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Supplementary material

A compendium of ecological knowledge for restoration of freshwater fishes in Australia's Murray–Darling Basin

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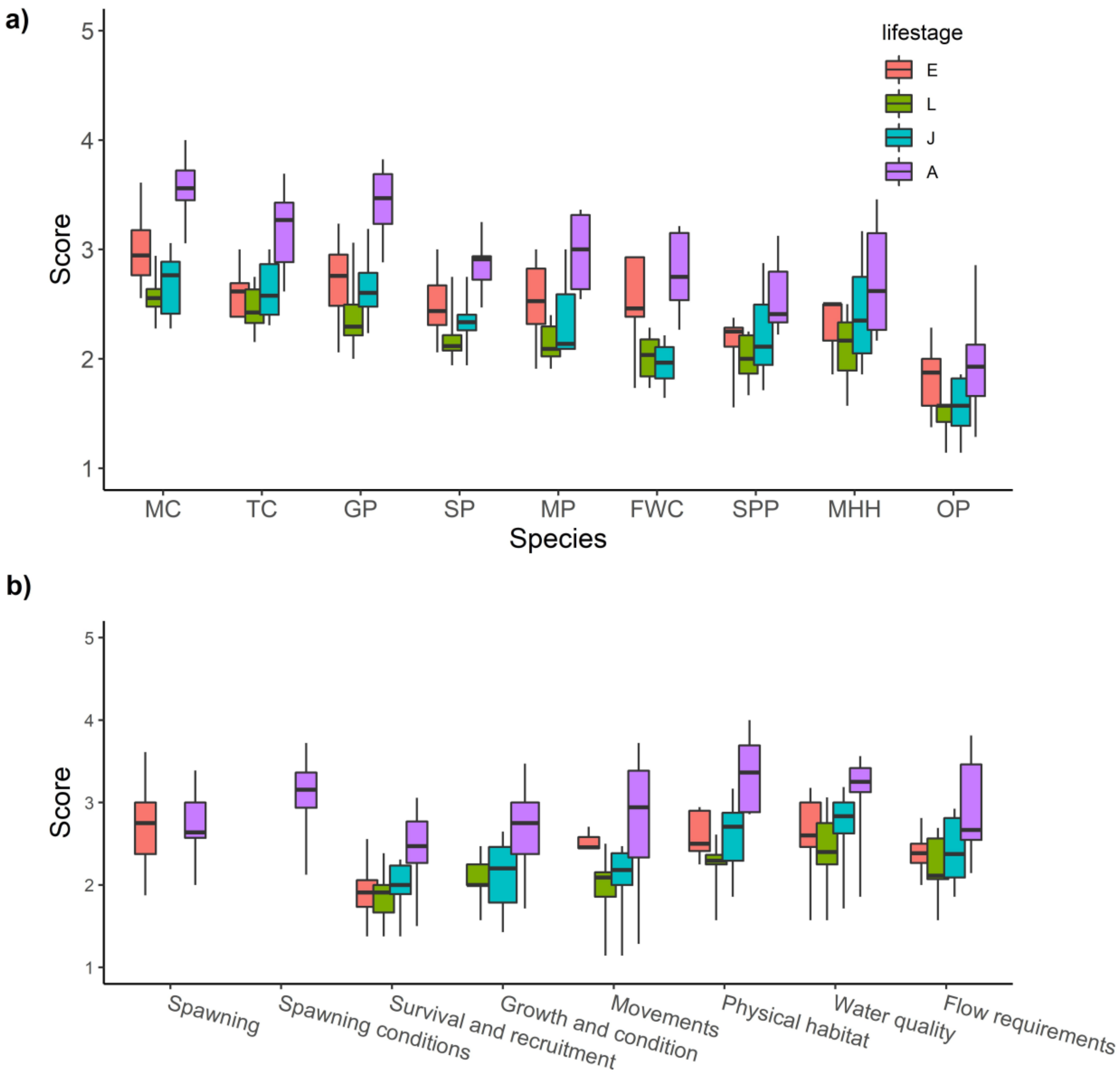

Fig. S1. Mean (with s.d. and range) knowledge assessment score for (*a*) each species by life stage, and for (*b*) each knowledge category. E, eggs, L, larvae, J, juveniles, A, adults, Species: MC, Murray cod; TC, trout cod; GP, golden perch; SP, silver perch; MP, Macquarie perch; FWC, freshwater catfish; SPP, southern pygmy perch; MHH, Murray hardyhead; OP, olive perchlet.

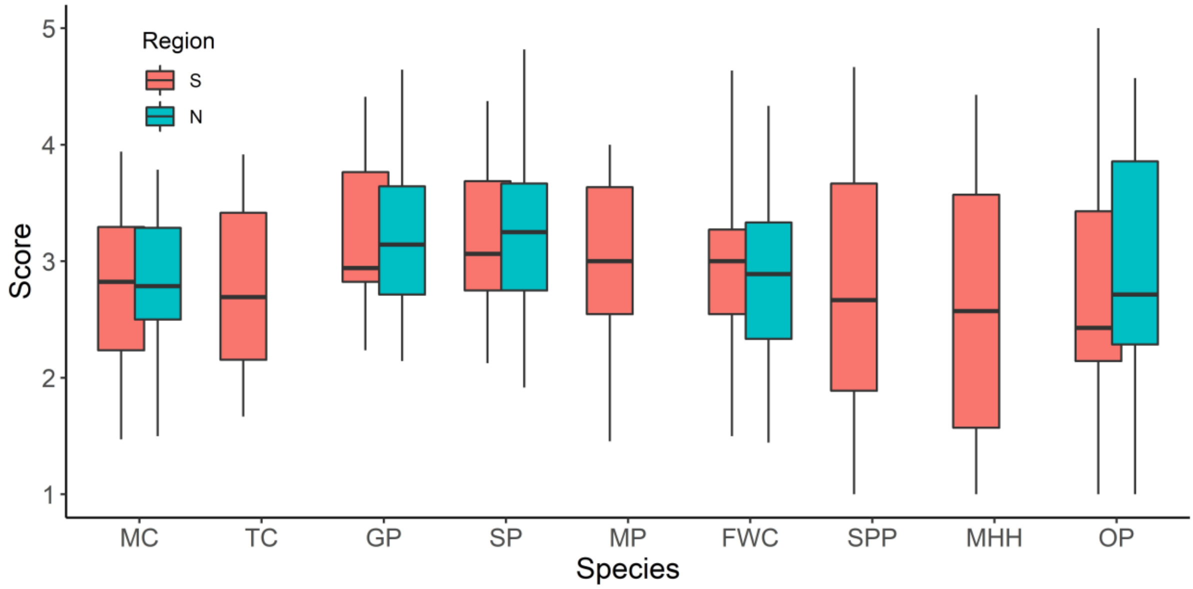

Fig. S2. Mean (with s.d. and range) knowledge assessment scores for each species by region. S, southern Murray–Darling Basin, N, northern Murray–Darling Basin. Species: MC, Murray cod; TC, trout cod; GP, golden perch; SP, silver perch; MP, Macquarie perch; FWC, freshwater catfish; SPP, southern pygmy perch; MHH, Murray hardyhead; OP, olive perchlet.

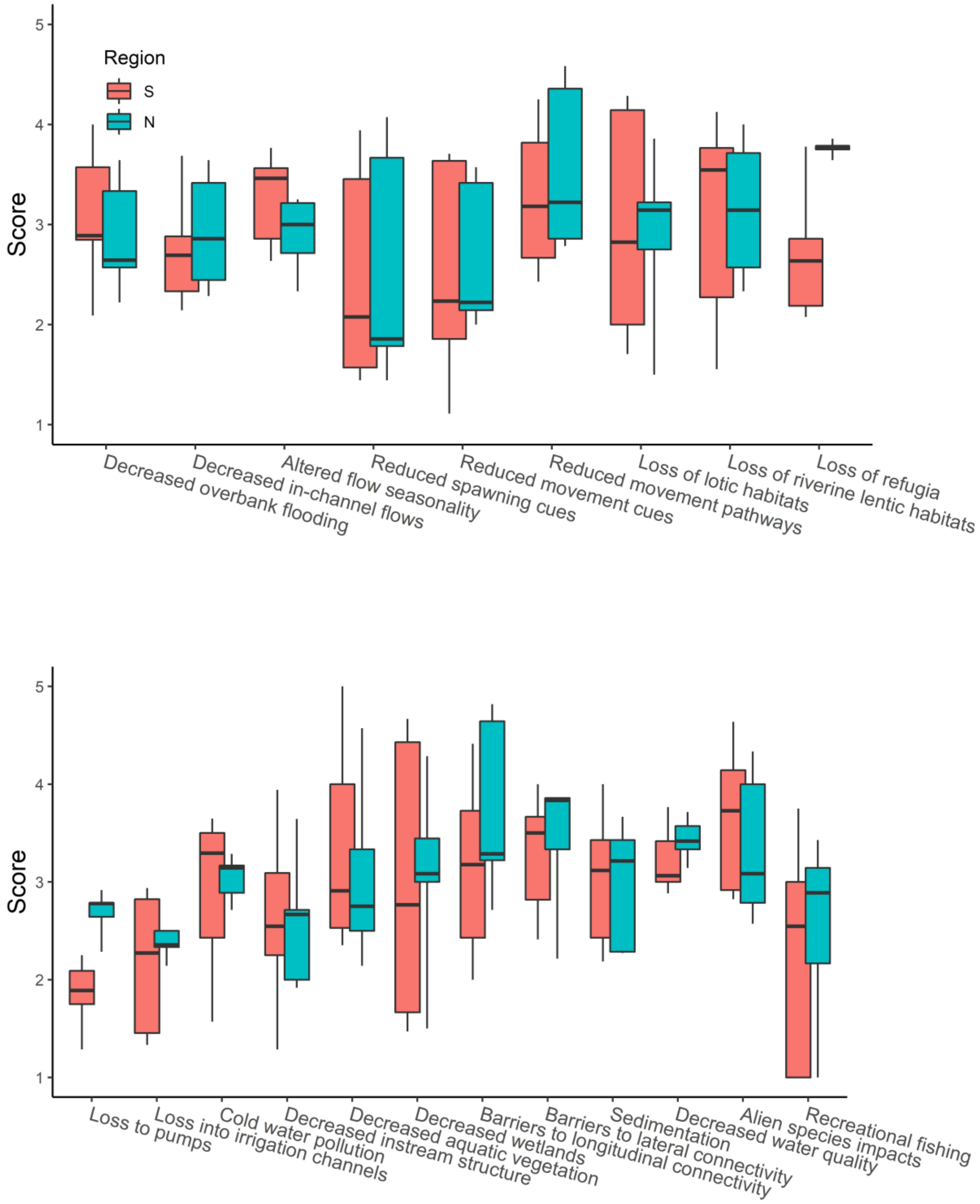

Fig. S3. Mean (with s.d. and range) assessment score for each (*a*) flow-threats and (*b*) non-flow threats for the southern (S) and northern (N) Murray–Darling Basin.

Table S1. Key environmental and ecological differences between the northern and southern Murray–Darling Basin that may influence the population processes of native fish species

Factor	NMDB	SMDB
ENVIRONMENTAL		
Rainfall	Summer-dominated	Winter-dominated
Temperature maxima	Long duration of warm periods	Medium duration of warm periods
Temperature minima	Short duration of cool periods	Medium duration of cool periods
Flow regulation	Partly regulated	Mostly regulated
Flow seasonality	Some natural	Mostly unnatural
Nature of water abstraction	Pumping, storage and floodplain harvest	Through distribution networks
Single-direction channel networks	Few, apart from main Darling channel	Dominant
Effluent channel networks	Dominant	Largely absent
Terminal Lakes	Present for many rivers	Mostly absent
Flow predictability	Highly unpredictable	More predictable
Intermittency	High	Low
Perennial flow	Medium	High
Time above thermal cue threshold for breeding	Extended period	Reduced period
ECOLOGICAL		
Rates of primary production	Higher	Lower
Early maturation of fish	Likely, especially in 'boom-bust' systems	Potentially later
Early growth rates of juveniles	Likely, especially in 'boom-bust' systems	Potentially slower rates
Longevity	Lower for some species (i.e. golden perch)	Higher
Reductions in population carrying capacity during waterhole drying phase	Likely	Would occur rarely and at only a few sites

Table S2. Descriptions and components included for the knowledge and threat assessments reported in Tables 2 and 3, Fig. 5 and S1, S2, S3

Knowledge description	Components included
Spawning	Fecundity, eggs, site, nesting, behaviour
Spawning conditions	Cues, temperatures, hydrology, hydraulics
Survival and recruitment	Mortality rates
Growth and condition	Growth and condition
Movements	Longitudinal, lateral, drift, proportion of population, distances
Physical habitat	Requirements; micro, macro
Water quality	Tolerances; dissolved oxygen, salinity, turbidity
Flow requirements	For functional population processes; frequency, sequence, extent
Threat	Description
Flow related	
Decreased overbank flooding	Extent and frequency of high flows; carbon inputs, productivity, plankton
Decreased in-channel flows	Extent and frequency of small-medium flows; carbon inputs, productivity, plankton
Altered flow seasonality	Temporal changes to the natural hydrograph
Reduced spawning cues	Pulses, floods
Reduced movement cues	Pulses, floods
Reduced movement pathways	Upstream, downstream, lateral, drift
Loss of lotic habitats	Creation of weir pools, reduced flows, loss of lateral channels
Loss of riverine lentic habitats	Increased flows, loss of backwaters, slack waters, floodplain wetlands
Loss of refugia	Flow diversions, pool pumping
Non-flow related	
Decreased wetlands	Decrease or degradation of wetland habitats; area, condition, diversity
Decreased aquatic vegetation	Decrease or degradation of aquatic vegetation
Alien species impacts	Carp, other species, predation, competition, habitat use or destruction
Sedimentation	All particle sizes, direct and indirect impacts
Decreased water quality	Dissolved oxygen, salinity, turbidity, blackwater, pollutants
Barriers to lateral connectivity	All types
Barriers to longitudinal connectivity	All types
Decreased instream structure	Decrease or degradation of instream woody or structural habitats
Cold water pollution	From dam releases
Loss into irrigation channels	All life stages
Loss to pumps	All life stages
Recreational fishing	Harvest, catch and release mortality

Key knowledge gaps and messages for restoration for each species

Murray cod Maccullochella peelii

Key knowledge gaps

- Stock assessment and quantification of angler harvest (Gwinn *et al.* 2020), catch-and-release mortalities, and stocking survival rates
- Recruitment to adults through age-specific survival between life stages, spatial differences in recruitment success and relationship with flows
- Larval drift distances
- Impact of low winter flows on juvenile survivorship
- Regional variation in biological characteristics (size, growth, fecundity, spawning times)
- Ways to minimise blackwater and fish kills and the availability of refuges across the appropriate spatial scales
- Quantification of the contribution of stocked fish to populations

- Habitats and movements of early life stages

Key messages for restoration

- At broad-scale implement hydrographs to support Murray cod populations, evaluate and refine. Avoid dramatic variations in water depth during spawning season to protect nesting and mitigate low winter flows (to more natural winter flows) (see Stuart *et al*. 2019; Fig. 11) in the SMDB to improve fish condition and recruitment
- Conservation and fishery management needs to be complementary (Koehn and Todd 2012)
- Ameliorate cold-water pollution
- Screening to prevent loss of larvae through pumps and irrigation infrastructure
- Protection of remnant waterholes (e.g. moratorium on pumping) during extended dry periods, especially in NMDB
- Increase instream structural woody habitats
- Increase hydrodynamic diversity
- Minimize blackwater events and potential fish kills
- Monitor stock structure and angler harvest (including catch-and-release mortalities)
- Translocation to re-establish NMDB populations in catchments with extirpated populations (e.g. Paroo River)

Trout cod Maccullochella macquariensis

Key knowledge gaps

- Recruitment to adults through age-specific survival between life stages
- Recruitment relationships with flows
- Larval drift distances
- Recolonisation rates
- Survival of hybrids with Murray cod
- Quantification of incidental capture and angler harvest
- Habitats and movements of early life stages

Key messages for restoration

- Establishment of additional populations is essential to improve conservation status
- Dramatic variations in water depth should be avoided during spawning season to protect nesting
- Ameliorate cold-water pollution
- Increase instream structural woody habitats
- Protection from angler harvest or catch-and-release mortality

Golden perch Macquaria ambigua

Key knowledge gaps and data limitations

- Rates of movement, including drift distances for eggs and larvae (distances over time) and the proportion of population moving for each life stage and purpose (e.g. spawning, recolonisation by 0+, 1+)
- Age-specific survival rates for each life stage, especially for eggs and larvae in weir pools
- Use of off-channel floodplain nursery areas
- Effect of blackwater on spawning and survival of eggs, larvae and 0+ fish; and interactions between populations
- Impacts of angler harvest on population structure

Key messages for restoration

- At broad-scales, implement hydrographs to support golden perch populations, evaluate and refine
- Coordinated flow management and large-scale connectivity (landscape-scale; river to basin-wide; >500 km) for this highly mobile and migratory species. Fish passage (upstream and downstream) at barriers, provision of appropriate flows for fishway operation or barrier drown-out
- Designed hydrograph (See Fig. 11) with elevated flows for spawning, recruitment and movements and protection of flows required over large spatial scales. Flows delivered in spring–early summer for spawning (e.g. within-channel rises coupled with temperatures >18°C), flow pulses delivered throughout spring-autumn to promote movement (January-March in SMDB) to facilitate dispersal of migrating juveniles into tributaries
- Identify and prioritise floodplain nursery habitats for restoration
- Multi-year flow sequences would be preferred for terminal lakes and wetlands: year one, filling for ecosystem priming of production; year two, spawning; year 3, flows to allow lateral reconnection and recolonisation of 1+ fish from the wetland back into the main river channel
- In arid NMDB rivers, vital refuge habitats such as waterholes need protection from water extraction, fish kills and cattle access, particularly during extended zero-flow conditions
- Remediation of cold-water pollution
- Screening to prevent loss of drifting eggs and larvae into irrigation infrastructure
- Restoration of flowing water habitats to maximise hydraulic habitats diversity

Silver perch Bidyanus bidyanus

Key knowledge gaps

- Rates of movement, including drift distances for eggs and larvae (distances over time) and the proportion of population moving for each life stage and purpose (e.g. spawning, recolonisation by 0+, 1+ fish)

- Recruitment dynamics, particularly causal links between individual life stages and flows and the key drivers of early life stage survival (egg and larvae), floodplain inundation and habitat use

- Age-specific survival rates for each life stage

- The population status and demographics of NMDB populations and interactions with the SMDB

- Population status in regulated SMDB tributaries and interactions with the Murray River population

- Drivers of movements and juvenile dispersal

- Blackwater impacts on survival of adult fish

- Dietary overlap with exotic species, particularly carp

Key messages for restoration

- At broad-scales, implement hydrographs to support silver perch populations, evaluate and refine

- As for golden perch, there is the need for landscape-scale management for this wide-ranging threatened species that requires appropriate flows, permanent flowing water and effective fish passage and connectivity. Small to moderate rises in flow (e.g. ‘freshes’) in the SMDB can promote juvenile movements, particularly between late summer and early autumn, including into tributaries of the mid-Murray River. Given a lifespan mostly less than seven years, flows to induce spawning should be implemented as 1-in-1 year within-channel events and should be based on the natural hydrograph in spring–early summer

- A need to strengthen the Murray River population and improve recruitment in its tributaries

- Need to implement a recovery plan for the NMDB

- Flows that inundate or allow access to productive off-channel habitats can enhance recruitment strength (see Tonkin *et al.* 2017)

- Restoration of flowing water habitats where weir pools now predominate (e.g. lower Murray River), through weir pool lowering, removal or increased discharge may be beneficial

Key knowledge gaps

- Research into captive breeding as hatcheries have been unable to breed Macquarie perch in sufficient numbers for widespread restocking
- Evidence that the use of environmental water to scour target habitats (e.g. riffles to improve spawning, pools to sustain refuges) improves populations
- Determination of spawning site selection (i.e. why do they only use a small subset of available sites)
- Temperature mortality rates for eggs and larvae
- Age-specific survival rates of each life stage
- Age-length relationships
- Predation by alien fish (particularly eggs, larvae and juveniles)
- Dissolved oxygen tolerances - important for dam filling or low summer flows when pools may stratify
- Impacts of angler harvest on population structure (including catch-and-release mortalities)
- Effects of genetic rescue to arrest declining genetic variability in small, isolated populations (see Pavlova *et al*. 2017; Weeks *et al*. 2011)

Key messages for restoration

- The small and fragmented nature of populations mean that they are at high risk and there is a need to protect existing and re-establish additional populations for conservation using hatchery reared fingerlings or translocations from wild populations (Lintermans 2013*c*)
- Unlike most other native species, managing water delivery to avoid great increases in discharge during the spawning period will provide the best recruitment outcomes (Tonkin *et al*. 2017). Environmental water should be targeted to maintain critical habitat attributes (riffles, pools, refuge pools in drought and water quality)
- Although water level manipulation in reservoirs to purely enhance species of conservation importance in multipurpose reservoirs like Lake Dartmouth is difficult, its use should still be considered as a viable management option for maintaining important populations (see Lintermans *et al.* 2010), particularly within smaller systems or under extreme circumstances, such as following several decades of high lake levels and poor recruitment (Tonkin *et al*. 2014) or following periods of prolonged recruitment failure
- Ensuring population sustainability from angler harvest and catch-and-release (Hunt *et al.* 2011)

Key knowledge gaps

- Effects of flow and temperature on spawning, recruitment and population dynamics, including rates of movement (longitudinal and lateral) and recolonisation patterns (e.g. larval dispersal)
- Validation of ages and population structure (including genetics)
- Age-specific survival rates
- Behaviour and movement patterns of larvae and juveniles
- Effects of sedimentation on spawning success and early-life stages
- Location and habitat requirements for larvae and juveniles, including the use of weir pools and wetlands
- Environmental cues (e.g. flow and water temperature) that stimulate critical movement and the ability to negotiate existing barriers and fishways
- Impacts of introduced species (e.g. predation from carp, redfin)
- Determination of potential re-introduction sites

Key messages for restoration

- Off-channel habitats can be protected or improved through provision of environmental water, reduce stock access and reduce or eliminate carp
- Protection and rehabilitation of macrophytes and complex woody or structural habitats
- Reductions in consistent, long-term, high velocity flows (usually for water delivery), especially during nesting periods
- Reduction in pest species
- Protection and maintenance of refuge pools, particularly in NMDB during droughts
- Provision of overbank flows and connections to off-stream habitats for recruitment and recolonisation to and from main river channels
- Protection of first post winter flow events
- Translocation to establish new populations in dams, small impoundments and rivers where they have been extirpated

Southern pygmy perch Nannoperca australis

Key knowledge gaps

- There is limited biological knowledge for this species and research is required to support conservation management (see Knight and Arthington 2008; Knight *et al.* 2007, 2009, 2012 for examples undertaken for the Oxleyan pygmy perch *Nannoperca oxleyana*)
- Magnitude, frequency and timing of flooding to support recruitment and colonisation, temperature for eggs to survive or hatch; survival rates of eggs and larvae and the habitat requirements for larvae
- Age-specific survival rates
- Determination of movements, including dispersal and recolonisation rates
- Quantification of important habitat parameters in refuge pools required to support the species (i.e. pool size, macrophyte density, woody habitats)

Key messages for restoration

- Existing populations need to be secured, as recruitment failure can lead to rapid localised extinction
- Protection of habitats from stock access to protect instream and riparian vegetation damage is important
- The protection and maintenance of refuge pools is paramount to ensure population persistence of fragmented populations, particularly during droughts
- Removal of alien fishes (e.g. redfin, carp and trout species)
- Translocation to establish new populations (Raymond and Day 2018)

Murray hardyhead Craterocephalus fluviatilis

Key knowledge gaps

- General biology and life history, including fecundity and development of oocytes within ovaries requires further investigation
- Larval mortality rates and preferred salinity levels in the wild
- Age-specific survival rates
- Understanding the number and distribution of populations required to support broader metapopulations
- Rates of movement (or facilitated transfer) between populations to ensure genetic integrity

Key messages for restoration

- Secure existing core populations, especially through periods of drought but also for the longer-term
- Establishment of new populations through translocation to reduce extinction risk (Ellis and Pyke 2010; Ellis *et al.* 2011; Stoessel 2012; Bice *et al.* 2013, 2014)
- Management of favourable habitat components, which may include watering, is required to manage salinity and productivity (Wedderburn *et al.* 2013)

- Environmental watering should aim to raise water levels early in the breeding season to promote spawning and beneficial trophic conditions (Wedderburn *et al.* 2013)
- Establish captive breeding program for population re-establishment

Olive perchlet Ambassis agassizzii

Key knowledge gaps

- More detailed ecological studies in the MDB are required as much of the available information is currently inferred from coastal catchments
- Egg or larval mortality and, survival, population age structure and dynamics
- Age-specific survival rates
- Impacts of carp, including the level of impact on populations at different densities and in different habitats

Key messages for restoration

- Maintain instream base flows, low or no flow periods (ideally in spring in the NMDB and summer in the SMDB) to encourage macrophyte growth
- Provide higher flows to create lateral connectivity to wetlands for breeding in summer in the NMDB, then follow-up reconnection of wetlands to allow recruits back to the river
- Protection of macrophytes from cattle, fencing and replanting of riparian vegetation
- Removal or exclusion of carp from wetlands
- Translocation to re-establish populations

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