Xylomelum scottianum	0.9940	0.0010	52	1
Zieria smithii	0.9660	0.0030	745	1

6.2 Conclusions

Through this study, we derived composite species-richness and weighted habitat suitability maps. The species richness map reflects the probable suitable habitats for the species to occur, while the weighted habitat suitability map shows the estimated cultural value of the predicted habitats. Although, we have used customary uses as weights in this analysis, the method is flexible to include a diverse range of species attributes for estimating the cultural worth of the habitat.

This study illustrates the potential of combining customary medicinal plant knowledge with spatial and environmental information using predictive modelling to explore complex human-plants interactions. Further, the results form the basis for understanding the impact of future climate changes induced due to unsustainable human activities.

Chapter 7: Climate change: another impending threat to customary medicinal plant species used by Australian Aborigines

7.1 Summary

Currently available evidence suggests that anthropogenic climate change in Australia has already triggered major changes to the natural environment, consequently impacting habitats and associated biodiversity. It is projected that if this trend continues, more profound impacts of climate change are likely to be experienced in future, resulting in substantial loss of habitats [53-57].

Apart from habitat loss, these projected environmental changes can have detrimental direct and indirect impacts on Australian Aboriginal communities, due to their close connection with the natural environment [58]. Probable shifts in the spatial distributions of habitats, as a result of climate change, will affect cultural activities including the use of customary medicinal plant species and the associated medicinal knowledge. However, due to the lack of long-term surveillance data on species and their biotic responses to changing climate, it will be difficult to predict and mitigate the adverse impacts on biodiversity and Aboriginal cultural practises.

In our previous study (Chapter 6), we presented a multi-species approach, integrating GIS and habitat suitability modelling, to identify species-rich areas and culturally valuable habitats, using current bioclimatic factors. In this chapter, we seek to identify the impacts on the spatial distributions of suitable bioclimatic conditions using GIS and habitat suitability modelling, under future climate change scenarios. For this study, we have chosen twelve culturally important customary medicinal plant species, having high multi-therapeutic values. Potential shifts in the spatial distributions of suitable bioclimatic conditions of these species were projected, centred on 2020, 2050 and 2080, across BCCR, CSIRO, INMCM and MIROC general circulation models (GCMs) [59, 60]. The habitat suitability modelling tool, Maxent [61] and point occurrence data from GBIF and AVH were used to project the shifts in spatial distributions.

Climate change: another impending threat to customary medicinal plant species used by Australian Aborigines

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Keywords:

Customary medicinal plants; Australian Aborigines; Species distribution modeling; Conservation areas; Species richness; Climate change; Maxent

Abstract

In Australia, substantial loss of culturally valuable habitats and associated biodiversity is projected, due to shifts in the spatial distribution of suitable climatic conditions, as a result of climate change. Consequently, these probable shifts will have a negative impact on the cultural practises of Australian Aboriginal communities including the use of customary medicinal plants. However, efforts to adapt and device conservation strategies to mitigate impacts on biodiversity and Aboriginal cultural practises are hampered due to the lack of long-term surveillance data on customary medicinal plant species distribution and its responses to changing climate.

In this study, the bioclimatic modeling tool, Maxent, was used to predict the probable shifts in the spatial distributions of suitable climatic conditions. Using a consensus approach, models were developed for twelve culturally important customary medicinal plant species having multi-therapeutic values across the four general circulation models, CSIRO, BCCR, INMCM and MIROC, centred at 2020, 2050 and 2080.

Models projected under current climate scenario identified potential spatial distributions of suitable climatic conditions across Australia. The projected consensus maps for Australia, based on the four general circulation models, clearly shows variable effect of climate change on twelve customary medicinal plant species across different time scenarios.

The predicted summed maps indicate shifts in the geographical distribution range of suitable climatic conditions over time, towards the North and East directions across Australia. Tropical regions in the northern parts of Queensland and Northern Territory, containing likely suitable climatic conditions for the maximum number of customary medicinal plant species, are predicted to experience further fragmentation by 2080. These shifts in the distributions of species range due to the climate change will adversely affect the sustenance of customary medicinal plant knowledge. In Australia, climate change will most likely cause multi-dimensional, as well as drastical and irrevocable impact, altering biocultural diversity.

Introduction

Human activities, such as the burning of fossil fuels and unsustainable land use, over the past century, appear to have influenced global climate. Since mid-1800s, the Earth's mean temperature has risen by approximately 0.74˚C along with changes in rainfall patterns. The latest Intergovernmental Panel on Climate Change (IPCC) projections predict that the global average temperature is likely to increase between 0.6 to 4.0˚C by 2099 (IPCC, 2007). Long-term data generated by several studies have indicated the possible effects of rapid global climate change on species spatial distributions, shifting climatic zones, abundance and phenology (Beaumont & Hughes 2002, Parmesan & Yohe 2003, Root *et al.* 2003). Further, if this current trend persists, approximately 30% of the assessed flora and fauna is likely to become extinct by the end of the century (Hassan *et al.* 2005). This projected future climate change thus poses a significant threat to currently deteriorating habitats and would affect ecosystem services crucial for human wellbeing (Hassan *et al.* 2005). Consequently, these dire predictions, relating to the loss of biological diversity due to climate change, have raised serious concerns.

From ancient times, humans have relied on the services provided by ecosystems including the use of medicinal plants for healthcare and wellbeing. Medicinal plants comprise a principal component of biodiversity and their co-evolution with humans has resulted in the development of local traditional medicinal plant knowledge and practices. Historically, indigenous knowledge systems, particularly those related to the medicinal plants have formed an inextricable link between biological and cultural diversity, while existing as a key contributor to biodiversity conservation and sustainable use (Hamilton 2004, Loh & Harmon, 2005). There are around 300,000 higher plants in the world (Govaerts 2001), of which 75,000 are used as medicinal plants by indigenous people (Farnsworth 1984).

According to the World Health Organization, approximately 80% of the developing world depends on traditionally used medicinal plants as a primary source of healthcare (Fabricant & Farnsworth, 2001, WHO, 2008). The anticipated impact of the global climate change on the ecosystem services inclusive of food, medicine, shelter and mental well-being will have a profound impact on indigenous culture and its associated traditional knowledge, including loss. Preliminary studies suggest that the Aboriginal communities in the northern hemisphere are already experiencing negative impacts, due to significant change in global climate (Cavaliere 2009, Ford & Pearce 2010, Furgal & Seguin 2006, Weinhold 2010).

Australian Aborigines have inhabited the continent for over 40,000 years (Roberts-Thomson *et al.* 1996) and have used locally available plants for their primary healthcare to treat ailments and diseases including coughs, stings, wounds, diarrhoea, fever, headaches and rheumatism (Hiddins 1999, Lassak & McCarthy 2008, Low 1990). The Aborigines relied on many commonly available species, such as *Corymbia terminalis* and *Eremophila freelingii,* having multiple therapeutic uses. The holistic medicinal plant knowledge related to the desirable season, time and place of collection, medicinal preparation and uses is passed from generation to generation orally in the form of dances, songs and stories (Barr *et al.* 1988).

In the late eighteenth century, when European settlers brought many exotic medicinal plant species such as *Sonchus oleraceus* and *Cinnamomum camphora* with them, native Aborigines assimilated the knowledge related to these species and started using them in their daily lives (Clarke 2003, Lassak & McCarthy 2008). At present, contemporary Aboriginal pharmacopoeia comprises native and exotic introduced medicinal plant species

(Gaikwad *et al.* 2008, Lassak & McCarthy 2008, Low 1990), dispersed across varied ecosystems and constitutes a potential source of novel bioactive compounds (Barlow *et al.* 2005, Harvey 2000, Newman & Cragg 2007, Wickens & Pennacchio 2002). Thus customary medicinal plant knowledge, comprising traditional and contemporary uses can form the basis for many potential novel drug discoveries and indigenous communities can, derive tangible benefits to improve their socioeconomic status.

Currently, Australian customary medicinal plant knowledge is declining due to the irreversible loss of habitats and acculturation. Diverse habitats supporting customary medicinal plant species are lost due to degradation, urbanization and the unsustainable use of natural resources (Barlow *et al.* 2005, Williams *et al.* 2001). Additionally, culturally valuable medicinal plant knowledge associated with these habitats is also lost at an alarming rate. Further, similar to events occurring in northern hemisphere, it is implied that future climate change will have a profound impact on the cultural and biological diversity of Australia, thus accelerating this loss (Green *et al.* 2009, Green & CSIRO 2006).

Akin to current global trends, profound changes in climate have been observed in Australia, such as a significant rise in air temperature and changes in precipitation patterns (Alexander *et al.* 2007, Collins & Della-Marta 1999, CSIRO & BOM 2007, CSIRO & BOM 2010, Hennessy *et al.* 1999, Nicholls & Lavery 1992, Timbal & Jones 2008). It is predicted that over the next 50 years, the annual mean temperature in Australia will rise between 0.8 to 3.9˚C, with overall decrease in precipitation (CSIRO 2001, Hulme & Sheard 1999). Some consequences already observed are a significant decline in snow cover, rise in sea temperature, shifts in the spatial distributions of species and an increase in El Niño events. The most likely future impact due to the change in temperature and precipitation include a substantial loss of habitats and biodiversity (Hughes 2003). Hence, the survival and sustenance of customary medicinal knowledge will highly depend on the condition and the nature of habitats in which customary medicinal plants are found. The impact due to the loss of bio-cultural diversity on the resilience of the ecosystems will be immense (Green *et al.* 2009).

During the ~40,000 years of habitation, Australian Aborigines have experienced major changes in climate, impacting on their knowledge, practices and associated species. However, records documenting adaptive responses to these changes over the years are unavailable, which may be comparable and help to understand the future projections. Currently, given the paucity of detailed information, efficient methods are required to evaluate the likely effects of projected future climate change on the spatial distributions of customary medicinal plant species, to devise appropriate strategies for species and knowledge conservation.

In this study, the statistical bioclimatic modeling technique was used for assessing the impact of climate change on the spatial distributions of customary medicinal plant species. Statistical modeling methods, correlating the bioclimatic envelope with current species distributions, are commonly used for predicting potential impacts of future climate change on the spatial distributions of the species (Beaumont & Hughes 2002, Erasmus *et al.* 2002, Hu *et al.* 2010, Levinsky *et al.* 2007, Papes 2007, Peterson *et al.* 2002, Skov & Svenning 2004, Thuiller 2003, Thuiller *et al.* 2005). However, the validity of this method has been questioned due to the exclusion of various factors such as physiological interactions and dispersal ability, which determines the geographical distribution of the species, apart from the bioclimatic envelope (Davis *et al.* 1998). Despite of these limitations, there are certain advantages of using bioclimatic factors for understanding the impact of future climate change, especially in situations where the available information is limited and the models are developed at the continental scale. Nonetheless, this technique helps to undertake a rapid analysis and such models should only be viewed as first approximations of the potential effects of climate change and need to be interpreted with caution (Heikkinen *et al.* 2006, Levinsky *et al.* 2007, Pearson & Dawson 2003, Thuiller 2004).

In our earlier work, we identified potential spatial distributions of customary medicinal plant species habitats and its associated cultural value using habitat suitability models (Gaikwad, Wilson & Ranganathan, unpublished results). For determining the cultural worth of the predicted habitats, medicinal uses from the customary medicinal knowledgebase (Gaikwad *et al.* 2008) were enumerated and multi-therapeutic Australian customary medicinal plant species were noted and identified as significant. The purpose of this study is to project the potential shifts in the distributions of favourable environmental conditions of these twelve multi-therapeutic and culturally important species, under different climate change scenarios (2020, 2050, and 2080), using general circulation models (CSIRO, BCCR, INMCM and MIROC) (Suppiah *et al.* 2007). For this purpose, habitat suitability models were developed using the current climatic conditions, and the future impacts on the suitable habitats projected, using Maxent (Phillips *et al.* 2006).

Data and methodology

Species for modeling

For developing the models, the most relevant medicinal plant species were selected from the 456 species listed in the Customary Medicinal Knowledgebase (CMKb) database

(Gaikwad *et al.* 2008) available at http://www.biolinfo.org/cmkb. The number of unique customary medicinal uses for the CMKb species range from one to fifteen. For this study, we selected the top customary medicinal plant species from CMKb (Table 1) based on their therapeutic value, ranging from nine to fifteen. These twelve species are known to occur in different habitats with wide as well as restricted distributions.

Species distribution data

The distribution data for the twelve selected species was downloaded from Australia's Virtual Herbarium (AVH; http://www.ersa.edu.au/avh/). AVH is a web-based portal providing access to plant specimen records and its associated occurrence data held by the participating herbaria across Australia. Further, to ensure full representation of the environmental conditions associated with the species (Beaumont *et al.* 2009, Broennimann & Guisan 2008, Pearson & Dawson 2003) and to offset any sampling bias, global scale distribution data was downloaded from the Global Biodiversity Information Facility (GBIF) data portal (http://data.gbif.org). The distribution data from AVH and GBIF was compiled and records with geocoding errors such as zero coordinates, textual localities and points outside land boundaries were discarded using the ArcGIS 9 software.

Bioclimatic datasets

For predicting the current potential distribution of the species, global scale bioclimatic variables with a spatial resolution of 2.5 arc-minutes were obtained from the WorldClim (Hijmans *et al.* 2005). WorldClim is a dataset of global scale climate grids, available at a spatial resolution of a square kilometre. From this dataset, 19 bioclimatic variables defined by Nix (Nix 1986) and Busby (Busby 1991) were extracted, out of which seven uncorrelated variables were selected for our assessment (Beaumont *et al.* 2009).

Annual precipitation, maximum temperature of warmest period, minimum temperature of coldest period, precipitation of driest period, precipitation of wettest period, precipitation seasonality and temperature seasonality, representing annual trends, seasonality and limiting climatic factors (Table 2), were selected. Despite errors and uncertainties in values *(Hijmans et al.* 2005), these bioclimatic variables were preferred as they are the best descriptors available for large geographical areas such as Australia.

Climate change scenarios

To model the potential shifts in the distribution of customary medicinal plant species-favourable climatic envelopes, we extracted decade averages for the seven bioclimatic variables (Table 2) centred on 2020, 2050 and 2080 across BCCR, CSIRO, INMCM and MIROC general circulation models (GCMs) (Solomon *et al.* 2007). The GCMs were downscaled to 2.5 arc-minutes spatial resolution and future projections were estimated from the current selected WorldClim bioclimatic variables, using bicubic spline interpolation method (Press *et al.* 2001). This approach was used to maintain the consistency of the climate layers for all the epochs. The selected GCMs for this study have been shown to model aspects of the current climate (1960-2000) in the Australian region quite well (Suppiah *et al.* 2007). However, recent analysis has shown strong uncertainties in GCMs, due to different simulation approaches. Nevertheless, they are the best available tool for simulating future climate change scenarios (Suppiah *et al.* 2007, Thuiller 2004).

Model building

Current and future potential geographic distributions were modelled using Maxent (Phillips *et al.* 2006, Phillips & Dudík 2008), which is based on a statistical mechanics approach, evaluating maximum entropy. Maxent uses presence-only data for calculating the target probability distribution of the species by finding the distribution of probabilities closest to uniform, provided the expected value of the features matches its empirical average. Recent studies have shown that Maxent outperforms other methods such as Domain and Bioclim and has better predictive ability across varied sample sizes (Elith *et al.* 2006, Hernandez *et al.* 2006, Wisz *et al.* 2008).

Following the evaluative study by Phillips and Dudik (Phillips & Dudík, 2008), default settings (maximum number of iterations = 500, convergence threshold = 0.00001, replicated run type = crossvalidate, feature classes = autofeature, background points = 10,000, regularization multiplier = 1) were selected for each model scenario (current and future). Along with these parameters, the logistic output format was selected for the presentation of the probabilities and easy interpretation. Also, the importance of each environmental variable during model development was measured using the in-built jackknife functionality. The distribution models were trained on the global scale current climate layers and then projected onto future climates in the Australian geographic region.

A consensus approach was used to select the commonality among the projections for each species across the ensemble of GCMs for the given climate scenarios (Araújo & New 2007, Thuiller *et al.* 2005). The results of this approach were converted to presence-absence maps, using the averaged maximum test sensitivity plus specificity logistic threshold values, generated by Maxent (Liu *et al.* 2005). Thus, the projected areas with values above the threshold were considered as ‘presence’ and below the threshold as ‘absence’.

Further, the thresholded presence-absence maps were summed to identify hotspots of potentially suitable bioclimatic conditions across Australia, under current and future climate scenarios.

Results

We projected twelve current and 144 future (=12 species x 3 epoch x 4 GCMs) habitat suitability models, using seven bioclimatic variables and 6387 occurrence points. On average, temperature seasonality (27.44) contributed the most, whereas precipitation seasonality (6.22) contributed the least information to the overall projected models (Table 2). For evaluating the predictive ability of the models, we used the average value of the area under the receiver operating characteristic curve (AUC). This is a threshold independent measure of relative model performance with values typically ranging from 0.5 for random to 1.0 for models with precise discrimination (Fielding & Bell 1997). Overall, the average AUC scores for the generated models were above 0.9, indicating robust performance of the predicted models (Table 3).

Current climate scenario

The models projected under the current climate scenario identified potential areas ranging from broad to narrow spatial distributions across Australia. Models for species such as *Cleome viscosa, Corymbia terminalis, Santalum lanceolatum* and *Sarcostemma australe* showed broad potential distribution range across Australia having suitable climatic conditions (Figure 1a), with regions in red indicating presence and green indicating absence. Relatively narrow range potentially suitable areas were identified for the remaining species confined to northern (Figure 1b), eastern and southern (Figure 1c), and central parts of Australia (Figure 1d). The summed map revealed overlapping areas having potentially suitable climatic conditions for the twelve customary medicinal plant species. Depending upon the number of overlapping species in a grid cell the hotspot values for the projected areas across Australia ranged from zero to nine.

The graphical representation of the summary map (Figure 2) shows 4774 grid cells representing suitable climatic conditions for the maximum number of customary medicinal plant species and 54,647 grid cells for having potentially suitable climatic conditions for less than two species. Further, 165,980 projected grid cells represented the largest geographical area across Australia, having suitable climate for four to five customary medicinal plant species. The locations of highly suitable areas for the maximum number of species are scattered from north-west to north-east tropical parts of Australia, while the areas in the southern part were identified suitable for lesser number of species.

Future climate scenarios

The projected consensus maps for Australia, based on the four general circulation models, clearly shows variable effect of climate change across different time scenarios. The narrow-ranged species such as *Melaleuca cajuputi* (Figure 1d), *Mentha satureioides* (Figure 1c) and *Planchonia careya* (Figure 1b) were predicted to suffer maximum geographic area loss with potential shifts in the suitable climate envelope by 2080, whereas species such as *Cleome viscosa* (Figure 1a) and *Ipomoea pes-caprae* (Figure 1b) were projected to have minor loss of suitable climatic conditions. For *Ipomoea pes-caprae* and *Mentha satureioides* minor shifts in the projected geographical distributions of suitable climatic conditions towards the south were identified (Figures 1b and 1c, respectively).

The graphical presentation of projected summary map (Figure 2) for the decade 2020 showed a declining trend in the areas with highly suitable climatic conditions (2472 grid cells). However, for the decade 2050, there is an increase in the predicted suitable areas (4102 grid cells). Further, in the decade 2080, loss of areas with suitable climatic conditions is seen (2888 grid cells) indicating a receding trend due to the change in climate.

The predicted summed maps indicate shifts in the geographical distribution range of the suitable climatic conditions towards the north and east directions over the time across Australia. Tropical regions in the northern parts of Queensland and Northern Territory, containing likely suitable climatic conditions for maximum number of customary medicinal plant species, are predicted to experience further fragmentation by 2080 (Figure 3).

Discussion

Despite the significant impacts observed on biocultural diversity, initiatives to systematically study the effects of climate change are fragmented and limited in scope across Australia (Green *et al.* 2009, Hughes 2003). Through this study, we aim to set the scene for understanding the likely effects of future climate change on the geographical distributions of suitable environmental conditions associated with customary medicinal plant species and consequently its impact on Aboriginal medicinal plant knowledge.

Australian biodiversity and Aboriginal communities have experienced changing climate over the generations and have evolved accordingly. But, due to the lack of relatively detailed documentation on the interactions between customary medicinal plants and

Aborigines, our ability to develop adaptive responses to the predicted future climate change has been hampered. Habitat suitability models developed by correlating species distribution with climate variables across various GCMs, provides a useful medium for predicting likely future spatial distributions of potentially suitable climatic conditions for customary medicinal plant species to facilitate conservation. Although, our results indicate further fragmentation of the suitable bioclimatic conditions, the derived results should be interpreted with caution, since the predictions are based on limited available information on species distribution, coarse spatial resolution and the uncertainties in the GCMs due to different modeling techniques.

The projected summary maps shown in Figure 3, indicating a receding range of suitable bioclimatic envelope over time for customary medicinal plant species, may be overestimated, because dynamics such as the biotic interactions between the species, plasticity, dispersal range, migration rate and suitable microhabitats are not considered. But, despite the uncertainties, we believe that the results from this study will provide valuable insights to explore the complex relationship between customary medicinal plant knowledge and spatial distributions of the species.

As a result of a close connection with nature, climate change will likely have a profound impact on Aboriginal communities due to their dependency on natural resources and sensitivity towards the changing environment. The shifts in the distributions of species range, due to climate change, will adversely affect the sustenance of the customary medicinal plant knowledge. The loss of customary medicinal plant species or inaccessibility will constrain the Aboriginal community's ability to maintain customary practices and as a consequence, will threaten their culture, health and lifestyle.

Aboriginal pharmacopeia has evolved over time, but drastic changes were experienced during the colonisation period. Today, the pharmacopeia of contemporary Australian Aborigines consists of endemic (e.g. *Eremophila freelingii*) and many exotic medicinal plant species, which have become invasive weeds (e.g. *Cleome viscosa*) and are considered culturally valuable. Several studies have indicated the ability of invasive species to accelerate and spread into native habitats due to the potential impact of climate change (Beaumont *et al.* 2009, Low 2008). However, Aboriginal Australians may have a different perspective on this aspect compared to the assessment made by non-indigenous ecologists. Thus, it will be a major challenge for policy makers and rangers to manage these culturally significant species under current accelerated rate of cultural erosion and future climate change scenarios.

In Australia, the likely impact of climate change can drastically and irrevocably alter biocultural diversity and can be multi-dimensional. Customary medicinal plants are of cultural importance and a vital source of novel bioactive compounds and drugs. Understanding the impacts of climate change on the geographical distribution of the species in a cultural context can help to devise holistic and adaptive management strategies for conservation. We believe that more active participation of Aboriginal communities and accelerated documentation of customary medicinal plant knowledge is required to further explore, understand and improve climate change adaptation planning.

Acknowledgements

JG is grateful to Macquarie University for the award of an MQRES PhD scholarship. We thank Dr Linda Beaumont (Macquarie University) for discussions and useful comments regarding this manuscript.

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Table 1. List of species with multiple customary uses from CMKb, selected for analysis, with details of habitats and the number of localities of occurrence.

Species	Unique Customary uses	Habitat (ANHSIR, 2009)	Localities
Alstonia constricta	Antiperiodic, Diabetes, Diarrhea, Dysentery, Fever, Malaria, Infectious sores, Influenza, Stomach complaints, Tonic, Typhoid	Red sandy soils, open forests, gully banks	432
Centella asiatica	Blood disease, Leprosy, Narcotic, Nervous system disease, Ozaena, Prickly heat, Skin disease, Sores, Syphilitic skin lesions, Tonic, Ulcerations, Wounds	Moist places, sandy loam, edge of marshy depression, grassy woodland surrounding swamp, rainforest, boggy grassland	463
Cleome viscosa	Boils, Sores, Cold, Diarrhea, Earache, Fever, Headache, Intestinal worms, Rheumatism, Swelling, Ulcers, Wounds	Sandy soil such as coral beaches, tropical, hummock grasslands, adjacent to permanent creeks, along rocky creek banks[3]	1077
Corymbia terminalis	Antiseptic, Burns, Chest and heart pain, Constipation, Diarrhea, Sickness, Sore eyes, Sore lips, Sore throat, Sores, Toothache	Pale sandy clay, open savannah woodlands with scattered *Eucalyptus* spp. and low shrubs, open woodlands, red sandy soil	1057
Eremophila freelingii	Body pain, Chest pain, Cold, Cough, Diarrhea, Headache, Sickness, Sores, Wounds	Mostly in Mulga communities, in rocky areas in hilly and ridge country	401
Flueggea virosa	Catfish stings, Chicken pox, Cuts, Heat rash, Internal pains, Itches, Leprosy, Open sores, Rashes, Rheumatism, Sickness, Stings	Found in open and close tropical savannah areas, river bank, rainforest edge, growing in sandy soil, usually in shade of larger trees, closed areas behind dunes	581

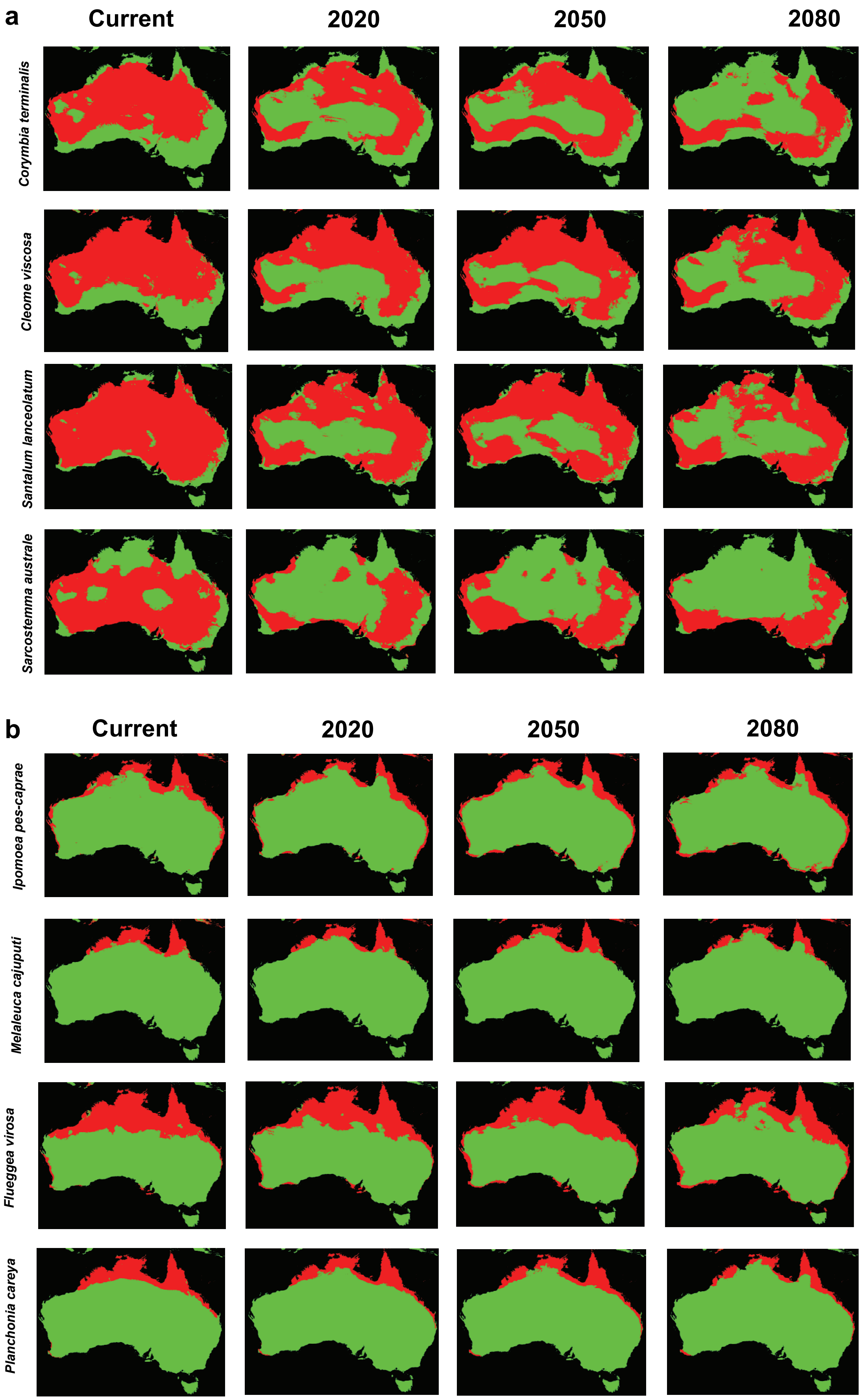
Ipomoea pes-caprae	Boils, Diuretic, Dropsy, Haemorrhoids, Inflammations, Insect stings, Laxative, Ringworm, Skin infections, Skin irritations, Snake bite, Sores, Stingray stings, Venereal disease, Whitlow	Coastal sand dunes, sand above high tide mark, mangrove swamp	353
Melaleuca cajuputi	Pain, Aches, Antispasmodic, Asthma, Colic, Cough, Cold, Earache, Headache, Neuralgia, Rheumatism, Stomach cramps, Toothache	Along edge of creek, in wet grassland, behind coastal dunes, salty swamps and mudflats, at back of mangroves	300
Mentha satureioides	Abortion, Aches, Alterative, Blood purifier, Catarrh, Cold, Cough, Dysmenorrhoea, Intestinal cramps, Irregular menstruation, Pain, Stomach cramps, Tonic	Black clays, clay loam on basalt, in damp ground, in grassy areas and in open woodland communities, widespread	269
Planchonia careya	Burns, Chicken pox, Infections, Itchy bites, Prickly heat, Rheumatism, Sickness, Skin irritation, Sores, Ulcers, Wounds	Swampy area, lateritic soil, dark brown loam, margin of gallery rainforest, grassland with scattered trees, at edge of monsoon forest on truncated lateritic podsol	311
Santalum lanceolatum	Boils, Chest complaints, Gonorrhoea, Itching, Purgative, Rheumatism, Skin sores, Strength, Tiredness	Sandy clay soil, Shrubland, Gentle slope of foothills, southern aspect, stony red clay loam, Rocky escarpment, Coastal headland, Mulga scrub	1106
Sarcostemma australe	Corns, Eye complaints, Increase lactation, Scurvy, Skin rashes, Smallpox, Sores, Sprains, Ulcers, Warts, Wounds	Stony hillside, Semi-evergreen vine thicket, Red loam, Mulga woodland	37

Table 2. List of bioclimatic variables used for modeling from the WorldClim dataset with its mean contribution to the overall predicted models. Values are the percentage contribution of each variable to the model as reported by Maxent.

Bioclimatic variables (2.5 arc-minutes resolution)	**Mean (range)**
Annual precipitation (mm)	9.39 (0.57-18.76)
Maximum temperature of warmest period (°C)	13.90 (2.21-50.11)
Minimum temperature of coldest period (°C)	27.25 (3.94-47.68)
Precipitation of driest period (mm)	8.06 (0.45-22.35)
Precipitation of wettest period (mm)	7.75 (0.40-33.0)
Precipitation seasonality (Coefficient of variation) (mm)	6.22 (0.32-19.81)
Temperature seasonality (Coefficient of variation) (°C)	27.44 (9.72-45.52)

Table 3. List of species with number of localities used by Maxent to develop models and AUC scores of the models.

Species	**No. of localities used by Maxent**	**AUC score**
Alstonia constricta	432	0.975
Centella asiatica	463	0.947
Cleome viscosa	1077	0.923
Corymbia terminalis	1057	0.946
Eremophila freelingii	401	0.978
Flueggea virosa	581	0.953
Ipomoea pes-caprae	353	0.946
Melaleuca cajuputi	300	0.976
Mentha satureioides	269	0.984
Planchonia careya	311	0.977
Santalum lanceolatum	1106	0.933
Sarcostemma australe	37	0.965


a
Current
2020
2050
2080
Corymbia terminalis
Cleome viscosa
Santalum lanceolatum
Sarcostemma australe
b
Current
2020
2050
2080
Ipomoea pes-caprae
Melaleuca cajuputi
Flueggea virosa
Planchonia careya

154

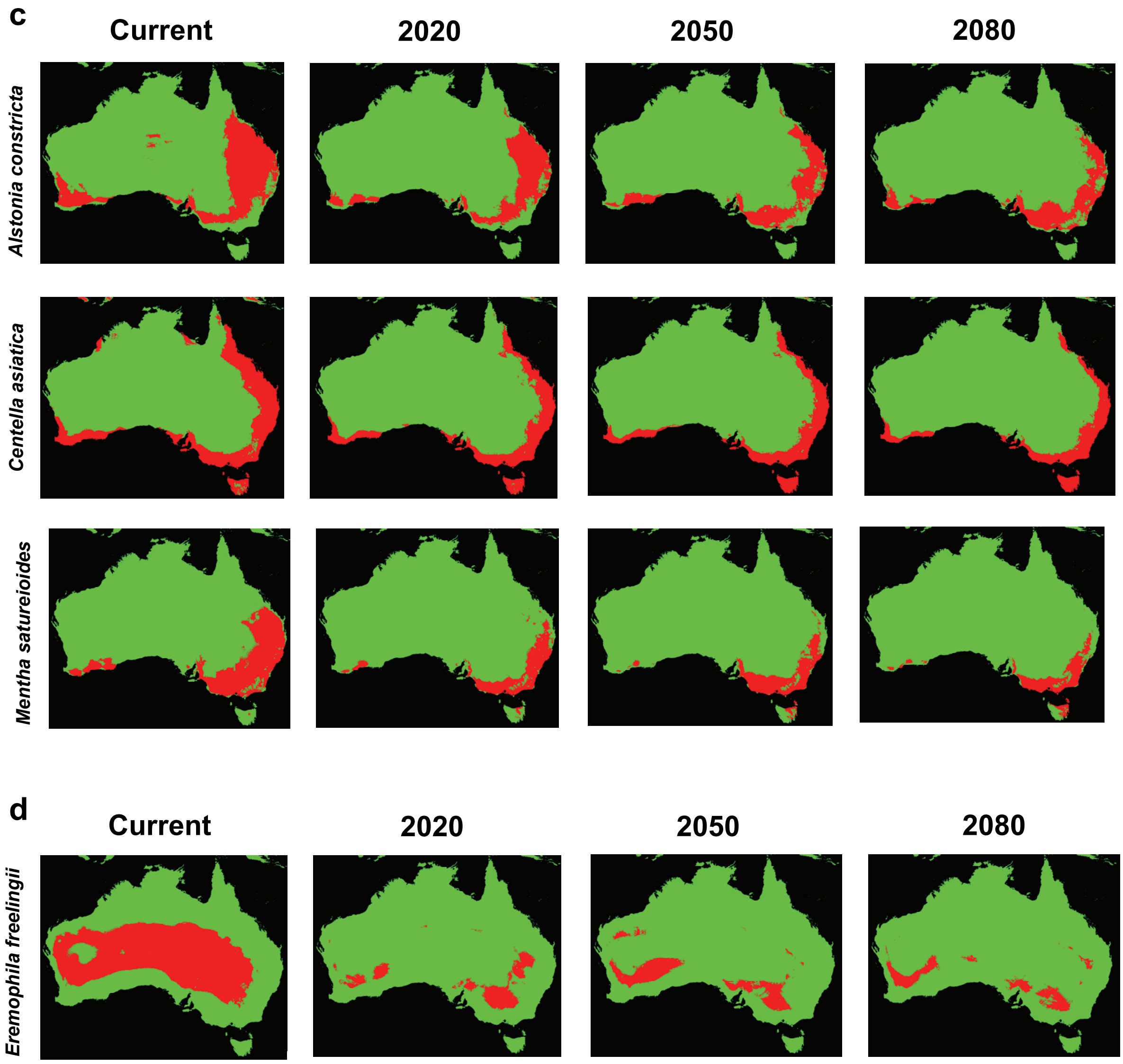


Figure 1. Projected presence-absence maps of suitable climate for twelve customary medicinal plant species obtained with an consensus approach across the four general circulation models CSIRO, BCCR, INMCM and MIROC centred at 2020, 2050 and2080. Areas in *Red* indicate presence while *Green* indicates absence of potential suitable bioclimatic conditions. Distribution of potential suitable climate **(a)** across Australia, **(b)** northern tropical, savannas and rainforest regions of Australia, (**c**) from north-east tropical to alpine and sub-alpine regions, and **(d)** central arid and semi-arid regions.

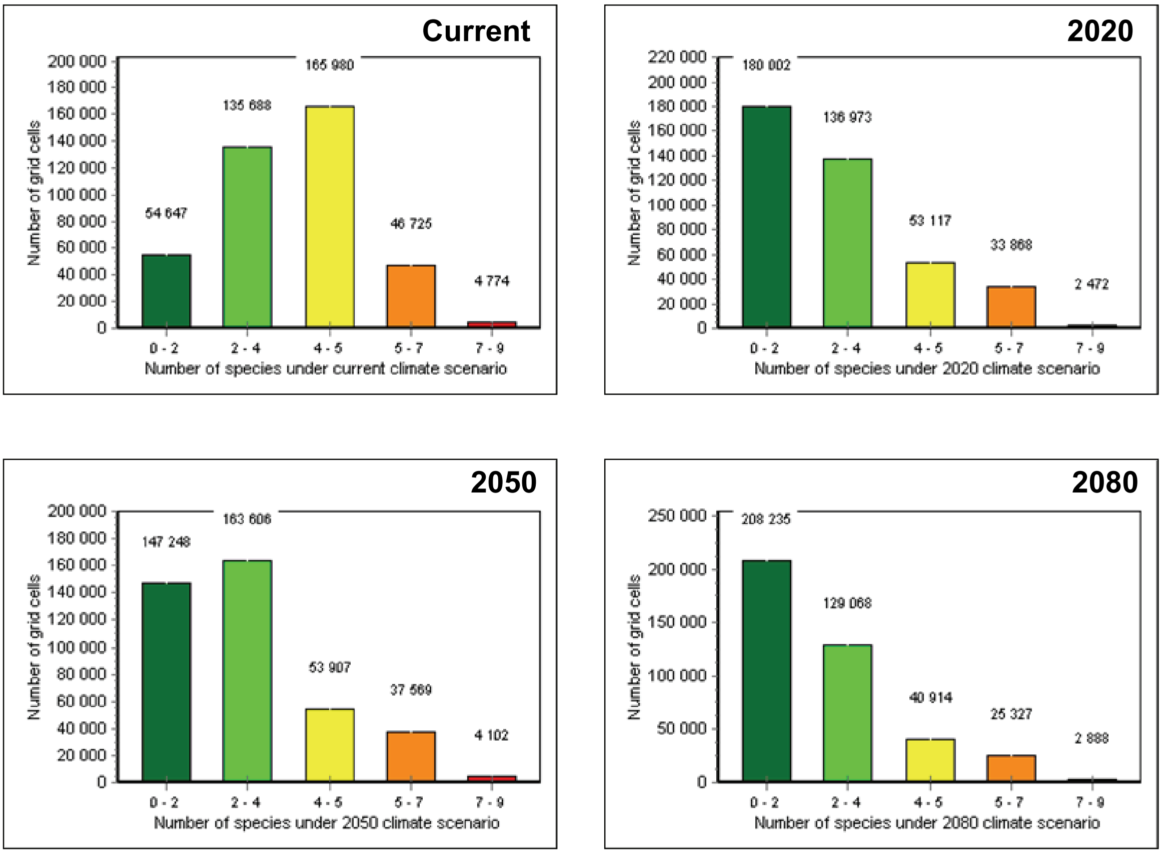


Figure 2. Frequency of grid cells containing potentially suitable climatic conditions for the species. Current and future scenarios of species distribution are presented. Australia-wide distribution maps corresponding to these grid cell distributions are in Figure 3.

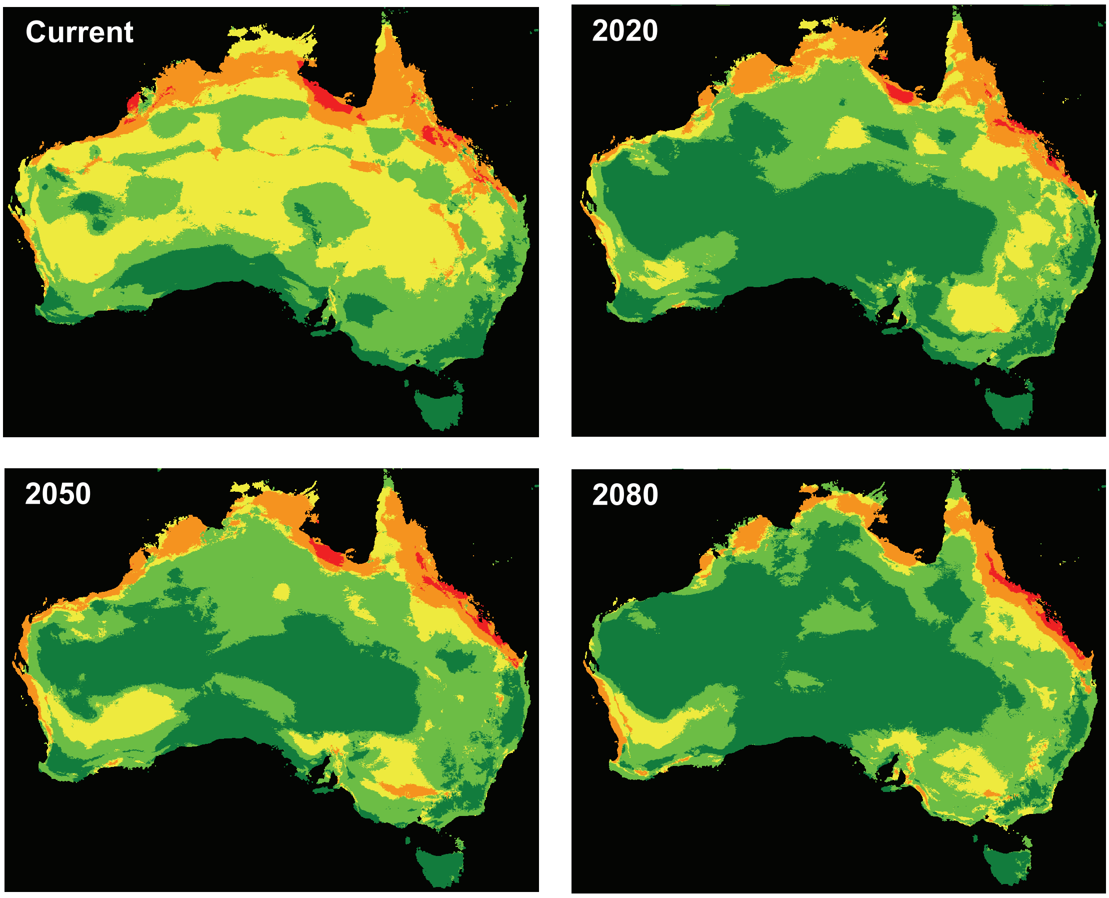


Figure 3. Summed maps derived using consensus approach showing shifts in the areas with highly suitable climatic conditions for the species across different time scenarios, corresponding to the frequency of grid cells in Figure 2.

7.2 Conclusions

Our findings suggest that there will be substantial fragmentation of suitable bioclimatic conditions for these twelve culturally important multi-therapeutic species by 2080. The summarised maps for different timelines show shifts in the spatial distributions of suitable bioclimatic conditions towards the North and East directions across Australia.

It is likely that these predicted potential shifts can consequently impact the sustenance of Aboriginal customary medicinal knowledge associated with these species. The results are based on a small number of customary medicinal plant species and have limitations due to inadequate information and variability in GCMs. Nevertheless, the study provides a valuable insight from the conservation perspective and an opportunity to draw several conclusions,

The study also demonstrates the unique use of the bioclimatic modelling technique to understand the probable impact of future climate change on customary medicinal plant species and its associated Aboriginal knowledge. Further, it also emphasises the significance of having comprehensive documented information to mitigate the likely multi-dimensional effects of climate change on currently dwindling Aboriginal culture and to develop holistic adaptive conservation strategies.

Chapter 8: Conclusions and future directions

8.1 Conclusions

Biodiversity informatics has enabled researchers to access, share, disseminate and analyse biodiversity related information, thus contributing towards global knowledge and conservation efforts. However, to gain a broad perspective, efficient computational tools to integrate disparate information on medicinal plants used by indigenous communities with biodiversity datasets have been lacking. This has resulted in the inefficient use of information and consequently restricted our ability to use inferential tools to understand biodiversity and facilitate sustainable conservation.

Customary medicinal plant species are a potential source of novel bioactive compounds and forms an integral part of Australian biodiversity [33, 34, 62, 63]. Unfortunately, customary medicinal plant diversity and associated Aboriginal knowledge is under continuous threat due to habitat destruction, loss of biodiversity, acculturation and potential impacts of climate change [24, 58, 64]. However, studies to prioritise conservation strategies and aid policy makers in taking informed decisions are hampered due to the lack of comprehensive pertinent information [65]. Currently, much of the information related to customary medicinal plant species is scattered in digital and non-digital formats across Aboriginal communities, universities, herbaria and research organisations. Further, most of the available information is limited in scope and geographically restricted. To facilitate the exchange of information between diverse groups of users and to conduct analytical studies efficient information infrastructure is required. We have used available biodiversity informatics tools and methods to address these impediments and to understand the complex relationship between biological and cultural diversity.

Overall, the specific outcomes of this thesis can be summarised as follows:

1. Currently available informatics tools and methods were critically evaluated to integrate biodiversity related ethnobotanical information and identified key components for data integration strategies. The proposed strategies are written in the form of a review article (Publication 1).
2. Based on the identified strategies and in collaboration with Aboriginal communities, we have developed a unique multi-disciplinary Customary Medicinal

Knowledge (CMKb) accessible at http://www.biolinfo.org/cmkb for integrating, visualising and analysing data on customary medicinal plants. CMKb is extensively used by indigenous communities from Australia and India, to archive and conserve their medicinal plant knowledge. As on November 2010, CMKb disseminates information on 456 customary medicinal plant species collated from public domain information resources and is accessed from 22 countries. As the knowledgebase is species centric, it can also be used for archiving knowledge related to medicinal fauna. Currently, CMKb is indexed by Atlas of Living Australia, which is a national biodiversity informatics initiative.

3. A questionnaire to facilitate the interview process for systematically documenting first-hand customary medicinal plant knowledge (Appendix 1) has been developed.

4. Hands-on training workshops for participants from Aboriginal communities and researchers have been conducted, for enabling them to efficiently manage medicinal plant knowledge archived in CMKb, with a user's manual (Appendix 2).

5. After the development of CMKb, a review was conducted on a small group of customary medicinal plants species from CMKb, occurring in New South Wales, Australia. The review focused on multi-disciplinary aspects of customary medicinal plants such as medicinal uses, phytochemistry, biological activities and habitat distribution. Based on this study, scope for further phytochemical and biological investigations of customary medicinal plants species was identified. The review also emphasised the importance of collaboration with Aboriginal communities.

6. A novel multi-species method was used to identify customary medicinal plant species-rich areas and to evaluate the cultural worth of the associated predicted habitats. For cultural valuation of the predicted habitats, the models were weighed using customary medicinal uses from CMKb. The highlight of this method is the flexibility to integrate diverse range of parameters related with the species to identify and calculate the worth of the associated habitats for prioritising conservation efforts. To the best of our knowledge this is the first time such method is used for calculating the cultural worth of the customary medicinal plant species-rich habitats.

7. Following the habitat suitability modeling of customary medicinal plant species-rich areas, we investigated the impact of projected future climate change on the spatial distributions of suitable bioclimatic envelope of customary medicinal plant species. For this analysis, out of 456 customary medicinal plant species from

CMKb, twelve representative species were selected based on their high multi-therapeutic values. The results were derived using consensus approach across BCCR, CSIRO, INMCM and MIROC general circulation models (GCMs) centred on 2020, 2050 and 2080. Our findings indicate further likely fragmentation of suitable environmental conditions of these culturally valuable twelve customary medicinal plant species by 2080.

Overall, by using biodiversity informatics tools and resources, we were able to deploy an efficient informatics infrastructure for documenting, digitising, disseminating, archiving and analysing customary medicinal plant knowledge. This thesis provides an example for the application of biodiversity informatics to integrate and analyse biodiversity related ethnobotanical information for prioritising conservation efforts and sustainable use.

8.2 Innovations

Biodiversity informatics is emerging as a field mainly focused on mobilising primary biodiversity data for conducting analytical studies leading to conservation. However, in this thesis, biodiversity informatics tools and resources were deployed in an innovative manner to facilitate conservation of biodiversity and customary knowledge. Listed below are some of the innovations:

1. Integration of biodiversity informatics with GIS, bioinformatics, chemoinformatics, ecoinformatics and Aboriginal customary knowledge.
2. Development of the multi-disciplinary CMKb for the conservation of customary medicinal plant knowledge and associated biodiversity.
3. CMKb complies with biodiversity informatics data standards such as Darwin Core, Economic Botany Data Standards and Dublin Core, enabling easy integration with national and international initiatives.
4. Integration of GIS and the inferential analytical tool Maxent from biodiversity informatics with cultural knowledge, in an innovative way for identifying species-rich hotspots and cultural value of the habitats for knowledge and biodiversity conservation.
5. Integration of GIS, habitat suitability modeling tool Maxent and General Circulation Models, with cultural knowledge to investigate the impact of future

climate change on twelve customary medicinal plant species having multi-therapeutic value.

8.3 Significance of this work

The work presented in this thesis adheres to the ethical guidelines set by United Nations Educational, Scientific and Cultural Organization (UNESCO) and National Health and Medical Research Council (NHMRC), Australia. The studies presented also comply with the UNESCO Participatory Action Research methodology.

Aboriginal communities were involved during the design and development of CMKb and indigenous intellectual property rights are acknowledged, protected and ensured.

CMKb is a unique Australian biodiversity informatics resource and has been accessed from 22 countries as on November 2010. CMKb archives first-hand information on customary medicinal plants shared by Australian and Indian indigenous communities. However, these data are password-protected and not available from the public database.

The research reported in this thesis addresses multiple goals of the Australian national research priorities of a. Sustainable use of Australia's biodiversity, b. Responding to climate change and variability and c. Smart use of information.

Overall, an integrated multi-disciplinary approach for the conservation of biodiversity and customary medicinal plant knowledge has been developed. Furthermore, the integration of GIS and habitat suitability modeling to explore the complex relationship between biological and cultural diversities has been attempted, while the effects of climate change on a representative set of multi-therapeutic medicinal plants has identified potential regions of habitat loss and customary knowledge depletion.

8.4 Future directions

Even though this work attempts to be as complete as possible, we are aware of its limitations. The effectiveness of informatics infrastructure presented in this thesis entirely depends on the involvement of Aboriginal communities, the availability and quality of the data and the biodiversity informatics tools that are available for data integration and analysis process.

There are sporadic efforts in Australia to document the diminishing Aboriginal customary medicinal plant knowledge. On many occasions, Aboriginal communities are viewed as mere providers of non-scientific information and not as collaborators in scientific endeavours. With the recognition and due respect accorded for cultural values, more Aboriginal communities will be encouraged to become part of such collaborative research partnerships.

Australian customary medicinal plant knowledge is fragmented. Most of the documented customary knowledge is contained in various journal articles, government reports, books and the like, which are difficult to obtain. Future availability of this information in digital format will not only fill the knowledge gaps but also help to further our understanding of biocultural diversity.

With an increase in the availability of digital information on customary medicinal plants, development of relevant schemas for integration and ontologies for efficient data retrieval will be needed. The development of such schemas and ontologies will further expand the scope for knowledge discovery.

In this thesis, we integrated GIS and habitat suitability modeling with customary medicinal plant knowledge for identifying culturally important areas for conservation. However, due to inadequate access to customary knowledge and species distribution data, the results have limitations. Future access to more comprehensive information and active participation of Aboriginal communities will help to extend this study and develop more robust models that can be validated in consultation with the knowledge custodians.

In Australia, like elsewhere in the world, little attention has been given by researchers to the topic of impact of climate change on indigenous culture. In our study, described in this thesis, we have attempted to understand the impact of climate change on the customary medicinal plant species and its associated knowledge. The scope of this study can be further expanded to cover many more floral and faunal culturally important species to devise adaptive strategies. Further, culturally valuable habitats can be identified associated with these species which may become vulnerable due to changing climate scenarios.

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Appendix 1: Questionnaire developed for collection of primary data on Australian Aboriginal medicinal plant knowledge

Questionnaire for documenting Australian customary medicinal plant knowledge

Date of collection: ____________________**Specimen collection no**.:__________________

Voucher number: ________________**Herbaria**:____________________________________

Locality: Village_____________________________ District ___________________________

State________________________________Country__________________________________

Distance and direction from major town____

GPS reading in decimals**: Longitude**__________________**Latitude**____________________

Habitat: ____

____

Is this plant used for medicine: YES ☐ NO ☐

Are there other uses for this plant?____

____

Scientific name *(if known):*____

Common name: ____

Vernacular/Native name: ____

What does this name mean? ____

____

Provisional identification: ____

____

Does this plant have any other popular names? __________________________________

____

What season of the year do you collect the plant? ______________________________

____

How did you come to know about this particular use? ___________________________

____

Is the plant difficult to find? ____

____

Are there special considerations for collecting this plant? ________________________

____

Do you plant this plant? ____

____

Type of Plant: (*Tick the appropriate one*)

Tree ☐ (approx height) __________ Herb ☐ Shrub ☐

Parasitic ☐ Liana ☐ Aquatic plant ☐ *Other* ☐

Other specify: ____

Bark description (e.g. colour, texture, features):___________________________________

____

____

Leaves description: (e.g. colour, size, texture, features) ____________________________

____

____

Flower description: (e.g. number of petals, size of flower, colour of flower, scent, abundance etc): ____

____

____

Fruit description: (e.g. size, colour, edible, seeds, skin, flesh etc) ___________________

____

____

Latex present______________________**Gum present**____________________________

Attacked by insects etc: ____

Disease or symptoms treated: ____

____

____

Parts used: *(Tick the appropriate boxes)*

Leaves ☐ Root ☐ Branches ☐ Bark ☐ Flowers ☐ Resin/Sap/Latex ☐

Fruits ☐ Seeds ☐ Stem Cortex ☐ Root cortex ☐ Whole plant ☐

Fresh ☐ **Dried** ☐

Are there any conditions when you do not use this plant? ________________________

____

____

Preparation:

Preparation method____

Amount of plant material used __________________________________

Application method ______________________________________

Quantity of preparation ____________________________________

Dose ____

Range/Frequency ____

Preparation colour ______________________________________

Preparation taste _______________________________________

Preparation odour

Storage method/Expiry

Remarks/ special instructions

Plant used together with the following plants

Additional notes/Remarks

Appendix 2: CMKb User's Manual

Pages 175-206 of this thesis have been removed as they contain published material. Please refer to the following citation for details of the article contained in these pages.

Department of Chemistry and Bimolecular Science (2010). *Customary Medicinal Knowledgebase: user's manual (version 1.1)*. Macquarie University.

http://biolinfo.org/cmkb