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Integrating a global agro-climatic classification with bioregional boundaries in Australia

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ABSTRACT

Aim Stratification of major differences in the biophysical features of landscapes at the continental scale is necessary to collectively assess local observations of landscape response to management actions for consistency and difference. Such a stratification is an important step in the development of generalizations concerning how landscapes respond to different management regimes. As part of the development of a comparative framework for this purpose, we propose a climate classification adapted from an existing broad scale global agro-climatic classification, which is closely aligned with natural vegetation formations and common land uses across Australia.

Location The project considered landscapes across the continent of Australia.

Methods The global agro-climatic classification was adapted by using elevation-dependent thin plate smoothing splines to clarify the spatial extents of the 18 global classes found in Australia. The clarified class boundaries were interpolated from known classes at 822 points across Australia. These classes were then aligned with the existing bioregional classification, Interim Biogeographic Regionalization for Australia IBRA 5.1.

Results The aligned climate classes reflect major patterns in plant growth temperature and moisture indices and seasonality. These in turn reflect broad differences in cropping and other land use characteristics. Fifty-two of the 85 bioregions were classified entirely into one of the 18 agro-climatic classes. The remaining bioregions were classified according to sub-bioregional boundaries. A small number of these sub-bioregions were split to better reflect agro-climatic boundaries.

Main conclusions The agro-climatic classification provided an explicit global context for the analysis. The topographic dependence of the revised climate class boundaries clarified the spatial extents of poorly sampled highland classes and facilitated the alignment of these classes with the bioregional classification. This also made the classification amenable to explicit application. The bioregional and sub-regional boundaries reflect discontinuities in biophysical features. These permit the integrated classification to reflect major potential differences in landscape function and response to management. The refined agro-climatic classification and its integration with the IBRA bioregions are both available for general use and assessment.

Keywords

Climate, IBRA bioregions, IBRA sub-bioregions, land use, thin plate smoothing splines, topography, vegetation.

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INTRODUCTION

It is becoming increasingly apparent that the impacts of humans on ecosystems need to be understood at landscape scale. Our

current knowledge of landscape response is built through the incremental accumulation of many studies, which are conducted in various contexts and in different environments. The Australian land mass encompasses a huge amount of biophysical complexity

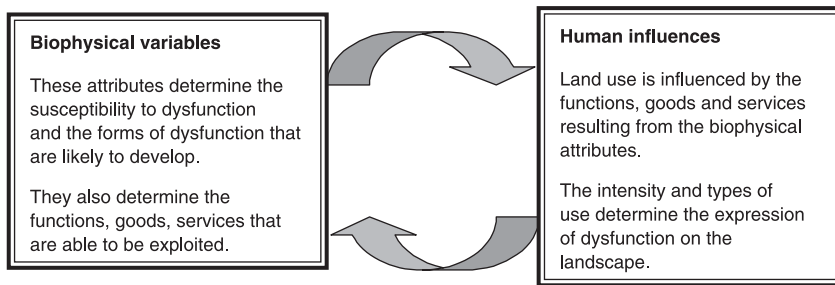


Figure 1 The interaction between the biophysical variation in the landscape and human influence as it relates to ecological dysfunction.

and therefore, the experiences of many people are drawn from specific regions. Individuals focusing on the complexity within their local regions may not see the need to generalize beyond. However, a problem arises when information and knowledge are being shared and differences in landscape response are revealed. It is too easy to submit to the barriers that these differences present, rather than to strive to understand landscape scale processes in a more general way. The issue is not whether we can generalize about landscape responses, but to identify the circumstances in which generalizations can be made, and where there are limits.

In an attempt to provide a broad context for research and communication about landscapes, our aim is to further develop the framework for landscape classification of McIntyre & Hobbs (1999) that describes landscape alteration states caused by human impacts. The effect of human land use on ecological health is highly interrelated with the biophysical environment. The types and intensity of land use are determined by the functions, goods and services made available by the biophysical environment (Fig. 1). These patterns of land use consequently impact the landscape, but the types and degree of expression of any ecological dysfunction is highly related to the biophysical features of that landscape.

We have chosen climate as the key biophysical variable, based on the fact that water and temperature are major drivers of primary productivity. They are a determinant of the occurrence of native biota across the landscape. The type and productivity of vegetation influence the nature of human exploitation. The sensitivity of a landscape to human exploitation is based both on the physical features of the site and how climate influences ecosystem function and the dynamics of water and nutrient availability to flora and fauna species throughout the year. The rapid growth of environmental modelling in recent decades to identify key habitats for flora and fauna species consistently highlights the importance of climatic variables in providing a strong relationship with the occurrence of many species (e.g. Nix, 1986).

Land use patterns broadly reflect major climatic zones, but the response and resilience of landscapes to agricultural practices or other land management may be quite different from region to region. For example, high rainfall may encourage intensive cropping use, but favourable conditions for plant growth may minimize erosion risk. Conversely, dry areas may be used only for extensive grazing, but the landscape may also be very sensitive to even low levels of grazing. The importance of climate in determining salinity hazard is also a factor in choosing climate as a

primary biophysical driver. Salinity hazard is higher where annual evaporation greatly exceeds annual rainfall, and is also related to the seasonal availability of water (Coram, 1998).

Additional biophysical factors certainly interact with climate to influence land use and the expression of dysfunction. Surface climate is directly modulated by topography, and the success of bioclimatic modelling has depended crucially on elevation-dependent spatial extension of observed climate (Hutchinson, 1991, 1995). Elevated topography associated with increased precipitation and steeper slopes may increase erosion risk, but reduce salinity hazard. Naturally fertile soil may influence land use patterns, although the use of irrigation and fertilizers means that land uses are less constrained by soil and climate limitations. While climate can be considered a principal driver of landscape processes, other factors such as ground elevation, geomorphology and soil are clearly important.

In this paper, we attempt to address major biophysical variation across the Australian continent on a single axis by integrating a global agro-climatic classification with an existing biogeographical regionalization. The agro-climatic classification is well-documented and is closely related to the distribution of natural vegetation formations and common land uses across Australia. In this way, we hope to provide a means by which particular regions and localities can be linked to broad climate groupings of national scale within their global context, which can also be differentiated on their specific bioregional attributes. The results of the analysis are freely available for further application and assessment and have been incorporated in the generalized landscape framework described for Australia by Hobbs and McIntyre (2005).

METHODS

Climate classification — background

A range of climatic maps are presented in various reports on the Australian environment, but they are not often linked to a documented classification. For example, in a scheme that is highly relevant to this exercise, in agro-ecological regions (Williams *et al.*, 2002), the climate classes are based on unpublished data, and the classes are named, but they are not described in the report. Similar situations relate to a range of recent reports on the Australian environment where the climate descriptions cannot be traced back to published documentation and the maps are of a very low resolution (e.g. State of the Environment Advisory Council,

1996; National Land and Water Resources Audit 2001a). Climate classifications are described in the *Atlas of Australian Resources* (Plumb, 1986) and by Stern *et al.* (2003).

The classification that was selected as being most suitable is that of Hutchinson *et al.* (1992), who modelled agro-climatic data from 4159 stations across the globe, including 1135 in Australasia. This classification provided a global context for the derived classes and the process was documented in detail. The plant growth model, GROWEST (Fitzpatrick & Nix, 1970; Nix, 1981; Hutchinson *et al.*, 2003), was used to convert monthly light, temperature and moisture data to model indices of crop growth. Each station was then classified using 30 GROWEST attributes variously describing seasonal and annual mean values of temperature, soil moisture and growth indices together with temperature extremes. The indices described the growth response of plants with moderate and warm temperature optima.

An objective multivariate analysis method was used to identify 34 classes worldwide that came under 10 broad categories reflecting global patterns in temperature and moisture regimes relating to plant growth. The particular advantages of this classification are its explicit dependence on the dynamics of plant growth and the objective nature of the classification process. The classification

is directly relevant to both native and human-managed vegetation, and the class boundaries were found to be in substantial agreement with the boundaries of the major natural vegetation formations of the world (Hutchinson *et al.*, 1992). The classification can also be related to common land uses across Australia as described below. The broadest divisions were based on temperature, except for the warm to hot desert regions, with secondary divisions based on moisture. Remarkably, this paralleled the primary and secondary Köppen divisions (Köppen, 1923), but with significant differences in detail.

The 10 global agro-climatic categories, together with their relationship to the Köppen classification, as documented in Strahler (1975), are listed and briefly described in Table 1. Australia is mostly associated with the warm to hot, very dry and seasonally wet or dry climates under categories E, G, H and I. Apart from very restricted areas in the wet tropics under category J, and higher latitude alpine areas under category B, the wetter climates in Australia are mainly associated with mid-latitude eastern maritime locations under categories D and F. Australia has no significant area with very cold polar and alpine climates included under category A, nor cool dry climates associated with higher latitude continental locations under category C.

Table 1 The 10 broad categories of the global agro-climatic classification of Hutchinson *et al.* (1992) and their relationship to the Köppen system

Code	Name	Description
A	Very cold	Polar and alpine climates too cold for significant crop growth. Corresponds to Köppen class E (ice climates).
B	Cold	Very cold winters with short warm summers that are wet enough to support significant growth. Includes Köppen class D (snow climates) and cooler portions of Köppen class Cf (temperate with sufficient precipitation in all months).
C	Cool, dry	Cold growth-limiting winters with dry to subhumid summers, occurring in higher latitude continental locations. Characterized within cool climates by low growth. Includes parts of Köppen classes BS, BW, Bs, Dw (dry and desert climates).
D	Cool, wet	Cold growth limiting winter with sufficient moisture for crop growth in some non-winter months, mostly occurring in mid-latitude locations with maritime influence. Includes parts of Köppen classes Cf, Cw, Df and Dw (temperate and snow climates with sufficient moisture all year or with a winter dry season).
E	Warm, seasonally wet/dry	Long hot summers and mild winters with significant moisture limits on growth. These include the Mediterranean and adjacent inland climates (where the dry season is in summer) and mid-latitude eastern continental climates with wetter summers and drier winters. Includes parts of Köppen classes BS, BW, Cw and Cs (dry and temperate climates with a dry summer or winter).
F	Warm, wet	Long hot summers and mild winters with a moisture regime that is non-limiting for most of the year. These climates are mainly associated with mid-latitude eastern maritime locations and some tropical high latitude locations. Includes parts of Köppen classes Cf, Cw and Aw (temperate and tropical climates with a summer or winter dry season).
G	Warm to hot, very dry	Long hot summers and mild winters with a moisture regime that is limiting for the whole year. This category includes the world's major mid-latitude continental and west coast deserts and most of Köppen class BW (desert).
H	Hot, dry	A semi-arid transition between the desert climates in category G and the seasonally wet/dry climates in category I. This category is too dry or very marginal for rainfed crops. Includes parts of Köppen classes BS and BW (steppe and desert climates).
I	Hot, seasonally wet/dry	High temperature for most of the year and a markedly seasonal moisture regime. Includes Köppen classes Aw and parts of Bs and Cw (tropical and temperate climates with a summer or winter dry season).
J	Hot, wet	Uniformly high temperature throughout the year with a moisture regime that is either uniformly wet or has at most a short dry season. Corresponds to Köppen classes Af, Am and Aw (tropical rainforest and monsoon climates).

Table 2 Description of 18 agro-climatic classes for Australia including broad location of region and common land uses. Codes according to the categories in Table 1 and as described by Hutchinson *et al.* (1992)

Code	Agro-climate	Location and land use
B1	Very cold winters with summers too short for crop growth	Alpine areas of NSW, Victoria and Tasmania. Water harvesting, hydroelectricity, tourism and nature conservation
B2	Less severe winters and longer moist summers suitable for some crops	Tasmanian highlands. Similar land uses to B1
D5	Moisture availability high in winter-spring, moderate in summer, most plant growth in spring	Tasmanian lowlands, southern Victoria, southern and northern Tablelands of NSW. Forestry, cropping, horticulture, improved and native pastures
E1	Classic "Mediterranean" climate with peaks of growth in winter and spring and moderate growth in winter	South-west WA and southern SA. Forestry, horticulture, winter cropping, improved pastures
E2	"Mediterranean" climate, but with drier cooler winters and less growth than E1	Inland of E1 in south-west WA, southern SA, north-west Victoria and southern NSW. Horticulture, winter cropping, improved pastures
E3	Most plant growth in summer, although summers are moisture limiting. Temperature limits growth in winter	Western slopes of NSW and part of the North Western Plains. Winter cereals and summer crops, grazing
E4	Growth is limited by moisture rather than temperature and the winters are mild. Growth is relatively even through the year	Unique in the World to sub-tropical continental eastern Australia and associated with the Brigalow belt of Queensland and NSW. Winter cereals (after summer fallowing), summer crops (including cotton) and sown pastures
E6	Semi-arid climate that is too dry to support field crops. Soil moisture tends to be greatest in winter	Southern edge of the arid interior in WA, SA, NSW and Queensland. Rangeland
E7	Moisture is the main limit on crop growth. Growth index lowest in spring	Maritime sub-tropical areas in southern Queensland. Sugar, crops and cattle grazing
F3	Cooler end of the warm, wet sub-tropical climates	The Sydney Basin and the NSW south coast. Cooler temperatures slightly favour temperate crops and sown pastures
F4	Warmer and wetter than F3	NSW North Coast, extending to southern Qld and the Great Sandy province. Horticulture, sown pasture and tourism. Potential for wheat, cotton and maize
G	Desert, supporting very little plant growth due to water limitation	Central Australia. Cropping possible only with irrigation. Rangeland, wildland
H	Semi-arid, with some growth in the warm season, but too dry for cropping	Transition between the wet/dry tropics and the arid interior in WA, NT and Qld. Rangeland
I1	Strongly developed wet and dry seasons with plant growth determined by moisture availability	NT, northern WA and Cape York Peninsula. Predominately rangeland. Potential for tropical field crops
I2	Temperature and moisture are more seasonal than for I1 and the growing season is shorter	Occurs inland of I1 and has some crop potential, but predominantly rangeland
I3	This has cooler winters than I1 and I2 with a growing season lasting at least six months	Occurs in the coastal and hinterland areas of north-east Qld, south of Cape York Peninsula. Sugar, cropping and rangelands
J1	Moisture and temperature regime supports growth for 8–9 months of the year, with a 3–4 month dry season	Limited areas in the Central Mackay Coast and the Wet Tropics. Sugarcane and horticulture
J2	As for J1 but with a shorter dry season	Limited areas on the east coast of Cape York Peninsula

Thus, of the 34 global agro-climatic classes, just 18 had significant spatial extent in Australia and were contained in eight of the 10 global categories. The 18 Australian agro-climatic classes are described in Table 2. This table describes how the classes manifest in Australia with particular emphasis on the nature of the associated cropping regimes. The global context of these climate classes can be ascertained by referring to Tables 1 and 2. In particular, class E4 has significant spatial extension in Australia but occurs nowhere else on the globe. It is closely aligned with the brigalow belt in Queensland and northern New South Wales (results shown in Table 3) and is an area with high priority for conservation (National Land and Water Resources Audit, 2002).

Bioregional classification

The Interim Biogeographical Regionalization for Australia (IBRA) is a landscape-based approach to classifying land surface using specialist ecological knowledge, combined with regional and continental scale data on climate, geomorphology, landform, lithology and characteristic flora and fauna (Thackway & Cresswell, 1995). The conceptual model used in the IBRA process is similar to that discussed in relation to climate *viz* physical processes that drive ecological processes, which in turn are responsible for determining the observed patterns of biological productivity and the associated patterns of biodiversity (Thackway

Table 3 Classification of bioregions and sub-bioregions into the 18 agro-climatic class codes described in Table 2. These are mapped in Fig. 4. Where sub-bioregions have been split, the portion in the different codes are indicated by N (north), S (south), E (east) and W (west)

Sub-bioregion name	Bioregion name (code) sub-bioregion codes	Climate code
NSW Alps (AA1)	Australian Alps (AA)	B1
Victorian Alps (VA)	AA2	B1
Arnhem Coast P1 (ARC1)	Arnhem Coast (ARC)	I1
Arnhem Coast P2	ARC2	I1
Arnhem Coast P3	ARC3	I1
Arnhem Coast P4 Groote	ARC4	I1
Arnhem Coast P5 Wessels	ARC5	I1
Arnhem Plateau P1 (ARP1)	Arnhem Plateau (ARP)	I1
Arnhem Plateau P2	ARP2	I1
Avon Wheatbelt P1 (AW1)	Avon Wheatbelt (AW)	E2
Avon Wheatbelt P2	AW2	E1
Townsville Plains (BBN1)	Brigalow Belt North (BBN)	I3
Bogie River Hills	BBN2	I3
Cape River Hills	BBN3	I3
Beucazon Hills	BBN4	I3
Wyarra Hills	BBN5	I3
Northern Bowen Basin	BBN6	I3
Belyando Downs	BBN7	E4
Upper Belyando Floodout	BBN8	E4
Anakie Inlier	BBN9	E4
Basalt Downs	BBN10	E4
Isaac–Comet Downs	BBN11	E4
Nebo–Connors Ranges	BBN12	I3
South Drummond Basin	BBN13	E4
Marlborough Plains	BBN14	I3
Claude River Downs (BBS1)	Brigalow Belt South (BBS)	E4
Woorabinda	BBS2	E4
Boomer Range	BBS3	E4
Mount Morgan Ranges	BBS4	E7
Callide Creek Downs	BBS5	E4
Arcadia	BBS6	E4
Dawson River Downs	BBS7	E4
Banana–Auburn Ranges	BBS8	E4
Buckland Basalts	BBS9	E4
Carnarvon Ranges	BBS10	E4
Taroom Downs	BBS11	E4
Southern Downs	BBS12	E4
Barakula	BBS13	E4
Dulacca Downs	BBS14	E4
Weribone High	BBS15	E4
Tara Downs	BBS16	E4
Eastern Darling Downs	BBS17	E4
Inglewood Sandstones	BBS18	E4
Moonie River–Commoron Creek Floodout	BBS19	E4
Moonie–Barwon Interfluve, Collarenebri Interfluve	BBS20	E4
Northern Basalts	BBS21	E3
Northern Outwash	BBS22	E4
Pilliga Outwash	BBS23	E4
Pilliga	BBS24	E3
Liverpool Plains	BBS25	E3
Liverpool Range	BBS26	E3
Talbragar Valley	BBS27	E3
	Ben Lomond (BEL)	D5
Barrier Range (BHC1)	Broken Hill Complex (BHC)	E6
Mootwingee Downs	BHC2	E6
Scopes Range	BHC3	E6
Barrier Range outwash, fans and plains	BHC4	E6
Burt Plain P1 (BRT 1)	Burt Plain (BRT)	G

Table 3 *Continued*

Sub-bioregion name	Bioregion name (code) sub-bioregion codes	Climate code
Burt Plain P2	BRT2	G
Burt Plain P3	BRT3	G
Burt Plain P4	BRT4	G
Central Arnhem P1 (CA1)	Central Arnhem (CA)	I1
Central Arnhem P2	CA2	I1
Cape Range (CAR1)	Carnarvon (CAR)	G
Wooramel	CAR2	G
Toko Plains, Toko Range (CHC1)	Channel Country (CHC)	G
Sturt Stony Desert	CHC2	G
Goneaway Tablelands	CHC3	G
Diamantina-Eyre, Diamantina Plains	CHC4	G
Cooper Plains	CHC5	G
Coongie-Lake Pure	CHC6	G
Lake Pure	CHC7	G
Noccundra Slopes	CHC8	G
Tibooburra Downs, Central Downs, Fringing Tablelands and Downs	CHC9	G
Core Ranges	CHC10	G
Bulloo, Bulloo Overflow	CHC11	G
Pentecost (CK1)	Central Kimberley (CK)	I2
Hart	CK2	H
Mount Eliza	CK3	I2
Mardabilla (COO1)	Coolgardie (COO)	E6
Southern Cross	COO2	E2
Eastern Goldfield	COO3	E6
Boorindal Plains (CP1)	Cobar Penepain (CP)	E6
Barnato Downs	CP2	E6
Canbelego Downs	CP3	E6
Nymagee-Rankins Springs	CP4	E = E3; W = E6
Lachlan Plains	CP5	E2
Whitsunday (CQC1)	Central Mackay Coast (CMC)	J1
Proserpine-Sarina Lowlands	CQC2	I3
Clarke-Connors Ranges	CQC3	I3
Byfield	CQC4	I3
Manifold	CQC5	I3
Mann-Musgrave Block (CR1)	Central Ranges (CR)	G
Wataru	CR2	G
Everard Block	CR3	G
Coen-Yamba Inlier (North & South) (CYP1)	Cape York Peninsula (CYP)	N = J1; S = I1
Starke Coastal Lowlands	CYP2	J1
Cape York-Torres Strait	CYP3	I1
Jardine-Pascoe Sandstones	CYP4	I1
Battle Camp Sandstones	CYP5	I1
Laura Lowlands	CYP6	I1
Weipa Plateau	CYP7	I1
(Northern) Holroyd Plain	CYP8	I1
Coastal Plains	CYP9	I1
	Daly Basin (DAB)	I2
	Darwin Coastal (DAC)	I1
Prairie-Torrens Creeks Alluvials (DEU1)	Desert Uplands (DEU)	H
Alice and	DEU2	H
Cape-Campaspe Plains	DEU3	I3
Fitzroy Trough (DL1)	Dampierland (DL)	H
Pindanland	DL2	H
Davenport Murchison Range P1	Davenport Murchison Range (DMR)	G
Davenport Murchison Range P2	DMR2	G
Davenport Murchison Range P3	DMR3	G
Balonne-Culgoa Fan, Culgoa-Bokhara (DRP1)	Darling Riverine Plains (DRP)	E6
Narran-Lightning Ridge	DRP2	E4
Warrambool-Moonie	DRP3	E4

Table 3 *Continued*

Sub-bioregion name	Bioregion name (code) sub-bioregion codes	Climate code
Macintyre–Weir Fan, Castlereagh-Barwon	DRP4	W = E6; E = E4
Bogan–Macquarie	DRP5	W = E6; E = E4
Louth Plains	DRP6	E6
Wilcannia Plains	DRP7	E6
Menindee	DRP8	E6
Great Darling Anabranch	DRP9	E6
Pooncarie–Darling	DRP10	E6
Georgetown–Croydon (EUI1)	Einiasleigh Uplands (EIU)	I2
Kidston	EIU2	I3
Hodgkinson Basin	EIU3	I1
Broken River	EIU4	I3
Undara–Toomba Basalts	EIU5	S = H; N = I3
Herberton–Wairuna	EIU6	I3
Fitzgerald (ESP1)	Esperence Plains (ESP)	E2
Recherche	ESP2	E2
Southern Yorke (EYB1)	Eyre Yorke Block (EYB)	E1
St Vincent	EYB2	E2
Eyre Hills	EYB3	S = E1; N = E2
Talia	EYB4	E1
Eyre Mallee	EYB5	W = E6; E = E2
Finke P1 (FIN1)	Finke (FIN)	G
Finke P2	FIN2	G
Tieyon, Finke P3	FIN3	G
Pedirka	FIN4	G
Mount Lofty Ranges (FLB1)	Flinders Lofty Block (FLB)	E2
Broughton	FLB2	E2
Olary Spur	FLB3	E6
Southern Flinders	FLB4	E6
Northern Flinders	FLB5	E6
Wilson's Promontory (FUR1)	Flinders (FLI)	D5
Flinders	FUR2	D5
Ashburton (GAS1)	Gascoyne (GAS)	G
Carnegie	GAS2	G
Augustus	GAS3	G
Myall Plains (GAW1)	Gawler (GAW)	E6
Gawler Volcanics	GAW2	E6
Gawler Lakes	GAW3	E6
Arcoona Plateau	GAW4	E6
Kingoonya	GAW5	E6
Lateritic Plain (GD1)	Gibson Desert (GD)	G
Dune Field	GD2	G
McArthur–South Nicholson Basins (GFU1)	Gulf Fall and Uplands (GFU)	I2
Gulf Fall and Uplands	GFU2	I2
Edel (GS1)	Geraldton Sandplains (GS)	G
Geraldton Hills	GS2	E2
Leseur Sandplain	GS3	E2
McLarty (GSD1)	Great Sandy Desert (GSD)	G
Mackay	GSD2	G
Great Sandy Desert P3	GSD3	G
Great Sandy Desert P4	GSD4	G
Great Sandy Desert P5	GSD5	G
Great Sandy Desert P6	GSD6	G
Gulf Coastal P1 (GUC1)	Gulf Coastal (GUC)	I2
Gulf Coastal P2 Pellews	GUC2	I2
Karumba Plains (GUP1)	Gulf Plains (GUP)	N = I1; W = I2
Armravnald Plains	GUP2	H
Woondoola Plains	GUP3	H
Mitchell–Gilbert Fans	GUP4	S = I2; N = I1
Claraville Plains	GUP5	N = I2; S = H

Table 3 *Continued*

Sub-bioregion name	Bioregion name (code) sub-bioregion codes	Climate code
Holroyd Plain–Red Plateau	GUP6	S = I2; N = I1
Doomadgee Plains, Gulf Plains	GUP7	I2
Donors Plateau	GUP8	N = I2; S = H
Gilberton Plateau	GUP9	H
Wellesley Islands	GUP10	I1
Shield (GVD1)	Great Victoria Desert (GVD)	E6
Central	GVD2	S = E6; N = G
Eastern, Maralinga	GVD3	E6
Kintore	GVD4	G
Tallaringa	GVD5	G
Yellabinna	GVD6	E6
	Hampton (HAM)	E6
Northern Jarrah Forest (JF1)	Jarrah Forest (JF)	E1
Southern Jarrah Forest	JF2	E1
Kangaroo Island (KAN1)	Kanmantoo (KAN)	E1
Fleurieu	KAN2	E1
	King (KIN)	D5
Rudall (LSD1)	Little Sandy Desert (LSD)	G
Trainor	LSD2	G
MacDonnell Ranges P1 (MAC1)	MacDonnell Ranges (MAC)	G
MacDonnell Ranges P2	MAC2	G
MacDonnell Ranges P3	MAC3	G
Eastern Mallee (MAL1)	Mallee (MAL)	E = E6; W = E2
Western Mallee	MAL2	E2
South Olary Plain, Murray Basin Sands (MDD1)	Murray Darling Depression (MDD)	E6
Murray Mallee	MDD2	E2
Murray Lakes and Coorong	MDD3	E1
Lowan Mallee, Lowan	MDD4	E2
Wimmera	MDD5	E2
Darling Depression	MDD6	E6
Mitchell Grass Downs P1 (MGD1)	Mitchell Grass Downs (MGD)	H
Barkly Tableland	MGD2	N = H; S = G
Georgina Limestone	MGD3	G
South-western Downs	MGD4	G
Kynuna Plateau	MGD5	G
Northern Downs	MGD6	H
Central Downs	MGD7	G
Southern Wooded Downs	MGD8	G
South-western Plateaus & Floodouts (NWH1)	Mt. Isa Inlier (MII)	N = H; S = G
Thorntonia	NWH2	H
Mount Isa Inlier	NWH3	S = G; N = H
West Balonne Plains (MUL1)	Mulga Lands (ML)	W = E6; E = E4
Eastern Mulga Plains	MUL2	E4
Nebine Plains, Block Range	MUL3	E6
Northeastern Plains	MUL4	E4
Warrego River Plains, Warrego Plains	MUL5	E6
Langlo Plains	MUL6	G
Paroo Sand Sheets, Cuttaburra-Paroo	MUL7	E6
West Warrego, Tablelands and Downs	MUL8	G
Northern Uplands	MUL9	G
West Bulloo	MUL10	G
Urisino Sandplains	MUL11	G
Warrego Sands	MUL12	E6
Kerribree Basin	MUL13	E6
White Cliffs Plateau	MUL14	E6
Paroo Overflow	MUL15	E6
Paroo-Darling Sands	MUL16	E6
Eastern Murchison (MUR1)	Murchison (MUR)	N = G; S = E6
Western Murchison	MUR2	G

Table 3 *Continued*

Sub-bioregion name	Bioregion name (code) sub-bioregion codes	Climate code
Northern Complex (NAN1)	Nandewar (NAN)	E3
Inverell Basalts	NAN2	E3
Kaputar	NAN3	E3
Peel	NAN4	E3
Bridgewater (NCP1)	Naracoorte coastal plain (NCP)	E1
Glenelg Plain	NCP2	D5
Lucindale	NCP3	E1
Tintinara	NCP4	E1
Bundarra Downs (NET1)	New England tableland (NET)	E3
Beardy River Hills	NET2	E3
Walcha Plateau	NET3	D5
Armidale Plateau	NET4	D5
Wongwibinda Plateau	NET5	D5
Deepwater Downs	NET6	D5
Glenn Innes-Guyra Basalts	NET7	D5
Ebor Basalts	NET8	D5
Moredun Volcanics	NET9	D5
Severn River Volcanics	NET10	E3
Northeast forest lands	NET11	D5
Tenterfield Plateau	NET12	E3
Yarrowyck-Kentucky Downs	NET13	D5
Binghi Plateau	NET14	E3
Stanthorpe Plateau	NET15	E3
Eastern Nandewars	NET16	E3
Tingha Plateau	NET17	E3
Nightcap	NET18	D5
Round Mountain	NET19	D5
Mitchell (NK1)	Northern Kimberley (NK)	I1
Berkeley	NK2	I1
Scenic Rim (NNC1)	NSW north coast (NNC)	F4
NSW North Coast	NNC2	F4
Upper Slopes (NSS1)	NSW southwestern slopes (NSS)	N = E3; S = D5
Lower Slopes	NSS2	E3
Northern band, Carlisle (NUL1)	Nullarbor (NUL)	E6
Central band, Nullarbor Plain	NUL2	E6
Yalata	NUL3	E6
Ord (OVP1)	Ord-Victoria Plains (OVP)	H
South Kimberley Interzone, Ord-Victoria Plains	OVP2	H
Ord Victoria Plains P3	OVP3	H
Ord Victoria Plains P4	OVP4	H
	Pine Creek (PCK)	I1
Chichester (PIL1)	Pilbara (PIL)	G
Fortescue	PIL2	G
Hamersley	PIL3	G
Roebourne	PIL4	G
Lachlan (RIV1)	Riverina (RIV)	E6
Murrumbidgee	RIV2	E2
Murray Fans	RIV3	E2
Victorian Riverina	RIV4	D5
Robinvale Plains	RIV5	E2
Murray Scroll Belt	RIV6	E6
	Sydney Basin (SB)	F3
Gippsland Plain (SCP1)	Southeast coastal plain (SCP)	D5
Otway Plain	SCP2	D5
Warrnambool Plain (WP)	SCP3	D5
East Gippsland Lowlands (SEC 1)	Southeast corner (SEC)	D5
East Gippsland Uplands	SEC2	E = F3; W = D5
Highlands-Southern Fall	Southeastern highlands (SEH)	D5
Highlands-Northern Fall	SEH2	D5

Table 3 *Continued*

Sub-bioregion name	Bioregion name (code) sub-bioregion codes	Climate code
Otway Ranges	SEH3	D5
Strzelecki Ranges	SEH4	D5
South-eastern Highlands	SEH5	D5
Burnett–Curtis Hills and Ranges (SEQ1)	Southeastern Queensland (SEQ)	E7
Moreton Basin	SEQ2	E7
Southeast Hills and Ranges	SEQ3	F4
Southern Coastal Lowlands	SEQ4	F4
Brisbane–Barambah Volcanics	SEQ5	E7
South Burnett	SEQ6	E7
Gympie Block	SEQ7	E7
Burnett–Curtis Coastal Lowlands	SEQ8	E7
Great Sandy	SEQ9	F4
Simpson–Strzelecki Dunefields P1 (SSD1)	Simpson–Strzelecki Dunefields (SSD)	G
Simpson Desert	SSD2	G
Dieri	SSD3	G
Warriner	SSD4	G
Strzelecki Desert, Western Dunefields	SSD5	G
Central Depression	SSD6	E6
Bulloo Dunefields	SSD7	G
Breakaways (STP1)	Stony Plains (STP)	G
Oodnadatta	STP2	G
Murnpeowie	STP3	G
Peake–Dennison Inlier	STP4	G
Macumba	STP5	G
Sturt Plateau P1 (STU1)	Sturt Plateau (STU)	H
Sturt Plateau P2	STU2	H
Sturt Plateau P3	STU3	I2
Dandarragan Plateau (SWA1)	Swan Coastal Plain (SWA)	E1
Perth	SWA2	E1
Tanami P1 (TAN1)	Tanami (TAN)	G
Tanami P2	TAN2	G
Tanami P3	TAN3	G
	Tasmanian central highlands (TCH)	B1
Tiwi–Cobourg P1 (TIW1)	Tiwi–Cobourg (TIW)	I1
Tiwi–Cobourg P2	TIW2	I1
	Tasmanian northern midlands (TNM)	D5
	Tasmanian northern slopes (TNS)	D5
	Tasmanian southeast (TSE)	D5
	Tasmanian southern ranges (TSR)	B2
	Tasmanian west (TWE)	B2
Victoria Bonaparte P2 (VB1)	Victoria Bonaparte (VB)	I2
Victoria Bonaparte P3	VB2	I1
Victoria Bonaparte P4	VB3	I2
Goldfields (VM1)	Victorian midlands (VM)	D5
Central Victorian Uplands	VM2	D5
Greater Grampians	VM3	D5
Dundas ands	VM4	D5
Victorian Volcanic Plain (VVP1)	Victorian volcanic plain (VVP)	D5
Mount Gambier	VVP2	E1
	Warren (WAR)	E1
Herbert (WET1)	Wet tropics (WET)	I3
Tully	WET2	J1
Innisfail	WET3	J1
Atherton	WET4	I3
Paluma–Seaview	WET5	NE = J1; SW = I3
Kirrama–Hinchinbrook	WET6	I3
Bellenden Ker–Lamb	WET7	J1
Macalister	WET8	J2
Daintree–Bloomfield	WET9	J1
	Yalgoo (YAL)	E2

& Cresswell, 1995). All states used geology, landform, soils and vegetation and some also took climate into account to determine their biogeographical regions (Environment Australia, 2000). In IBRA version 5.1, 85 bioregions and 354 subregions were recognized. While the boundaries of these areas are still being refined, the major landforms and landscape features have been delineated in this scheme.

Spatial extension of the Australian agro-climatic classes

The agro-climatic classification of Hutchinson *et al.* (1992) was a global scheme and accordingly, the manually-drawn spatial boundaries of the climate classes in Australia were of low resolution in the original published world map. In order to clarify the spatial boundaries of the agro-climatic classification, and to make the classification available for application and analysis, over 800 Australian locations from the original classification were used to explicitly re-calculate the spatial extension of the Australian agro-climatic classes. Since these classes are largely controlled by monthly mean climate, and the spatial distribution of monthly mean climate (particularly temperature and precipitation) is strongly controlled by ground elevation (Hutchinson, 1991, 1995), it was appropriate to use a spatial extension method that incorporated a strong dependence on ground elevation.

This was done by fitting thin plate smoothing spline functions of horizontal location and vertically exaggerated elevation to indicator data defined by the original classification of the Australian locations. The indicator data were defined in general as follows. Given N locations $(x_i, y_i, h_i, i = 1, \dots, N)$ allocated to K classes define K indicator data vectors $(z_j, j = 1, \dots, K)$, each of length N with entries $(z_{ij}, i = 1, \dots, N)$ defined by:

$z_{ij} = 1$ if the i th location is in class j

$z_{ij} = 0$ if the i th location is not in class j

The location of each site was defined by setting x_i and y_i to the longitude and latitude of the site in degrees, respectively, and h_i to the elevation of the site in kilometres. Because one degree of longitude or latitude measures approximately 100 km on the ground, this amounts to exaggerating the elevation of each site by a factor of 100. This is the same vertical exaggeration determined in the spatial climate analyses of Hutchinson (1991, 1995). A total of K trivariate thin plate smoothing spline surfaces $(f_j, j = 1, \dots, K)$ were then fitted to the K indicator data vectors $(z_j, j = 1, \dots, K)$ by minimizing

$$\sum_{i=1, N} (f_j(x_i, y_i, h_i) - z_{ij})^2 + \rho J_2(f_j)$$

for each j where $J_2(f_j)$ is a measure of the roughness of the function f_j in terms of an integral of second order partial derivatives of f_j , and ρ is a positive smoothing parameter that controls the amount of data smoothing (Wahba, 1990). A single smoothing parameter ρ was chosen in this case to minimize the total generalized cross validation (GCV) over all K surfaces. This gave rise to a consistent level of data smoothing over all K surfaces.

The class at an arbitrary location x, y, h over the Australian continent could then be determined as the class j for which $f_j(x, y, h)$

was the maximum amongst all values $f_k(x, y, h)$ ($k = 1, \dots, K$). Thus, a regular 0.025 degree grid of class values could be calculated over the entire Australian continent by using the 0.025 degree regular grid digital elevation model (DEM) of Australia derived by Hutchinson and Dowling (1991). The minimum GCV trivariate spline surfaces were calculated and interrogated in this way using specially modified procedures from version 4.3 of the ANUSPLIN package (Hutchinson, 2004). An approximate spline procedure employing 400 knots derived from the more than 800 data points used. The approximate spline procedure permitted use of all data points but significantly reduced the computation time by simplifying the structure of the fitted spline function. This is permissible provided that the signal, or number of degrees of freedom of the fitted spline is significantly less than the number of knots (Hutchinson, 1993, 2004). In this case, the signal of about 180 was very acceptable.

Initially, this procedure was applied to indicator data for the 24 agro-climatic classes in which there existed at least one corresponding point location in Australia. The initial analysis and extension over the Australian DEM yielded no or very small numbers of grid points for six of these classes. Data points in these six classes were removed from later analyses. This agreed with the original hand drawn global delineations that omitted the same classes from the Australian analysis. The initial spline analysis also revealed several errors in station locations and deficiencies in some remote coastal areas on Cape York Peninsular with very few data points where the analysis failed to accurately delineate known areas of climate classes J1, J2 and I3. Errors in station locations were corrected and 23 points in these classes were estimated using expert local knowledge and added to the data set. Similarly, five points in remote arid locations around the Gulf of Carpentaria in class H were estimated and added to the data set to better delineate the boundaries of this class with classes G and I2. These five points had very little impact on the alignment of the classes with the IBRA regions, and are in an area that is too dry to support cropping. Apart from the classes on Cape York Peninsula, the boundaries of classes that support cropping are well supported by the available data points. After all data deletions and corrections were made, and the estimated 28 points were added to the data, a total of 822 points were submitted to the final analysis. These points belonged to the 18 classes described in Table 2 and plotted in Fig. 2. The spatially extended agro-climatic classes are shown in Fig. 3. Figure 2 also shows that the boundaries of the spatially extended classes agree closely with the point data. The additional points had virtually no impact on class boundaries away from the areas where the points were added. Similarly, the removal of the six classes had virtually no impact on the derived class boundaries.

Integrating the schemes

The spatially extended agro-climatic regions were overlaid on the map of the bioregion and subregional boundaries and each IBRA subregion was assigned to the climate class that occupied the largest portion by area of the subregion. The assignment of each subregion was then manually checked. In some cases, subregions

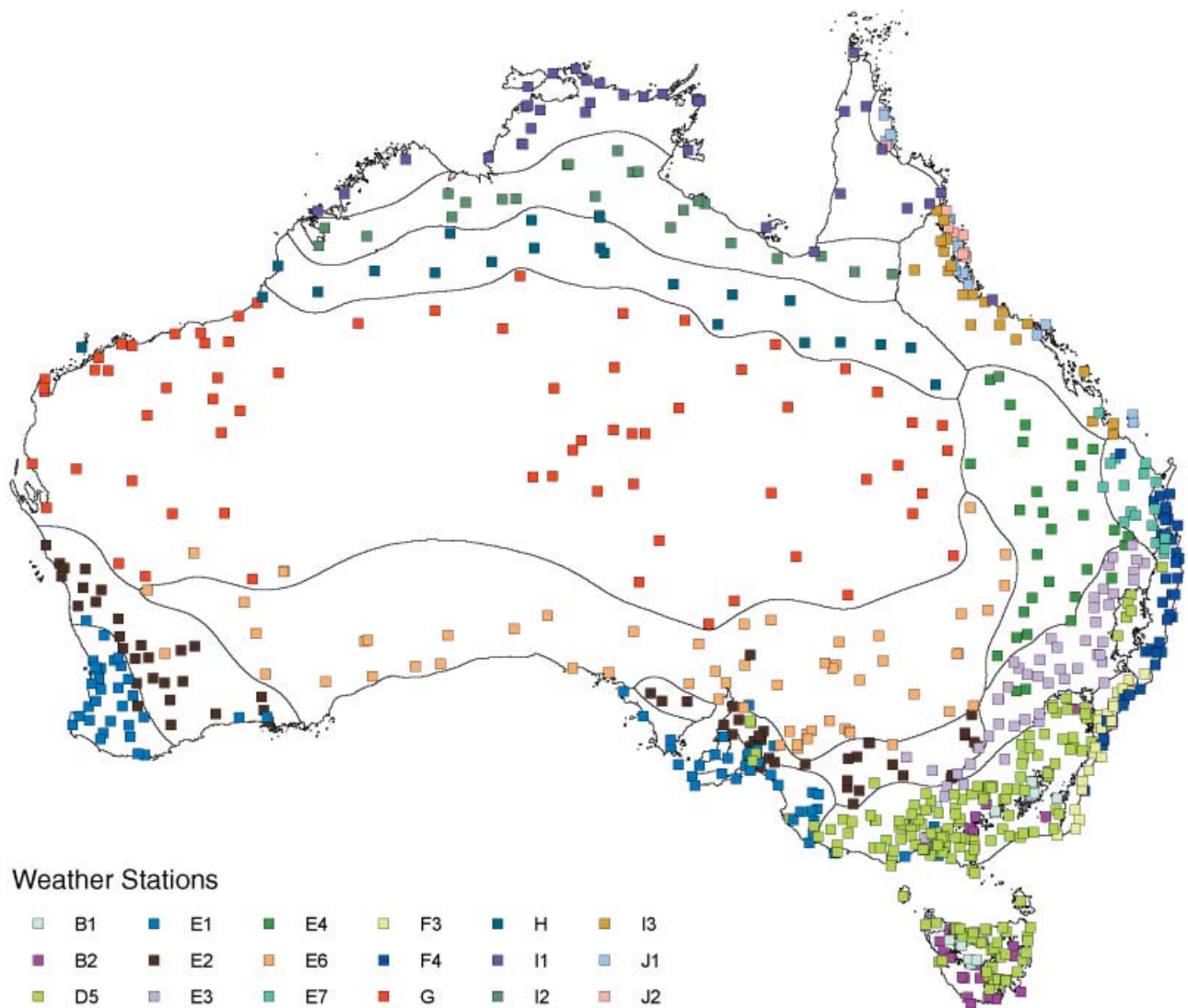


Figure 2 Location of 822 weather stations used in the agro-climatic classification. Colours indicate the agro-climatic classes (as described in Table 2) to which each weather station was classified. Black lines indicate the boundaries of the 18 agro-climatic classes as determined by topographically dependent thin plate smoothing splines.

were then assigned to two classes if major class boundaries divided them equally, but on the whole, the integrity of the subregions was maintained by allocating them to a single climate class.

RESULTS

The automated trivariate spline analysis used to spatially extend the agro-climatic classes gave rise to appropriately smooth class boundaries consistent with the point data, as shown in Fig. 2, and the level of detail appropriate for a global climate classification. The map shown in Fig. 3 was mostly in close agreement with the original hand-drawn global map (Hutchinson *et al.*, 1992) but notably identified significant spatial extent of class D5 in the New England highlands in northern New South Wales. This was neglected in the original hand drawn analysis because the extent of D5 was obscured by the small number of corresponding locations in this area. The automated analysis similarly

refined the spatial extensions of the highland classes B1 and B2 in the southeastern mainland and in Tasmania. It also clarified the locations of the classes F3 and F4 along the New South Wales coast adjacent to the Great Dividing Range. All of these refinements are directly resulting from the incorporation of strong elevation dependence in the automated analysis. Of direct significance for the application here, the topographic dependence of the revised class boundaries simplified and facilitated the integration of the climate classes with the IBRA subregions in highland areas.

The 18 climate classes of the revised map shown in Fig. 3, belonging to the eight broad categories that occur in Australia, are described in Tables 1 and 2. The alignment of each IBRA subregion into these classes is given in Table 3. The alignments have been adjusted where necessary to allow for mismatches between the climate classes and the IBRA subregions. The map of climate boundaries aligned to bioregions and subregions is illustrated in Fig. 4. Fifty-two bioregions were allocated entirely into one of the

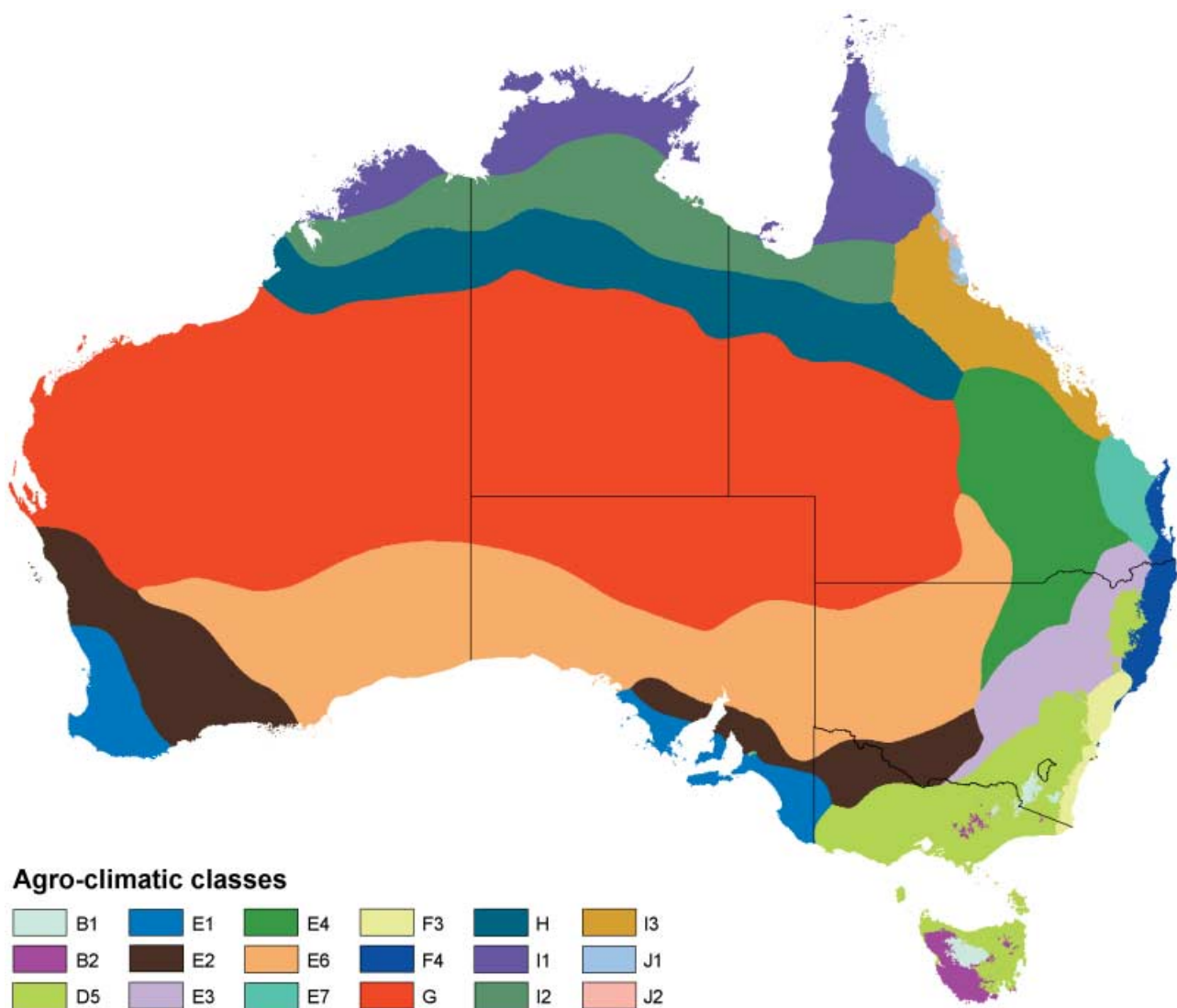


Figure 3 Spatial extension of the 18 agro-climatic classes in Australia, by fitting thin plate smoothing spline functions of horizontal location and vertically exaggerated elevation to indicator data defined by the original classification of the 822 Australian locations.

18 climate classes. The remaining 33 had subregions falling into two or more classes. In deciding whether to divide subregions into more than one class, we tried to be conservative. However, 22 of the 354 subregions were subdivided into two classes to reflect climatic boundaries more accurately (Fig. 3, Table 3).

DISCUSSION

The global agro-climatic classification of Hutchinson *et al.* (1992) was employed in this analysis because it is well-documented and has a moderate number of classes that are closely aligned with natural vegetation formations and common land uses. It also places the Australian classes in global context. It differs from the Köppen scheme and later variants of the Köppen scheme by relating the classes directly to the dynamics of plant growth. The growth index in particular, effectively integrates the combined effects of temperature and soil moisture. The classification is also defined objectively by the natural associa-

tions of the observed climate locations rather than by being specified in a 'top-down' manner by prescribing particular ranges of climate values. Nevertheless, the classification gave rise to a hierarchy of groups with the broadest divisions based on temperature and moisture in a similar fashion to the principal divisions of the Köppen classification. The classes can also be associated with natural vegetation formations, the basis of the original Köppen scheme.

One of the more obvious differences with the Köppen classification is a northward shift of the main desert region of Australia. This is presumably driven by the higher evaporation rates in northern Australia and their impact on the moisture and growth indices. The shift appears to be consistent with the distribution of hummock grasslands in Australia according to the 1988 natural vegetation map of Carnahan (National Land and Water Resources Audit, 2001c). The climate classification identifies a hot/dry transition zone between the desert and the hot seasonally wet/dry regions in northern Australia. It also distinguishes

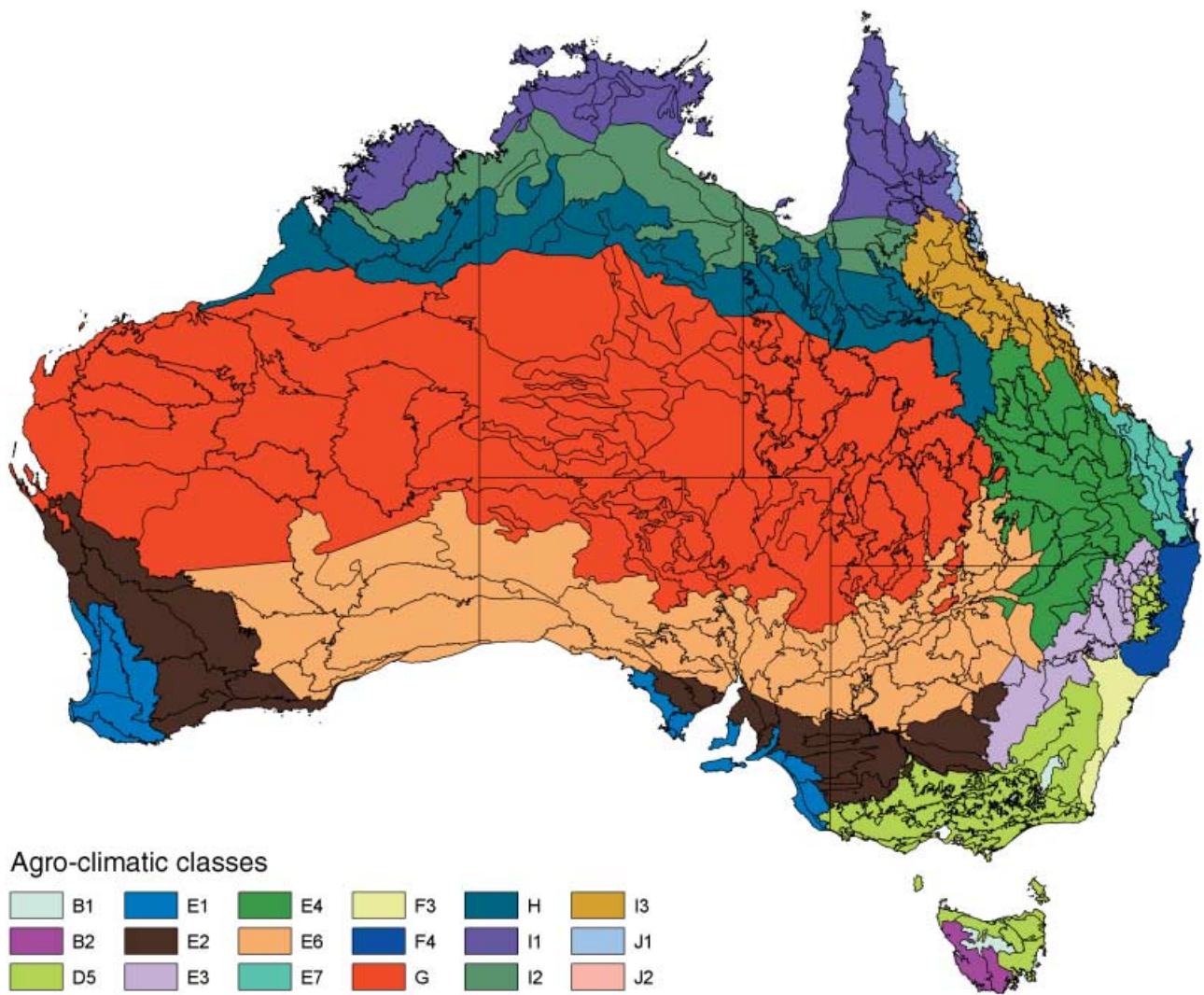


Figure 4 The agro-climatic classes as defined in Figure 3, with boundaries aligned to IBRA bioregions and subregions as detailed in Table 3.

between the southern dry summer and the northern dry winter regions fringing the desert. These differences have some parallels with the modified Köppen scheme described by Stern *et al.* (2003), although that scheme retains the more southerly distribution of the desert.

The application of spline methods to classification problems, in a similar fashion to the method previously described, is well established in the statistical literature (Hastie *et al.*, 2001). The novel feature here is the use of elevation as a predictor to establish class boundaries that are in accord with the strong topographic control on surface climate. It played a significant role in clarifying the class boundaries across Australia from a limited number of sample points. It also facilitated the integration of the resulting climate classes with the IBRA subregions in highland areas. Clarification of the spatial extent of the cool wet zone D5 in highland areas in northern New South Wales has significance for agriculture. Sweeney and Davies (2004) have noted that D5 is closely aligned with areas of higher quality of olive oil production.

Using the classification

The use of bioregions enables boundaries to reflect major changes in biophysical attributes that may have more significance than relying on the climatic analysis alone. Ideally, a climate analysis such as the one presented here could have been performed as part of the IBRA process, as climate may have provided a better delineation of some bioregions or subregions. The ultimate value of the classification will lie in two areas: first, that users will be able to classify specific locations into climate classes with ease, and second, that a small enough number of meaningful classes has been identified. We have tried to address the first through the use of bioregions to define climate boundaries. These are currently being used as a framework for some by the National Land and Water Resources Audit (Morgan, 2001; National Land and Water Resources Audit, 2001c). We have tried to minimize the use of subregions to delineate boundaries because the subregional boundary data are not yet freely available.

The critical link for the use of the classification will be the availability of maps of appropriate scale for users to classify localities to bioregions and subregions (i.e. to be able to identify localities to the regions listed in Table 2). Currently, this is available for bioregions but not yet for subregions. An individual wishing to allocate a particular landscape to an agro-climatic class may be able to identify these using the map or the table, which provide subregion names. Bioregional boundaries and their updates can be viewed at <<http://www.ea.gov.au/parks/nrs/ibra/index.html>> and more detailed maps can be viewed through the mapmaker facility of the Australian Natural Resources Atlas (<http://audit.ea.gov.au/ANRA/atlas_home.cfm>). The 0.025-degree grid defining the Australian agro-climatic classes as shown in Fig. 3 is also available directly from the first author.

In terms of landscape function, our aligned climate classes should reflect major differences in land use patterns and landscape sensitivity to human impacts. In reality, the potential for dysfunction is difficult to determine, and land use and expression of dysfunction tend to be highly related. For example, the most extensively cleared areas (Morgan, 2001), which align most closely with the Mediterranean, temperate subhumid and the two subtropical categories (Fig. 3), have the most extensive areas of forecasted dryland salinity (National Land and Water Resources Audit, 2001b). The 'temperate cool-season wet' climate contains significant areas of retained forest in elevated regions, where salinity hazard is low. The 'dry' region lacks excess rainfall that could contribute to elevated watertables. Although we can suggest differences between our categories, ultimately they represent hypothesized differences, whose utility can only be tested through usage and their contribution to generalizations in landscape ecology and management.

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