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NOTE

Expanding the known range and practical conservation issues of the Endangered Australian brook lamprey *Mordacia praecox*

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ABSTRACT: Parasitic and non-parasitic lamprey 'species pairs' are an ongoing source of taxonomic uncertainty globally. The geographic range of the only non-parasitic lamprey in the Southern Hemisphere, the Endangered Australian brook lamprey *Mordacia praecox*, has remained ambiguous since its description in 1968. The conservation of this species is complex as it is presently genetically and, for most of its lifecycle, morphologically indistinguishable from its parasitic paired species, short-headed lamprey *M. mordax*, the conservation status of which is Least Concern. Difficulty in their identification, coupled with their cryptic behaviour, has resulted in limited knowledge of the species' ecology and distribution. This is further complicated by the sympatric geographic ranges of the paired species. Using incidental captures, targeted surveys, and open-access wildlife information database records, we describe the discovery and confirmation of lamprey populations from tropical and sub-tropical Australia and the associated ~1400 km (5-fold) northward extension of the known geographic range of Australian brook lamprey. Surveys yielded non-parasitic lampreys of all life-history stages across 6 tropical and sub-tropical coastal watersheds of eastern Australia. We also highlight major issues associated with the conservation of a cryptic and poorly understood species and discuss potential conservation actions that may, at least in part, ameliorate such issues.

KEY WORDS: Paired species · Lamprey · *Mordacia* · Conservation · Tropical

1. INTRODUCTION

While the shift between anadromous and potamodromous life histories has occurred in many fish species (McDowall 1997), the concept of 'paired species' is unique to lampreys (Zanandrea 1959). The majority of lamprey species exist as paired parasitic/non-parasitic species, in which non-parasitic potamodromous species are believed to descend from the parasitic lampreys (Zanandrea 1959). While many are established as separate species, some paired species show no difference in the mitochondrial genome and are argued to be ecotypes of one species (Carim et al. 2023). Larval lamprey, known as ammocoetes, are morphologically indistinguishable in many paired species (Renaud 2011). During the larval stage, microphagous individuals remain buried in the substrate of freshwater watercourses, feeding on organic detritus. Lampreys generally metamorphose from ammocoetes after 4–7 yr (Potter 1980), undergoing substantial morphological and physiological changes, including the development of eyes, a toothed oral disk, enlarge-

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ment of fins and modification of the foregut (Hardisty & Potter 1971). At the point of metamorphosis, paired species diverge in behaviour and morphology. As juveniles, parasitic forms generally move to downstream river reaches or the sea to feed, grow and mature to adults before returning upstream to spawn. Nonparasitic forms forego migration, feeding and growth phases altogether and spawn and die within months of metamorphosis to the adult stage (Docker 2009).

The dichotomy of adult lamprey feeding types, in conjunction with a general lack of morphological differences, has contributed to substantial taxonomic uncertainty within the group. Up to 47 lamprey species are recognised (Docker & Potter 2019, Naseka & Renaud 2020, Riva-Rossi et al. 2020), with almost half of those species being based on morphologically similar lampreys with different adult feeding types. Ammocoetes of all paired species are difficult, if not impossible, to distinguish based on morphology, and adults are commonly only differentiated based on geographic location and body length (Docker 2009). Identification is further complicated by many species pairs presently being indistinguishable by means of genetic data (Docker & Potter 2019, Carim et al. 2023).

The conservation of lampreys is of concern globally (Docker & Hume 2019), particularly due to their significance to research on the evolution of vertebrates, vertebrate physiology and biochemistry, phylogeography and mechanisms of speciation (York et al. 2019). Only 5 species from 2 families are known from the Southern Hemisphere (Renaud 2011, Riva-Rossi et al. 2020), with the pouched lamprey *Geotria australis*, short-headed lamprey *Mordacia mordax* and Australian brook lamprey *M. praecox* occurring in Australia; the latter 2 being paired species. Australian brook lampreys are only known from a few waterways of the Moruya, Tuross and East Gippsland river regions of southeastern New South Wales, where they are sympatric with short-headed lamprey (Gilligan 2019a). Each species' exact distribution is currently ambiguous due to their sympatry and their being indistinguishable through both genetic analyses and morphological examination of ammocoetes (Potter 1968, Renaud 2011, Garbutt 2015). Adults, which are identifiable to species, are unlikely to be encountered due to their short lifespan (Potter 1980) and the species' cryptic behaviour. While the life history of Australian *Mordacia* is not entirely clear, ammocoetes of this species pair are thought to metamorphose at 3.5 yr of age. The 2 species are distinguishable in freshwater habitats by a combination of dentition and size for less than a year of their lives. Australian brook lamprey spawn and die in their natal stream within 6 mo of metamorphosis, while short-headed lamprey are anadromous and return to fresh water after 1–2 yr (Renaud 2011). Australian brook lamprey were recently listed as Endangered under Australian legislation (EPBC Act 1999; DCCEEW 2023) and the IUCN Red List (Gilligan 2019a), whereas the short-headed lamprey is listed by the IUCN as Least Concern (Gilligan 2019b). This presents a difficult question: How do managers practically conserve a cryptic species that is mostly indistinguishable from a sympatric, non-protected species? There is a high risk that Australian brook lamprey may be misidentified as short-headed lamprey and excluded from conservation actions.

Following the incidental capture of lampreys in 2 geographically distant Queensland waterways in 2001 (DCCEEW 2023), we used targeted sampling and incidental captures to investigate the occurrence of lampreys in coastal central eastern Australia. As records of lamprey captures in the region have so far been seldom and taxonomically ambiguous, we aim to organise, correct, and extend existing knowledge on lampreys in sub-tropical and tropical eastern Australia. Further, we redefine the northern range of Australian brook lamprey and discuss practical conservation issues arising from the disparity in conservation status of the 2 Australian *Mordacia* species.

2. MATERIALS AND METHODS

Lampreys were incidentally captured on multiple occasions during ecological research and monitoring in Southeast Queensland, Australia, during 2001–2022. These catches primarily arose from single-pass backpack electrofishing operations as part of rapid fish-based ecological condition assessments. We collated unconfirmed Australian *Mordacia* records from the Global Biodiversity Information Facility (GBIF), Atlas of Living Australia (ALA) and Queensland WildNet open-access wildlife information databases, as well as from grey literature and unpublished reports, to inform targeted sampling and better define the distribution of both *Mordacia* species. Searches were performed in September 2023, and duplicate records among databases were filtered using date and location.

Targeted electrofishing of Queensland *Mordacia* populations was undertaken between 2010 and 2021 by D. B. Moffatt to gain further data and identify the species in question. Data collected during this work included the total length (TL, ±1 mm) and developmental stage of each individual, physicochemical water quality (water temperature, pH and electrical conductivity) and sampling effort by sample location.

Life history stage was categorised as ammocoete, early transformer, late transformer or adult as per Hardisty & Potter (1971). We have avoided defining the phase of the lamprey life cycle at the end of metamorphosis as 'macrophthalmia', as the defining criteria for non-parasitic lamprey species is ambiguous (Renaud 2011). A subset of individuals was euthanised using isoeugenol (AQUI-S Aquatic Anaesthetic) and retained as voucher specimens for morphological examination in the laboratory using a binocular dissection microscope.

3. RESULTS

A total of 1139 Australian records for *Mordacia* were collated from the GBIF, ALA and Queensland Wildnet databases after filtering duplicates. Only 4 of these records were designated as Australian brook lamprey *M. praecox* (Fig. 1), none of which occurred in latitudes north of 35.90° S. All 5 sub-tropical and tropical *Mordacia* records were listed as short-headed lamprey *M. mordax* in their respective database. Three sub-tropical and tropical records have associated preserved specimens (Queensland Museum specimens i33302, i33152, and Australian Museum specimen i.24282-001). These specimens consisted of 2 pre-transformation ammocoetes (i33302, i.24282-001) and a late transformer (i33152).

A total of 1403 lampreys were caught from all surveys at 26 sites across 6 catchments between 22.76 and 30.63° S, consisting of 1304 ammocoetes, 40 transforming ammocoetes and 59 adults (Table 1). Lampreys were recorded in all Queensland waterways where they have been found previously and for the first time in the Macleay and K'gari (Fraser Island) catchments of northern New South Wales and southern Queensland, respectively (Fig. 1). Lampreys caught ranged in size from 14 to 162 mm TL with fully transformed adults being of a mean length of 103.8 ±

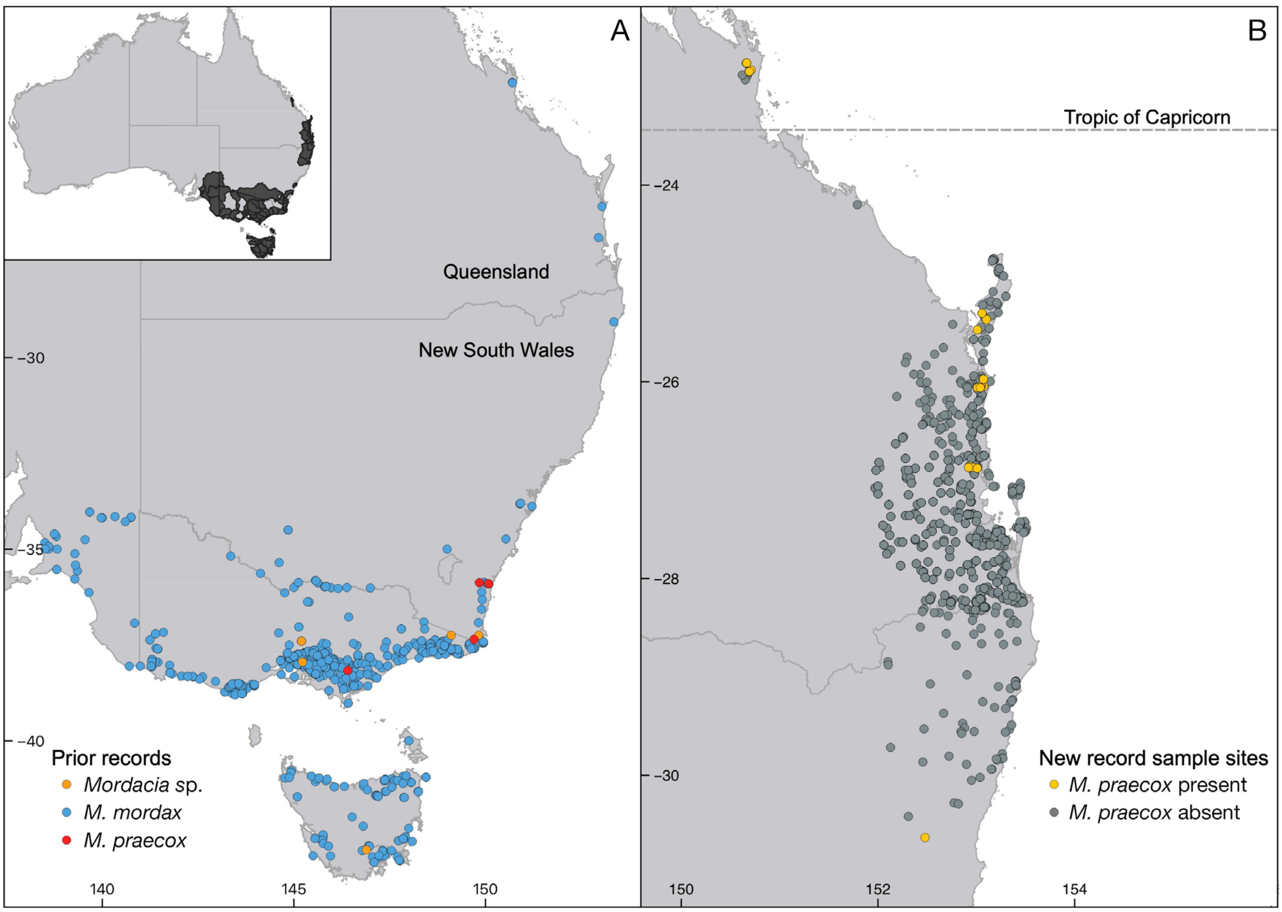

Fig. 1. Locations of the occurrence of collated historic *Mordacia* records in Australia by (A) species and targeted sampling sites between 22 and 31° S, showing (B) new *M. praecox* records, with *Mordacia* record and sample site catchments highlighted in Australia (inset). Open-access wildlife information database records generated by this study have been omitted from prior records map

Table 1. Total number and lengths (mean ± SD) of lampreys caught grouped by life history stages and river catchment

Life history stage	Catchment	No.	Total length (mm)
Ammocoete	K'gari (Fraser Island)	4	89.5 ± 3.11
	Maroochy River	22	124.68 ± 29.07
	Noosa River	1129	58.44 ± 15.63
	Searys Creek	119	71.29 ± 15.32
	Water Park Creek	30	93.2 ± 20.09
Early transformer	Maroochy River	4	147.75 ± 6.08
	Noosa River	5	71 ± 4
	Searys Creek	2	92.5 ± 0.71
Late transformer	Noosa River	23	74.57 ± 7.14
	Searys Creek	6	82 ± 4
Adult	Macleay River	1	130
	Maroochy River	2	149.5 ± 0.71
	Noosa River	2	73.5 ± 3.53
	Searys Creek	3	84.33 ± 7.64
	Water Park Creek	51	103.8 ± 8.58

14.2 mm (mean ± SD; Table 1). Lampreys were caught in water temperatures between 17 and 27°C, in mostly sand-bottomed, tannin-stained coastal waterways.

Examination of the external morphology of all lampreys caught (Fig. 2) was consistent with the genus *Mordacia* (Potter 1968, Renaud 2011), particularly the presence of 2 triangular and tricuspid supraoral laminae (SO) in late transformers and adults (Fig. 2B,C). Adult individuals were identified as Australian brook lamprey by dentition, as per Potter (1968). Late transforming individuals featured a conspicuous outer ring of radial plates (Fig. 2B) joining both inner (IR) and outer (OR) radial teeth. This plate became less evident with ongoing development, such that plates completely disappeared in adult specimens leaving the IR and OR teeth separated (Fig. 2C). Developed infraoral laminae (IO) with prominent cusps pointing towards the oesophageal opening (OO) were also present on adult lampreys (Fig. 2C). Dentition was examined only for individuals from Water Park and Maroochy River catchments due to logistical constraints.

4. DISCUSSION

4.1. Species and range

The identity of lampreys caught in our targeted surveys and incidental captures were consistent with a non-parasitic species of *Mordacia*, nominally Australian brook lamprey *M. praecox*. The dentition of examined specimens was concordant with the diagnostic features of Australian brook lamprey (Potter 1968), and life history traits

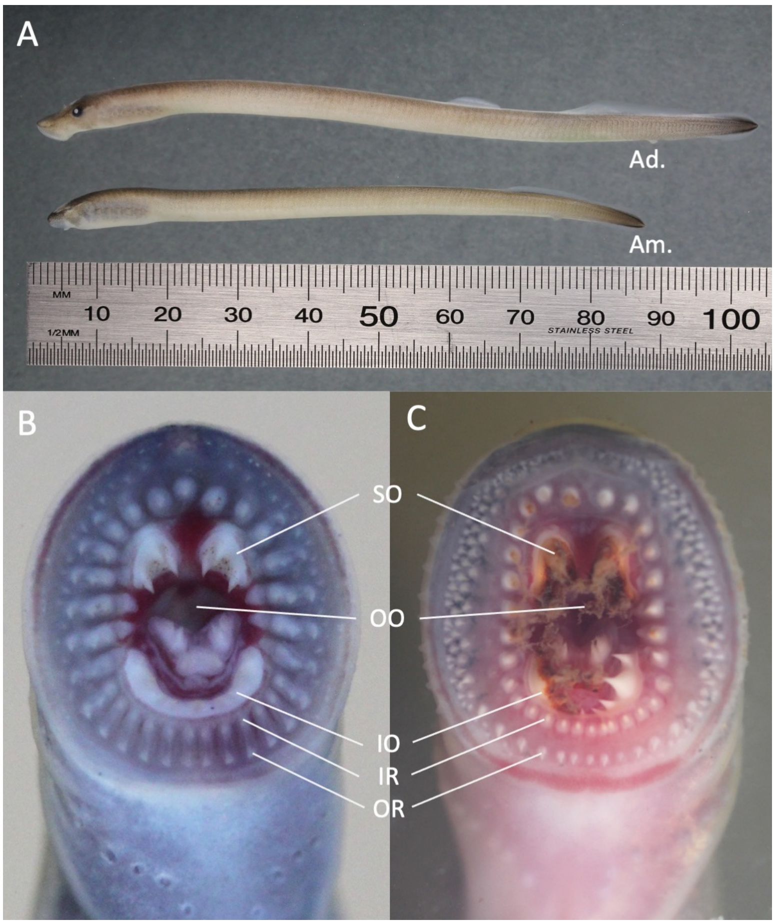

Fig. 2. (A) Adult (Ad.) and ammocoete (Am.) *Mordacia praecox* from Water Park Creek. (B) Dentition of 115 mm late transformer Australian brook lamprey from Water Park Creek (Queensland Museum specimen i41308), showing radial plates before breakdown and tricuspid supraoral laminae (SO). OO: oesophageal opening; IO: infraoral laminae; IR: inner radial teeth; OR: outer radial teeth. (C) Dentition of 150 mm adult Australian brook lamprey from Coochin Creek (Queensland Museum specimen i41309), showing IR and OR teeth not joined by radial plates, and large IO cusps facing OO. Note: white colouration in eye of adult specimen is due to preservation

were also consistent with the species. Adults of paired feeding and non-parasitic lampreys can be distinguished by body size alone (Docker 2009), and no adults caught in this study exceeded the size range of Australian brook lamprey. While parasitic lampreys continue to grow as feeding juveniles, non-parasitic forms do not, and adults are typically smaller than the largest ammocoetes, shrinking during maturation as they cease feeding. The fragmented populations observed in this study are consistent with life history of non-parasitic lampreys, which do not have a large migratory adult stage and spawn in their natal streams. Anadromous parasitic lampreys are not philopatric and spawn in a general area, rather than a specific river (Docker & Hume 2019). There are also no records of the occurrence of lamprey parasitism or associated wounds on host species in tropical and sub-tropical waters.

Short-headed lamprey has been used as a default identification for lampreys caught in sub-tropical and tropical Australia due to a belief that these captures represented vagrants from southern populations. This confusion stems from a combination of Australian brook lamprey being impossible to identify as ammocoetes and possessing an extremely limited and contracting range (Gilligan 2019a), as well as the fact that water temperatures in sub-tropical and tropical areas often exceed 28–30°C, which was thought to be the maximum thermal tolerance of ammocoetes (Macey & Potter 1978, Potter 1980).

Until now, the northern range of Australian brook lamprey has been difficult to define due to the sparsity of lamprey records from tropical and sub-tropical Australian waters and the difficulty in reliably identifying ammocoetes. Considering the number of individuals from all life history stages recorded during this study, we are able to confirm the existence of several persistent populations of Australian brook lamprey in coastal sub-tropical and tropical rivers as far north as 22.76° S. Lamprey have been recorded on several occasions in the Maroochy River region of southern Queensland from 2001 to 2021, for example, well exceeding the expected longevity of the species (approximately 5 yr; Potter 1980). Given the 'anti-tropical' distribution of lamprey species across the globe (Potter 1980, Renaud 2011), it is surprising to find new lamprey populations extending into the tropics. While the Mexican lamprey *Tetrapleurodon spadicea* and its non-parasitic counterpart, the Mexican brook lamprey *T. geminis*, are known from the tropics, they are restricted to high altitude cool watersheds in the highlands of central Mexico (Lyons et al. 1994, Renaud 2011). The Water Park Creek population of Australian brook lamprey marks the northern extent of the species' range and thus is only truly tropical lamprey in the world. The southern extent of the range of Australian brook lamprey remains ambiguous due to sympatry with short-headed lamprey (Potter 1968); however, future studies may be able to differentiate sympatric species using possible nuclear genomic divergence, as observed in some populations of other species pairs (Mateus et al. 2013, Souissi et al. 2022).

4.2. Conservation complexity

Over one-quarter of all lamprey (Petromyzontiformes) species are at risk of disappearing in the wild (Docker & Hume 2019). The conservation of imperilled lampreys is complicated due to the compounding issues of not being considered charismatic organisms and the limited information we have about their distributions and ecology (Docker & Hume 2019, Lucas et al. 2021). With regard to the latter, new populations of Australian brook lamprey discussed here had remained undiscovered until recently, despite their close proximity to major urban areas. Further complication arises for conservation efforts due to difficulty in morphological and genetic identification among species pairs (Potter 1980, Docker & Potter 2019). In cases where a protected species has been misidentified as a non-protected paired species, the former is effectively unprotected.

A practical solution in the case of Australian brook lamprey is to list the non-protected paired species, short-headed lamprey, as the same conservation status as the threatened species. Legislation exists in some countries that provides grounds to include similar species with an existing protected species. For example, in Australia, subsection 186(4) of the Environmental Protection and Biodiversity Conservation (EPBC) Act 1999 makes provisions for a non-listed species to be included in the category of a listed species if it is difficult to differentiate between the 2 species and this difficulty poses a threat to the already listed species. For Australian brook lamprey, listing short-headed lamprey as Endangered under the EPBC Act 1999 would ensure that regardless of a given population's ambiguous identity, Australian brook lamprey would be protected. In the case of the 2 adult feeding types being ecotypes of the same Linnean species, the evolutionarily significant unit (ESU) concept may be a more applicable model for conservation, in relation to current geographic separation and potential adaptation of phenotypes (Casacci et al. 2014). Several precedents for the use of lamprey ESUs already exist globally (Lucas et al. 2021). Tropical and sub-tropical populations of *Mordacia* in Australia would fulfill the criteria of an ESU, or multiple ESUs, based on population fragmentation and the distinct habitat that they inhabit, owing to possible local adaptions for higher thermal tolerance.

The future of lamprey conservation will be most improved by genetic and genomic advancements, particularly for threatened lampreys in species pairs such as Australian brook lamprey. The discovery of genomic divergence between Australian *Mordacia* species, as has been done for some populations of other lamprey species pairs (Mateus et al. 2013, Souissi et al. 2022), would allow for reliable distinction of species for all life history stages. This would also enable the development of environmental DNA (eDNA) assays. At present, eDNA detection of lampreys has been met with variable success (Gingera et al. 2016), possibly due to substrate-inhabiting ammocoetes liberating small amounts of genetic material into the water column. With further development, eDNA could become a useful complementary tool to traditional survey methods, providing economical and rapid species detection.

Being part of the most ancient groups of extant vertebrates, lampreys are widely used as model organisms for research on embryonic development, organ differentiation and phylogenetics and have greatly contributed to the understanding of vertebrate evolution (York et al. 2019). With a maximum of only 47 species remaining today (Docker & Potter 2019, Naseka & Renaud 2020, Riva-Rossi et al. 2020), the conservation of all extant lamprey species will be valuable to future research discoveries. Understanding the full spectrum of lamprey taxonomy, ecology, and biogeography is essential for the conservation of species under threat from anthropogenic changes. With projected eustatic sea levels rises (Horton et al. 2014), many of the coastal streams that Australian brook lamprey inhabit are likely to suffer saltwater incursion, drastically reducing suitable habitat for the species. Additionally, global temperature increases (IPCC 2018) are sure to contract the habitable range of many of these mostly 'anti-tropical' species.

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LITERATURE CITED

Carim KJ, Larson DC, Helstab JM, Young MK, Docker MF (2023) A revised taxonomy and estimate of species diversity for western North American *Lampetra.* Environ Biol Fishes 106:817–836

Casacci LP, Barbero F, Balletto E (2014) The 'evolutionarily significant unit' concept and its applicability in biological conservation. Ital J Zool 81:182–193

DCCEEW (Department of Climate Change Energy, the Environment and Water) (2023) Conservation advice for *Mordacia praecox* (precocious lamprey). DCCEEW, Canberra

Docker MF (2009) A review of the evolution of nonparasitism in lampreys and an update of the paired species concept. In: Brown LR, Chase SD, Mesa MG, Beamish RJ, Moyle PB (eds) Biology, management, and conservation of lampreys in North America. Proc Am Fish Soc Symp, Bethesda, MD, p 71–114

Docker MF, Hume JB (2019) There and back again: lampreys in the 21st century and beyond. In: Docker MF (ed) Lampreys: biology, conservation and control. Springer, Dordrecht, p 527–557

Docker MF, Potter IC (2019) Life history evolution in lampreys: alternative migratory and feeding types. In: Docker MF (ed) Lampreys: biology, conservation and control. Springer, Dordrecht, p 287–409

Garbutt J (2015) The complete mitogenome of two Australian lampreys: *Mordacia mordax* and *Mordacia praecox*. BSc (Hons) dissertation, Murdoch University, Perth

Gilligan D (2019a) *Mordacia praecox* (errata version published in 2020). The IUCN Red List of Threatened Species 2019:e.T13851A174779500. https://dx.doi.org/10.2305/IUCN.UK.2019-3.RLTS.T13851A174779500.en (accessed 25 Aug 2022)

Gilligan D (2019b) *Mordacia mordax*. The IUCN Red List of Threatened Species 2019: e.T122898736A123382016. https://dx.doi.org/10.2305/IUCN.UK.2019-3.RLTS.T122898736A123382016.en (accessed 25 Aug 2022)

Gingera TD, Steeves TB, Boguski DA, Whyard S, Li W, Docker MF (2016) Detection and identification of lampreys in Great Lakes streams using environmental DNA. J Gt Lakes Res 42:649–659

Hardisty MW, Potter IC (1971) The general biology of adult lampreys. In: The biology of lampreys. Academic Press, New York, NY, p 127–206

Horton BP, Rahmstorf S, Engelhart SE, Kemp AC (2014) Expert assessment of sea-level rise by AD 2100 and AD 2300. Q Sci Rev 84:1–6

IPCC (Intergovernmental Panel on Climate Change) (2018) Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels in context of strengthening response to climate change, sustainable development, and efforts to eradicate poverty. World Meteorological Association, Geneva. https://www.ipcc.ch/sr15/

Lucas MC, Hume JB, Almeida PR, Aronsuu K and others (2021) Emerging conservation initiatives for lampreys: research challenges and opportunities. J Gt Lakes Res 47: S690−S703
Lyons J, Cochran PA, Polaco OJ, Merino-Nambo E (1994) Distribution and abundance of the Mexican lampreys (Petromyzontidae: *Lampetra*: Subgenus *Tetrapleurodon*). Southwest Nat 39:105−113
Macey DJ, Potter IC (1978) Lethal temperatures of ammocoetes of the Southern Hemisphere lamprey, *Geotria australis* Gray. Environ Biol Fishes 3:241−243
Mateus CS, Stange M, Berner D, Roesti M and others (2013) Strong genome-wide divergence between sympatric European river and brook lampreys. Curr Biol 23: R649−R650
McDowall RM (1997) The evolution of diadromy in fishes (revisited) and its place in phylogenetic analysis. Rev Fish Biol Fish 7:443−462
Naseka AM, Renaud CB (2020) Morphology-based taxonomic re-assessment of the Arctic lamprey, *Lethenteron camtschaticum* (Tilesius, 1811) and taxonomic position of other members of the genus. ZooKeys 991: 1−67
Potter IC (1968) *Mordacia praecox*, n. sp., a nonparasitic lamprey (Petromyzonidae), from New South Wales, Australia. Proc Linn Soc N S W 92:254−262
Potter IC (1980) The Petromyzoniformes with particular reference to paired species. Can J Fish Aquat Sci 37: 1595−1615
Renaud CB (2011) Lampreys of the world. An annotated and illustrated catalogue of lamprey species known to date. Food and Agriculture Organization of the United Nations, Rome
Riva-Rossi C, Barrasso DA, Baker C, Quiroga AP, Baigún C, Basso NG (2020) Revalidation of the Argentinian pouched lamprey *Geotria macrostoma* (Burmeister, 1868) with molecular and morphological evidence. PLOS ONE 15:e0233792
Souissi A, Besnard AL, Evanno G (2022) A SNP marker to discriminate the European brook lamprey (*Lampetra planeri*), river lamprey (*L. fluviatilis*) and their hybrids. Mol Biol Rep 49:10115−10119
York JR, Lee EMJ, McCauley DW (2019) The lamprey as a model vertebrate in evolutionary developmental biology. In: Docker MF (ed) Lampreys: biology, conservation and control, Vol 2. Springer, Dordrecht, p 481−526
Zanandrea GSJ (1959) Speciation among lampreys. Nature 184:380

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