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Conservation of an inauspicious endangered freshwater fish, Murray hardyhead (*Craterocephalus fluviatilis*), during drought and competing water demands in the Murray–Darling Basin, Australia

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Abstract. Approximately 40% of Australian freshwater fish species are of conservation concern, largely because of the impacts of river regulation, habitat fragmentation and alien fishes. Murray hardyhead is a threatened fish endemic to the southern Murray–Darling Basin in Australia, which has declined significantly in range and abundance since European settlement. Conservation of the species has relied largely on environmental watering of off-channel wetlands where isolated populations persist. This became problematic during recent drought (1997–2010) because of competing demands for limited water, and resentment towards environmental watering programs from communities that themselves were subject to reduced water entitlements. In response, emergency conservation measures prioritised the delivery of environmental water to minimise applied volumes. Captive maintenance programs were established for fish rescued from four genetically distinct conservation units, with varying levels of breeding success. Several translocations of wild and captive-bred fish to surrogate refuge sites were also conducted. Future recovery of the species should secure existing natural and stocked populations and translocate fish to additional appropriate sites to spread risk and reinstate natural pathways for dispersal. The approach to the conservation of Murray hardyhead during extreme environmental conditions provides insights to inform the management of fishes in other drought-prone regions of the world.

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Introduction

Freshwater habitats are among the most endangered ecosystems worldwide, stemming primarily from human exploitation of and competition for freshwater resources (Sala *et al.* 2000; Malmqvist and Rundle 2002; Duncan and Lockwood 2001; Dudgeon *et al.* 2006; Grafton *et al.* 2013). Anthropogenic disturbances that threaten freshwater fishes include flow modification, water extraction, habitat degradation and the impacts of alien species (Collares-Pereira and Cowx 2004; Dudgeon *et al.* 2006; Jelks *et al.* 2008). Leidy and Moyle (1998) suggested that more than 20% of freshwater fish species are at risk of extinction, whereas 37% of freshwater fish assessed by the IUCN Red List of Threatened Species were recently considered threatened (IUCN 2012).

The Murray–Darling Basin (MDB) in south-eastern Australia includes 21 major rivers, covers an area of over one million square kilometres and is inhabited by at least 46 native freshwater fish species (Lintermans 2007). Since European settlement ~200 years ago, human exploitation of freshwater resources has contributed to the decline in native fish numbers in the MDB to an estimated 10% of pre-European levels, and more than half of the native species are now recognised as rare or threatened (MDBC 2004; Koehn and Lintermans 2012). In particular, river regulation and water extraction for domestic and agricultural use

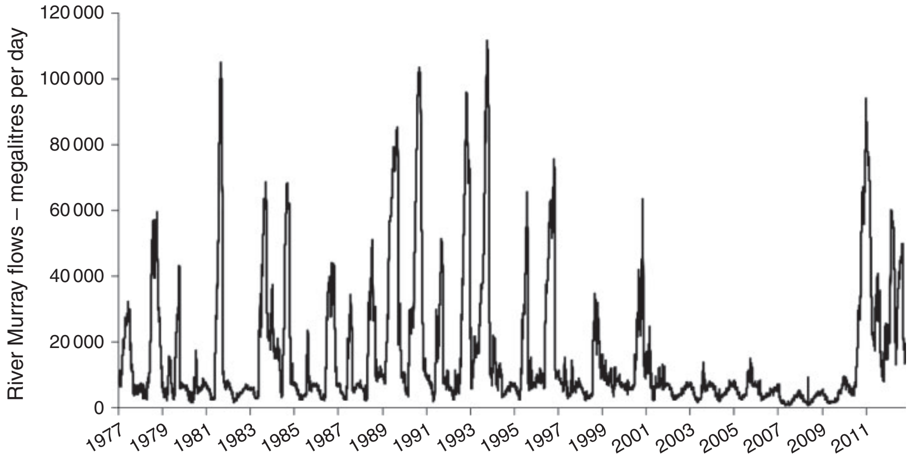

Fig. 1. River Murray flows since 1977 at the Victorian–South Australian border, downstream of major tributary inflows (data courtesy of Water Connect, Government of South Australia).

over the past century have reduced the frequency, duration and magnitude of flood events throughout the MDB (Walker 2006; Pratchett *et al.* 2011; Grafton *et al.* 2013). This modification of the natural flow regime is implicated in the demise of many native fishes through associated impacts on physiology, spawning, recruitment, movement and habitat availability (Gehrke and Harris 2001; Balcombe *et al.* 2011).

From 1997 to 2010, much of south-eastern Australia, including the MDB, experienced severe drought (the Millennium Drought), which resulted in substantially reduced river flows (see Fig. 1, data provided by Water Connect 2012). The impacts of reduced run-off and river flows throughout the drought were exacerbated by human modifications to rivers and their catchments (Lintermans and Cottingham 2007; Bond *et al.* 2008; Wedderburn *et al.* 2012). The effects of the drought were most acute between 2007 and 2010 when extreme water shortages and competing demands for dwindling water (irrigation vs environment) necessitated action by natural resource management (NRM) organisations across the MDB to prevent the extinction of several fish species.

Although the drought ended in early 2010 with the first significant flooding in the lower MDB in over a decade, one of the greatest threats to freshwater fishes in coming decades is predicted to be ongoing reductions in the availability of surface water and riverine flow under climate change (Balcombe *et al.* 2011; Pratchett *et al.* 2011). Climate models project reductions in flows of up to 69% in the MDB (see Grafton *et al.* 2013). Because aquatic species have limited options for escaping warmer water and drier places, in regions where water will become scarcer with climate change, many species will face rising competition with humans for water that remains (Abell 2002). Climate change may compound localised threatening processes and, as such, is expected to have a severe impact on freshwater fish that have a limited range or specific habitat requirements (Morrongiello *et al.* 2011).

Murray hardyhead, *Craterocephalus fluviatilis*, was among the species severely affected by the recent drought in the MDB. As a small-bodied fish (total length <8 cm), Murray hardyhead is endemic to lowland floodplains of the Murray and Murrumbidgee river systems of the MDB (Fig. 2). Although historically common, its range has declined substantially over recent decades (Lloyd and Walker 1986; Morris *et al.* 2001; Ebner *et al.* 2003; Hammer *et al.* 2009; Ellis and Pyke 2010). Ongoing decline is likely to be a consequence of compounding factors, including habitat fragmentation, river regulation, altered irrigation practices (e.g. saline water disposal and improvements in water-use efficiency), interactions with alien fishes and recent drought (Ivantsoff and Crowley 1996; Ellis 2005; Stoessel 2010; Wedderburn *et al.* 2012). Murray hardyhead is listed as *Endangered* under the federal *Environment Protection and Biodiversity Conservation Act 1999* (http://www.deh.gov.au/epbc/index.html, accessed 7 January 2013), *Endangered* under the International Union for the Conservation of Nature (IUCN) Red List (IUCN 2004), *Threatened* under the *Victorian Flora and Fauna Guarantee Act 1988* (DSE 2012) and *Critically Endangered* in South Australia (Hammer *et al.* 2009).

Murray hardyhead is perhaps unfortunate in that its adaptation for survival in marginal drought-prone freshwater habitats has made it particularly susceptible to human processes that affect river hydrology, water quality and the isolation of wetlands across its range (Ellis *et al.* 2012). Furthermore, Murray hardyhead is inauspicious and relatively unknown, with little perceived value economically or recreationally. A common perception of small non-game fishes as 'minnows', and their existence in environments where few persons ever see them, makes mustering public support for their conservation difficult (Sheldon 1988). Such species are not easily protected in societies that have a strongly exploitative relationship with nature, and conflicts between environmental and economic values exist (Ehrenfeld, 1976). For example, reduced flows (primarily resulting from water extraction) and associated habitat destruction have resulted in substantially reduced range for the Rio Grande silvery minnow (*Hybognathus amarus*) in North America (Scharpf 2001). Efforts to save the Rio Grande silvery minnow have culminated in one of the lengthiest legal and political battles in the history of endangered species (Scharpf 2001).

Freshwater-fish conservation programs are commonly reactive, focussing on protection or restoration of small areas of

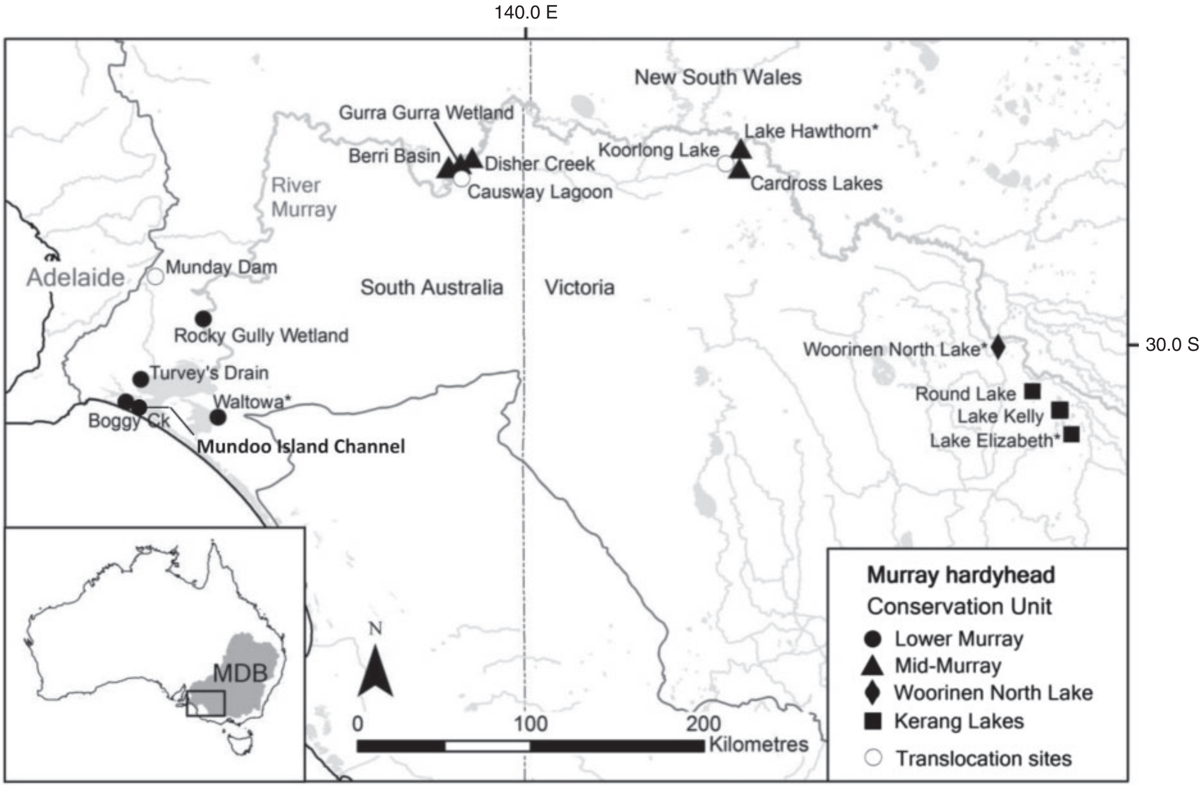

Fig. 2. Locations of remnant and recently extirpated Murray hardyhead populations (2012). Closed symbols indicate allocation of each population to one of four genetic conservation units (Kerang Lakes, Woorinen North Lake, mid-Murray and lower Murray; Adams *et al.* 2011). The Boggy Creek population was a remnant of a significant population in the Hindmarsh Island area (others not shown). Open circles indicate wetlands to which Murray hardyhead have been translocated, and * indicates localities of recent wild extirpations. MDB = Murray–Darling Basin.

habitat and restocking. Where habitat restoration occurs, there is often little consideration of adjacent aquatic and terrestrial ecosystems or the connectivity between river channels and floodplains (Collares-Pereira and Cowx 2004; Dudgeon *et al.* 2006). This has been the case for Murray hardyhead, where conservation management strategies have primarily involved the preservation of small populations, mostly in isolated wetlands, and captive maintenance of subpopulations rescued from threatened sites. Although these strategies may successfully prevent the extirpation of isolated populations, they contribute little to the long-term recovery of the species (Ellis *et al.* 2012).

The aim of the present paper is to summarise current knowledge regarding the biology of Murray hardyhead, detail the management actions undertaken to prevent its extinction during the drought, and identify future threats to population viability. Through this process, we further aim to identify management options that will contribute towards conserving the few remaining populations and the recovery of the species. The information presented in the current paper provides insights for the management of threatened small-bodied fishes in the MDB and other drought-prone catchments worldwide.

Biology of Murray hardyhead

The ongoing decline of Murray hardyhead, which has been exacerbated by drought, has driven research and the generation of knowledge regarding its biology (e.g. Lyon and Ryan 2005; Dixon 2007; Wedderburn *et al.* 2007; Hammer and Wedderburn 2008; Wedderburn and Walker 2008; Stoessel 2010; Ellis 2012). Murray hardyhead has predominantly been recorded in saline lakes, which are moderately acidic to highly alkaline (pH 6.0–10.4), have relatively low turbidity, wide-ranging temperatures (8–34°C) and variable dissolved oxygen concentrations (3.5–25.0 $mg\,L^{-1}$) (Lloyd and Walker 1986; Hardie 2000; Ebner *et al.* 2003; Ellis 2005; Stoessel 2010). Adults have been recorded in salinities as low as 0.4 $g\,L^{-1}$ in Riverglades Wetland in South Australia and as high as 58.9 $g\,L^{-1}$ in Lake Kelly, Victoria (Wedderburn *et al.* 2007; Stoessel 2013). Although this demonstrates that the species can survive in both fresh and saline environments, salinity tolerances may be variable between distant populations (Wedderburn *et al.* 2008) and adults may be more tolerant than early life stages (Dixon 2007). Importantly, when conditions were extremely harsh in the latter stages of the recent drought, the persisting occupied habitats may not have been representative of preferred habitat, but of marginal refugia (Hammer *et al.* 2009; Stoessel 2010).

A schooling species, Murray hardyhead, is typically found in association with submerged aquatic vegetation that provides cover and a spawning substrate (Ebner *et al.* 2003; Ellis 2005; Hammer and Wedderburn 2008). Its diet consists predominantly of microcrustaceans, with larger individuals also eating larger food items such as dipteran larvae (Ellis 2006; Wedderburn *et al.* 2010). Murray hardyhead is a batch spawner, with eggs at various stages of development apparent in mature females (Ellis 2005; Hammer and Wedderburn 2008). The species has a prolonged breeding season from September to March (spring and summer), with peak spawning activity usually from October to November (Ellis 2005). In ideal conditions, individuals spawned early in a breeding season appear able to reach maturity in the same season, and breed themselves as late as March (Ellis *et al.* 2011). The abundance of adults declines at the end of the breeding season, with replacement by the maturing young-of-the-year cohort. This implies that the species is largely annual (populations dominated by 0+ individuals) and heavily dependent on yearly recruitment (Ellis 2005).

Distribution

Although historically common but patchy throughout the River Murray floodplains in south-eastern Australia, the range and abundance of Murray hardyhead has declined significantly over recent years (Lloyd and Walker 1986; Morris *et al.* 2001; Ebner *et al.* 2003; Hammer *et al.* 2009; Ellis *et al.* 2011). Murray hardyhead was described a century ago from specimens collected in North Yanco Creek, near Narrandera in New South Wales (McCulloch 1912), but has not been recorded in the state since 1997 (Schiller *et al.* 1997). Throughout its range, the species is extinct in at least 17 sites at which it has historically been documented (McGuckin 1999; Hardie 2000; Backhouse *et al.* 2008; Ellis and Pyke 2010; Bice *et al.* 2011; Stoessel 2013; Wedderburn and Barnes 2012).

Recent wild extirpations in Victoria have been documented in Lake Elizabeth (2004), Lake Hawthorn (2009) and Woorinen North Lake (2010) (Ellis and Pyke 2010; Stoessel 2010). Additionally, South Australian populations in Gurra Gurra Wetland and Causeway Lagoon (translocated) have not been detected since flooding in 2011 (Suitor 2012). In the lower River Murray region at the terminus of the MDB in South Australian, two large freshwater lakes (Lake Alexandrina and Lake Albert) previously supported abundant populations of Murray hardyhead (Wedderburn and Hammer 2003). With the intensification of drought, these populations became confined to several connected irrigation drains that retained surface water and habitat (Wedderburn *et al.* 2012; Hammer *et al.* 2013). Since 2010, low numbers have been captured at only a few sites in both lakes, signalling a major decline in abundance and area of occupancy and uncertainty over the status of Murray hardyhead in the region (Wedderburn and Barnes 2012).

Only eight populations of Murray hardyhead are currently known to persist in Australia (and thus the world). Five of these populations are historic (Round Lake, Cardross Basin 1, Berri Saline Water Disposal Basin, Rocky Gully and the lower River Murray region), one is established by translocation (Lake Koorlong), and one was recently established (Lake Kelly) following flooding in 2011 (Stoessel 2011; Ellis *et al.* 2012). Murray hardyhead was also translocated to Munday Dam, a medium-term artificial refuge site in upper Reedy Creek, South Australia (Bice *et al.* 2012). The locations of surviving and recently extirpated populations are shown in Fig. 2.

Identification of conservation units

Maintaining genetic diversity is critical to species resilience, particularly in the face of changing environmental conditions (Moore *et al.* 2010). Genetic data imply that there have been natural barriers to dispersal of Murray hardyhead in pre-European history, with population substructure apparent at broad scales (Adams *et al.* 2011). Migration of individuals among sites is now constrained by anthropogenic factors (e.g. weirs), but historically gene mixing occurred between regional riverine environments and isolated off-stream lakes and wetlands during periods of high river flows (Adams *et al.* 2011).

Among extant populations sampled in the past 10 years, the following four genetically distinct conservation units (management units) were described by Adams *et al.* (2011) (Fig. 2): (1) Kerang Lakes (Round Lake, Lake Kelly and Lake Elizabeth populations), (2) Woorinen North Lake, (3) Mid-Murray (Cardross Lakes, Lake Hawthorn, Disher Creek and Berri Saline Water Disposal Basin), and (4) Lower–Murray (Rocky Gully and lakes Alexandrina and Albert). All extant populations exhibit some degree of genetic distinctiveness, and, consequently, each is highly valuable from a genetic conservation perspective (Adams *et al.* 2011). Notably, the Lower–Murray population is unique, because it shares genes with the closely related Darling hardyhead (*C. amniculus*), which inhabits the upper Darling River catchment (Adams *et al.* 2011). To ensure preservation of the remaining limited genetic diversity of the species, management strategies need to preserve each unique conservation unit, and should also aim to conserve all extant populations, and secure or increase current population size (Frankham *et al.* 2010).

Approaches to conservation of Murray hardyhead

Although the historic range of Murray hardyhead includes sections of the MDB across three Australian states (Fig. 2), the species is considered extinct in New South Wales, and conservation efforts are limited to Victoria and South Australia. A National Recovery Plan for the species was drafted in 2006 under the *Commonwealth Environment Protection and Biodiversity Conservation Act 1999* (Backhouse *et al.* 2008). The broad objectives of the plan were to minimise the probability of extinction of Murray hardyhead in the wild, and to increase the probability of important remnant populations becoming self-sustaining in the long term.

In Victoria and South Australia, management of remnant populations has been undertaken collaboratively by multiple government agencies, water managers and researchers (e.g. Hall *et al.* 2009; DEH 2010; Ellis *et al.* 2012; Stoessel 2013; Hammer *et al.* 2013). An informal Murray hardyhead Recovery Group, consisting of researchers and representatives of Victorian and South Australian NRM organisations was also formed in 2008, to promote collaboration between stakeholders from Victoria and South Australia, and inform decision making based on the best available data during the drought.

Several approaches have been adopted in the conservation management of Murray hardyhead over the past decade, with the differing locations and attributes of each site requiring individual strategies. Broadly, these approaches include (1) research to increase our understanding of the species biology and environmental requirements (e.g. genetics, reproduction, habitat and diet), (2) monitoring of extant populations, (3) environmental watering, (4) captive maintenance and breeding and (5) translocation to new sites. Research conducted into the species biology has been discussed earlier, and the other approaches are discussed in greater detail below.

Population monitoring

Monitoring has been crucial to enhancing our understanding of many aspects of Murray hardyhead ecology, such as breeding biology and seasonal variability in population structure. Monitoring programs generally involve seasonal netting and water-quality surveys to document variations in the abundance and structure of Murray hardyhead populations, thus identifying recruitment events. These programs have been largely funded by state NRM organisations, and are either conducted internally or by research agencies and environmental consultants.

In some cases, monitoring programs have been invaluable in providing early warning of population crashes, allowing emergency strategies to be implemented to manage threatening processes or the rescue of subpopulations for temporary captive maintenance. For example, declines in abundances prompted intervention to salvage a subpopulation from Lake Hawthorn before its extirpation, which was then maintained in captivity. Monitoring has also provided valuable insight into the effectiveness of management interventions, such as the delivery of environmental water and translocation of fish to new sites, thus informing future management strategies.

Provision of environmental water

The conservation of threatened fish species within existing wild sites (as opposed to *ex situ* maintenance) is regarded as a preferred strategy because it poses less overall risk of localised extinction. Specifically, fish remain in their preferred habitat with appropriate food and other resources, minimal fish handling is required and disease risk is low (see Snyder *et al.* 1996). In many cases, the preservation of existing habitats for Murray hardyhead has been achieved through the addition of water from environmental allocations or reserves. In Victoria, an annual environmental water allocation (EWA) is distributed among regional NRM organisations on the basis of the prioritisation of environmental watering projects. In South Australia, NRM organisations apply directly to Federal Government environmental water holders (the MDB Authority and the Commonwealth Environmental Water Holder) for EWAs. On receipt of an EWA, regional NRM organisations in Victoria and South Australia coordinate the delivery of the water to the proposed site either by pumping from source water (rivers) or through use of irrigation or drainage infrastructure where appropriate.

Many wetlands that have supported Murray hardyhead (including Round Lake, Lake Kelly, Woorinen North Lake, Cardross Lakes, Lake Hawthorn, Berri Saline Water Disposal Basin and Disher Creek) are used for irrigation drainage-disposal or groundwater salt-interception schemes (e.g. Ellis 2005; Backhouse *et al.* 2008; Suitor 2012). Such wetlands present as good targets for environmental watering given they are often contained, off-channel wetlands (as opposed to fluctuating stream habitat) where relatively small volumes of water can infer significant benefits (e.g. Cardross Lakes and Boggy Creek). However, these sites are effectively isolated from river systems, except during major flood events, and inflows to most of these locations have declined in recent decades as a result of improved irrigation efficiencies and protracted drought. The delivery of environmental water to these sites to support habitat formerly maintained by drainage inflows can require expensive infrastructure or logistically difficult temporary pumping strategies. In cases where existing drainage infrastructure (such as irrigation supply channels) can be utilised to reduce delivery costs of environmental water, the timing of delivery may be subject to restrictions whereby the needs of irrigators must be met before the infrastructure is available for environmental watering purposes. In these cases, the availability of delivery infrastructure may not necessarily coincide with the seasonal pattern in water requirements for Murray hardyhead.

Environmental water is ideally delivered to Murray hardyhead sites so that the managed hydrological regime in an aquatic ecosystem mimics natural variability in flows and water level. This is because aquatic species have evolved life-history strategies primarily in direct response to the natural flow regimes (Bunn and Arthington 2002). In larger wetlands, environmental watering strategies have generally aimed to raise water levels during the breeding and recruitment season of Murray hardyhead (September–March), to provide maximum substrate for egg deposition and cover from predators. Water levels are then allowed to decrease naturally or through managed drawdown during autumn and winter (March–August). This annual fluctuation in water level aims to promote a range of beneficial trophic processes such as nutrient cycling and completion of planktonic life cycles, thus promoting an abundance and diversity of food sources for all life-history stages of Murray hardyhead (Ellis 2006). The management of hydrological regimes to support Murray hardyhead can be difficult in small or shallow wetlands (such as Boggy Creek near the terminus of the River Murray) where minor reductions in water level expose critical submerged habitat and increase the risk of adverse water-quality events and predation. In these situations, where there is little margin for error, environmental water is generally supplied intermittently on an 'as needed' basis to maintain habitat, which inevitably presents the need for regular monitoring to prevent inadvertent drying of a site or exposure of critical habitat.

At the height of the drought, the volumes of environmental water available for conservation programs in the MDB became scarce. In 2007, an emergency watering plan (EWP) was developed to prevent the extinction of Murray hardyhead in Victoria and involved the prudent use of water entitlements legally set aside for the environment, combined with a captive management and translocation program. Similarly, in South Australia, emergency action was undertaken by a consortium of State and Federal Government and non-government organisations where sites deemed as 'High Priority' for the survival of Murray hardyhead were targeted for critical environmental watering, whereas other sites received no additions (Hall *et al.* 2009). Small subpopulations of Murray hardyhead were also salvaged from four sites in South Australia, to be maintained in captivity until water availability improved or alternate surrogate sites could be located. A summary of environmental water delivered to each site known to contain Murray hardyhead in recent years is presented in Table 1.

Captive maintenance

In 2007, a dedicated captive maintenance and hatchery program was established at The Murray–Darling Freshwater Research

Table 1. Volumes of environmental water delivered annually to sites for the conservation of Murray hardyhead populations since 2003
NC, data were not confirmed at the time of writing

Population	Approximate surface area (ha)	2004–05	2005–06	2006–07	2007–08	2008–09	2009–10	2010–11	2011–12
Lake Elizabeth	94	307	613	471.5	0	0	0	0	0
Round Lake	41.7	199.8	300	419	518	400.4	254	76	167
Lake Kelly	300.4	0	0	0	0	0	0	0	0
Woorinen North Lake	62.9	NC	NC	NC	NC	NC	NC	NC	NC
Cardross Basin 1	171	1702	1060	810	145	138	119	1012	820
Lake Hawthorn	200	350	0	0	0	0	0	0	0
Koorlong Lake	9	0	0	0	0	36	93	0	0
Disher Creek	1 (now 17)	0	0	0	0	0	0	0	0
Berri Basin	153	0	0	0	0	0	0	0	1200
Gurra Gurra Wetland	799	0	0	0	0	0	0	0	0
Causeway Lagoon	13.3	0	0	0	0	0	0	156	0
Rocky Gully	5.4	0	0	0	0	11	8	0	0
Boggy Creek	10	0	0	0	0	0	7.5	0	0
Turvey's Drain	5	0	0	0	0	4	26	0	0

Table 2. Approximate numbers of Murray hardyhead rescued from wild sites, reared in captivity each breeding season, and released to translocation sites
n.a., not available

Source population	Number rescued	Year(s) of rescue	Number reared in captivity					Number translocated
			2007–08	2008–09	2009–10	2010–11	2011–12	
Lake Hawthorn	400	2008	5	390	182	195	345	195[A]
Cardross Basin 1	240	2008, 2010	30	175	245	140	140	175[A]
Round Lake	200	2010, 2011	n.a.	n.a.	15	45	17	
Woorinen North Lake	60	2009	n.a.	n.a.	8	0	0	
Lake Kelly	800	2011, 2012	n.a.	n.a.	n.a.	n.a.	0	300[B]
Disher Creek	70	2009	n.a.	n.a.	88	40	50	50[C]
Berri Basin	80	2009, 2010	n.a.	n.a.	86	370	210	85[C]
Rocky Gully	95	2010	n.a.	n.a.	n.a.	80	n.a.	85[D]
Boggy Creek	100	2009, 2010	n.a.	n.a.	79	113	n.a.	135[D]
Munday Dam	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	3500[E]

[A]Translocation to Koorlong Lake.
[B]Translocation from Lake Kelly to Woorinen North Lake.
[C]Translocation to Causeway Lagoon.
[D]Translocation to Munday Dam (a surrogate refuge site).
[E]Translocation from Munday Dam to Mundoo Island Channel.

Centre in Mildura to preserve two Victorian subpopulations of Murray hardyhead rescued from vulnerable sites for 3–12 months as insurance against extirpation (Cardross Basin 1 and Lake Hawthorn). As drought conditions worsened, the duration of captivity was extended, and Murray hardyhead from additional sites in Victoria and South Australia were included in the captive-maintenance program as a backup measure for wild stocks (Hammer *et al.* 2009; Ellis *et al.* 2011). The temporary captive-maintenance program was approved under the *Victorian Flora and Fauna Guarantee Act 1988* by the Victorian Department of Sustainability and Environment (Permit number 10005673), and by Primary Industries and Resources South Australia (ref. F2009/0000119902233).

Captive populations from five Victorian sites (Cardross Lakes, Lake Hawthorn, Round Lake, Woorinen North Lake and Lake Kelly) and four South Australian sites (Boggy Creek, Rocky Gully, Disher Creek and Berri Saline Water Disposal Basin) were established between 2007 and 2011 (Table 2). In some cases, the collection of Murray hardyhead for the captive maintenance was timely, with the species subsequently extirpated in several sites soon after collection (i.e. Woorinen North Lake, Cardross Basin 1 West, Lake Hawthorn and Disher Creek). Although captive maintenance is costly and labour intensive, it undoubtedly preserved important subpopulations of Murray hardyhead as the drought in south-eastern Australia deepened, providing opportunity for longer-term conservation strategies to develop.

Translocation

Translocation of wild fish and stocking of hatchery-reared fish are common approaches to re-establishing populations of threatened species (Minckley 1995). Translocation of Murray

Table 3. Management approaches employed in the conservation of Murray hardyhead at each site

Site	Population monitoring	Environmental water delivery	Captive maintenance	Translocated to new site	Received translocated fish
Lake Elizabeth	✓	✓			
Round Lake	✓	✓	✓		
Lake Kelly	✓		✓		
Woorinen North Lake	✓	✓	✓		
Cardross Basin 1	✓	✓	✓	✓	
Lake Hawthorn	✓	✓	✓	✓	
Koorlong Lake	✓	✓	✓		✓
Disher Creek	✓	✓	✓	✓	
Berri Basin	✓	✓	✓	✓	
Gurra Gurra Wetland	✓				
Causeway Lagoon	✓	✓			✓
Rocky Gully	✓	✓	✓	✓	
Boggy Creek	✓	✓	✓	✓	
Munday Dam (refuge)	✓			✓	✓
Mundoo Island Channel	✓				✓
Turvey's Drain	✓	✓			

hardyhead has involved the stocking of individuals from both wild locations and a captive-maintenance program to alternate sites in which habitat was deemed suitable within the natural range of a conservation unit. Translocation sites were assessed for their suitability as long-term sites (>5 years) or as medium-term (1–5 years) artificial refuges such as farm dams and recreated wetlands, from which stock can be reintroduced back into wild habitat when conditions improve. In both cases, environmental conditions are carefully managed to match the individual requirements of the species (Hammer *et al.* 2009). Because salinity appears to be a key factor influencing the distribution of Murray hardyhead (Wedderburn *et al.* 2007), locating suitable translocation habitat is more complicated than it may be for other threatened freshwater fish species.

Murray hardyhead translocations to long-term sites have been attempted with varying success at Woorinen North Lake and Koorlong Lake in Victoria, and at Causeway Lagoon, and Mundoo Island (near the terminus of the River Murray) in South Australia (Table 2). Murray hardyhead was also established at Munday Dam, a medium-term artificial refuge site in upper Reedy Creek, South Australia.

Management and status of known populations

A summary of the management approaches implemented at sites containing Murray hardyhead (from each conservation unit) is provided below (also presented in Table 3), along with the current status of each population.

Kerang Lakes conservation unit (northern Victoria)

Round Lake

In response to declining Murray hardyhead abundances, Round Lake has been supplemented with environmental water since 2003 (Table 1). Although these additions have preserved a small population, 200 individuals were also collected for temporary captive maintenance throughout 2010 and 2011 as a backup. Breeding success in captivity by these fish has been poor (Table 2).

Lake Kelly drainage system

In 2011, a previously unrecorded population of Murray hardyhead was identified in the Lake Kelly drainage system (Stoessel 2012). The species is believed to have colonised Lake Kelly during extensive regional flooding in 2011, from a nearby as-yet-undiscovered population (Stoessel 2011). Lake Kelly has not received any environmental water and without further intervention, the population at the site is expected to perish in 2013. As a temporary measure, 800 fish were collected in 2011–12, which currently persist in captivity, albeit with low breeding success. A further 300 Lake Kelly fish were translocated to Woorinen North Lake in 2012 in an attempt to re-establish a Woorinen North Lake population. The success of this translocation is as yet to be determined (Stoessel 2013).

Lake Elizabeth

Murray hardyhead has not been detected in Lake Elizabeth since 2004, and is presumed extirpated despite environmental water additions from 2005 to 2007 (Stoessel 2008).

Woorinen North Lake conservation unit (northern Victoria)

The Murray hardyhead population in Woorinen North Lake was described by Adams (2011) as a genetically distinct conservation unit. Although Woorinen North Lake has received environmental water since 2004, annual delivery volumes could not be confirmed at the time of writing. In 2009, the population was in decline and 60 individuals were placed into captive maintenance. These fish failed to breed and attempts to manually strip gonads of captive adults to facilitate fertilisation were unsuccessful. The last of the captive Woorinen North Lake Murray hardyhead perished in 2011, and the status of the conservation unit is currently undetermined (Stoessel 2013). The success of attempts to translocate 300 Murray hardyhead from nearby Lake Kelly into Woorinen North Lake in 2012 is also currently undetermined (Stoessel 2013).

Mid-Murray conservation unit

The Mid-Murray conservation unit consists of Murray hardyhead populations located in River Murray wetlands in north-western Victoria, and eastern South Australia (Fig. 2). Most of these wetlands are used for disposal of irrigation drainage water or saline groundwater. As a result of improved irrigation practices and protracted drought, these wetlands have experienced a decline in the water level and corresponding increases in salinity over the past 10–20 years.

Cardross Lakes

The Cardross Lakes are a series of inter-connected drainage basins that, despite regular environmental water delivery since 1996, have experienced declining water levels (see Raadik 2001; Ellis *et al.* 2012). By 2004, only the terminal basin in the Cardross Lakes system (Basin 1) contained Murray hardyhead (Ellis 2005). At the height of the drought in 2007, a levee was constructed to confine environmental water delivery to a small section of Basin 1, and 240 Murray hardyhead individuals were salvaged for captive maintenance as a contingency. These fish demonstrated good breeding success, with multiple generations of offspring being reared. When the drought broke in 2010, a section of the levee was removed and Murray hardyhead rapidly dispersed throughout the whole of Cardross Basin 1 (Ellis *et al.* 2012). All captive Murray hardyhead individuals from the Cardross Lakes were returned to the site in 2012 and the population is currently considered stable (Ellis *et al.* 2012).

Lake Hawthorn

Although 800 ML of environmental water was allocated to Lake Hawthorn in 2005, only 350 ML was delivered because of delivery constraints, and none has been allocated since. To prevent complete loss of the population, ~400 Murray hardyhead individuals were rescued in 2008 for captive maintenance before the lake drying; these fish demonstrated good breeding success and multiple generations of offspring were reared (Ellis *et al.* 2012). Lake Hawthorn refilled in 2010 during a River Murray flood event, and relevant NRM organisations and stakeholders are assessing the potential to return Murray hardyhead to the site from the captive program. No release had occurred at the time of writing because the responsibilities and obligations of each stakeholder, with regard to Murray hardyhead conservation at the site, are unclear.

Koorlong Lake (translocated population)

In 2009, environmental water was delivered to Koorlong Lake in north-western Victoria to provide a translocation site for captive Murray hardyhead originating from Lake Hawthorn and Cardross Basin 1. Approximately 370 adult and juvenile captive-bred fish were released into Koorlong Lake in 2009, and three subsequent years of successful recruitment *in situ* have been detected (Ellis *et al.* 2012). Small additions of environmental water are delivered as required to maintain critical habitat.

Berri Saline Water Disposal Basin (Berri Basin)

Berri Saline Water Disposal Basin (Berri Basin) is a floodplain wetland which has largely been dry in recent decades, although Murray hardyhead persisted in a small creek between the main basin and the River Murray (Suitor 2009). Approximately 50 fish were salvaged for captive maintenance between 2007 and 2009. The fish bred successfully in captivity, and 85 individuals were later translocated to Causeway Lagoon in 2010 (see below). In 2010, floodwaters inundated the whole of Berri Basin, and an additional 1.2 GL of environmental water was later delivered to maintain water quality in the newly inundated habitat (Table 1). All surviving captive Murray hardyhead individuals from Berri Basin were returned to the site in 2012, and the population is currently considered stable.

Disher Creek

In recent decades, Murray hardyhead has largely been confined to a small drainage outfall pond (<1 ha) in Disher Creek where drainage inflows have maintained salinity at levels lower than in the rest of the wetland (Wedderburn and Walker 2008; Bice *et al.* 2010). Regulatory structures have recently been installed to increase available habitat by controlled diversion of River Murray water and saline groundwater to the site (Suitor 2009). Approximately 70 Murray hardyhead individuals were salvaged for captive maintenance in 2009. Although breeding success was limited, 50 individuals from the captive population were released into Causeway Lagoon in 2010 (see below). Despite all remaining captive Murray hardyhead being returned to the site in 2012, the species has not been detected in monitoring surveys since Disher Creek connected to the River Murray during a flood event in 2010 (Wedderburn and Suitor 2012).

Gurra Gurra Wetland

Murray hardyhead was identified in Gurra Gurra Wetland in September 2010 (Suitor 2012), and represented a potentially significant addition to recovery planning. However the species has not been detected at the site since it was inundated during flooding in late 2010, and no management actions for the population are proposed.

Causeway Lagoon (translocated population)

In early 2010, environmental water was delivered to Causeway Lagoon to provide a translocation site for Murray hardyhead. In 2010, 135 Murray hardyhead individuals from captive maintenance (consisting of adults originally salvaged from Berri Basin and Disher Creek, and their captive-bred progeny) were released in Causeway Lagoon. Although subsequent monitoring detected recruitment by these fish within weeks, the species has not been recorded at the site since it was subsequently inundated during flooding in late 2010.

Lower Murray conservation unit (South Australia)

Low river flows during the drought resulted in extreme low water levels throughout the lower River Murray in South Australia. The water level in Lake Alexandrina and Lake Albert near the terminus of the River Murray decreased to below that of sea level (Aldridge *et al.* 2011). This lead to the salinisation of previously freshwater environments, loss of preferred habitat (e.g. submerged macrophytes), and the drying of many wetlands and drainage channels in which Murray hardyhead had previously been recorded (e.g. the only known population in Lake Albert at Waltowa, see Fig. 2). Several modified sites (e.g. channels) in which Murray hardyhead had historically been recorded but were not managed through the drought are not discussed here (see Wedderburn and Barnes 2009).

Rocky Gully

Rocky Gully is a constructed wetland which receives stormwater run-off from local creeks, and formerly received effluent water from an adjacent meatworks. Decreased inflows resulted in disconnection and salinisation of the wetland. A total of 19 ML of environmental water was pumped to the site in 2009 and 2010, preserving a small population of Murray hardyhead (Bice *et al.* 2011). As a backup, 95 Murray hardyhead individuals were collected for a captive program in 2010, before later translocation into a surrogate refuge site (Munday Dam, see below) in 2011.

Boggy Creek

Boggy Creek is a small wetland on Hindmarsh Island in Lake Alexandrina, near the terminus of the River Murray. Because of the extended disconnection from Lake Alexandrina, Boggy Creek was supplemented with 6 ML of environmental water during 2009–10 and 100 Murray hardyhead individuals were rescued for captive maintenance. These captive fish (including juveniles bred in captivity) were later translocated to a surrogate refuge dam, along with those salvaged from Rocky Gully. Although a small population also persisted in Boggy Creek during drought, no fish have been detected since the site reconnected with Lake Alexandrina during flooding in late 2010 (Wedderburn *et al.* 2010). The species may have dispersed throughout adjacent connected habitat during flood connection.

Munday Dam (translocated population)

In 2011, Murray hardyhead was released at an artificial refuge site (Munday Dam, upper Reedy Creek) in South Australia. Initially, 220 wild fish and first-generation captive-bred offspring originating from Boggy Creek and Rocky Gully were released in 2011. The population has exhibited annual recruitment and is now considered abundant (Bice *et al.* 2012).

Mundoo Island (Channel 2)

In 2012, ~3500 individuals of Murray hardyhead from an artificial refuge site (Munday Dam, see above) were released into a modified channel on Mundoo Island, located in Lake Alexandrina near the terminus of the River Murray. Although the species had historically been abundant at this site, none has been recaptured since the release (Bice *et al.* 2012).

Turvey's Drain

Turvey's Drain is an irrigation channel on the western side of Lake Alexandrina that became disconnected in 2008. It was the last of several small populations known in the area before 2007. Despite delivery of 30 ML of environmental water in 2008–09, Murray hardyhead has not been recorded at Turvey's Drain since 2009 (Bice *et al.* 2012).

Discussion

Competition with humans for limited freshwater resources is the primary reason freshwater fish are among the most imperilled faunas on Earth (Leidy and Moyle 1998; Duncan and Lockwood 2001; Jelks *et al.* 2008). The scarcity of water in the MDB during recent drought exacerbated the competition between human and environment users. Government NRM organisations were unprepared for the severity and duration of the recent drought, resulting in reactive management responses for many threatened aquatic species. The conservation of Murray hardyhead *in situ* became problematic because the volume of water required to secure all remaining populations was unavailable. Furthermore, the delivery of available water was in many cases logistically difficult and expensive. There also existed significant community resentment towards environmental watering programs. These factors resulted in suboptimal conservation strategies for Murray hardyhead that targeted small sections of habitat, and relegated the future of several populations to captive maintenance. Important considerations for the management of Murray hardyhead, which are also relevant to other threatened species that coexist alongside human populations, are described in the following sections.

Environmental water

In times of water shortages, the volumes of environmental water available for conservation projects are limited, and may be subject to the same restrictions as irrigation entitlements. Under these circumstances, environmental water in the MDB is subject to prioritisation based on risk, legal obligations of relevant state or federal agencies, likelihood of achieving intended outcomes, required volumes and financial cost. Inevitably, compromises are made and individual environmental watering programs are potentially abandoned. For example, because of infrastructure limitations in 2007, insufficient environmental water could be delivered to maintain critical habitat for the Lake Hawthorn Murray hardyhead population. Environmental watering of Lake Hawthorn was discontinued and the habitat was ultimately lost. Environmental water was instead directed to other Murray hardyhead populations in Victoria (Round Lake, Woorinen North Lake and Cardross Basin 1) for which water delivery was more feasible. To assist with the prioritisation of environmental watering projects, contingency management plans for each site should be developed to increase preparedness for future events in which the availability of environmental water may be limited.

It should be noted that simply supplying water to a site may not be sufficient to save the target species. Many life-history traits of fish and their food sources are dependent on the timing and amplitude of seasonal variations in water level, and changes in flow regime (or water level) that do not align with seasonal cycles may have an impact on individual species (Humphries *et al.* 1999; Bunn and Arthington 2002; Dudgeon *et al.* 2006). Water delivery, therefore, needs to ensure that benefits are maximised by aligning with the biology of the target species and its food sources (e.g. zooplankton), and through the maintenance of habitat for critical life stages. If managed correctly, environmental watering also benefits other native fish, invertebrates, water birds and aquatic vegetation. For example, spring flooding of Boggy Creek near the terminus of the River Murray in South Australia with environmental water resulted in a zooplankton bloom that was utilised by many organisms, including the resident Murray hardyhead population (Wedderburn *et al.* 2010). Consequently, the population underwent successful recruitment, and was preserved until river flows recommenced in late 2010.

Monitoring

Understanding historical, current and impending threats to freshwater ecosystems is necessary for protecting and recovering species, populations and natural communities (Jelks *et al.* 2008). To understand the seasonal trends and variations within an individual Murray hardyhead population, a rigorous monitoring program is required (for each population). Monitoring should ideally be conducted at a frequency that enables the identification of seasonal recruitment events or population declines, and should consider assessments of water quality, food and habitat availability, as well as species abundances. A commitment to such monitoring does not currently exist across the range of Murray hardyhead, and only infrequent monitoring (if any at all) is conducted at most sites. This is largely a consequence of recent funding limitations for conservation of threatened species.

Multi-jurisdictional management of a site

Sommerwerk *et al.* (2010) highlighted the challenges faced *in trans*-boundary water management that can emerge from administrative complexity, the multiple and often competing water uses and difficulties enforcing the law. Most remnant populations of Murray hardyhead persist in water bodies managed by multiple stakeholders. For example, Lake Hawthorn in north-western Victoria is managed by local water authorities as an irrigation drainage basin, whereas the local council authority diverts stormwater to the lake. In addition, the Victorian Department of Sustainability and Environment (DSE) has a responsibility under Commonwealth and State law to take action to protect threatened species (in this case Murray hardyhead), and implements strategies to do so through local Catchment Management Authorities. Local residents, community groups and a school also have strong connection to, and interest in, the management of Lake Hawthorn. Where multi-jurisdictional management of a site exists, protracted debate among stakeholders may delay implementation of conservation strategies, resulting in increased risk to threatened populations. To ameliorate this, a greater emphasis needs to be placed on conservation planning and stakeholder collaboration during non-drought periods, when conflict over water use will be minimised, and the status of threatened populations is less critical. Although crises such as the recent drought can provide an important catalyst and opportunity for water-reform processes (Grafton *et al.* 2013), management of threatened species needs to be proactive and sustained rather than solely reactive to critically threatening incidences.

The responsibilities or obligations of a stakeholder with regard to conservation of threatened species at a particular site may be unclear, and confusion over accountability with regard to management of threatened species can also significantly hinder conservation programs. Interpretation of federal legislation has, at times, resulted in a restrained conservation action because of the long-term accountability associated with water delivery, possible impacts on or changes to stakeholder objectives at a site, and/or financial cost. Conservation legislation is useless if enforcement and restoration programmes are not effectively carried out (Bruton 1995). Clearly, State and Federal Governments should address this issue through legislative correspondence, and synergies among the competing water users need to be established. A commitment by primary stakeholders to conservation responsibilities (to be stipulated in the species Recovery Plan or sites Management Plan, for example) would enable faster decision making and strategy implementation.

Community support

Murray hardyhead is not a well known species, with few perceived values or uses to local communities. Additionally, wetlands used for drainage or saltwater disposal are, generally, considered to hold little ecological value, and, consequently, management programs for Murray hardyhead populations surviving in these wetlands have received little community support. At the height of the drought, the volume of water available for domestic and agricultural purposes, as well as for environmental conservation programs, was limited. Significant resistance towards environmental watering programs was encountered from some sections of the community, particularly within irrigated farming communities which were also subject to large reductions in water allocations. Many community members perceived competition between Murray hardyhead and irrigators for dwindling water supplies, and, in some cases, local media further aggravated the issue through the provision of ill-informed or misguided information (e.g. Sunraysia Daily, 8 October 2007; 'Fish fury – farm leaders blast 'water waste' to save species').

This scenario is not peculiar to Murray hardyhead. Scharpf (2001) documented a situation where farmers in North America argued that their livelihoods should not be sacrificed to the existence of a small, drab, silvery fish (in this case Rio Grande silvery minnow). Sentiments published in local newspapers such as 'Hungry? Out of work? – Eat a silvery minnow' echo those printed in local Australian newspapers during recent drought when locals commented 'Fish are only good with chips!', and 'Who the hell thinks a damn fish is more important than farmers?' Clearly, in conflicts over water resources, inauspicious small fish can have many detractors.

Conversely, some sites such as Rocky Gully, Boggy Creek and Koorlong Lake (a translocation site) received strong landholder and community support. This suggests that improved community-engagement strategies regarding threatened species management may ameliorate community discontent.

The National Recovery Plan for Murray hardyhead includes 'increased community awareness of Murray hardyhead conservation' as one of seven primary objectives, to be achieved through actions publicising the results of research investigations, and the promotion of community awareness and involvement in conservation programs. Although several promotional activities do already exist (such as the development of a children's story book about Murray hardyhead), there is as yet no coordinated strategy to achieve meaningful progress towards the objective of 'increased community awareness of Murray hardyhead conservation'.

Educational activities have been conducted in the MDB for other threatened species, which may serve as good templates for future programs intending to increase the community awareness of Murray hardyhead. Examples include threatened species hatcheries located in schools, establishing artificial-refuge sites in private farm dams, and the organisation of community events (such as fish releases). These types of programs increase environmental awareness and involvement, while providing practical contributions to reintroduction programs (Hammer *et al.* 2012), and we suggest that the implementation of similar activities for Murray hardyhead would benefit conservation and recovery efforts.

Captive maintenance

The impacts of the recent drought in south-eastern Australia were widespread and prolonged, and relevant agencies were unprepared for managing threatened fish populations (Lintermans and Cottingham 2007). This in turn led to the reliance on captive maintenance for the conservation of Murray hardyhead and several other MDB fish species (see Hammer *et al.* 2013). Captive-breeding programs carry inherent risks associated with establishing self-sustaining captive populations, reintroduction success and domestication (Snyder *et al.* 1996; Lynch and O'Hely 2001). Because the genetic diversity within each captive population of Murray hardyhead discussed here was derived from a small number of wild-caught parent fish, subsequent generations are likely to display reduced genetic variability (Philippart 1995; Araki *et al.* 2007; Moore *et al.* 2010). Although the lifespan of Murray hardyhead in captivity can be prolonged, the number of eggs and surviving young produced per adult fish declined with successive breeding season in most captive populations, and the captive Woorinen North Lake population failed to breed in captivity at all (Ellis *et al.* 2012). Consequently, there is a risk that extended captive-breeding programs will fail to produce enough captive-reared fish to enable the establishment self-sustaining populations when released to the wild (Frankham 1995; Araki *et al.* 2007).

Captive-reared fish are also likely to display reduced foraging and survival behaviour, compared with their wild ancestors, further decreasing the probability of success for stocking (Frankham 1995; Philippart 1995; Lynch and O'Hely 2001). For example, third- and fourth-generation captive-bred Murray hardyhead fish are noted to display greatly reduced schooling behaviour in large aquariums, when compared with groups of recently captured wild fish (I. M. Ellis, unpubl. data). This may have significant implications for predator avoidance if captive Murray hardyhead is returned to the wild, given that predators may constitute a major cause of fluctuating fitness in natural populations (Vrijenhoek 1998).

Captive maintenance can also divert attention from the problems originally contributing to a species decline, leading to reduced urgency towards the preservation and restoration of existing wild ecosystems (Philippart 1995; Snyder *et al.* 1996). The maintenance of captive populations of Murray hardyhead was originally intended to span less than 12 months, and yet, some populations have been maintained in captivity for up to 5 years. Although most captive Murray hardyhead fish will be released by the middle of 2013, in most cases, they will be returned to sites that already hold (or previously held) populations, rather than additional managed translocation sites, which would increase the distribution of the species (and reduce the risk of extinction). The identification of multiple sites suitable for translocation of Murray hardyhead should have been conducted in parallel with the captive-breeding program, with a commitment to conduct the translocations when environmental conditions improved. Scarcity of suitable sites for the re-establishment of wild stocks is a common challenge for captive-maintenance programs (Bruton 1995).

It is well documented that captive breeding should not be considered a long-term conservation strategy and, when adopted as a recovery technique, should always be integrated with strategies to maintain wild populations (Philippart 1995; Snyder *et al.* 1996). Future conservation efforts for Murray hardyhead will benefit from having Murray hardyhead breed under natural conditions *in situ* where possible, with any parent stock maintained in captivity insurance against extirpation, regularly released to wild sites, to be replaced by freshly captured wild individuals. Such a program necessitates dual strategies that conserve wild populations in their natural habitat concurrently with captive-maintenance programs. The information presented herein highlights the need for multiple management strategies, and should eliminate (or in the least ameliorate) the dependence on captive maintenance in future crisis scenarios.

Conservation or recovery

The over-arching objective of the National Murray hardyhead Recovery Plan is to minimise the probability of extinction of the species in the wild, and to increase the probability of important populations becoming self-sustaining in the long term (Backhouse *et al.* 2008). Although management intervention in the past decade has generally been successful in conserving Murray hardyhead during a period of unprecedented environmental change and critical threat to the survival of the species, progress towards recovery of the species is minimal.

The maintenance of genetic diversity and gene flow in species threatened with extinction is a vital consideration for species-recovery programs (Bruton 1995; Frankham *et al.* 2010). Despite recent flood events in the MDB, the numbers of sites in which Murray hardyhead currently survives in the wild are fewer than those at the height of the drought in 2009. This is because the species has not been detected in some locations since they were inundated during flood events in 2010 (Wedderburn and Suitor 2012), whereas a specific conservation unit (Woorinen North Lake) and its related evolutionary potential are now extirpated (Stoessel 2013). The reduction in the number of extant populations has consequently reduced the genetic viability of Murray hardyhead across its range, and the number of secure locations from which Murray hardyhead can now be sourced for future translocation is also reduced. As a result, the potential for extinction of the species may actually have increased.

Post-flood status

Historically, flooding in the MDB was likely to be important in influencing the distribution and structure of Murray hardyhead populations. Recent flood events provided an opportunity for Murray hardyhead at some locations to disperse when reconnection to the River Murray occurred (e.g. Disher Creek, Gurra Gurra Wetland, and Boggy Creek). Unfortunately, the fragmented nature of the species recent distribution, coupled with low abundances of the species at these locations before flooding, may have compromised the potential for this dispersal to occur. Ironically, large floods may now be a disturbance inferring potentially negative outcomes for rare species with fragmented distributions. Evidence for post-flooding recovery of Murray hardyhead from a range of locations will be gauged only by future assessments and monitoring.

Future directions

The competing demands for scarce water during the recent drought resulted in suboptimal environmental watering plans that targeted small areas of habitat and neglected others, relegating the future of several Murray hardyhead populations to captive maintenance. Despite recent flooding of vast areas of habitat within the MDB, several populations of Murray hardyhead persist largely in captivity, with their future undetermined. The current post-flood period, in which water is more available for environmental conservation programs than it was during drought, should be treated as an opportunity for environmental managers to reinforce threatened species-recovery programs, and not a period in which to be complacent.

Future management of Murray hardyhead will ideally focus on the recovery of the species (rather than crisis management), addressing the objectives detailed in the National Recovery Plan. In particular, strategies should aim to increase the probability of important populations becoming self-sustaining in the long term. As a first priority, core populations of Murray hardyhead should be secured, which means securing long-term water supply and the associated infrastructure required for delivery. These secure core populations should be regarded and managed as 'primary populations', from which stock for future translocation programs can be sourced.

The second recovery priority should ideally be to establish an increased number of secondary populations via translocation of fish from secured primary populations (e.g. Hammer *et al.* 2009). This strategy would further decrease the likelihood of extinction of the species by spreading risk (Bruton 1995; Minckley 1995), and is of particular importance in the preservation of remaining conservation units. These secondary populations could be located in small managed sites such as dams or drainage systems as temporary risk mediation, or in floodplain wetlands which are close to water sources, thus facilitating easy delivery of environmental water. Secondary populations in floodplain wetlands could also act as dispersal nodes during future flood connectivity, improving the chances for recovery of the species.

Understanding historical, current and impending threats to freshwater ecosystems are necessary for protecting and recovering species, distinct populations and natural communities (Jelks *et al.* 2008). Some of the environmental watering programs conducted successfully conserved small populations of Murray hardyhead *in situ* through the drought (e.g. Cardross Basin 1, Round Lake, Boggy Creek), whereas others failed (e.g. Woorinen North Lake). The particular circumstances that contributed to this varied success are, however, largely undetermined, because monitoring programs have not been sufficiently thorough to identify the reasons for success or failure. Importantly, however, these monitoring programs have demonstrated that the timing of water delivery may be as critical to a population's conservation as the volume of water that is delivered. Monitoring of trends for both primary and secondary populations is therefore essential to the recovery of the species, so as to identify future declines, and inform our ability to adopt responsive management strategies.

In the future management of Murray hardyhead, we suggest that captive maintenance should be used only as a last resort in response to the impending extirpation of a wild population. Given the genetic and phenotypic changes that occur in captive environment, the objective of captive maintenance should be to maintain a proportion of a population temporarily (i.e. for months, not years), before returning captive fish to a natural system (Philippart 1995; Snyder *et al.* 1996). In light of the variable breeding success demonstrated by captive populations of Murray hardyhead maintained during the recent drought, we suggest that additional research be conducted before establishing any future captive-maintenance programs. This research would investigate diet and rearing techniques to maximise fecundity, recruitment and genetic viability for Murray hardyhead from a range of locations (and thus variable tolerances and preferences).

The effects of drought on fish communities may persist for years after normal conditions return, and, consequently, drought-management plans need to extend well beyond the end of the drought (Lintermans and Cottingham 2007). Furthermore, reductions in the availability of surface water and riverine flow predicted under climate change are predicted to be major threats to freshwater fishes world wide in coming decades (Xenopoulos *et al.* 2005; Balcombe *et al.* 2011; Pratchett *et al.* 2011). In particular, climate change is expected to affect heavily the freshwater fish with limited range or specific habitat requirements (Ficke *et al.* 2007; Morrongiello *et al.* 2011). As such, recovery actions for these species (including Murray hardyhead) should be ongoing and not suspended during non-drought periods, to await the next critical downturn in water availability. Unfortunately, the breaking of the Millennium Drought in 2010 was closely followed by widespread reduction in funding for threatened-species conservation strategies and monitoring programs. The lack of commitment to on-going monitoring and adaptive-management programs may compromise many positive outcomes already achieved in the management of Murray hardyhead.

The persistence of Murray hardyhead is contingent on future management, vigilant monitoring, the dedication and accountability of staff, and complex intergovernmental and stakeholder co-operation. Despite the post-flood reductions in conservation urgency and funding for Murray hardyhead recovery, the formation of cross-agency partnerships and increased community involvement during the recent drought has hopefully increased the capacity for future conservation management of the species. Overall, there are valuable lessons and cautions from recent management of Murray hardyhead to guide local and broader conservation of aquatic biota in variable and modified freshwater systems, particularly those prone to drought. These lessons must be heeded now rather than re-learnt when the next significant drought arises.

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