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Recovery of the endangered trout cod, *Maccullochella macquariensis*: what have we achieved in more than 25 years?

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Abstract. Recovery of threatened species is often necessarily a long-term process. The present paper details the progress towards the recovery of trout cod, *Maccullochella macquariensis*, an iconic, long-lived fish species first listed as threatened in the 1980s. The objectives, actions and progress over three successive national recovery plans (spanning 18 years) are assessed, documenting changes to population distribution and abundance and updating ecological knowledge. Increased knowledge (especially breeding biology and hatchery techniques, movements, habitats and genetics) has greatly influenced recovery actions and the use of a population model was developed to assist with management options and stocking regimes. Key recovery actions include stocking of hatchery-produced fish to establish new populations, regulations on angling (including closures), education (particularly identification from the closely related Murray cod, *M. peelii*) and habitat rehabilitation (especially re-instatement of structural woody habitats). In particular, the establishment of new populations using hatchery stocking has been a successful action. The importance of a coordinated long-term approach is emphasised and, although there is uncertainty in ongoing resourcing of the recovery program, much has been achieved and there is cautious optimism for the future of this species.

Additional keywords: Australia, conservation, endangered species, freshwater fish, recovery, rehabilitation.

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Introduction

Freshwater fishes are imperilled world-wide (Sala *et al.* 2000), with 30–60% of species considered threatened (e.g. Smith and Darwall 2006; Jelks *et al.* 2008). Riverine fishes are susceptible to a range of anthropogenic threats both directly and to their habitats (Malmqvist and Rundle 2002; Dudgeon *et al.* 2006; Cooke *et al.* 2012). Large, long-lived species can be especially susceptible to exploitation (Hogan *et al.* 2004; Dudgeon *et al.* 2006; Jelks *et al.* 2008). In Australia, native freshwater fishes are no different; being subjected to a similar range of threats (Cadwallader 1978; Lintermans 2013*a*) with serious population declines as a result (Wager and Jackson 1993). The Murray–Darling Basin (MDB) in south-eastern Australia (Fig. 1), for example, has a naturally depauperate native fish fauna consisting of only 44 species, 24 of which are considered threatened at the national, state or regional level (Koehn and Lintermans 2012). It is estimated that MDB native fish populations are now at ~10% of their pre-European levels (Murray–Darling Basin Commission 2004; Koehn and Lintermans 2012). Trout cod, *Maccullochella macquariensis*, along with three closely related freshwater ‘cod’ species (genus *Maccullochella*: eastern freshwater cod *M. ikei*, Mary River cod *M. marienis* and Murray cod *M. peelii*), are all listed as threatened nationally (Lintermans *et al.* 2005).

Trout cod is a large, iconic Australian freshwater Percichthyid fish, endemic to the rivers of the MDB. This species has suffered major declines in range and abundance (Cadwallader and Gooley 1984; Douglas *et al.* 1994; Fig. 1) and only one ‘natural’ population (remnant from pre-European settlement) remains, although this is now accompanied by several populations re-established via translocation and

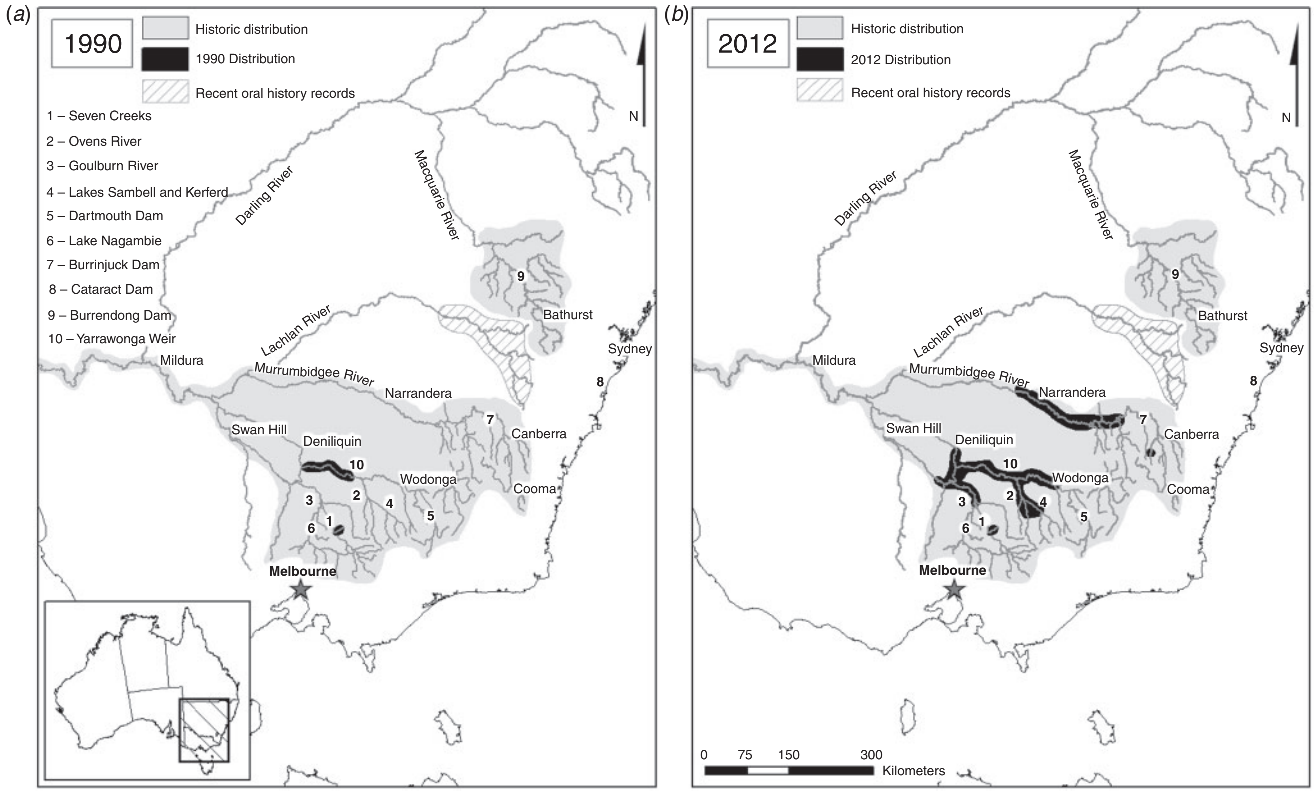

Fig. 1. Historic and recent distribution of trout cod in Australia. (*a*) 1990, (*b*) 2012.

stocking. Trout cod is listed as endangered under both national (www.environment.gov.au/biodiversity/threatened/index.html, accessed 22 July 2013) and State legislation (New South Wales Department of Primary Industries 2006; ACT Government 2007; Department of Sustainability and Environment 2007; Hammer *et al.* 2009). Prior to the first formal conservation listing in 1980 (Burbidge and Jenkins 1984), concerns had been expressed about its conservation status (Lake 1971; Berra 1974). At this time, there were no legislative obligations for recovery plans or actions. A national recovery plan (the first for an Australian fish) was published following its national conservation listing (Douglas *et al.* 1994). This recovery plan has now been through three iterations over an 18-year period (Douglas *et al.* 1994; Brown *et al.* 1998; Trout cod Recovery Team 2008*a*). Even though trout cod is a nationally listed species, the implementation of management and recovery actions for this and other threatened species is largely undertaken by individual state jurisdictions and their agencies (see Koehn and Lintermans 2012).

The present paper (1) summarises recovery actions for trout cod since its taxonomic description and subsequent listing as a threatened species 40 years ago, with a focus on the past 25 years, (2) provides an update on biology, ecology, distribution and threats, (3) reviews the progression of three consecutive recovery plans, assessing the success of on-ground recovery actions, (4) illustrates actions with regional case studies and (5) provides an assessment of the future for this species.

Study species

Prior to the formal description of trout cod (Berra and Weatherley 1972), it had been suspected that this species was a taxon separate from the closely related Murray cod, *Maccullochella peelii* (see Cadwallader 1977). Lake (1971) had pre-empted this description and, indeed, had considered the species as threatened. Even after its first conservation listing in 1980, there was limited understanding of trout cod biology, ecology, distribution, population status or threats and its biology was often assumed to be 'similar to' that of the closely related Murray cod (Koehn and O'Connor 1990).

Species description and ecology

Trout cod is a relatively large, fusiform-bodied fish that has been recorded to 850 mm in total length and 16 kg, but is now usually <5 kg (Lintermans 2007). It is a lotic species, with microhabitat preference for in-stream woody structure (Koehn and Nicol 1998; Growns *et al.* 2004; Nicol *et al.* 2004). Adults exhibit high site fidelity, generally undertaking limited movements but with occasional large-scale excursions (Koehn *et al.* 2008; Ebner and Thiem 2009). The diet is dominated by shrimps and crayfishes (75%) but includes other aquatic and terrestrial macro-invertebrates and some fishes (Baumgartner 2005, 2007). Maximum life-span is thought to be 20–25 years (Todd *et al.* 2004), with sexual maturity reached at 3–5 years of age. Spawning occurs in spring at a water temperature of ~15°C (Koehn and Harrington 2006). Females produce 1200–11 000

Table 1. Timeframes, objectives, actions, percentage actions completed and costs of the three national recovery plans for trout cod
C = mostly (>80%) completed, N = not (<20%) completed, PC = partially completed (20–80%)

Attribute	Recovery plan 1	Recovery plan 2	Recovery plan 3
Timeframe	1994–1999	1998–2003	2008–2013
Number of objectives	3	7	13
Number of actions	22	21	55
%Actions completed	C = 44	C = 44	C = 15
	PC = 33	PC = 41	PC = 50
	N = 23	N = 15	N = 35
Cost (AU × 1000)	3600	3900	3500
Reference	Douglas *et al.* (1994)	Brown *et al.* (1998)	Trout cod Recovery Team (2008*a*)
Comment	Many objectives, probably over ambitious		Many smaller more site-specific actions; lack of national funding

relatively large (2.5–3.6-mm diameter) adhesive eggs that are attached to hard substrates and tended to and guarded by the male. Larvae hatch after 5–10 days at 6–9 mm, then disperse by drifting in the water column (Koehn and Harrington 2006). Trout cod is renowned for its aggression and fighting qualities as a sport fish (Berra 1974; Cadwallader 1977) and, as a top-order predator, could be viewed as both a 'keystone' (Paine 1966, 1969) and 'flagship' species (Simberloff 1998).

Distribution and abundance

Because of the early taxonomic confusion and misidentification with Murray cod, much of the information regarding the historic distribution of trout cod has been uncertain. Originally, trout cod was considered endemic to the southern MDB, north as far as the Macquarie River (Berra and Weatherley 1972; Cadwallader 1977; Douglas *et al.* 1994; Fig. 1). Recently, historical records for the occurrence of trout cod (up until the late 1960s) have been documented for the Lachlan River (Trueman 2011). Trout cod has been translocated into several waters, including Cataract Dam (Nepean Catchment, New South Wales) before 1910 (Douglas *et al.* 1994), Seven Creeks (Goulburn Catchment, Victoria) in the early 1920s and Lake Sambell (Ovens Catchment, Victoria) in 1928 (Cadwallader and Gooley 1984; Fig. 1). The species underwent an extensive decline in range and abundance, apparently within only a few decades (Cadwallader and Gooley 1984). Until at least 1950, trout cod was present in the Murray River, as far downstream as Mildura (Lake 1971; Cadwallader 1977), although they were considered rare downstream from Echuca (Cadwallader 1977). By the late 1970s, the only remaining potentially sustainable breeding populations of trout cod were the naturally occurring population in the Murray River (New South Wales); occupying the reach from Yarrawonga Weir downstream to Cobram (Cadwallader and Gooley 1984; Ingram *et al.* 1990; Douglas *et al.* 1994) and the translocated population in Seven Creeks (Cadwallader 1979; Morison and Anderson 1987; Richardson and Ingram 1989). The translocated population in Lake Sambell apparently died out in a fish kill in 1970 (Cadwallader and Gooley 1984) and the trout cod and Murray cod translocated into Cataract Dam are known to hybridise (Wajon 1983; Harris and Dixon 1988). The last reported trout cod in the lower Murrumbidgee was collected at Narrandera (Fig. 1) in 1969 (Gilligan 2005). The Australian Capital Territory (ACT) population of trout cod in the upper Murrumbidgee River disappeared only in the 1970s, (Lintermans *et al.* 1988), as did the population in the Mitta Mitta River following the construction of Dartmouth Dam, which was completed in 1979 (Koehn *et al.* 1995; Ryan and Koehn 2001).

Recovery plans and actions

Following the brief description of recovery actions for trout cod and many Australian freshwater fishes (Wager and Jackson 1993), there have been three consecutive national recovery plans and four state/territory recovery plans (Douglas *et al.* 1994; Brown *et al.* 1998; ACT Government 1999, 2007; Department of Sustainability and Environment 2003; New South Wales Department of Primary Industries 2006; Trout cod Recovery Team 2008*a*) dedicated to trout cod, spanning 18 years (Table 1). Some recovery actions have been underway longer than this, but most concerted efforts have occurred over the past 25 years. There have, however, been significant time lags between recovery plan development, recognition and adoption. For example, the latest national plan, adopted in 2008, was finalised in draft form in 2004.

Trout cod is subject to a range of threats that are often cited as being responsible for the declines of many Australian native fish species (Cadwallader 1978; Ingram and Douglas 1995; Lintermans *et al.* 2005; Table 2). Recovery actions for trout cod have concentrated on monitoring and assessment, determining biological-knowledge requirements, habitat restoration, population re-establishment (restocking), education, and review of status and legislation. Some actions in the three national recovery plans overlap in time with some actions continuing across plans (e.g. recovery teams, monitoring; see Table S1, available as Supplementary Material for this paper). Estimates of the cost of implementing individual plans (undertaken at the time of their preparation) are similar and reflect the on-going nature of recovery actions. The current plan, however, has been subject to more disparate funding opportunities, handled on an individual state, catchment and site basis with no national funds provided for implementation of the current recovery plan.

A summary of national recovery plan actions and review of progress is given in Table 1 (see Table S1, available as Supplementary Material for this paper), along with timelines for significant ecological and management actions (Fig. 2). Overall, a substantial number of actions have been completed or partially completed (74% and 85% for Plans 1 and 2,

Table 2. Description of threats relevant to trout cod

Threat	Description	References
Habitat modification		
Removal of woody habitats	Removal of in-stream wood is widespread especially mid-river, close to the deep, fast-flowing water (preferred trout cod habitat).	Koehn and Nicol (1998), Growns *et al.* (2004), Koehn *et al.* (2004*a*), Nicol *et al.* (2004)
Sedimentation	Sand sediments in Seven Creeks and post-fire inputs.	Saddlier *et al.* (2002), Lyon and O'Connor (2008)
Fish kills	As a result of poor water quality, including blackwater events.	Koster *et al.* (2004), King *et al.* (2012)
River regulation		
Alteration of flow regimes	Reduced flooding and altered seasonality in the Murray River; extraction from Seven Creeks.	Close (1990), Close (2002)
Cold water dam releases	Caused loss of the trout cod population in Mitta Mitta River.	Koehn *et al.* (1995), Todd *et al.* (2005)
Barriers	Movements of adults appear limited but subadults exhibit greater movements;	Koehn *et al.* (2008), Ebner and Thiem (2009)
	Risks to safe fish passage at Yarrawonga Weir.	Thorncraft and Harris (1997), Stuart *et al.* (2010)
Irrigation infrastructure	Loss of drifting larvae into irrigation channels, through pumps and passing over weirs.	Koehn and Harrington (2006), Koehn *et al.* (2004*b*), King and O'Connor (2007), Baumgartner *et al.* (2006, 2009)
Alien fishes		
Predation	Brown trout, redfin perch.	Cadwallader (1996), McDowall (2006)
Competition	Impacts of carp, *Cyprinus carpio*, are unknown.	Koehn *et al.* (2000)
Removal by fishing	An aggressive predator susceptible to angling; captured by commercial fishing operations in the past, some angler take (either illegally or through misidentification).	Berra (1974), Rowland (1989), Trout cod Recovery Team (2008*a*), Lintermans (2007)
	Injury and post-release mortality of concern (2–15% mortality estimated for Murray cod).	Muoneke and Childress (1994), Bartholomew and Bohnsack (2005), Douglas *et al.* (2010), Hall *et al.* (2012)

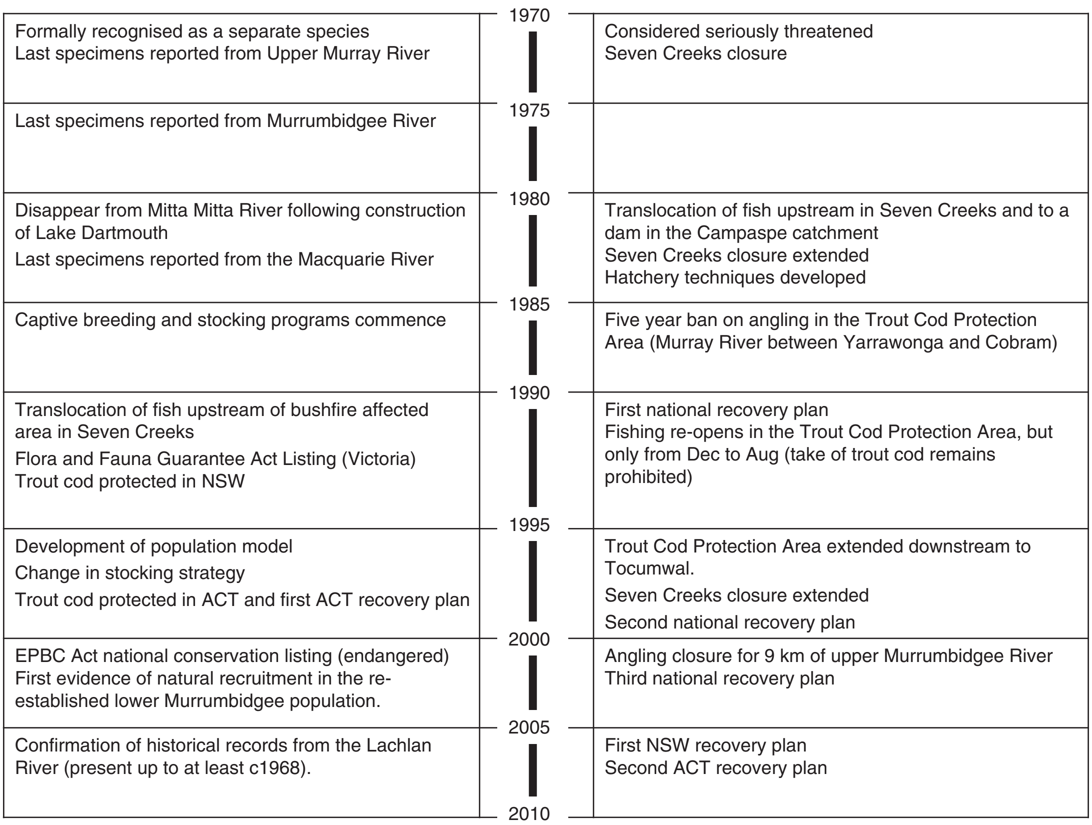

Fig. 2. Timeline of important events for the conservation of trout cod.

respectively). In many cases, partial completion has meant that the action has been undertaken only at some sites and a lack of sampling consistency among sites has led to difficulties in determining population status. Fewer actions have been completed for the current plan (only 15%), which is current until 2013 (Trout cod Recovery Team 2008*a*) and for which there has been less certainty of funding. In particular, the lack of completion of communication actions is very evident.

Ecology and knowledge to inform recovery

Recovery plans have been supported by compendiums of knowledge (Douglas *et al.* 1995; Trout cod Recovery Team 2008*b*) to inform particular recovery actions. The generation of new knowledge has been considerable in recent years (Table S2, available as Supplementary Material for this paper) and, importantly, new knowledge and 'grey literature' have been incorporated. A search of the Scopus database using 'trout cod' or '*Maccullochella macquariensis*' in the title or as a keyword revealed a total of 29 publications, with the number of publications increasing substantially over the decades since trout cod was recognised as a distinct species (Berra and Weatherley 1972), including two in the 1970s, two in the 1980s, seven in the 1990s, and 18 in the 2000s.

Legislation

The recognition of trout cod as distinct from Murray cod highlighted its restricted distribution, which subsequently prompted the enactment of protective legislation. In 1973, about 7 km of Seven Creeks were closed to angling and in 1993 this was extended a further 4 km downstream (Barnham 1995). In 1987, New South Wales introduced a 5-year ban on the taking of both Murray cod and trout cod from a 67-km reach of the Murray River downstream of Yarrawonga Weir (the trout cod protection area; TCPA) to protect the remnant wild population. In 1992, the recreational Murray cod fishery within the TCPA was re-opened, but with an ongoing annual 'spawning' seasonal closure (1 September to 30 November). In 1998, the downstream boundary of the TCPA was extended a further 33 km in consideration of the new spatial extent of the trout cod population. In 1991, Victoria prohibited the taking and or possession of trout cod state-wide, and New South Wales enacted similar restrictions in 1993. The ACT listed trout cod as an endangered species in 1996 and, in 2000, a complete fishing closure was imposed along 9 km of the Murrumbidgee River, downstream of the Angle Crossing stocking site (ACT Government 2007).

Captive breeding

In an attempt to establish new trout cod populations, captive breeding programs were established at both New South Wales and Victorian government hatcheries (Narrandera and Snobs Creek, respectively) (Ingram *et al.* 1990). Techniques to induce hatchery spawning in trout cod were developed in the mid-1980s (Rimmer 1987; Ingram and Rimmer 1992), and since then, juvenile fish have been produced for release within the presumed historical range (Table 3). These programs have provided much of the information regarding the reproduction and early life history of trout cod. Captive breeding methods have been described by Ingram and Rimmer (1992), Douglas *et al.* (1994) and Ingram (2009). Wild-caught broodstock have been sourced mainly from the Murray River population. Fish are held in earthen ponds but unlike other *Maccullochella* spp., trout cod does not readily spawn unassisted in captivity. As a consequence, during September–October (with water temperatures rising to ~16°C), mature broodstock are removed from the ponds and injected with gonadotrophin after which eggs (up to 5600 eggs kg^{-1}; mean 3300 eggs kg^{-1}) and sperm are manually stripped. The eggs are adhesive, 2.7–3.5 mm in diameter and take 5–10 days to hatch at 18–20°C. Hatch success rates vary from 0% to 98% (mean 50%) and the larvae (6.0–8.8 mm in length) begin exogenous feeding after 10 days. Following commencement of feeding, fry are stocked into fertilised earthen ponds for on-growing. Harvested fingerlings are then held for a short period in the hatchery and in recent years, have been chemically marked (oxytetracycline or calcein) before release to discriminate stocked fish from those naturally recruited.

Stocking

The first stocking of trout cod fingerlings occurred in 1986/1987, with 1000 fish released into the upper Murray River (Fig. 1). Since then, a total of 1.56 million trout cod individuals has been released into 17 areas (32 sites) across eight river catchments (Table 3). Most fish (>99%) have been released as fingerlings (0.5–1.5 g), although a small number (11 430) were released as yearlings (10–50 g). As hatchery production increased through the early 1990s, more fish became available, resulting in higher numbers stocked at more sites (Table 3; Douglas *et al.* 1994). A range of criteria was developed for site selection (Douglas *et al.* 1994) with an early preference for pristine habitats, without Murray cod (to avoid hybridisation) or redfin perch (*Perca fluviatilis*) (to reduce predation), relative isolation from population centres (to reduce angling pressure) but accessible for monitoring (Douglas *et al.* 1994). These factors, combined with the example of a successful historical translocation to Seven Creeks, initially led to the stocking of many smaller, upland streams (Table 3). Following a lack of apparent long-term success at these sites, there was a change in stocking philosophy from small creeks and few fish to larger waters and many fish over the longer term (Table 3). These subsequent stocking regimes for trout cod have been more successful, with natural recruitment observed or inferred in at least six of the areas. What might be described as 'self-sustaining' populations now occur in the mid-Murrumbidgee (Gilligan 2005; Ingram and Thurstan 2008), the lower Ovens River (Lyon *et al.* 2012) and mid-Goulburn Rivers (Koster *et al.* 2004; Table 3). Monitoring frequency and effort, however, have been variable and the time between initiating stocking and observing recruitment has been 5–13 years (Lyon *et al.* 2012; M. Lintermans, pers. comm.).

Genetics

Currently, there are no genetically discrete populations of trout cod (Moore *et al.* 2010). Stocking programs have often been criticised heavily because of perceived impacts of hatchery-bred fish breeding with wild populations, resulting in a loss of genetic diversity or reduced viability (Allendorf 1991; Philipp *et al.* 1993). Using mitochondrial DNA, Bearlin and Tikel (2003)

Table 3. Stocking-site details for trout cod

River catchment	Area	Stocking period	Seasons stocked	No. stocked	No. of sites	Years since initial stocking	Recruitment observed	Comments
Broken	Broken R. (incl. Ryans Ck)	1987/1988–1993/1994	7	19 400	2	24	Yes	Recruitment recorded in Loombah Weir (1998), but no monitoring since then
Campaspe	Coliban R.	1990/1991–1993/1994	4	10 950	1	21	No	
Goulburn	Hughes Ck.	1987/1988–1990/1991	3	1610[A]	1	24	No	Recent (2012) anecdotal report
	Mid-Goulburn R. (below L. Nagambie)	1993/1994–1996/1997	4	58 550	3	18	Yes	Comment on recent kill?
Lachlan	Upper Lachlan R. (Abercrombie R.)	1992/1993–1993/1994	2	13 600	1	19	No	
Macquarie	Mid-Macquarie R. (below Burrendong Dam)	1998/1999, 2000/2001, 2002/2003–2004/2005	5	232 000	3	14	?	Small size classes reported by anglers – but none confirmed.
	Upper Macquarie R. (above Burrendong Dam)	1991/1992–1993/1994, 2009/2010–2011/2012	6	109 900	13	20	No (?)	No recruitment observed from initial stockings. Too early to tell for most recent stockings.
Murray	Burrumbuttock Farm dams	1986/1987–1987/1988	2	680	5	25	No	Refuge population created at beginning of conservation program. The population did not survive.
Murrumbidgee	Cotter R. (Bendora Dam)	1989/1990–1990/1991	2	8740	3	22	Yes	Recruitment observed in Bendora Dam
	Mid-Murrumbidgee R. (below Burrinjuck Dam)	1992/1993–2001/2002	10	320 800	6	19	Yes	
	Tumut R. (Talbingo Res.)	1990/1991–1996/1997	2	16 000	1	21	No	
	Upper Murrumbidgee R. (above Burrinjuck Dam)	1988/1989–2008/2009	18	326 200	8	23	?	2011 capture of potential natural recruit at a single site
Ovens	Kerferd L.	2007/2008–2010/2011	4	9080	1	4	No	Recent stocking
	Upper Ovens R. (Buffalo Ck, Buffalo R. and Rose R.)	1989/1990–1994/1995	6	15 790[A]	3	22		
	Lower Ovens River[A]	1996/1997–2005/2006	10	281 440[A]	2	15	Yes	
	Sambell L.	2009/2010–2011/2012	3	6825	1	2	No	Recent stocking
Upper Murray	Upper Murray R. (above Hume Dam, incl. Koetong Ck)	1986/1987–1997/1998	8	68 110	4	25	No	
	Upper Mitta Mitta R. (above L. Darmouth)	1992/1993–1995/1996	4	56 400	2	19	No	
Total			26	1 556 075	61			

[A]Includes some yearlings.

found the Murray River population (11 haplotypes) to be significantly different from both the translocated Seven Creeks population (2 haplotypes) and the stocked population in the Ovens and King Rivers (6 haplotypes). A recent microsatellite-marker study showed that although there were more alleles detected in the stocked population of the Ovens River (total 55) than in the Murray River population (total 49), these populations were genetically homogeneous (Lyon *et al.* 2012). This outcome is likely to be the result of successful application of breeding-program protocols, which were established early in the stocking program and aimed to maximise the genetic diversity of the fish produced. These included regular replacement of broodstock, maintaining a sex ratio of 1 : 1, undertaking single-pair matings, avoiding repeat matings of the same pairs of fish, and mixing progeny from all matings together before release (Douglas *et al.* 1994). A low level of natural hybridisation between trout cod and Murray cod is observed in the Murray River, which has not appeared to affect the genetic status of either species (Douglas *et al.* 1995).

The use of a population model

A stochastic population model for trout cod was developed to assess the viability of the Murray River population and the importance of management strategies, as well as to guide future research and management actions (Todd *et al.* 2004). Model development used input from key stakeholders to garner a consensus (Burgman and Possingham 2000) and examined a range of factors, including the sensitivity of management decisions for trout cod, model structure, statistical distributions of uncertainties, parameter values and the relative importance of identified knowledge gaps. The model was influential in changing the process and design of hatchery production and stocking regimes (Lyon *et al.* 2012).

Community education

Public support for trout cod conservation is vital to management of the species. Important education issues for trout cod conservation include the need to assist anglers to distinguish between trout cod and the closely related Murray cod (Douglas *et al.* 1994), methods to release any trout cod by-catch to minimise damage, and information about threats. There have been various activities targeted at increasing public awareness, including advisory signs along the trout cod management zone, information in recreational angling guides and websites (http://www.dpi.nsw.gov.au/aboutus/news/all/2012/trout-cod-in-mistaken-identity-crisis, accessed 22 July 2013), magazine and internet articles, information pamphlets, interpretation of scientific results for the public and field-day displays including live fish, trout cod information, and videos. Angler and other interest groups have produced various educational websites, brochures and trout cod promotional information (e.g. Native Fish Australia; www.nativefish.asn.au, accessed 22 July 2013). The promotion of trout cod as an icon species has not been fully realised but has much potential.

Habitat rehabilitation

The restoration of degraded aquatic habitats is a key driving action in the recovery of many threatened fishes (Barrett 2004; Murray–Darling Basin Commission 2004; Nagayama and Nakamura 2010). Trout cod is strongly associated with structural woody habitats (Koehn and Nicol 1998; Growns *et al.* 2004; Nicol *et al.* 2007), and habitat restoration is seen as a key recovery action. Techniques for restoring large woody habitats have been developed and trialled in the trout cod reach of the Murray River (Nicol *et al.* 2002, 2004). These trials found that all species of large-bodied fish (Murray cod, golden perch, *Macquaria ambigua*, and trout cod) utilised restored habitats. Subsequent habitat-rehabilitation works have been undertaken in the Murray River upstream of Yarrawonga weir (Lake Mulwala), the Ovens River near Wangaratta, Tarcutta Creek near Wagga Wagga and Wodonga Creek. In response to sediment (sand) accumulation in the upper Murrumbidgee River, installation of rock groynes resulted in increased hydraulic and habitat diversity by creating scour pools (Lintermans 2005). In Seven Creeks, a 3-km reach at the lower extent of the trout-cod range was restored with groynes, rock, structural wood and riparian revegetation (Saddlier *et al.* 2002). Trout cod has been recorded utilising these new habitats in a variety of locations (Lintermans 2005; Stoessel 2008).

Case studies

Murray River

The Murray River trout cod population (Fig. 1) is vital to any national conservation effort. Concern had been expressed regarding the viability of this population and surveys were recommended as an urgent action to establish its status (Douglas *et al.* 1994). Data from population surveys (undertaken since 1994) has been used in the population model (Todd *et al.* 2004) to evaluate the longer-term risks to this population, which is now considered relatively stable (Fig. 3). The population has expanded downstream to Torrumbarry, and is now common to Barmah (Douglas *et al.* 2012). Despite the installation of a fish lift in October 1999, upstream expansion of the population remains limited by Yarrawonga Weir. Only a relatively small number of trout cod individuals (254 to February 2012: Goulburn–Murray Water, unpubl. data) has negotiated this barrier (2% of fish passing though the fish lift), compared with trout cod comprising 30–69% of the large-bodied fish population in the river downstream (J. Lyon, unpubl. data) during that time. The lift was designed for the passage of Murray cod and other native species, with little consideration given to trout cod and there is the potential for injury during fish passage (Stuart *et al.* 2010).

Murrumbidgee River

Historically, trout cod occurred throughout the entire length of the lower Murrumbidgee River and ~200 km of the upper Murrumbidgee (above Burrinjuck Dam; Fig. 1), with the species being last recorded from the river in 1976. In an attempt to restore trout cod populations, both the upper and mid-reaches of the Murrumbidgee River have been stocked. In excess of 326 000 trout cod fingerlings have been stocked across eight sites in the upper Murrumbidgee River since 1988 (average 40 775, range 18 000–99 500 fingerlings; Table 3). Regular monitoring at some sites has demonstrated survival and growth of stocked individuals, but no recruitment or establishment of

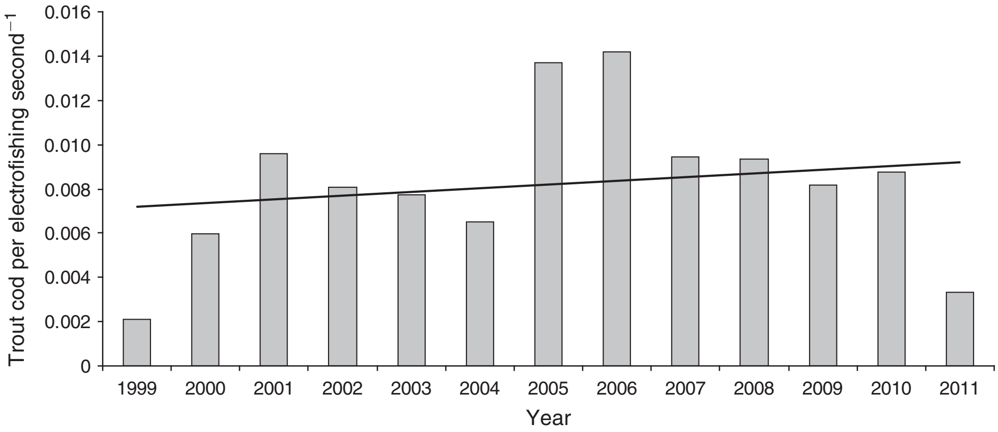

Fig. 3. Trout cod catch per unit effort (CPUE) for fish over 200-mm length from the Murray River between Yarrawonga weir and Tocumwal with trend line ($N = 9092$). Note that 2011 had high flows and reduced capture rates.

self-sustaining populations has occurred. Detection of stocked individuals >3 years old at riverine sites has been unsuccessful, except at one site where 3+-year-old trout cod individuals are being regularly recorded (ACT Government, unpubl. data). Angle Crossing received the greatest stocking effort (99 500 fingerlings over 9 years to 2005) and the collection of a single small fish (<190 mm TL) in 2011 (>5 years after stocking ceased) may be an indication that some breeding by stocked fish has occurred (ACT Government, unpubl. data). However, stocking of 8740 fingerlings over 2 years in Bendora Reservoir (on the Cotter River; a tributary of the upper Murrumbidgee) has resulted in recruitment from stocked fish more than a decade after stocking (ACT Government 2007; Lintermans 2007) and these recruits now dominate the population.

Trout cod was reintroduced into the mid-Murrumbidgee downstream of Burrinjuck Dam (Fig. 1) between 1992 and 2001 (320 800 fingerlings at six locations; Table 3). An average of 11 881 (range 2500–20 000) fingerlings were stocked annually for three to seven consecutive years (Table 3). Population monitoring suggests that since 2001, the average electrofishing catch per unit effort (CPUE) has remained stable (from 0.13 ± 0.04 in 2001 to 0.12 ± 0.07 in 2012) and is similar to that of the remnant population in the Murray River (0.16 ± 0.04). The re-introduced population has expanded at least 81 km downstream of the lowest release site and trout cod individuals have been collected at 77% of sites sampled. The collection of young-of-year trout cod individuals (<190 mm TL) in eight of the past nine years indicates natural recruitment. The proportion of recruits over the past 5 years (23%) has been similar to that observed during the same period in the Murray River population (19%).

Ovens River

Trout cod became extinct in the lower reaches of the Ovens River (Fig. 1) by the early 1980s. A 10-year stocking program commenced in 1997 with >277 000 fingerlings of trout cod stocked in a 15-km reach of river downstream of Wangaratta (Lyon *et al.* 2012; Table 3). Population monitoring was sporadic until 2007, after which more targeted surveys were undertaken. Results show that the population now consists of a variety of size cohorts, and although CPUE data are variable, the population has expanded at least 50 km upstream (in the Ovens, King and Buffalo Rivers) and ~100 km downstream to the Murray River. Trout cod has now also been found in the Murray River upstream as far as Wodonga (~200 km from the original stocking sites) and in the lower reaches of the Kiewa River (J. Lyon, pers. comm.).

Goulburn River

The lower Goulburn River (downstream from Lake Nagambie) was stocked with >58 000 trout cod individuals between 1993 and 1997 (Table 3). Drifting trout cod larvae and some 1-year-old juveniles were collected in November and December 2003 (Koster *et al.* 2009), indicating successful breeding. In January 2004, a fish kill involving many hundreds of fish, including at least 20 trout cod individuals, was recorded. Subsequent annual surveys from 2004 to 2007 failed to detect any trout cod, but small numbers of adults have been recorded every year from 2007 to 2011, with larvae being collected in 2007/2008 and 2008/2009 (W. Koster, unpubl. data).

Seven Creeks

Seven Creeks is a small (5–7 m wide) stream with rock, gravel and sand substrates, and pools <2 m deep interspersed with rapids and cascades. Some cascades, together with the larger Goorum Falls, are natural barriers to upstream fish movement. Population surveys conducted on an *ad hoc* basis (e.g. Morison and Anderson 1987; Anderson 1991; Saddlier and Harrington 1997; Kearns *et al.* 2012) have indicated downstream displacement of the trout cod population over time. To prevent the main population being relocated into less favourable habitats in the lower reaches, trout cod individuals have been collected using electrofishing and relocated back upstream. In 1991, fire affected the Seven Creeks Catchment and over 100 trout cod individuals were relocated upstream before rains washed ash into the stream (Anderson 1991). Despite the persistence of a self-sustaining trout cod population, Seven Creeks remains vulnerable to many threats. The populations restricted distribution and small size makes it vulnerable to stochastic events (such as fires) and the encroachment of alien species such as carp

(*Cyprinus carpio*), and more particularly, the predatory redfin perch. The collection of young-of-the-year trout cod individuals in the gut contents of redfin perch in the lower reaches of this site suggests that urgent action is required (Kearns *et al.* 2012).

Macquarie River

Historically, trout cod has occurred throughout the upper reaches of the Macquarie River Catchment (type specimen collected near Bathurst in 1824), but it was thought to have become extinct in ~1984 (Trueman 2011). Trout cod fingerlings have been stocked upstream (17 900 at four sites in 1991–1993 and 92 000 at 10 sites in 2009–2011) and downstream of Burrendong Dam (232 000 fingerlings in 1998–2004; Table 3). Opportunistic scientific data and reports from recreational fishers indicate that trout cod survives in both the upper and lower catchments; however, there has been no dedicated monitoring undertaken in the Macquarie to establish whether or not self-sustaining populations have established.

Other sites

The New South Wales Rivers Survey (Harris and Gehrke 1997) sampled 27 sites within the likely historical range of trout cod (1994–1996) and captured no individuals. From 2004 to 2012, extensive sampling across the MDB by the Sustainable Rivers Audit captured a total of 43 trout cod individuals from 4 of the 26 river valleys (Ovens: 21 individuals; Central Murray (remaining wild population: 20); Upper Murray: 1; Kiewa: 1) (Davies *et al.* 2008; Murray–Darling Basin Authority, unpubl. data). The fish from the Kiewa and upper Murray are likely to represent stocked fish, rather than evidence of self-sustaining populations. There are many stocking locations (particularly smaller sites) where the establishment of populations has not been successful, although in some areas, small numbers of individuals have been observed (e.g. Douglas and Brown 2000). This has included major stocking sites such as the upper Murray River (>68 000 fingerlings released over 8 years), the upper Mitta Mitta River (above Lake Dartmouth) and a range of lesser sites, including Talbingo Dam (Tumut River), Ryans, Koetong, Buffalo and Hughes creeks, Abercrombie, Broken, Coliban, and Buffalo and Rose rivers (Table 3).

Cataract Dam is believed to have been stocked with translocated trout cod and Murray cod in 1914, and trout cod exhibits high levels (32–50% of the population) of hybridisation with Murray cod (Wajon 1983). The future of 1600 fingerlings stocked into lakes Kerferd and Sambell (2008–2011) to establish a recreational fishery is uncertain and Lake Sambell has recently (2011–2012) been partially drained for maintenance. There is currently no stocking being undertaken solely for the purpose of trout cod conservation in Victoria.

Discussion

Assessment of recovery actions shows that much has been achieved in the recovery of trout cod, through the implementation of three successive national recovery plans. Managing fish across multiple jurisdictions and agencies in the MDB has previously been identified as problematic (Koehn and Lintermans 2012) and the present study has highlighted the benefits of a dedicated, multi-jurisdictional recovery team that can coordinate across state boundaries and agencies in the implementation of a long-term, committed, coordinated approach. The differing responsibilities and objectives (e.g. management of water, habitat, fishery, fish production and conservation) of the many state agencies has posed difficulties for consistent communication, consensus and coordinated actions. For example, the need for consistency among different State legislation and regulations. However, there remains much work to be done and changes to funding arrangements mean that the progression of trout cod recovery actions will remain challenging.

Trout cod is typical of many large, long-lived freshwater fishes that are subject to angling and other pressures (Hogan *et al.* 2004; Cooke *et al.* 2012) and its progress towards recovery provides lessons for other similar species, including those of the same genus (Lintermans *et al.* 2005). Clear, well designed and written recovery plans, together with funding and completion of recovery actions, are key components to threatened species recovery (Abbitt and Scott 2001; Crouse *et al.* 2002). Funding for conservation is often directed towards 'charismatic' species (Male and Bean 2005) and because trout cod is a large, iconic species, with an interest by anglers, its recovery has been given more attention and resources than that of other smaller Australian fishes (see Saddlier *et al.* 2013). This has enhanced recovery progress, as demonstrated in the present paper.

Trout cod has undergone serious declines in both range and abundance and this causes an issue of 'shifting baselines' that can be an impediment to recovery when recovery targets are set too low (Lintermans *et al.* 2005; Humphries and Winemiller 2009). Managing public perception of when a fish has 'recovered' can be problematic when anglers see a surge in abundance of the target species, but do not appreciate that they are all stocked individuals, or what the historic levels of the fishery originally were. Such misconceptions of ecology and historical abundance can lead to calls for premature relaxation of protective legislative controls and cessation of recovery actions. In this respect, the value of angler knowledge and historical records (Trueman 2011) has been illustrated through clarification of the true historical range and relative abundance of the species (e.g. the presence of trout cod in the Lachlan River).

The expansion of the remnant population and establishment of new populations reduce the extinction risk of a threatened species and, despite some early failures, the long-term commitment to re-establishment of trout cod throughout their former range has been a key tenet to the recovery of this species. The stocking-strategy and adaptive-management approach outlined by Bearlin *et al.* (2002) and Todd *et al.* (2004) for trout cod has been successful for some populations. Lyon *et al.* (2012) postulated that an important facet of a long-term stocking program for recovery of an endangered species is the increased chance of a stocked cohort encountering favourable environmental conditions that promote local survival, particularly immediately following release. In the Ovens River, fish stocked in 2003 and 2004 were more highly represented in sampling programs than those from other years, supporting the conservative approach of releasing stock over a longer period of time (Lyon *et al.* 2012). Further, stocking yearling trout cod had no discernable impact on the final population size or structure (Lyon *et al.* 2012). Ebner *et al.* (2007, 2009) found that

2-year-old and adult hatchery-reared trout cod individuals had high mortality rates after release into the Murrumbidgee and Cotter Rivers, probably because of behavioural deficits of such on-grown fish (Brown and Day 2002; McDermid *et al.* 2010). Consequently, releasing larger and more mature on-grown fish via conventional hatchery practices seems unlikely to provide major advances in trout cod recovery.

Apart from translocations, there are few options other than stocking for population establishment. Translocation is widely used in threatened species conservation (Seddon *et al.* 2007; Lintermans 2013*b*) and, historically, has been used to establish populations of trout cod and other freshwater angling species (Cadwallader 1981; Cadwallader and Gooley 1984). Lake Sambell, Seven Creeks and Cataract Dam trout cod populations were all established through translocations; however, recently this has not been pursued as an alternative to stocking. Importantly, there is only a single source population (Murray River) potentially able to sustain the loss of translocated individuals. This lack of alternate source populations may be alleviated as self-sustaining populations become established at other sites and reach sufficient abundances to sustain the harvest of fish for translocation.

It is recognised that there is a need to better engage recreational anglers in the management and conservation of fishes (Granek *et al.* 2008). This aspect of trout cod recovery has not been undertaken as well as for the other *Maccullochella* species and increased community involvement and participation would be valuable. The national recovery team has not been able to secure an ongoing community representative, whereas eastern freshwater cod and Mary River cod both have considerable community involvement in their recovery programs (NSW Fisheries 2004; Lintermans *et al.* 2005). The inclusion of anglers in the conservation of Murray cod is proving fruitful (Koehn 2010; Koehn and Todd 2012), helping real and perceived conflicts between conservation and recreational-fishery objectives to be resolved (Koehn 2010). Because of its recognition by anglers, trout cod is an ideal candidate to be used as a 'flagship' species (Simberloff 1998) that can be then used to convey conservation messages for other species.

Angling is an important and popular pastime in Australia, with Murray cod being a popular target species where it occurs (Henry and Lyle 2003). While the take of trout cod is currently prohibited, accidental captures are common, especially in highly fished areas such as the remnant Murray River population, where the trout cod population may be affected by post-release mortalities. The impacts of such mortalities are likely to be greater for long-lived species such as trout cod (Coggins *et al.* 2007). Short-term release mortalities for Murray cod are considered to be relatively low (Douglas *et al.* 2010; Hall *et al.* 2012) but such impacts are not transferable between species (Bartholomew and Bohnsack 2005), can be cumulative (with multiple captures), change with conditions and fishing methods (Bartholomew and Bohnsack 2005) and sublethal effects need to be considered (Cooke and Suski 2005). The protection of larger, older fish in the population is seen as important for fish species such as trout cod (Birkeland and Dayton 2005) and the education of anglers in species-specific fishing and catch-and-release procedures (e.g. barbless or circle hooks, lure only fishing) (Cooke and Suski 2005) to reduce any impacts should be seen as a priority.

The prospect of once again allowing fishing for trout cod is popular with anglers and this has been recognised in the latest recovery plan, with steps taken to establish trial fisheries in a few small lakes in Victoria and New South Wales. There is, however, a clear need to manage public expectations because no timelines or measures for success have been provided for these fisheries. The active involvement of anglers contributing substantially to conservation measures for this species could greatly improve both conservation and fishery outcomes, as without a down-listing of conservation status, it is unlikely that any take of trout cod from existing populations will be allowed in the near future.

The long-term nature of the recovery of trout cod was recognised by Brown *et al.* (1998) in the second recovery plan, by setting a recovery objective of downgrading of trout cod conservation status from endangered to vulnerable within 25 years (by 2023). Achieving this objective is, however, dependent on the availability of funding and completion of appropriate recovery actions, supported by adequate population monitoring to ensure that the required criteria have been met. IUCN threatened species criteria are highly sensitive to the number of mature individuals and to uncertainty in parameter values; hence, they are reliant on reliable data on population numbers to support any down-listing (Nicol 2005). A lack of data to show unequivocal change in populations or a lack of precision in such data will only delay down-listing (Nicol 2005). Although establishing new populations reduces the overall risk to the species, monitoring of population status has been variable; a common failing in threatened species recovery efforts (Campbell *et al.* 2002). Monitoring must not only be directed at the focal species, but also at current and emerging threats (e.g. in the present case, at climate change, blackwater events, sedimentation, predation by redfin perch; Campbell *et al.* 2002). Replication of the monitoring program undertaken for the Ovens River population (Lyon *et al.* 2012) at other sites, together with predictions made using an updated population model, would assist such assessments.

Climate change has the potential to affect Australian freshwater fishes in multiple ways (Koehn *et al.* 2011). Changes to reproduction (Pankhurst and Munday 2011), range contractions (particularly in upland areas; Bond *et al.* 2011), changes to habitats (e.g. water quality or reductions in refuge pools; Balcombe *et al.* 2011; Pratchett *et al.* 2011), expansion of other native or alien species (such as golden perch, which may compete or predate; Bond *et al.* 2011) and the combination of many other ecosystem changes (Koehn *et al.* 2011) may all have an impact on trout cod populations. Some potential impacts relating to the reduced flows predicted for south-eastern Australia as a result of climate change were highlighted during the 'millenium' drought (Murphy and Timbal 2008). Trout cod was assessed to be among the freshwater native fish species most susceptible to drought impacts (Crook *et al.* 2010). Climate change has not been adequately considered in the trout cod recovery plans and this needs to be rectified for this and all threatened freshwater fishes (see Koehn *et al.* 2011).

Recently, trout cod recovery has become less certain as a result of a lack of dedicated funding for both a recovery team and recovery actions. The certainty of recovery-plan progression and coordination is vital, because species for which there has been increased spending on recovery actions are more likely to show population improvements and are less likely to continue to decline (Male and Bean 2005; Kerkvliet and Langpap 2007). Species with recovery coordinators have more recovery actions implemented and species with a higher proportion of planned recovery actions implemented are more likely to show positive population trends (Lundquist *et al.* 2002). The continuation of a National Recovery Team for this species is essential.

Recovering species with large geographical ranges, at low population levels when listed and with multiple and difficult threats, has been demonstrated to be problematic (Abbitt and Scott 2001); this is also the case for trout cod. Although a diverse range of recovery actions has been implemented for trout cod, the benefits of some actions such as legislation (e.g. closure to fishing) and education (e.g. correct species identification), habitat rehabilitation, environmental flows and fishways have either not been monitored or their benefits to trout cod are difficult to quantify (e.g. King *et al.* 2009). Many other actions have been successful, and, in addition, there is a range of broader fish-related management actions (e.g. fishways, riparian planting, alien species control) that may help trout cod conservation. In particular, these include actions such as those in the Native Fish Strategy for the MDB (Murray–Darling Basin Commission 2004; Koehn and Lintermans 2012) for other sympatric species such as Murray cod (National Murray cod Recovery Team 2010; Koehn and Todd 2012).

There is of course, much still to be done before trout cod can be removed from threatened species lists. The current national recovery plan is due for revision in 2013 and assessments in the present paper suggest that the following actions need consideration:

- re-instate a funded national recovery team,
- greater inclusion of climate-change and extreme-events planning (fires, floods, droughts),
- need for additional recovery-success criteria (e.g. delisting criteria),
- greater surety of funding for recovery actions,
- expanded monitoring (species and threats),
- re-evaluation of the Yarrawonga Weir fish lift to pass trout cod as well as provision of fish-passage facilities at barriers within the ranges of re-establishing populations,
- habitat rehabilitation or enhancement where necessary and appropriate,
- further research into the species flow requirements, so as to advise effective environmental-flow delivery programs,
- resumption of conservation stocking in Victoria to establish further populations,
- engagement of anglers and other stakeholders to establish trout cod as an icon fish species,
- education of anglers in low-impact fishing and catch-and-release procedures,
- renewal and/or installation of trout cod information at all priority trout cod sites,
- updating the trout cod population model, incorporating new knowledge and model functions (see Koehn and Todd 2012), and
- actions to prevent redfin perch predation impacts on the Seven Creeks population and assessment for other sites.

The present paper has provided a valuable case study for the time, effort, actions and difficulties of recovering a long-lived, iconic native fish species across multiple jurisdictions. It has highlighted the need for a long-term, committed, coordinated approach; in the present case, over three consecutive national recovery plans. Actions have been supported by considerable new knowledge (breeding biology, movements, habitats, genetics) and use of a population-modelling tool. Population protection and regulations on angling (including closures), and education materials/programs, have all played important roles, and, in particular, the stocking of hatchery-produced fish has established several new populations to reduce extinction risk. Such stocking, however, needs to be planned, with adequate stocking numbers being sustained over the appropriate long-term time frame. There remains a need to align conservation and recreational-angler objectives and involve this latter stakeholder group in the recovery effort and the promotion of trout cod as a flagship species. The establishment of additional breeding populations and expansion of the largest natural population (Murray River), together with other actions over the past 25 years, provides cautious optimism for the ultimate recovery of this species.

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