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Paleoclimate studies and natural-resource management in the Murray-Darling Basin II: unravelling human impacts and climate variability

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The management of the water resources of the Murray-Darling Basin (MDB) has long been contested, and the effects of the recent Millennium drought and subsequent flooding events have generated acute contests over the appropriate allocation of water supplies to agricultural, domestic and environmental uses. This water-availability crisis has driven demand for improved knowledge of climate change trends, cycles of variability, the range of historical climates experienced by natural systems and the ecological health of the system relative to a past benchmark. A considerable volume of research on the past climates of southeastern Australia has been produced over recent decades, but much of this work has focused on longer geological time-scales, and is of low temporal resolution. Less evidence has been generated of recent climate change at the level of resolution that accesses the cycles of change relevant to management. Intra-decadal and near-annual resolution (high-resolution) records do exist and provide evidence of climate change and variability, and of human impact on systems, relevant to natural-resource management. There exist now many research groups using a range of proxy indicators of climate that will rapidly escalate our knowledge of management-relevant, climate change and variability. This review assembles available climate and catchment change research within, and in the vicinity of, the MDB and portrays the research activities that are responding to the knowledge need. It also discusses how paleoclimate scientists may better integrate their pursuits into the resource-management realm to enhance the utility of the science, the effectiveness of the management measures and the outcomes for the end users.

KEY WORDS: southeastern Australia, climate change, wetlands, tree rings, speleothems, water resources, climate reconstruction.

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INTRODUCTION

Determining how much of the Millennium drought (1997–2010) in southeastern Australia was caused by natural, decadal-scale variability and/or anthropogenic climate change projected for the mid-latitudes of the globe has been the focus of major research. Future climate change will influence the availability and quality of freshwater resources in the Murray-Darling Basin (MDB), land cover, and ecosystem diversity, stability and resilience. Understanding responses to past environmental change provides insights for long-term sustainable development and management.

Paleoenvironmental and paleoclimate data can be used to infer how biological and environmental systems have responded to past climatic perturbations (e.g. in terms of water quality and freshness and seasonality of rainfall). For example, climate changes between glacials and interglacials have been shown to impact on ecosystems; however, following these rapid changes, systems had the chance to recover during periods of stability (Jones *et al.* 2000). Processes associated with land degradation (e.g. salinity and erosion) have also occurred as a result of climate change. For example, following a relatively wet phase from 34–26 kyr BP, salinity affected large parts of the MDB as aridity accompanied the onset of the glacial maximum some 20 kyr ago (Bowler & Wasson 1984). Increased evaporation, combined with a high water-table and reduced vegetation cover, led to the concentration of salt in the groundwater. Over large parts of the MDB, saline groundwater is actively discharged into a number of lake basins as shown by relict hyper-saline groundwater and subsurface gypsum deposits. These early periods of erosion and salinity were caused by natural processes and took hundreds or thousands of years to recover. Today similar problems exist caused by land-use change in little over 100 years, which has resulted in the loss of productivity in natural and human systems and compounding problems associated with climate change. Understanding the impacts of past climate changes on vegetation and salinity will contribute to our knowledge and ability to manage these sensitive systems, particularly under a changing climate (Jones *et al.* 2000).

The paleorecord has demonstrated that non-linear responses occur when critical thresholds, within these systems, are exceeded. Our understanding of threshold changes for many global systems is limited, and Australia is no exception. Coupled with natural climate variability, the anthropogenic modification of both the climate and environment (reducing the resilience of many ecosystems) may cause further thresholds to be crossed, beyond which lie alternative system states (Figure 1). Only through the careful analyses of similar changes in the past can scientists, natural-resource managers and policy makers understand the potential challenges posed by future changes.

Paleoenvironmental research of the most recent 2000 years provides context and allows the range of natural climate variability to be estimated under boundary conditions similar to the present day. Currently, projections concerning the trends, significance and consequences of natural climate changes, and the modulation of the climate and environment by anthropogenic forcing, rely on the functioning of earth-climate system models (Jones *et al.* 2000). To date, models applied to the Southern Hemisphere have not been well validated owing to the lack of sufficient regional syntheses of paleoclimate data, and those for the Northern Hemisphere tend to misrepresent changes in the Southern Hemisphere (Harle *et al.* 2007). Reliable, well-dated, high-resolution paleoclimate data can provide a critical test of global circulation models. Such paleoenvironmental and paleoclimate research within the MDB has the potential to provide an extension to the baseline for efficient long-term management of natural resources available from instrumental records covering the past 100–150 years (Olago & Odada 2004; Mills *et al.* 2013b). Knowledge of long-term natural climatic variability is essential for understanding the nature and context of historical change and present conditions now being forced by anthropogenic factors.

There are, potentially, several climate and environmental proxy records available within the MDB, most notably: tree rings, terrestrial wetland sediment archives and terrestrial morphology. In addition, many key sites with high temporal resolution (annual to decadal) for understanding climate changes within the

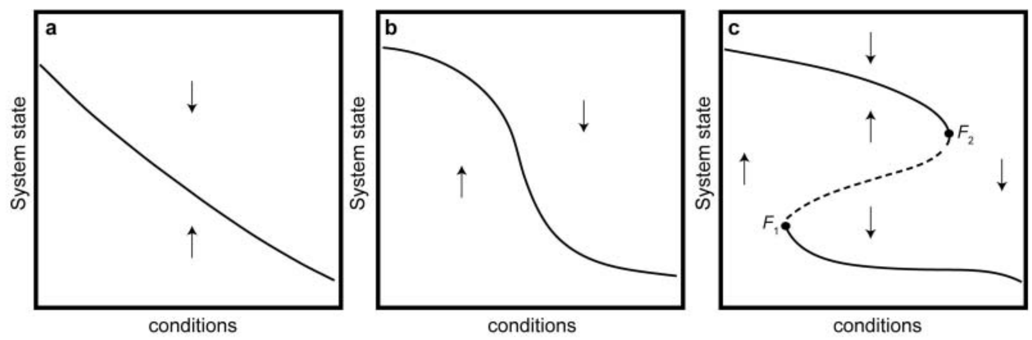

Figure 1 Schematic representation of ways in which the equilibrium state of a system can vary with changing environmental conditions, such as nutrient loading exploitation, or a rise in temperature. Some systems may respond to environmental changes smoothly (a), or can respond to some threshold condition (b). In some instances, when thresholds are crossed, the system can have two alternative equilibria (c), separated by an unstable equilibrium (dashed line), which separates the two alternative stable states. Redrawn from Scheffer & Westley (2007).

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MDB lie on the margins of the MDB catchment (e.g. speleothems and lake sediment archives). These sites are well placed to document the various external climatic regimes that influence precipitation and temperature over the MDB. Improving the spatial coverage of paleoclimate data will ultimately enhance our knowledge of the effects of high impact events such as fire, drought, storms and floods (Harle *et al.* 2007; Battarbee & Binney 2008).

This paper provides a review of the high-resolution evidence for climate and catchment change and its relevance to natural-resource management within the MDB. The aim is to provide up-to-date information on the suite of paleoclimate and paleoenvironmental data available within eastern Australia that is directly relevant to the understanding of climate change and variability across the MDB through time. The recent drought, and subsequent flooding and fire events, have focused scientific, public and media attention on intrinsic climate variability, and the confounding effect of human activity within sensitive catchment systems, a review of this kind is pertinent in understanding how land managers and policy holders can move forward under the current climate stress, especially in terms of water resource management. There are many policy and research reviews that make statements about future planning of water resources, but which give little consideration to long-term and future climate change (Gell *et al.* 2012; Reeves *et al.* 2013). A companion paper (Mills *et al.* 2013b) provides a lower-temporal resolution, longer-term paleoclimate perspective to the MDB and surrounding region, and reviews a range of paleoclimate proxies which provide the geological context to current and future changes in the Basin.

THE PALEORECORD AND NATURAL-RESOURCE MANAGEMENT

In order to manage natural systems under a changing climate, evidence is required to place the contemporary condition in the context of its response to its long-term climate and catchment history (Gell *et al.* 2012). The paleorecord provides evidence of past responses to changing hydrological regimes and can be used to: (a) understand if a shift in regime has occurred; (b) assess whether the system is operating within its historical range of variability; and (c) ascertain which systems are at risk of regime change.

Evidence of long-term changes to over 40 wetlands across the MDB illustrate the impact of catchment modification and river regulation on waterways, and how anthropogenic changes overwhelm the measurable impact of recent climate change and variability. For example, sedimentation rates and changes in water quality exceed those that could be attributable to climate change and natural variability alone. Contemporary restoration measures include environmental watering or lake level drawdown to re-establish variability in a regulated system (Alexander *et al.* 2008).

Lake and wetland sediments, and tree rings, also archive evidence for past fire regimes. The integration of many records of fossil charcoal and fire scars under the Global Palaeofire Database, provides evidence for the link between climate and the prevalence of fire, spatial variability in this relationship, evidence of any departure of present fire regimes from the historic range, and give context to assess the appropriateness of fire management policies and actions (Marlon *et al.* 2008, 2013; Mooney *et al.* 2011; Daniau *et al.* 2012; Power 2013).

Wetlands of the MDB

Paleoliminological evidence from selected wetlands across the MDB show considerable stability in conditions in the centuries leading up to European settlement (Ogden 2000; Reid *et al.* 2002; Gell *et al.* 2005a, b; Fluin *et al.* 2007). These sites show abrupt changes in conditions soon after settlement. Changes inferred from microfossil remains include increasing salinity, as early as the 1880s, and sustained increases in pH, from an extended baseline of slightly acid conditions to alkaline. Increased sediment flux, which has occurred owing to increased catchment flux or increased net accumulation, is a feature of many systems (Gell *et al.* 2009).

From the late 1880s, the liberation of fine sediments has led to shifts from earlier clear water, aquatic macrophyte-dominated communities to turbid, phytoplankton-dominated systems evident today (Ogden 2000; Reid *et al.* 2007; Reid 2008; Gell 2010; Grundell *et al.* 2012). The regulation of the catchment through the construction of weirs established this switch in most river-linked wetlands driving an almost universal dominance of phytoplankton (Gell *et al.* 2005a, b, 2007; Gell & Little 2006; Reid *et al.* 2007; Reid 2008; Grundell *et al.* 2012). Several, seemingly non-impacted, sites have increased in salinity (Gell *et al.* 2007). Wetlands have suffered from multiple stressors of salinisation, sedimentation and eutrophication owing to surface processes simultaneously releasing increased fluxes of sediments, salts and sediment-bound nutrients from catchments (Gell *et al.* 2012).

Regulation of flow and pool level has increased sedimentation rates and led to the reduction in accumulating sulfate salts. These changes, through direct catchment modification, have been exacerbated by the recent extended drought that caused unprecedented falls in river and wetland level, widespread wetland drying and exposure of sediment to oxygenation leading to acid sulfate risk. The direct impact of catchment management seems to have overwhelmed evidence for responses to climate variability and change evident elsewhere.

RESPONSE OF WETLANDS TO WETTING AND DRYING

An array of plants can be found on wetlands across the MDB, including species that are adapted to dry, almost terrestrial conditions, aquatic conditions, and the various intermediate conditions. They may be short- or long-lived perennials, biennials or short-lived annuals, or large woody trees. It is also important to realise that, at times, terrestrial plants may dominate these 'wetlands.'

Drought and flood cycles can be natural, but others have been brought about by anthropogenic activity and this is when sustained changes to the vegetation are likely to occur. When water levels drop, or the wetland dries, plants can persist in several ways: (a) as growing plants that are drought tolerant; (b) as drought resistant

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tubers or fragments in the soil; or (c) as seeds in a soil seed bed. If, and when, a wetland floods again the drought-resistant species are refreshed and the tubers and seeds are stimulated to grow.

Changes in the river red gum (*Eucalyptus camaldulensis*) woodlands in the Booligal wetlands on the Lachlan River are signifying the decline in the ecological health of rivers and their floodplains (Armstrong *et al.* 2009). This species can live for hundreds of years and has survived long periods of drought in the past, but the impacts of river regulation/diversion, and the current drought, have caused high tree mortality along the rivers and in some swamps and marshes.

In the Booligal wetlands the range of flows has halved with river regulation—low flows have increased and the number of periods with zero flow has decreased (Armstrong *et al.* 2009). With increased water extraction following regulation the frequency of large floods to the wetlands has decreased by 50%. The number and duration of key, flood-forming flows have decreased by 40%, and the seasonality of flows has changed. As a consequence, the estimated tree canopy cover has decreased by 85% from 1993 to 2008, a decline that has accelerated in the last three years. In contrast, 'control' red gums, although affected by the drought with a recent loss of canopy cover, remain mostly alive. Flood events are needed every three years to sustain healthy river red gum trees; they are also needed for germination and to ensure successful seedling survival and recruitment. While seeds are held in the aerial seed bed for a minimum of two years, the volumes of seeds in stressed trees are much reduced.

The response, to inundation, of other wetland plants has been investigated in the Central Murray region (Alexander *et al.* 2008). Here, many temporary wetlands would have received water every 1 in 5 years under natural conditions, with large floods 1 in 10 years. As many of the wetlands in the Central Murray region have not received water for 30 years, their seed bed composition may have changed drastically owing to the lack of seed input, with the potential loss of diversity revealed once these wetlands are re-flooded. The response of plants was tested at 21 wetlands that had not been inundated for 10 years by monitoring response after inundation for 3 months. The majority of wetlands showed an increase in native aquatic plant cover, no increase in introduced aquatic plant cover, and a decrease in the cover of non-aquatic plants. Overall, nine wetlands registered increases in native aquatic species cover after flooding. This highlights that the natural recovery potential remained, at least partially, intact despite prolonged periods without flooding. However, some sites did not show increases in the cover of native aquatic plants. Many wetland plants have a persistent, long-lived seed bed. After prolonged drying, germination failed in more than 50% of pre-existing wetland species, even after a period of inundation, suggesting a decline in the seed bed. Watering of long-dry, temporary wetlands that were dominated by terrestrial species can result in increased cover of aquatic species, with wetlands showing a high degree of compositional individuality. Although some wetlands may have reduced biodiversity owing to extended drought, Alexander *et al.* (2008) suggested that environmental flows could be used to promote and maintain biodiversity. This remains dependent on the natural flooding regime and availability of environmental water in the future, both of which are dependent on future climate.

FIRE

The record of fire, detected by quantifying sedimentary accumulations of charcoal, provides evidence for the controlling influence of glacial–interglacial cycles (Lynch *et al.* 2007), the initial impact of indigenous people on the landscape and the use and frequency of fire by post-European communities. Prior to the arrival of people fire was influenced by the availability of fuel and the dryness of vegetation to enable ignition. In wet forests, charcoal increased in conjunction with drier, glacial phases (Kershaw 1986) that caused drying of fuels, which allowed and sustained burning. In drier biomes increased rainfall permitted expansion of woody vegetation providing fuel to sustain fire, and so high charcoal fluxes have also been associated with warmer interglacial periods.

Several records show increased charcoal with the impact of indigenous people, at levels that appear to override the influence of climate, or occurred simultaneously with El Niño–Southern Oscillation (ENSO) variability to affect vegetation change. The causative relations are however, unclear as in some instances charcoal peaks lag vegetation change, and in others they precede it (Kershaw *et al.* 2007). Holocene charcoal records show variability, in accord with temperature variations (e.g. Bickford & Gell 2005), attesting to the continued control of climate on fire regime. High effective rainfall through the mid-Holocene appeared sufficient to suppress much fire activity across southeastern Australia despite little change in vegetation (Lynch *et al.* 2007). Evidence exists for increased burning associated with the late Holocene intensification of human activity, although this may be attributable to a return to increased climatic variability. Despite this, there is no demonstrable link between human occupation of the Sydney Basin and charcoal deposition. Here, there has been an historic control of climate on fire, mediated by the regional climate–vegetation relations, with additional fire linked to transitional phases of climate and vegetation change (Black & Mooney 2006). In particular, there was a steady decline in burning to a recent minimum during the Little Ice Age with widespread increase with post-industrial warming.

Early European settlement saw widespread increase in the use of fire in forests attributable to the management regime of settlers (Banks 1988; Gell *et al.* 1993; Bickford *et al.* 2008). Through the 20th century there was a global reduction in charcoal accumulation (Marlon *et al.* 2008) that has been attributed to the increased proportion of land modified for agriculture.

The control of climate on past fire regimes raises the prospect of more frequent, more widespread and more intense fires under a warming climate. The 2009 wildfires of Victoria attest to greatly increased fire danger ratings as forecast by Williams *et al.* (2001). How this transpires, in terms of fire frequency and intensity, is

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mediated by a vastly more complex landscape in terms of potential ignition sources, fuel control technologies and vegetation cover more recently, and into the future. While few of these records are from within the MDB, the record of past fire–climate–vegetation relations suggest that warmer, drier climates will encourage fire in forested landscapes but that drier biomes may experience less burning where drying, or humans, lead to reduced fuel.

Fire in the tall, wet, ash-species (e.g. *Eucalyptus regnans*, *E. delegantensis*, *E. nitens*) forests that border the southeast of the MDB leads to substantial reductions in water yield. The model of Kuczera (1987) attests to reductions in the order of 50% of pre-fire yields attributable to increased evapotranspiration of the rapidly regenerating eucalypt stand. This maximal effect is attained at around 25 years post-fire, and pre-fire yields may not return for a century. This impact has been demonstrated from paleoecological evidence (Wilby & Gell 1994) that has shown wetland response to modelled drying after post-logging regeneration. Such models have also been used to propose substantial reductions in Murray River flows on account of single large fire events (Lawrie & Williams 2004). Fire and vegetation relations therefore, play an important role in mediating the water yield responses to climatic conditions and are critical to understanding water resource availability under variable and changing climates.

HIGH-RESOLUTION PALEOCLIMATE RECORDS WITHIN THE MDB

Climate variability is a major driver of environmental change in the MDB. Effective natural-resource management depends on obtaining high-quality and long-duration, baseline, climate information to enable planning and decision-making that is sufficiently robust and resilient to cope with natural variability, as well as climate change, into the future.

In Australia, the observational meteorological record is relatively short (typically less than 100 years) and is insufficient to capture the full range of multi-decadal to centennial-scale climate variability. However, these data can be extended further back in time through the use of: (a) historical observations made by early settlers and sailors to Australia; (b) paleoclimate proxies of either climate or large-scale drivers of the climate (such as ENSO, Interdecadal Pacific Oscillation) (Verdon & Franks 2007); and (c) climate model simulations. In this section, we consider (i) high-temporal-resolution, paleoclimate proxies derived from archives such as tree rings, speleothems (cave deposits), pollen, corals and lake sediments; and (ii) climate, spatial field reconstructions of meteorological observations using multiple paleoclimate records.

Fine-resolution lake sediments

Lakes accumulate sediment from externally derived (e.g. dust and pollen) and autochthonous material (e.g. microorganisms and carbonate precipitates). The quantity of internal and external inputs into lakes varies seasonally and annually. Consequently, lake sediment records can provide a highly detailed paleoclimatic record of historical changes in the condition of a lake and its (catchment) vegetation at decadal and centennial scales. Ideal sites for fine-resolution lake records are those with a continuous sedimentary history (i.e. are permanent water bodies) that have multiple proxies preserved in the sediment column, and that have a high sedimentation rate and a relatively small catchment area.

The requirement of a small catchment area excludes many MDB lakes, which are intermittently connected to the Murray River, and therefore may be displaying climate signals transported from distant regions and contrasting climatic influences. A suitable alternative exists in the numerous crater lakes that lie within the volcanic plains of Western Victoria. Climate histories from lakes in the Western Plains region have been correlated with paleoflow regimes of the River Murray (Cann *et al.* 2000; Gingele *et al.* 2007). Fine-resolution, paleoclimate reconstructions based on lake sediments from this region have used proxies such as pollen (Mooney 1997), ostracods (Radke 2000) and diatoms (Gell 1998; Mills *et al.* 2013a). Recent studies, utilising the diatom record (Barr 2010), have indicated greater amplitude wetting and drying phases in the past, than in the historical period, overlaying periods of both extended aridity and humidity.

Speleothems

Speleothems (cave stalagmites, stalactites) develop from water saturated with respect to calcite that drips through the ceilings of caves. There are direct hydrological connections between surface water supply, and the resultant growth and geochemical composition of speleothems; as such, they represent excellent terrestrial archives of high-resolution, paleoclimate information (Treble *et al.* 2003, 2005).

Speleothems have the capacity to preserve records of rainfall variability, which can be precisely dated, and that can extend back tens of thousands of years or longer. Rainfall isotopes (linked to rainfall characteristics, including amount, season and air-mass trajectory) are preserved in the speleothem calcite, as are trace elements reflecting water residence times, the amount of vegetation/soil microbial activity and weathering, all of which are influenced by local hydrology.

Previous reconstructions of paleorainfall (Ayliffe *et al.* 1998; Desmarchelier *et al.* 2000; McDonald 2000) are limited by speleothem growth interval and coarse resolution sampling. However, more recent research in southwest Western Australia, using young stalagmites continuously sampled at high-resolution, has demonstrated the utility of the oxygen isotope and trace-element signals to record the rainfall decrease that has affected this region since 1970 (Treble *et al.* 2003, 2005).

A further discovery stemming from this work was the sensitivity of the speleothem oxygen isotope signal to switches in the source of oceanic moisture (Fischer & Treble 2008). This discovery will enable the reconstruction of long-term, large-scale, atmospheric circulation patterns for southern Australia, which is the focus of ongoing work and being used at sites directly relevant to the MDB (Figure 2). Other emergent research includes a forward model that simulates the response of

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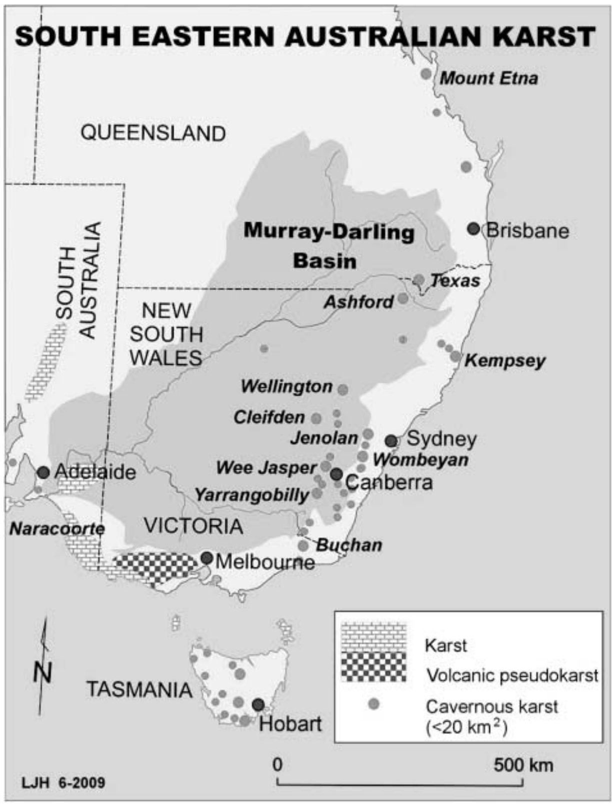

Figure 2 Eastern Australia cavernous karst areas relevant to paleoclimate research. Grey circles indicate active speleothem studies in progress (e.g. Wombeyan, Yarrangobilly, Cleifden) and potential future study sites relevant to the Murray-Darling Basin.

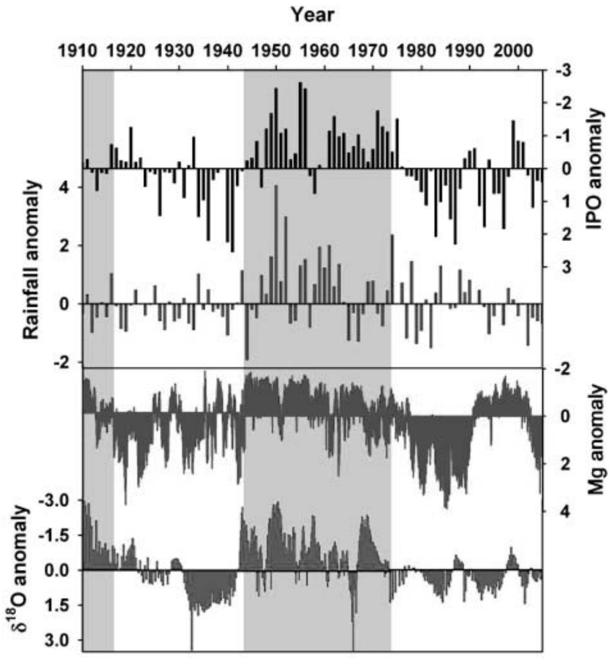

Figure 3 Speleothem oxygen isotope (δ^{18}O) and magnesium (Mg) anomalies (lower two panels) since 1910 compared with the local rainfall and Interdecadal Pacific Oscillation (IPO) anomaly (upper two panels). Except for rainfall, all axes are inverted to show 'wet' at the top and 'dry' at the bottom. The speleothem (stalagmite WM4) is from Wombeyan Caves (100 km SW of Sydney), and was active at the time of collection (June 2005). The site lies adjacent to the eastern margin the MDB. The speleothem δ^{18}O is sensitive to cool-season rainfall amounts, with lower δ^{18}O anomalies generally corresponding to higher rainfall. The Mg is primarily responsive to the amount of water passing through the limestone bedrock above the cave, with higher values corresponding to drier intervals. The grey vertical bands are IPO negative phases, during which time stronger La Niñas are experienced (more intensive floods). The white bands are IPO positive phases, when El Niños are generally stronger (more intensive droughts). Source: McDonald *et al.* (unpublished data).

speleothem proxies to the instrumental climate record. This model is being used as an investigative tool to understand the sensitivity of particular sites and methods to reconstruct climate modes (Fischer & Treble 2009).

Present collaborative research is being undertaken to construct multi-centennial to multi-millennial records of past rainfall from speleothems for two key, water resource regions in southeast Australia: Wombeyan Karst Conservation Reserve (eastern margin of the Basin) and Yarrangobilly Caves (headwaters of the Murray River). Such information will provide critical, baseline, climatic data to better quantify, and provide new insights into, southeast Australia's historic climate variability.

To date, the main outcomes of this speleothem research include: (a) verification that drip water discharge and trace-element geochemistry respond to episodes of drought at Wombeyan Caves (Figure 3) (McDonald *et al.* 2004, 2007); (b) a robust relationship between multi-decadal changes in instrumental rainfall data and stable isotope and trace-element variations in Wombeyan Caves stalagmites, demonstrating that these stalagmites reliably record site hydrology (Figure 4); (c) similar results in the Yarrangobilly Caves, where research is focusing on a comparison between the instrumental record and two 20th-century stalagmites and ongoing cave monitoring to investigate the links between hydrology/drip water chemistry and surface climate (Treble *et al.* unpublished data); and (d) multi-decadal, paleorainfall proxy records, extending at least the past 1000 years, are being assembled from Wombeyan Caves, utilising proven geochemical signatures of wet/dry intervals from 20th century stalagmites.

Given the known sensitivity of the MDB to changes in interdecadal Pacific oscillation, El Niño-Southern Oscillation (Gallant *et al.* 2012), and the wide distribution of karst areas along the eastern margin of the Basin, enormous potential exists for the generation of high-resolution multi-proxy records of paleohydrology. Ayliffe *et al.* (1998) showed how major warm intervals of the past were also periods of reduced moisture.

Dendrochronology

Dendrochronology, the study of tree rings, has been widely used to reconstruct historical variation in environmental conditions. Because trees are widely distributed, long-lived, and often form annual growth rings, they can provide unique insights into inter-annual

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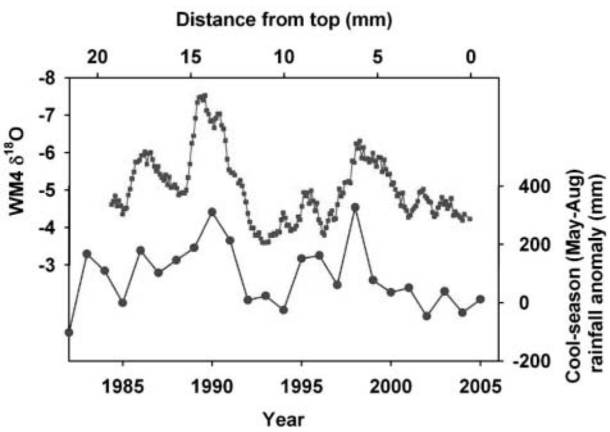

Figure 4 High-resolution oxygen isotope (δ^{18}O) record from the top section of stalagmite WM4 collected from Wombeyan Caves (squares, on a depth scale) and the cool-season rainfall anomaly (circles) for the Wombeyan area. Close association between speleothem properties and instrumental rainfall measurements enable cautious extrapolation back beyond the commencement of weather data collection. Stalagmites can thus act as weather gauges for the past. Extrapolation using this technique is currently underway for the past *ca* 1000 years using older Wombeyan stalagmites. Source: McDonald *et al.* (unpublished data).

variation in growth, mortality and recruitment of native forests.

Where tree growth is limited by climate (e.g. temperature, rainfall), variation in the width, density and/or chemical composition of the annual growth rings can provide insights into climate variability for decades or centuries into the past. Dendrochronology in Australia has lagged far behind that on other continents owing to the preponderance of *Eucalyptus* and *Acacia* species (Brookhouse 2006), which often do not form discernible annual growth rings, and a highly variable climate, characterised by persistent droughts and infrequent, but severe, flooding.

Most dendrochronological research in Australia has focused on using the long-lived conifers of Tasmania (e.g. *Lagarostrobos franklinii*, huon pine; Cook *et al.* 1991), *Phyllocladus aspleniifolius* (celery-top pine; Allen *et al.* 2001), and *Athrotaxis* spp. (king billy pine and pencil pine; Allen *et al.* unpublished data) to reconstruct climate. Recently, however, several tree-ring reconstructions of climate have been published for other areas, including southwest Western Australia (Cullen & Grierson 2009), the Northern Territory (Baker *et al.* 2008; D'Arrigo *et al.* 2008), Queensland (Heinrich *et al.* 2006, 2009) and the Australian Alps (McDougall *et al.* 2012).

Few tree-ring studies have been conducted directly within the MDB owing to the predominance of *Eucalyptus* spp. in the area. While the assumed longevity of river red gum (*E. camaldulensis*) suggests that it may hold dendrochronological potential (Argent *et al.* 2004), recent radiocarbon dating has demonstrated severe difficulties in achieving accurate dating of red gum tree rings.

One of the more promising species is snow gum (*E. pauciflora*). In the Australian Alps, snow gum holds genuine potential for reconstructing climate and river-flow variability in the catchments of the MDB and its surrounds (Brookhouse *et al.* 2008; Brookhouse & Bi 2009). In addition, spatially gridded drought data for eastern Australia may enable reconstruction of MDB hydroclimatic conditions from tree-ring chronologies located within the Australian region, but not inside the MDB (e.g. D'Arrigo *et al.* 2008).

Tree rings can also be used to reconstruct historical disturbance regimes and stand- and landscape-scale responses to disturbances. Research on the Australian Alps (Banks 1988), the Central Highlands of Victoria (Simkin & Baker 2008) and western New South Wales (Davies & Baker, unpublished data) has shown the potential for using dendrochronology to reconstruct fire histories and fire impacts on complex forested landscapes. These ecological reconstructions have a unique potential to use past forest dynamics to inform future natural-resource management, particularly under uncertain future climatic conditions and fire regimes.

Regional climate reconstructions

A suite of global and Northern Hemispheric multi-proxy reconstructions of climate variations over the past 1000 years has emerged during the last decade. However, global reconstructions suffer from inadequate estimates of Southern Hemisphere variability (Jansen *et al.* 2007; Jones *et al.* 2009), let alone regional climate variability.

Multi-proxy reconstructions of Southern Hemisphere climate variability are limited by a relative lack of data and research effort in comparison with the Northern Hemisphere and there is a clear need to generate and synthesise paleoclimate data in the Australian region (Harle *et al.* 2007). Although efforts have been initiated to reconstruct Australia-wide, mean annual temperatures, this has only been achieved for the last glacial termination and with limited success (Turney *et al.* 2006, 2008).

Recently, D'Arrigo *et al.* (2008) showed that experimental, spatial field reconstructions of drought variability for the Australasian region, using four tree-ring and coral records for the 1787–2002 period, were able to successfully capture around 40% of observed variability in the Palmer Drought Severity Index. Similarly, Nicholls *et al.* (2006) showed that around 40% of observed Australian mean annual maximum temperature variability could be estimated from three paleoclimate records, suggesting that even a small number of proxies for the Australian region may be able to provide a useful reconstruction.

Researchers at the University of Melbourne have recently completed research that directly targeted the southeast Australian region, including the MDB (http://climatehistory.com.au). This project aimed to fill a critical gap in Australian climate science by assembling a range of pre-20th century data to develop annual, climate reconstructions (temperature, rainfall, atmospheric pressure) for southeastern Australia for the past 200–500 years.

Results from this research suggest that it is possible to provide annual rainfall reconstructions for the southeastern Australia and River Murray streamflow using a limited number of records from the Australasian region (Gergis *et al.* 2012; Gallant & Gergis 2011). This confirms the conclusion of the team's previously developed ENSO reconstructions that considerable skill is achievable

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using a few, well-dated proxy records back to A.D. 1525 (Gergis *et al.* 2006; Braganza *et al.* 2009; Gergis & Fowler 2009). For example, Braganza *et al.* (2009) showed that up to 52% of observed ENSO variability, which greatly influences climate variability in the MDB region, could be captured by as few as eight paleoclimate records. These results were utilised to develop an extended rainfall index for NSW from 1788 to 2008 using documentary and early instrumental data from the region (Fenby & Gergis 2012; Gergis & Ashcroft 2012) .

Comparing regional temperature, rainfall and pressure reconstructions from the southeastern Australia region with independent reconstructions of large-scale climate modes (e.g., ENSO, Southern Annular Mode, Indian Ocean Dipole, Pacific Decadal Oscillation, Subtropical Ridge) will be helpful for characterising the long-term stability of the dominant drivers of Southern Hemisphere climate variability in the Australian region (Verdon & Franks 2007; Murphy & Timbal 2008; Gallant *et al.* 2012) and, more specifically, in the MDB.

Annual reconstructions of pre-20th century climate variability, using paleoproxies, historical documentary records and early weather station data by Gergis (2008) and Gergis *et al.* (2009) were the first to provide spatial and temporal coverage in the Southern Hemishpere that characterises the Australian region. While the limited number of paleoclimate proxies currently available directly from the MDB hampers a specific reconstruction for the area, broad scale climate reconstructions will go a long way towards improving the description of the large-scale, circulation features that influence climate variability in the MDB region.

High-resolution climate records make important contributions towards understanding climate variability and the management of Australia's natural resources by: (a) assisting in the evaluation of contemporary water management policies adopted by government agencies, e.g. the rules determining irrigation allocations by providing a long-term baseline of pre-20th century climatic information that will assist in the evaluation of contemporary water management; (b) testing, calibrating and constraining the reliability of the general circulation and regional climate models; (c) providing opportunities to statistically distinguish intrinsic, natural climate variability from anthropogenic climate change using detection and attribution techniques; and (d) determining the changes in regional rainfall and temperature patterns under a range of future climate change scenarios based on the examination of large-scale atmospheric and ocean circulation patterns, and how these have changed historically, and what such changes mean for regional patterns under a range of future climate change scenarios.

DISCUSSION

To understand future climate changes, modellers need, and demand, better paleoclimate data to constrain their model projections (Kiem & Verdon-Kidd 2011; Gallant *et al.* 2012; Reeves *et al.* 2013). Through understanding how natural systems have varied in the past, within an appreciation of the increasing pressure from human activity within catchments and anthropogenically enhanced climate change, we can work towards a scientific framework on which sound decision-making can be based. The use of paleoscience as a tool for understanding potential future climate changes and managing natural resources is not a new concept (Turney *et al.* 2006; Harle *et al.* 2007); however, past reviews are generic and lack the focus and detail required for the information to be successfully applied to natural-resource management in individual catchments such as the MDB.

While much paleoclimatic research has been undertaken, there remains a paucity of climate records developed across the MDB itself. Most available evidence is from the periphery of the MDB, or in catchments of contrasting geomorphic and hydroclimatological conditions. While marginal sites are relevant to the MDB, there is a need to develop high-quality, high-resolution records of climate change and variability from within the MDB to evaluate the responsiveness of within-basin climates to regional atmospheric circulation patterns, although the development of methods that utilise paleoclimate information external to the target catchment are also now plausible (Ho *et al.* 2013).

There are potentially many records of wetland, river and landscape change available from within the MDB. Sites located in the upper reaches are 'response' sites that record the effect of climate change and variability, to a degree distilled by catchment processes. Many of the sites in the MDB are affected by the influence of anthropogenic catchment changes, so their records contain accounts of changes most relevant to the natural-resource management of the MDB. However, in these sites, particularly those in the lower reaches of the system, distinguishing between climate and catchment drivers can be problematic. This can be overcome by co-ordinating a suite of research endeavours on sub-catchment scales that have climate sensitive archives, usually located in the upper catchment, with matching downstream response sites.

The study of sub-catchments that lie in latitudes sensitive to atmospheric circulation changes could supply managers with information useful for determining the likely response of hydrological systems to shifts in future patterns of rainfall and evaporation by understanding those that have existed in the past. This will then inform debates over appropriate measures to be taken under present and future climate regimes.

CONCLUSIONS

This review identifies several future research needs directed at increasing the capacity of paleoclimate science to better inform the natural-resource policy and management needs of the MDB. While a considerable body of research currently exists on the past climates of southeastern Australia, this has not been collated and validated over large spatial scales. The consolidation of paleoclimate science relevant to natural-resource management in the MDB would allow the assessment of the extent of: (a) data coverage; (b) the reliability of the data; (c) the confidence with which conclusions can be made about past climate change and variability; and (d) the responsiveness of the system to such change.

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High-resolution paleoclimatology can fulfil a recognised management need of agencies like the MDB Authority for extended estimates of regional-scale climate variables by providing estimates of pre-20th-century climate variability. Given the large number of extreme climate events that the region has experienced recently, this review advocates the collection of new paleoclimate data that would allow MDBA management to gain a more detailed understanding of how recently observed changes fit into the longer-term (i.e. pre-instrumental) context of paleoclimate changes, and provide an opportunity for constraining regional climate change projections using extended estimates of natural climate variability. Although such paleoclimatic data should ideally be derived from sites within the MDB, recent work by Ho *et al.* (2013) highlights the potential for regions outside the MDB to yield relevant hydrological information.

There is a perception among the paleoclimate science community that the managers and policy makers have not fully acquired the value of understanding past climate change and variability and its application to the management of natural systems. However, most research on past climatic changes and variability takes the form of peer-reviewed journal articles that are not particularly suited to management needs. As such, while it is clear that better evidence for the historical range of climate variability and the trajectories and cycles of change represents a valuable knowledge base upon which society should evaluate the allocation and management of its water resources, a gap exists between the researchers and the end users. So, there is a clear need for the paleoclimate science community to actively interpret its findings in a manner accessible and relevant to the natural-resource-management community. Improved estimates of past climate variability, and a broader spatial coverage of robust paleoclimate data, will help contextualise future change scenarios and the natural-resource-management measures required to address them. Support for, and so the success of, such a program depends as much upon the researchers engaging with water-resource managers as the managers seeking out evidence upon which to base their policies and practices.

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