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Alien fish ascendancy and native fish extinction: ecological history and observations on the Lower Goodradigbee River, Australia

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ABSTRACT

Context. The Murray–Darling Basin – Australia's largest river system – is heavily dominated by alien fish. Native fish species have suffered numerous localised extinctions and ~47% are listed on federal and/or state threatened species lists. **Aims.** This paper explores the hypothesis that alien fish and alien fish stockings can be the primary cause of decline and localised extinction of large-bodied native fish species, as opposed to habitat degradation and river regulation. The Lower Goodradigbee River, which is unregulated, in excellent instream health over the great majority of its course, and replete with high quality habitat, is utilised as a case study. **Methods.** I investigated the hypothesis by synthesising historical records with contemporary scientific research and recent field observations. The role of alien fish species, particularly alien trout species (*Oncorhynchus mykiss* and *Salmo trutta*) and constant stockings of them, were closely examined. **Results.** Data support the hypothesis that domination by alien trout species and their continual stocking have lead to historical declines and localised extinctions of large-bodied native fish species. Continued alien trout stockings, along with more recent invasions of alien carp (*Cyprinus carpio*) and alien redfin perch (*Perca fluviatilis*), are inhibiting native fish recovery. A suspected field sighting of the alien fish pathogen atypical *Aeromonas salmonicida* is reported, and the status of the declining native crayfish Murray cray (*Euastacus armatus*), and potential alien fish impacts upon them, are examined. **Conclusions.** The impacts of alien fish and alien fish stocking in Australia require major re-evaluation and dedicated research. **Implications.** It is strongly recommended that stocking of alien trout into the Lower Goodradigbee River for angling cease in order to conserve surviving native fish and Murray cray populations. Conservation stockings to effect a Murray cod (*Maccullochella peelii*) recovery in the Lower Goodradigbee River are warranted.

Keywords: alien species, atypical *Aeromonas salmonicida*, *Bidyanus bidyanus*, *Cyprinus carpio*, ecological history, ecosystem change, *Euastacus armatus*, extinction, fish stocking, freshwater ecosystems, *Gadopsis bispinosus*, habitat degradation, invasive species, *Maccullochella peelii*, *Macquaria australasica*, native fish, native fish decline, *Oncorhynchus mykiss*, river regulation, *Salmo trutta*, threatened species.

Introduction

Invasive alien species are recognised as a growing global problem (IUCN 2000; Seebens *et al.* 2017, 2021; Pyšek *et al.* 2020). They are a frequent result of the human propensity for moving and introducing species into areas outside their natural range; a practice that has been occuring for centuries (Hulme 2009; Bellard *et al.* 2016; Seebens *et al.* 2017) or in some cases, millenia (Gherardi 2010; Oskarsson *et al.* 2011; Balme *et al.* 2018). Invasive alien species and their profound impacts have traditionally been an under-recognised problem. Habitat degradation and habitat destruction are more obvious and dramatic, and claim more attention and attribution for environmental impacts, particularly in regards to declines and extinctions of endemic species (hereafter termed 'native' species) (e.g. Invasive Species Council (ISC) 2018).

While the relevant contributions and potential synergies of habitat degradation versus invasive alien species has been debated (e.g. Didham *et al.* 2005, 2007; Strayer 2010;

Doherty *et al.* 2015), it is increasingly recognised that alien species can be a severe threat to native fauna in their own right (Dickman 1996; Clavero and García-Berthou 2005; Salo *et al.* 2007; Woinarski *et al.* 2015; Bellard *et al.* 2016; Kearney *et al.* 2019). Clavero and García-Berthou (2005) found 20% of the 680 species extinctions listed by the IUCN were directly caused by alien species invasions. Bellard *et al.* (2016) found alien species were the second most common threat associated with IUCN Red List species that have become extinct since AD 1500. In the Australian context, Kearney *et al.* (2019) found invasive species affect the largest number of native species (1257 species, or 82% of all threatened species) listed under the Commonwealth or federal *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). Population level extinctions (i.e. localised extinctions) are a further layer of impact; these are not readily tallied but leave native species fragmented and primed for future extinction and represent significant biodiversity loss (Ricciardi 2004). Such global and nation-based threatened species lists and databases inevitably underestimate the true impact of invasive alien species on native species due to the historic nature of many alien species introductions (Cadwallader 1996; Dickman 1996; Lintermans 2000*a*, 2002; Cambray 2003*a*, 2003*b*; Abbott 2011); the practical difficulties in rigorously recording impacts of invading alien species then or now (Strayer 2010; Bellard *et al.* 2016); and a lack of interest in or even an outright reluctance to record those impacts (Cadwallader 1996; Cambray 2003*a*, 2003*b*; Nustad 2018).

However, in relatively undisturbed ecosystems, particularly where the confounding factor of habitat degradation is absent or can be partitioned out (due to fortuitous geography or geomorphology (e.g. waterfalls) or by experimental design), invasive alien species have been shown in many cases to be the sole cause of declines, localised extinctions and complete extinctions of native faunal species (e.g. Kinnear *et al.* 1988; Townsend and Crowl 1991; Ault and White 1994; Raadik *et al.* 1996; Townsend 1996; Kinnear *et al.* 1998; Lintermans 2000*b*; Gillespie 2001; Raadik *et al.* 2010; Raadik 2014; Woinarski *et al.* 2015; Lintermans *et al.* 2020). Such studies also demonstrate that alien species can invade pristine or near-pristine habitats successfully and rebut the popular notion that alien species need the 'helping hand' of habitat degradation to successfully invade; often only the 'releasing hand' of humans is necessary.

Invasive alien species are a particular problem in freshwater systems of the world. Multiple studies and reviews show river systems in more populated parts of the globe carry substantial and growing numbers of alien fish species, to the detriment of native species (e.g. Lintermans 2004; Leprieur *et al.* 2008; Gherardi 2010; Pyšek *et al.* 2020; World Wildlife Fund (WWF) 2020). A number of factors are involved, including a global sport fishing/recreational fishing culture that insists on the introduction of certain alien fish species for 'sport' and/or 'recreation' around the world, whilst simultaneously ignoring profound negative ecological and social impacts and meritorious local native species (e.g. Cambray 2003*a*, 2003*b*; McDowall 2003, 2006; Jackson *et al.* 2004).

Research and literature reviews reveal severe and detrimental impacts of invasive alien fish on native fish species in freshwater systems. Lowe-McConnell (1993) estimates approximately 200 species of native cichlid became extinct in Lake Victoria following the invasion of the Nile perch (*Lates niloticus*). Clavero and García-Berthou (2005) found alien fish species invasions to be the second main cause of native fish extinctions in North America (27 out of 40 spp.) and the world (11 out of 23 spp.). Light and Marchetti (2007) used an information theoretic approach to conclude that alien species invasions are the primary driver of extinctions and population declines of native fish in California. Schooley *et al.* (2008) report the razorback sucker (*Xyrauchen texanus*) of North America has successful annual reproduction but near-total recruitment failure due to predation of larvae by non-native fishes. Leprieur *et al.* (2008) noted that alien species invasions were a principal driver of a human-induced biodiversity crisis, and reported 20% of freshwater fish species listed by the IUCN are threatened by alien species. Leprieur *et al.* (2008) also identified six hot spots for alien fish invasion, including southern Australia. Gherardi (2010) noted the establishment of globally spread alien species is associated with the eventual extirpation of native species.

The Murray–Darling Basin in south-eastern Australia sits within the southern Australia invasion hotspot of Leprieur *et al.* (2008) and encapsulates the problems that beset freshwater systems globally (Duncan and Lockwood 2001; Dudgeon *et al.* 2006; Reid *et al.* 2019; Tickner *et al.* 2020; World Wildlife Fund (WWF) 2020). This includes a native fish fauna that has declined to 10% or less of its former abundance (Murray–Darling Basin Commission (MDBC) 2004; Humphries 2012; Murray–Darling Basin Authority (MDBA) 2020) and waterways heavily dominated by invasive alien fish species, both numerically and in terms of biomass (Llewellyn 1983; Harris and Gehrke 1997; Gilligan 2005; Davies *et al.* 2008, 2012; Stuart *et al.* 2021).

The Goodradigbee River is a major perennial tributary of the Murray–Darling Basin. A striking aspect of the Goodradigbee River is its excellent instream environmental condition in the great majority of its upper and lower reaches, in contrast to many streams in the Murray–Darling Basin. The Goodradigbee River is not dammed nor has it suffered any significant instream degradation except for its final several kilometres. In fact, the Goodradigbee River is noted as one of the most rugged, remote and least impacted rivers of the Murray–Darling Basin (Pratt 1979; New South Wales National Parks and Wildlife Service (NSW NPWS) 2021*a*, 2021*b*, 2021*c*, 2021*d*; Waterways Guide 2021). Despite this, present day reports or records of native fish from it are lacking. Most discussion of the Goodradigbee River centres on invasive alien trout species – rainbow trout

(*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) – which formed strong breeding populations in it long ago, and are also continually stocked.

Such incongruities prompted a 2020 field trip to the Lower Goodradigbee River, to assess the instream environmental condition of the river, to make visual observations of the fish and crayfish fauna, and to conduct sampling for fish via recreational lure fishing. This field trip was in turn a catalyst to further investigate and publish an ecological history of the fish fauna of the Lower Goodradigbee River, and to explore the hypothesis that alien fish introductions and alien fish stockings alone can cause localised extinction of native fish species in Australian temperate streams, particularly large-bodied species such as Macquarie perch (*Macquaria australasica*) (federal EPBC Act: endangered) and Murray cod (*Maccullochella peelii*) (federal EPBC Act: vulnerable). The Lower Goodradigee River is an excellent case study for the exploration of this hypothesis as it is relatively free of the confounding factors of instream habitat degradation and river regulation to which native fish declines and extinctions – particularly in large-bodied species – are otherwise invariably attributed.

Materials and methods

Study location

The Goodradigbee River is situated in New South Wales (NSW), Australia. The Goodradigbee commences at an altitude of 1260 m ASL and gradates from a montane river to a slopes river over its course. It arises in Kosciuszko National Park and flows through an undisturbed mountainous catchment before enterering the largely cleared 15.2 km long Brindabella Valley (Lintermans 2000*a*, 2002). The Goodradigbee River is essentially unregulated. A small diversionary aqueduct exists in its extreme headwaters (Lintermans 2000*a*, 2002), with minimal downstream effects (Bevitt *et al*. 2009), and the last several kilometres of its course have been inundated by the impounded waters of Burrinjuck Reservoir since 1928.

For the purposes of the study, the Goodradigbee River is delimited into two sections, the Lower Goodradigbee and the Upper Goodradigbee (Fig. 1). The Lower Goodradigbee River is the focus of this paper. The confluence of Flea Creek with the Goodradigbee River, above which large-bodied native fish species appear unable to traverse due to a 5.5 km long cascade zone, forms a natural boundary and marks the start of the Lower Goodradigbee, at an altitude of 500 m ASL. For convenience, the entire 9.5 km section between Brindabella Road bridge at the base of Brindabella Valley and the Flea Creek confluence is labelled the 'Cascade Zone' and treated as the demarcation between the Upper Goodradigbee and the Lower Goodradigbee.

The present day Lower Goodradigbee River flows through a mixture of mountainous native forest and partially cleared valleys and has a course length of approximately 32.2 km, terminating at the commencement of inundation by Burrinjuck Reservoir at Wee Jasper Bridge (innundation occasionally extends slightly further upstream at maximum water level). There is some plantation forestry on the western edge of the Lower Goodradigbee catchment, and a handful of rural properties with light livestock grazing in parts of its valley (Lintermans 2000*a*, 2002). However natural forest cover is still substantial, and the eastern edge of the Lower Goodradigbee abuts Brindabella National Park for the first 25.7 km of its 32.2 km course (Figs 1 and 2*a*). At the 20 km mark, the 400 m contour is crossed and the river theoretically transitions from an upland river to a slope river according to widely used altitudinal habitat categories (e.g. Davies *et al*. 2008, 2012) (Fig. 2*b*).

Much of the Goodradigbee catchment experienced bushfires in January 2003. The Upper Goodradigbee recovered rapidly from any post-fire siltation and this is attributed to its natural flow regime and lack of dams and regulation (Southwell and Thoms 2012); a similar recovery is apparent in the Lower Goodradigbee. Indeed, healthy corridors of native riparian vegetation (primarily native river she-oak *Casuarina cunninghamiana*) are present for the first 27.4 km of the Lower Goodradigbee's course, at which point they become more patchy, but are only completely lost at 30.8 km, where the indundation zone of Burrinjuck Reservoir commences (at maximum level). A very small amount of cropping activity commences in the valley (east bank) at 26.8 km (Fig. 2*a, b*).

Due to the relatively natural state of much of its catchment, its natural hydrology, and largely intact native riparian vegetation, the Lower Goodradigbee River has high water clarity, a rapid-and-pool morphology, a riverbed dominated by coarse substrates, boulder and bedrock, minimal siltation, and a natural flow regime with substantial perennial base flows – as evident in numerous fishing, kayaking, camping and outdoor activity publications and websites (e.g. Pratt 1979; New South Wales National Parks and Wildlife Service (NSW NPWS) 2021*a*, 2021*b*, 2021*c*, 2021*d*; Waterways Guide 2021), and in scientific papers and articles (e.g. Fulton *et al*. 2012; Starrs *et al*. 2015; Fulton and Noble 2016; Noble and Fulton 2017).

Indigenous history

Scientific and management literature, historical records in books, and historical records in the National Library of Australia's online TROVE newspaper archive (National Library of Australia (NLA) 2021) were searched for evidence of Indigenous occupation and use of the Lower Goodradigbee River.

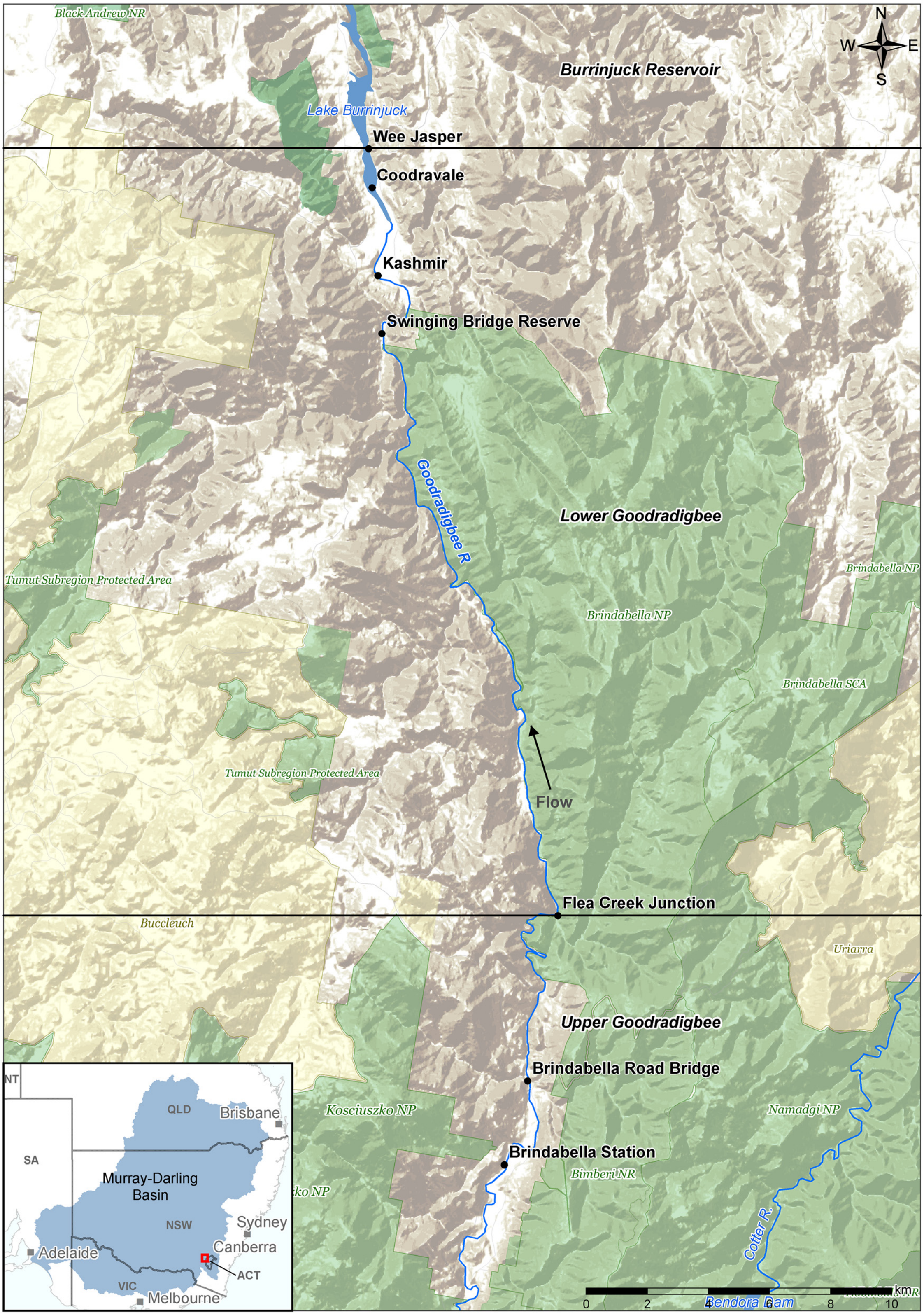


Fig. 1. The Goodradigbee River and key sites.

(*a*)

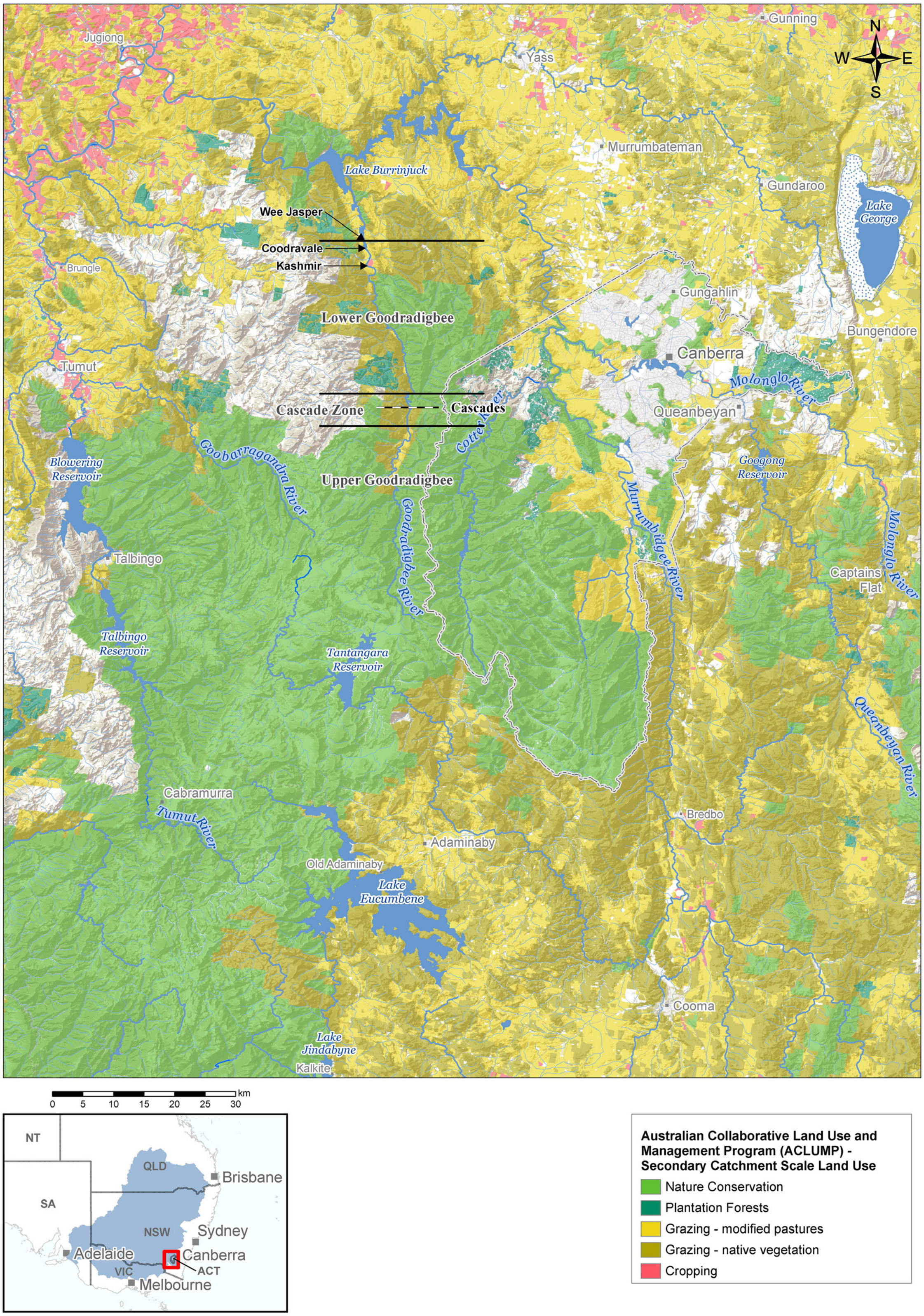


Fig. 2. (*a*) Land use in the Goodradigbee and surrounding catchments. (*b*) Land use, locations and habitat trends over the Lower Goodradigbee's course.

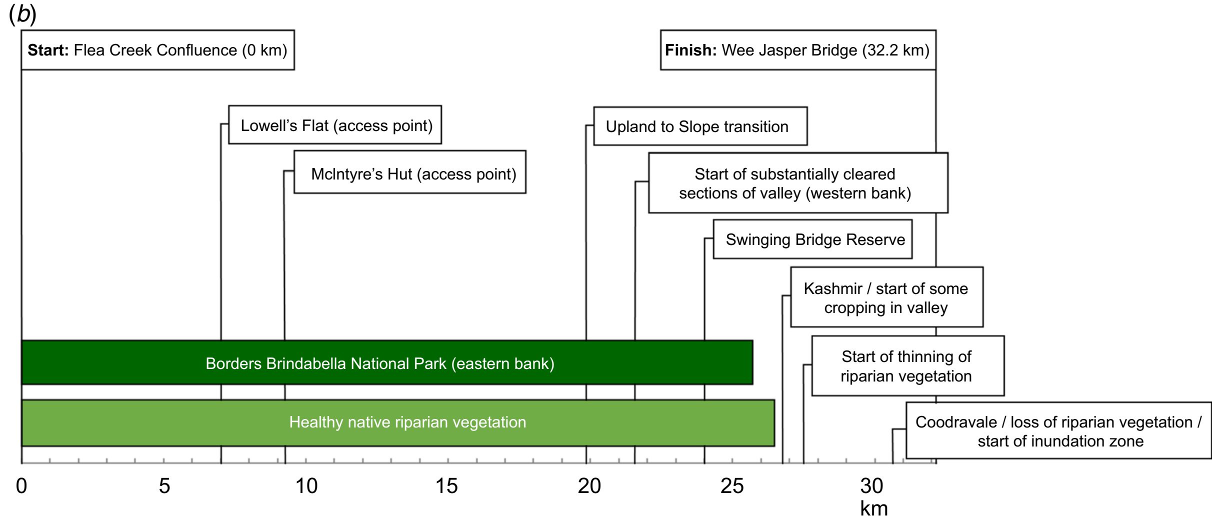


Fig. 2. (*Continued*).

Historical baseline for native fish and crayfish

Rationale

The use of historical data to elucidate former native fish abundance and native fish declines in the Lower Goodradigbee River was considered appropriate given the paucity of museum records and other scientific data. The use of historical data is now well established in the field of ecology (i.e. historical ecology), and is considered both appropriate and necessary, particular with fish and fisheries where scientific data is typically limited to several decades (e.g. Pauly 1995; Roberts and Sainty 1997; Robertson *et al.* 2000; Jackson *et al.* 2001; Boulton *et al.* 2004; Pinnegar and Engelhard 2008; Humphries and Winemiller 2009; McClenachan *et al.* 2012; Alleway and Connell 2015).

Historical evidence

Diverse historical records were utilised, including historical books, hard copy historical records accessed through the National Library of Australia's physical collection, and electronic historical records found and accessed through the NLA's online TROVE newspaper archive (National Library of Australia (NLA) 2021). In addition, older and rarer scientific literature was drawn on from the author's and colleagues' collections. Limited historical sampling data was obtained through the online Atlas of Living Australia (ALA) (2021).

Museum records

Museum records were accessed through the Atlas of Living Australia (ALA) (2021) and the online Australian Museum collection (Australian Museum 2021*a*).

Contemporary fish and crayfish status

Data was derived from 'The Distribution of Fish in NSW' (Llewellyn 1983); the NSW Rivers Survey (Harris *et al.* 1996; Harris and Gehrke 1997); Fish Communities of the Murrumbidgee Catchment (Gilligan 2005) and the Sustainable Rivers Audit 1 (2004–2007) (Davies *et al.* 2008).

Alien trout introductions and stockings

Information on alien trout introductions and historical alien trout stockings was sought in the National Library of Australia's online TROVE newspaper archive (National Library of Australia (NLA) 2021). Information on contemporary alien trout stockings was obtained from the Fish Stocking Page of NSW DPI's website (New South Wales Department of Primary Industries (NSW DPI) 2021*a*).

2020 field trip on the Lower Goodradigbee River

Over 3 days on 27–29 December 2020, the author and a colleague undertook an observational kayak journey along the entire Lower Goodradigbee River. By river, this is a distance of approximately 32.2 km. This distance was covered relatively slowly to make observations and engage in fish sampling via lure fishing. High quality polaroid glasses were worn by both observers and the river was continually scanned for free-swimming native fish and Murray crays (*Euastacus armatus*). Although crayfish size is typically measured by occipital carapace length (OCL), estimated total length (TL) was used for this study as the crayfish were being observed, not captured and measured, and TL is easier to estimate from observations than a sub-set of TL such as OCL. All suitable native fish habitat was fished with lures equipped with barbless hooks; both the author and colleague are experienced and successful catch-and-release anglers for Murray cod and golden perch (*Macquaria ambigua*) and utilised lure types (e.g. spinnerbaits, sinking 'vibes') that have been highly successful for these species in neighbouring streams (e.g. Upper Murrumbidgee River).

Results

Indigenous history

Occupation

Sparse archaeological evidence indicates Indigenous people have inhabited Canberra and the surrounding region for at least 21 000 years. Occupation patterns were strongly shaped by the build-up to and subsequent recession of harsh cold conditions associated with the Last Glacial Maximum (16 000 years b.p.) (Flood *et al.* 1987; Aplin *et al.* 2010; ACT Heritage Council 2015).

Origin of name

Indigenous people, probably of the Ngunawal/Ngunnawal group (AIATSIS 2021), bequeathed the name 'Goodradigbee/ Coodradigbee' to the river, alternatively transcribed as 'Gudarigby' by Bennett (1834). Cultural legend has the name meaning 'water falling over rocks' – clearly in reference to the Goodradigbee River's high flows and numerous rocky rapids.

Fishing

While records are lacking, it is almost certain that Indigenous people of the region utilised the Lower Goodradigbee River for abundant native fish and Murray crays, as they did in other rivers of the region (e.g. Tumut River; Bennett 1834). Only two records for Indigenous fishing in the Lower Goodradigbee River were found. The first is a somewhat poignant record of Indigenous people sight fishing for newly invading alien trout in the Lower Goodradigbee with baited lines in the same manner that they fished for Murray cod. They were puzzling over their lack of success, unaware of the more finicky nature of the newly invading alien species compared to the obligingly voracious nature of the native Murray cod they were used to (Sydney Morning Herald (SMH) 1939). The second is an oral history project that reveals Indigenous families continued to line-fish the Lower Goodradigbee around Wee Jasper for silver perch (*Bidyanus bidyanus*) (federal EPBC Act: critically endangered) until the species completely disappeared in the mid-1980s (Frawley *et al.* 2011).

Historical baseline for native fish and crayfish

Historical evidence – native fish

Historical literature provided useful insight into the original native fish fauna of the Lower Goodradigbee. The first written record of native fish in the Lower Goodradigbee River was that of a few fish caught in a 'fine little [tributary] stream' – possibly Wee Jasper Creek – by men of the Hume and Hovell expedition in January 1825 (Bland 1831). The interesting corollaries of this record are two-fold: (1) given the coarse nature of the tackle being used, the fish were likely to be of the large-bodied native fish species and not the intermediately sized two-spined blackfish (*Gadopsis bispinosus*) (ACT legislation: vulnerable) or the small-bodied mountain galaxias (*Galaxias olidus*) (not listed); and (2) the original presence and abundance of large-bodied native fish species in the Lower Goodradigbee River extended to some tributary streams as well.

Following on from this record are S. M. Mowle's recollections of the Goodradigbee River. Mowle's traverses through the Goodradigbee River valley commenced in 1839, droving stock to the high plains for grass during the severe 1837–1839 drought, and continued for some years thereafter. The routes described suggest these observations are predominately in the Lower Goodradigbee River, at and downstream of the Flea Creek confluence, and thus involve large-bodied native fish species:

> 'The valley of the Coodradigbee, at the foot of the Brindabella mountain ... In appearance it is as lovely a spot as can be imagined – a valley formed by the steepest of mountains, with a river abounding with fish meandering through it; its waters are the most pearly and pellucid ...' (Evening News 1891; Gundagai Times 1902; Wilson 1968)

Prominent Queanbeyan identity John Gale visited the Lower Goodradigbee River at Flea Creek confluence in 1906. He stated:

> '... down where we were there are besides [alien] trout, cod and bream, which can't get up as far as Brindabella on account of some high falls intervening.' (Evening News 1906)

The high falls intervening are in reality the 9.5 km Cascade Zone between the Brindabella road bridge and Flea Creek confluence. Gale also reported:

> 'We saw several of the bream[1] – big fellows, up to 4 lb [1.8 kg] in weight – in the backwater here and there, and we were informed that they afford fine sport in the legal season.' (Evening News 1906)

In 1908, 1909 and 1911 fishing columnists advised of good cod and perch fishing to be had in the Lower Goodradigbee River (Evening News 1908; Sunday Sun 1909;

[1]The terms 'perch' and 'bream' were regrettably interchangeable for the species Macquarie perch (*Macquaria australasica*) and silver perch (*Bidyanus bidyanus*) historically, though there was usually consistency within catchments/localities. In the Canberra region, 'perch' usually referred to Macquarie perch. Therefore there is some ambiguity in this observation as to which species was involved, but Macquarie perch is considered to be more likely.

Sydney Mail 1911). In 1919, a fishing columnist expressed surprise at the number of sizeable Murray cod amongst other fishes that the Lower Goodradigbee supported, as revealed by a bushfire-ash-induced fish kill:

> 'In the Goodradigbee River and elsewhere [in the region], heavy rain, following on a bush fire, washed the ashes into the river, and this killed many fish, even cod [ranging in size] up to 20 lb [9.0 kg] being found dead.' (Sydney Mail 1919)

Records such as these were almost exclusively written by anglers targeting alien trout and are consequently strongly focused on alien trout. It is likely they frequently failed to mention native fish captures – considered largely irrelevant in the pursuit of trout – or mentioned them only in passing. Fly-fishing targeting alien trout species (i.e. using very small artificial flies) is also specifically ineffectual in by-catching Murray cod, due to their preference for larger prey. Notwithstanding, these and subsequent records are sufficient to establish that a substantial native fish fauna of Murray cod, Macquarie perch, silver perch and two-spined blackfish originally inhabited the Lower Goodradigbee River (Table 1).

Historical evidence – crayfish

Surprisingly, no historical baseline could be established for Murray crays in the Lower Goodradigbee River. Some information was expected as the species grows to a large size in upland stream habitats (200–300 mm TL; larger in lowland stream habitats), is reputed to be good eating, and has been keenly sought after. However, Starrs *et al.* (2015) noted a paucity of data on montane/upland populations of this species. Sparse anecdotal reports from local anglers place the species in the Lower Goodradigbee River in decades past.

Museum records – native fish

Museum records were of little use in establishing an historical baseline for native fish in the Lower Goodradigbee River (Table 2). For much of the 1900s, there was little scientific interest or research in documenting the endemic native fish fauna of Australian montane and upland streams. Instead, the emphasis was on the establishing and furthering of alien trout species in these streams. This is reflected by the numerous museum records lodged for alien rainbow trout from the Goodradigbee River and is reflected in references such as Anderson (1931), McKeown (1934, 1937) and Butcher (1945).

Museum records – crayfish

Only one museum record was found for Murray crays in the Goodradigbee River. This was a specimen found in the Australian Museum collection (Registration Number P. 13036), collected at Coodravale in 1951 (Australian Museum 2021*b*).

Alien trout introductions and stockings

The first introductions of alien trout species to the system took place in the Upper Goodradigbee River, where they were noted as having rapidly extirpated the native mountain galaxias species present (Sunday Times 1910). The stockings commenced in 1884 with 'a jar' of brown trout fry (Canberra Times (CT) 1934). This was followed in 1891 by another 300 brown trout fry (Age 1907*a*), followed by more well-known introductions of rainbow trout in 1899, 1900 and 1901 (Queanbeyan Observer 1905). Introductions and stockings of alien trout into the Lower Goodradigbee commenced subsequently. Strong breeding populations of alien trout, predominately rainbow trout, formed swiftly after stockings. Large catches of alien trout also followed on swiftly from stockings. By 1905/1906 copious catches by anglers indicate alien trout species dominated both the Upper and Lower Goodradigbee River, from headwaters to terminus (e.g. Albury Banner 1905; Evening News 1906).

Alien trout species rapidly achieved dominance in both the Upper and Lower Goodradigbee River, and sustained their dominance through strong natural recruitment. Although stockings were unnecessary, alien trout species have been repeatedly stocked in the river since their introduction in 1884 (Queanbeyan Observer 1905; New South Wales Department of Primary Industries (NSW DPI) 2021*a*). Historical stockings are difficult to quantify, but innumerable TROVE newspaper articles with statements such as 'the well-stocked Goodradigbee' and the 'heavily stocked Goodradigbee' indicate historical alien trout stockings were substantial, often unregulated, often poorly recorded, and mostly annual. There were even complaints from trout anglers about the Goodradigbee River (amongst other local rivers) being *overstocked* with trout (Australian Town and Country Journal 1906; Sydney Morning Herald (SMH) 1908*a*, 1908*b*; Daily Telegraph 1913; The Sun 1913). Some articles provide regional tallies of annual alien trout stockings (i.e. Tumut region, Cooma region, Yass region) which include Goodradigbee stockings. Where specific stocking records for the Goodradigbee River were listed, they were compiled into Table 3. Annual alien trout stockings continue in the Goodradigbee River to this day – 50 000 alien rainbow trout have been released into the Lower Goodradigbee, and 141 500 released into the Upper Goodradigbee – in the past 10 years (2009–2010 to 2019–2020) (Table 4*a*, *b*).

Contemporary fish and crayfish status

Llewellyn's (1983) New South Wales Fish Survey sampled 299 sites in NSW over 10 field trips and 166 field days in 1975–1976. Fish collections recorded at the Australian Museum between 1960 and 1976, and Llewellyn's personal

Table 1. Historical records of native fish in the Lower Goodradigbee River.

Year	Native fish species	Common name	Key statement	Reference
1825	Unspecified large-bodied native fish species	–	a few fish caught in a 'fine little [tributary] stream'	Bland (1831)
1839	Unspecified native fish species	–	'The valley of the Coodradigbee ... with a river abounding with fish meandering through it ...'	Evening News (1891)
Late 1800s?	*Macquaria australasica* *Bidyanus bidyanus*	Macquarie perch silver perch	'... when he was a boy. On a hot day one could see hundreds of perch and bream in the Little River ...'	Tumut and Adelong Times (1938)
1904	*Maccullochella peelii* *Macquaria australasica* *Bidyanus bidyanus*	Murray cod Macquarie perch silver perch	'... it is only for a comparatively short distance along its lower reaches that the indigenous fish of the Murrumbidgee – Murray cod, perch, and bream – can make their way. Further migration is interrupted by a high waterfall [at Flea Creek junction].'	Queanbeyan Observer (1905)
1905	*Maccullochella peelii* *Macquaria australasica*	Murray cod Macquarie perch	'In both the Cotter and Goodradigbee ... Cod and perch will also be found in these waters.'	Sydney Mail (1905)
1906	*Maccullochella peelii* *Macquaria australasica*	Murray cod Macquarie perch	'Down where we were [Flea Creek junction] there are, besides [alien] trout, cod and bream ... We saw several of the bream – big fellows, up to 4 lb [1.8 kg] in weight – in the backwater here and there ...'	Evening News (1906)
1908	*Macquaria australasica*	Macquarie perch	'... the Goodradigbee is the chief angling river ... it is well sheltered by [casuarina] oaks, and fishable all the way into the rough country above the junction of the Micalong, which also contains [alien] trout. The Macquarie perch is also plentiful.'	Sydney Morning Herald (SMH) (1908*a*)
1908	*Maccullochella peelii* *Macquaria australasica*	Murray cod Macquarie perch	'... members of the New South Wales Rod Fishers Society explored the waters of the lower Goodradigbee in the neighbourhood of Wee Jasper ... Immediately below the bridge the water was in greater volume and 'heavier' and more suitable for cod and perch, which were there in numbers.'	Sydney Morning Herald (SMH) (1908*b*)
1909	*Maccullochella peelii* *Macquaria australasica*	Murray cod Macquarie perch	'Messrs. A. J. and J. Dilworth returned to town last Saturday after a visit to the Goodradigbee River ... The river at this part simply teems with [alien] trout ... there are also cod and perch. Some of the latter were caught by local anglers with worms.'	Sunday Sun (1909)
1911	*Bidyanus bidyanus* *Maccullochella peelii*	silver perch Murray cod	'By the way, there is good perch and cod fishing to be had in the Murrumbidgee, the Goodradigbee, and the Little rivers.'	Sydney Mail (1911)
1917	*Macquaria australasica*	Macquarie perch	'With regard to Macquarie or eastern perch ... They are rarely got in the river as far down as Narrandera, though the Goodradigbee up above Burrinjuck, is full of them ...'	The Land (1917)
1919	*Maccullochella peelii*	Murray cod	'In the Goodradigbee River and elsewhere [in the region], heavy rain, following on a bush fire, washed the ashes into the river, and this killed many fish, even cod [ranging in size] up to 20 lb [9.0 kg] being found dead.'	Sydney Mail (1919)
1921	*Macquaria australasica*	Macquarie perch	'The Macquarie perch, while plentiful in the higher reaches of the Goodradigbee ... is never caught ... in the Murrumbidgee near Narrandera.'	Port Adelaide News (1921)
1931	*Maccullochella peelii* *Bidyanus bidyanus* *Macquaria australasica* *Gadopsis bispinosus*	Murray cod silver perch Macquarie perch two-spined blackfish	'In the Goodradigbee ... are also Murray cod (*Maccullochella macquariensis*), Macquarie Perch (*Macquaria australasica*), and Silver Perch (*Terapon bidyanus*), which gets the name Grunter ... Another fish which is sometimes unintentionally hooked is the 'slippery' or river blackfish (*Gadopsis marmoratus*) ...' [Continues to describe capture of two Macquarie perch and sighting of one silver perch during a fishing session.]	Anderson (1931)
1934	*Macquaria australasica*	Macquarie perch	[Stomach contents of six Macquarie perch captured in the Lower Goodradigbee in 1931 are reported.]	McKeown (1934)
1935–36	*Maccullochella peelii*	Murray cod	'In 1935–1936 there were any amount of [alien] trout and cod there [Wee Jasper] ...'	Yass Tribune-Courier (1938)
1937	*Bidyanus bidyanus*	silver perch	'Grunter have been biting well in the Goodradigbee River, the fish taken by anglers being up to 3 lb [1.4 kg] weight.'	Referee (1937)
1937	*Gadopsis bispinosus* or *Galaxias olidus?*	two-spined blackfish or mountain galaxias?	'The value of the gudgeon as trout food was strongly evidenced in the Goodradigbee River. Last season gudgeon appeared in large numbers, and scale readings showed that the growth of the trout increased, in one season, by as much as the total of the previous five years.'	Tumut and Adelong Times (1937)

Table 2. Museum records of fish from the Goodradigbee River – Lower and Upper – from the Atlas of Living Australia (ALA) (2021).

Year	Species	Common name	Locality	Latitude	Longitude
1900	*Hypseleotris klunzingeri*	western carp gudgeon	Lower Goodradigbee River (upstream Micalong Creek junction)	35.216S	148.7E
1928	*Oncorhynchus mykiss*	rainbow trout (alien)	Upper Goodradigbee River (above the falls)	35.216S	148.7E
1928	*Oncorhynchus mykiss*	rainbow trout (alien)	Upper Goodradigbee River (above the falls)	35.216S	148.7E
1929	*Oncorhynchus mykiss*	rainbow trout (alien)	Lower (?) Goodradigbee River	35S	148E
1931	*Gadopsis bispinosus*	two-spined blackfish	Lower Goodradigbee River (three miles [4.8 km] from Wee Jasper)	35S	148E
1931	*Gadopsis bispinosus*	two-spined blackfish	Micalong Creek (tributary of Lower Goodradigbee River)	35.25S	148.566E
1932	*Oncorhynchus mykiss*	rainbow trout (alien)	Upper Goodradigbee River	35.216S	148.7E
1955	*Oncorhynchus mykiss*	rainbow trout (alien)	Upper Goodradigbee River (Coolamon Caves)	35.666S	148.716E
1956	*Hypseleotris klunzingeri*	western carp gudgeon	Lower Goodradigbee River (Wee Jasper: Burrinjuck Dam)	35.116S	148.683E
2002	*Galaxias olidus*	mountain galaxias	Flea Creek (Powerline Road ford) (tributary of Lower Goodradigbee River)	35.2874S	148.791E
2018	*Leiopotherapon unicolor*[A]	spangled perch	Micalong Creek (downstream of Micalong Creek Reserve) (tributary of Lower Goodradigbee River)	35.18902S	148.68963E
2018	*Gadopsis bispinosus*	two-spined blackfish	Micalong Creek (downstream of Micalong Creek Reserve) (tributary of Lower Goodradigbee River)	35.18902S	148.68963E

Location descriptions appended for clarity.
[A]This record is clearly erroneous, given the known distribution and temperature tolerances of spangled perch.

data from 1963 to 1976, were also included in this study. Llewellyn's sampling techniques included gill nets, haul nets, drum nets, dip nets, electrofishing, rotenone, angling and spotlighting. Sampling sites appear as dots on coarse resolution maps of NSW; one dot indicates he sampled the Lower Goodradigbee at Coodravale, which Harris *et al.* (1996) and Harris and Gehrke (1997) confirm. Llewellyn (1983) states the native species Murray cod, silver perch, Macquarie perch and golden perch[2] were recorded at this site between 1960 and 1976, along with the standard suite of invasive alien species: rainbow trout, brown trout, goldfish (*Carassius auratus*), carp (*Cyprinus carpio*) and redfin (*Perca fluviatilis*). No further information is provided. Llewellyn's records of carp and redfin, if correct, are noteworthy. Assuming they came from the 1975–1976 sampling period, they capture the absolute earliest stages of the invasion of Burrinjuck Reservoir and tributaries by (illegally released) alien carp. Conversely, Llewellyn's record/s of alien redfin are earlier than the known invasion timeline for this alien species in these waterways (i.e. 1986) (Lintermans *et al.* 1990; Lintermans 2000*a*, 2002; Kaminskas 2021).

The 1996 NSW Rivers Survey re-used Llewellyn's (1983) Coodravale site (and many others) for comparison purposes (Harris *et al.* 1996; Harris and Gehrke 1997). Sampling techniques were three fyke nets, three panel nets and nine Gee traps (set 3 h before sunset to 2 h after), boat electrofishing (10 × 2 min shots), and backpack electrofishing (2 × 50 m riffles), with four survey events (Harris *et al.* 1996). The NSW Rivers Survey results for Coodravale show an extreme abundance of alien carp, low numbers of alien trout species, and very low numbers of Macquarie perch (Table 5). The number of alien redfin (i.e. one) are strikingly low compared to the next available site data for the species in the Sustainable Rivers Audit 1 (2004–2007) (Davies *et al.* 2008).

Intervening between the NSW Rivers Survey 1996 and the Sustainable River Audit 1 (2004–2007) was Gilligan's (2005) extensive survey of Murrumbidgee catchment fish fauna. Sampling techniques were boat electrofishing, backpack electrofishing and shrimp traps. Gilligan (2005) reported Macquarie perch from Coodravale on the Lower Goodradigbee River in prior sampling in 1999 and 2002 but failed to capture Macquarie perch – or silver perch or Murray cod – from the site in the study's 2004 sampling. No specific information on alien fish captures at this site is provided, though Gilligan (2005) recorded an extreme dominance of alien fish, numerically and biomass-wise, across the entire Murrumbidgee catchment that was exacerbated with increasing altitude (i.e. montane and upland zones) and alien trout species.

The Sustainable Rivers Audit 1 (2004–2007) results are relatively comparable geographically as it sampled the Kashmir vicinity of the Lower Goodradigbee, approximately 3.2 km upstream of Coodravale (Davies *et al.* 2008). Fish were sampled by large boat electrofishing for 1 day. These results support a now-consistent trend of extremely

[2]The commencement of the construction of Burrinjuck Dam in 1907 blocked the highly migratory golden perch, which at that time appear to have been on a downstream migration leg, from Burrinjuck Dam and tributaries. Consequently, they were absent from Burrinjuck Dam and tributaries until reintroduced via stockings in approximately 1967. Hence golden perch records must be from 1967 onwards.

Table 3. Some historical alien trout stockings in the Goodradigbee River.

Year	Key persons	Newspaper	Article date	Article title	Species	Upper Goodradigbee	Lower Goodradigbee	Goodradigbee (unspecified)
1884	John McLaughlin	Canberra Times	12 June 1934	First trout in the ACT	brown trout (presumed)	'a [large] jar'		
1891	John McLaughlin	Queanbeyan Age	4 January 1907	Trout in the Goodradigbee	brown trout	300		
1892	John Gale, Fred Campbell	Canberra Times	23 January 1951	Public opinion – selection of Canberra	brown trout			'some'
1899	F. Campbell	Queanbeyan Observer	8 September 1905	Our trout streams – how they were stocked	rainbow trout			400
1899	T. Travers-Jones	Queanbeyan Observer	8 September 1905	Our trout streams – how they were stocked	rainbow trout			400
1900	F. Campbell	Queanbeyan Observer	8 September 1905	Our trout streams – how they were stocked	rainbow trout			400
1909	G. E. Southwell	Queanbeyan Age	15 January 1907	Local & general	rainbow trout	majority of 816		
1918		Queanbeyan Age	31 October 1918	Trout acclimatisation	not specified		12 000	
1922–1938		Canberra Times	14 November 1939	Work of six years reviewed	ainbow trout, brown trout			18 400
1927	E. Killen	Goulburn Evening Post	28 November 1927	Rainbow trout fry	rainbow trout			not specified
1927		The Manaro Mercury	28 November 1927	Trout eat bees in Burrinjuck reservoir	not specified			'many thousands'
1930		Canberra Times	11 November 1930	Fish hatchery provides 100 000 trout for F.C.T. rivers	not specified			70 000
1933	W. M. Holliday G. Reed R. Smith	The Sydney Morning Herald	11 October 1933	Trout fry liberated	rainbow trout		10 000	
1934		Manilla Express	19 October 1934	Trout fishing	rainbow trout, brown trout			12 000 to be liberated
1937		Canberra Times	10 September 1937	Trout fishing at Canberra	rainbow trout, brown trout			portion of 50 000 annually
1946		Daily Telegraph	9 December 1946	Trout released in three rivers	rainbow trout, brown trout			portion of 150 000 annually

abundant alien carp, few and declining alien trout species, and absent native fish species. Notable is the strong increase in alien redfin perch numbers from previous surveys, the disappearance of Macquarie perch from sampling results, and the continued absence of silver perch and Murray cod (Table 6).

For Murray crays, studies by various authors indicate a viable population persists in parts of the Lower Goodradigbee River near Flea Creek confluence (Fulton *et al.* 2012; Starrs *et al.* 2015; Fulton and Noble 2016; Noble and Fulton 2017).

Elucidated changes in fish and crayfish fauna

Historical records confirm that in the 1800s and early 1900s the Lower Goodradigbee River abounded in both large-bodied and small-bodied native fish species (Table 1). The large-bodied native fish species were Murray cod with possibly some unrecognised trout cod (*Maccullochella macquariensis*) (federal EPBC Act: endangered), Macquarie perch and silver perch. The two-spined blackfish was intermediate in size and the small-bodied native fish species were mountain galaxias species and carp-gudgeon.

Table 4. (*a*) Contemporary alien rainbow trout stockings into Lower Goodradigbee River, 2009–2020. (Note: stockings are ongoing). (*b*) Contemporary alien rainbow trout stockings into Upper Goodradigbee River, 2009–2020. (Note: stockings are ongoing.)

Site	Coordinates	2009–2010	2010–2011	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016	2016–2017	2017–2018	2018–2019	2019–2020	Site totals
a													
Flea Creek Junction	35.34S, 148.75E		1,500	1000	1000	1500	2000	2000	1500	1500	1500	1500	15 000
Limestone Creek Junction	35.24S, 148.72E	2000			1000	1500			1000	1000	1000	1000	8500
Nottingham Road	35.17S, 148.69E	2000	3000	3000	2000	2000	2000	2500	2500	2500	2500	2500	26 500
2009–2020 Lower Goodradigbee total													50 000
b													
McLeod's Fire Trail Crossing	35.46S, 148.72E	1000	2000										3000
Downstream McLeod's Fire Trail Crossing	35.46S, 148.72E			2000	1500	2000	2000	2000	2000	2000	2000	2000	17 500
McLeod's Fire Trail Terminus	35.45S, 148.72E	2000	2000	2000	1500	2000	2000	2000	2000	2000	2000	2000	21 500
Brindabella Valley Road Terminus	35.45S, 148.72E	2000	2000	2000	1500	2000	2500	2500	2750	5000	3000	2500	27 750
Upstream Half Moon Creek Junction	35.41S, 148.74E				1500	2000	2500	3000	2750	2500	2500	2500	19 250
Downstream Half Moon Creek Junction	35.40S, 148.75E	1000	2000	2000									5000
Upstream Brindabella Creek Junction	35.49S, 148.74E			2000	1500	2000	2500	3000		3000	3000	2750	19 750
Downstream Brindabella Creek Junction	35.39S, 148.74E	3000	2000						2750				7750
Brindabella Road Bridge	35.38S, 148.74E	1000		1000	1000	2000	2500	2500	3000	2000	2000	3000	20 000
2009–2020 Upper Goodradigbee total													141 500

Table 5. NSW Rivers Survey (Harris *et al.* 1996; Harris and Gehrke 1997) results for Coodravale (35.1289S, 148.6692E), Lower Goodradigbee River, highlighting the comparative abundance of two alien fish species compared to a previously abundant native fish species.

Site		Species	Caught				Observed				Total	
No.	Name		Surv1	Surv2	Surv3	Surv4	Surv1	Surv2	Surv3	Surv4	Caught	Obs.
32	Coodravale	*Cyprinus carpio*	30	46	25	33	0	9	14	7	134	30
		Macquaria australasica	0	3	0	0	0	0	0	0	3	0
		Oncorhynchus mykiss	1	2	1	4	0	3	0	1	8	4
		Perca fluviatilis	0	1	0	0	0	0	0	0	1	0
		Salmo trutta	0	1	1	2	0	0	0	1	4	2
	Coodravale Sum		31	53	27	39	0	12	15	9	150	36

Totals: *P. fluviatilis* = 1, *C. carpio* = 134, *O. mykiss* = 8, *S. trutta* = 1, native *M. australasica* = 3.

Historical alien trout stockings into the Goodradigbee River were highly effective. By 1905, alien trout species, predominately rainbow trout, already dominated the Lower Goodradigbee River near Wee Jasper; eight men reported catching 300 alien trout up to 1.8 kg in a week's fishing, with the river 'teeming with trout' and 'some very large fish were hooked, but not successfully landed . . .' (Albury Banner 1905). By 1906, far upstream at Flea Creek confluence, at the commencement of the Lower Goodradigbee, Gale reported the capture of 60 alien trout of legal size and upwards, with many more smaller fish released, by three anglers over 2 days (Evening News 1906).

In the 1930s an evident decline in native fish species in the Lower Goodradigbee had commenced, while alien trout species were reaching their zenith. This decline sparked widespread concern and controversy in local anglers not focused on alien trout species (e.g. Tumut and Adelong Times 1938; Yass Tribune-Courier 1938; Frawley *et al.* 2011). In fact, in the 1930s alien rainbow trout dominance of the Lower Goodradigbee River was so extreme that it extended to the entire Burrinjuck Reservoir and inflowing Murrumbidgee River as well (Sydney Mail 1927; Tumut and Adelong Times 1938; Greenham 1981).

'Using a net one night at Burrinjuck . . . [the fisheries inspector] caught 3 cwt [152.5 kg] of fish, and with a legal size net a fisherman caught 50 lb [22.7 kg] to 60 lb [27.2 kg] a night, including many trout up to 15 lb [6.8 kg] and 16 lb [7.3 kg]. ' (Burrowa News 1931)

In Burrinjuck Reservoir alien rainbow trout were recorded predating on immense quantities of juvenile Macquarie perch and Murray cod:

'The net fishermen . . . are after cod and bream but can net practically nothing but trout. The trout when opened up are full of young fish – cod and bream – up to three inches in length. Is that the reason why stories of big hauls of cod seem only distant dreams?' (Burrowa News 1932)

'. . . in certain portions of the lake, over 90 per cent of the fish caught in the nets, on one occasion, were trout. These latter were found to be gorged with small cod, being vomited by the trout after capture.' (Yass Tribune-Courier 1934)

At the time anglers and netters targeting native fish in Burrinjuck Reservoir considered alien trout species to be destroying Murray cod stocks (e.g. Burrowa News 1932; Tumut and Adelong Times 1933; Yass Tribune-Courier 1934; Sydney Mail 1938).

'These [net fishing] men hate the trout with a bitter hatred, as they claim that they destroy the young cod – the most payable market fish of any they catch. Therefore, when they do catch a trout it is pitched as far up the bank as they can throw it.' (Sydney Mail 1938)

Similar sentiments were expressed about alien trout impacts on Macquarie perch and silver perch in the Lower Goodradigbee River proper:

'On a hot day one could see hundreds of perch and bream in the Little River [Goodradigbee], but today he would defy anyone to find them there. The trout had driven them out or destroyed them.' (Tumut and Adelong Times 1938)

Detailed examination of TROVE newspaper records (too numerous to tabulate) reveal reports of Murray cod captures in the Lower Goodradigbee became rare from the start of the 1940s onwards. Where reported, they were usually at the extreme lowest reaches at and downstream of Wee Jasper. Reports of good fishing for Macquarie perch and silver perch continued but again, were generally from the extreme lowest reaches of the river around Wee Jasper, suggesting a predatory and competitive displacement of

Table 6. Sustainable Rivers Audit 1 results (Davies *et al.* 2008; Murray–Darling Basin Authority (MDBA) 2021) for Kashmir (35.1465S, 148.683E), Lower Goodradigbee River, showing an abundance of alien fish species and complete absence of native fish species.

Date	Species	Common name	Length (mm)	Number
1 February 2007	*Cyprinus carpio*	carp	311	1
1 February 2007	*Cyprinus carpio*	carp	319	1
1 February 2007	*Cyprinus carpio*	carp	347	1
1 February 2007	*Cyprinus carpio*	carp	349	1
1 February 2007	*Cyprinus carpio*	carp	373	1
1 February 2007	*Cyprinus carpio*	carp	375	1
1 February 2007	*Cyprinus carpio*	carp	379	1
1 February 2007	*Cyprinus carpio*	carp	403	1
1 February 2007	*Cyprinus carpio*	carp	406	1
1 February 2007	*Cyprinus carpio*	carp	413	1
1 February 2007	*Cyprinus carpio*	carp	427	1
1 February 2007	*Cyprinus carpio*	carp	432	1
1 February 2007	*Cyprinus carpio*	carp	445	1
1 February 2007	*Cyprinus carpio*	carp	447	1
1 February 2007	*Cyprinus carpio*	carp	459	1
1 February 2007	*Oncorhynchus mykiss*	rainbow trout	171	1
1 February 2007	*Oncorhynchus mykiss*	rainbow trout	180	1
1 February 2007	*Oncorhynchus mykiss*	rainbow trout	223	1
1 February 2007	*Oncorhynchus mykiss*	rainbow trout	242	1
1 February 2007	*Oncorhynchus mykiss*	rainbow trout	419	1
1 February 2007	*Perca fluviatilis*	redfin	67	1
1 February 2007	*Perca fluviatilis*	redfin	68	1
1 February 2007	*Perca fluviatilis*	redfin	71	1
1 February 2007	*Perca fluviatilis*	redfin	72	3
1 February 2007	*Perca fluviatilis*	redfin	73	2
1 February 2007	*Perca fluviatilis*	redfin	74	2
1 February 2007	*Perca fluviatilis*	redfin	75	4
1 February 2007	*Perca fluviatilis*	redfin	77	1
1 February 2007	*Perca fluviatilis*	redfin	78	2
1 February 2007	*Perca fluviatilis*	redfin	79	1
1 February 2007	*Perca fluviatilis*	redfin	80	1
1 February 2007	*Perca fluviatilis*	redfin	84	1
1 February 2007	*Perca fluviatilis*	redfin	86	3
1 February 2007	*Perca fluviatilis*	redfin	88	1
1 February 2007	*Perca fluviatilis*	redfin	89	1
1 February 2007	*Perca fluviatilis*	redfin	92	1
1 February 2007	*Perca fluviatilis*	redfin	93	2
1 February 2007	*Perca fluviatilis*	redfin	95	1
1 February 2007	*Perca fluviatilis*	redfin	96	1
1 February 2007	*Perca fluviatilis*	redfin	120	1
1 February 2007	*Perca fluviatilis*	redfin	127	1
1 February 2007	*Perca fluviatilis*	redfin	131	1
1 February 2007	*Perca fluviatilis*	redfin	138	1
1 February 2007	*Perca fluviatilis*	redfin	259	1

Totals: *P. fluviatilis* = 35, *C. carpio* = 15, *O. mykiss* = 5.

these native fish species from the majority of the Lower Goodradigbee River by alien trout species.

Native fish decline continued and by the mid-1980s, remnant Macquarie perch populations in the Lower Goodradigbee were approaching functional extinction, even in the Kashmir/Coodravale/Wee Jasper vicinity, while silver perch underwent a rapid localised extinction in the Lower Goodradigbee as well as Burrinjuck Reservoir and the inflowing Murrumbidgee River (Lintermans 2000*a*, 2002; Frawley *et al.* 2011; Kaminskas 2021). The 1980s also saw further alien fish species in the form of carp and redfin invade the Lower Goodradigbee River via the Murrumbidgee River and Burrinjuck Reservoir (Lintermans 2000*a*, 2002; Kaminskas 2021), with Llewellyn (1983) possibly sampling some early colonists in the mid-1970s. At present, based largely on rare anecdotal reports, Murray cod persist in the Lower Goodradigbee, but are evidently close to being functionally extinct given their consistent absence in fish sampling results. Based on the extreme rarity of sampled specimens, two-spined blackfish in the mainstem Lower Goodradigbee would also appear to be close to functional extinction.

Crayfish

Due to an inability to establish a historical baseline for Murray crays in the Lower Goodradigbee River, no obvious trends in Murray crays could be discerned. Anecdotal reports place the species in the Lower Goodradigbee River in decades past, and studies such as Fulton *et al.* (2012) and Starrs *et al.* (2015) confirm the species persists in parts of the Lower Goodradigbee.

Summary

Contemporary fish sampling data support the changes elucidated from historical evidence; namely native fish decline and extinction, and alien fish domination. Fish sampling indicates functionally extinct to wholly extinct native fish species in the Lower Goodradigbee River, and a Lower Goodradigbee dominated by alien fish, namely carp, redfin, and to a lesser and decreasing extent, rainbow trout (Tables 5 and 6).

2020 field observations on the Lower Goodradigbee River

River and weather conditions

Flows ranged from approximately 177 to 253 ML/day, with flow volume increasing over the course of the kayak journey due to inflow from tributaries (Water NSW 2020). However, river levels dropped 10 mm per day. Water clarity was high, with crayfish and objects in the water able to be seen to at least 1.5 m in depth. Rapids were substantial but most were navigable; only two extremely large rapids were portaged. Weather was mostly sunny with moderate temperatures and variable winds.

Instream environmental condition of the Lower Goodradigbee River

The Lower Goodradigbee was in excellent instream environmental condition for the great majority of its course. Damage from the 2003 fires was not apparent except for a handful of dead river she-oaks (*C. cunninghamiana*) in the initial ~2 km of its course. Cleared areas of the valley (western bank) are ostensibly used for very light cattle grazing but no cattle were observed. Obvious degradation of native riparian vegetation and observable instream impacts were not discernible until Swinging Bridge Reserve, 24 km into the river's 32.2 km course. These impacts were localised to the immediate vicinity of Swinging Bridge Reserve, and immediately downstream the river reverted to a final tract of high quality instream habitat, as evidenced by a final sighting of a Murray cray at the start of this tract. Some thinning of riparian vegetation was apparent at 27.4 km; however, complete loss of riparian vegetation and significant instream impacts were only evident at 30.8 km, which is where the zone of occasional inundation commences. Siltation was minimal until this point. These observations confirm that the great majority of the Lower Goodradigbee River's course: (1) offers an abundance of superb habitat, spawning sites and spawning substrates for Murray cod, Macquarie perch, silver perch and two-spined blackfish; and (2) displays no evidence of instream degradation or impact remotely sufficient to explain catastrophic native fish declines and extinctions.

Observed/sampled fish and observed crayfish

No free-swimming native fish were sighted on the Lower Goodradigbee River, with the exception of several small shoals of Australian smelt (*Retropinna semoni*) in the final km or two before the impounded waters of Burrinjuck Reservoir. One Murray cod (estimated 600 mm TL) was hooked in the upper (upland) reaches but shed the barbless hook before a photo could be taken. Another Murray cod (estimated 750 mm TL) was hooked in the middle (upland) reaches, caught and released (Fig. 3). Both were hooked by blind casting lures to likely habitats. However, many hundreds more blind casts to innumerable high quality habitat locations in the first 30 km of river failed to capture

Fig. 3. Sampled Murray cod (*Maccullochella peelii*), estimated 750 mm TL. Image: Grant Peelgrane.

any large-bodied native fish or elicit any indication of large-bodied native fish presence (e.g. following fish).

Conversely, copious numbers of alien carp, all large in size (estimated 300–600 mm TL), and small numbers of small alien redfin perch (estimated 100–150 mm TL), were sighted over the entire course of the kayak journey. Four alien rainbow trout were sighted (estimated 150–400 mm TL), and a fifth caught and removed (estimated 300 mm TL), all in the upper half of the Lower Goodradigbee River. No rainbow trout were sighted in the lower half of the Lower Goodradigbee River.

Eight Murray crays were observed, primarily in the middle reaches of the Lower Goodradigbee River. The last individual was sighted slightly downstream of Swinging Bridge Reserve, after a long period without sightings. One particularly remote pool in the middle reaches yielded both the largest individual sighted (Fig. 4) and the only sighting of an aggregation – in this case, of three individuals. In agreement with Noble and Fulton (2017), this pool could effectively be described as a 'glide pool', with significant quantities of gravel and boulder, areas of greater depth, and significant current flowing through. In agreement with Starrs *et al.* (2015), the feeding site was a patch of accumulated *C. cunninghamiana* needles and twigs (Fig. 5), and these individuals, while appearing to maintain a very small minimum distance, fed in close proximity to each other for several hours without aggression. However, the largest individual was missing the tip of one chela, suggesting an aggressive encounter in the past. This individual was also extraordinarily active, and was observed repeatedly ranging over an approximately 8×2 m section of the pool for several hours.

Ulcerated carp

A substantial number of ulcerated alien carp were observed in the middle reaches of the Lower Goodradigbee River. The ulcers took the form of circular pink craters, estimated at 15–20 mm in diameter, in the head portion of the fish, usually behind the eyes and often towards the dorsal surface of the head. No fish were observed with more than one ulcer, although it is possible some fish may have had a second ulcer on the flank facing away from the observers.

Fig. 4. Murray cray (*Euastacus armatus*). The largest individual sighted, estimated 220 mm TL. Image: Simon Kaminskas.

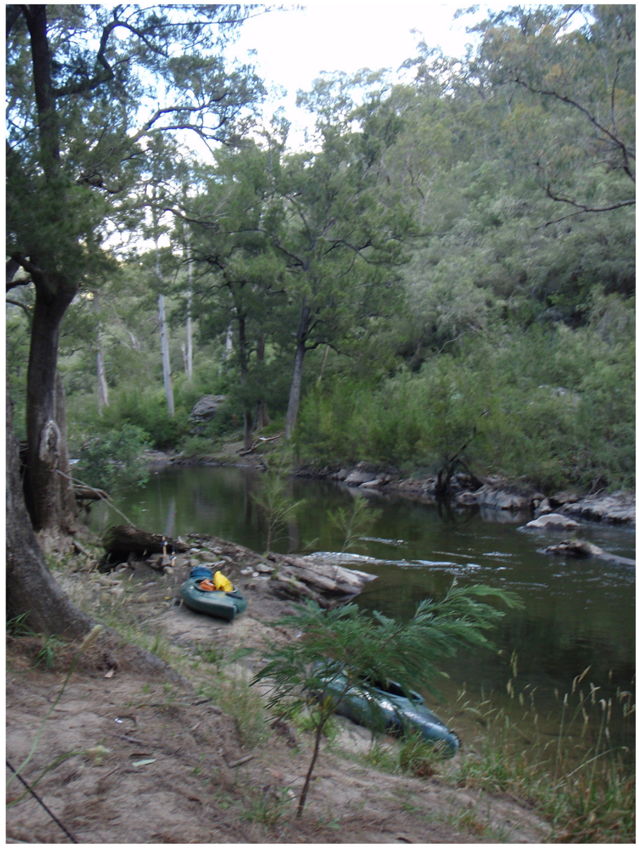


Fig. 5. Feeding site for multiple Murray crays (*Euastacus armatus*). Accumulations of casuarina needles and twigs – the food source – can be seen on the river bed in the foreground. Image: Simon Kaminskas.

Photographic records of the ulcerated carp were not possible due to issues with water reflection and the lack of a polaroid filter on the camera. However, a photo of one pool where a particularly high number of ulcerated carp were observed is provided at Fig. 6*a*, with an aerial view providing locational context at Fig. 6*b*. These images also serve to demonstrate the healthy riparian vegetation adjacent to the river.

Discussion

Alien fish ascendancy leads to native fish decline and extinction in the Lower Goodradigbee River

The absence of native fish and extreme abundance of alien fish in the Lower Goodradigbee River is of great concern. The Lower Goodradigbee River does not suffer from river

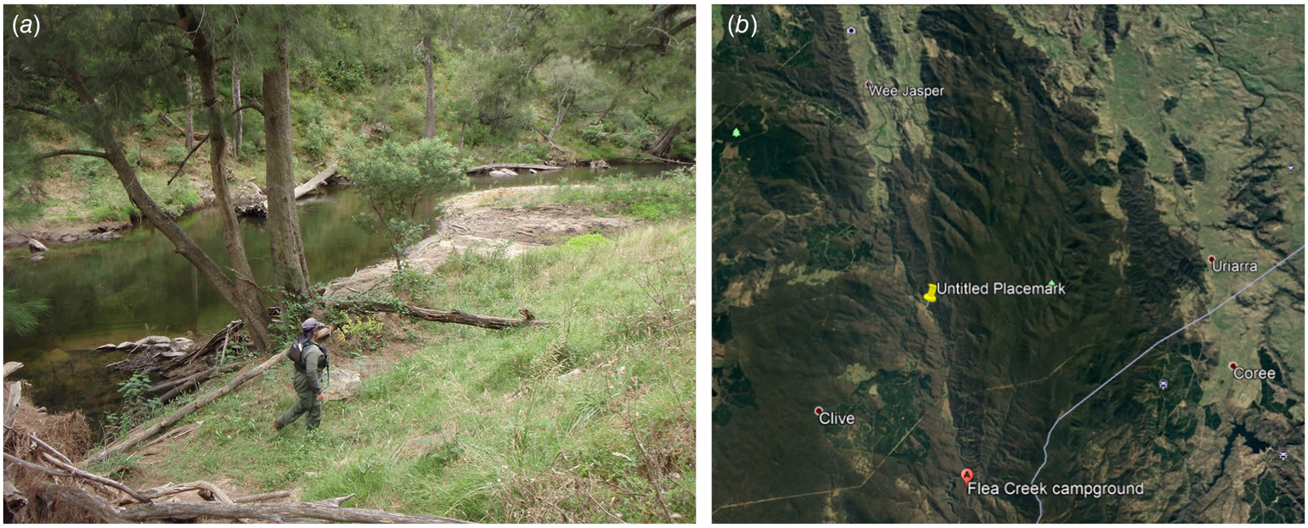


Fig. 6. (*a*) The head of a Lower Goodradigbee River pool where particularly high numbers of ulcerated alien carp (*Cyprinus carpio*) were observed. (*b*) The pool (yellow pin) in context of the observational kayak journey from Flea Creek to Wee Jasper. Image: Simon Kaminskas.

regulation and is in excellent instream environmental condition over the great majority of its length. It continues to offer extremely high quality native fish habitat and natural perennial flows (Fig. 7). Despite this, its formerly abundant native fish fauna are effectively lost (Llewellyn 1983; Harris and Gehrke 1997; Davies *et al.* 2008; Frawley *et al.* 2011; these observations). In particular, silver perch are completely extinct (Harris and Gehrke 1997; Gilligan 2005; Davies *et al.* 2008; Threatened Species Scientific Committee (TSSC) 2012) and Macquarie perch are functionally extinct (Lintermans 2000*a*, 2002, 2008; Department of Environment and Energy (DoEE) 2018). In addition, Murray cod and two-spined blackfish appear to be nearing functional extinction in the Lower Goodradigbee. Murray cod have not been detected in Lower Goodradigbee sampling since Llewellyn (1983). Two-spined blackfish have not been detected in Lower Goodradigbee sampling and Lintermans (1998) noted two-spined blackfish are largely absent from the Goodradigbee River or present only in low numbers. Finally, a lack of sampling records and sightings indicate mountain galaxias species are extinct in the Lower Goodradigbee mainstem and persist only in small tributaries (Raadik 2014; Atlas of Living Australia (ALA) 2021). Thus, in the absence of river regulation, and with a lack of significant instream habitat degradation, siltation or overfishing over the great majority of its course, the long-term domination of the Lower Goodradigbee River system by alien fish species (>115 years), aided by the constant stocking of some of those alien species, is concluded to be the explanation for the near-complete extinction of native fish in its waters.

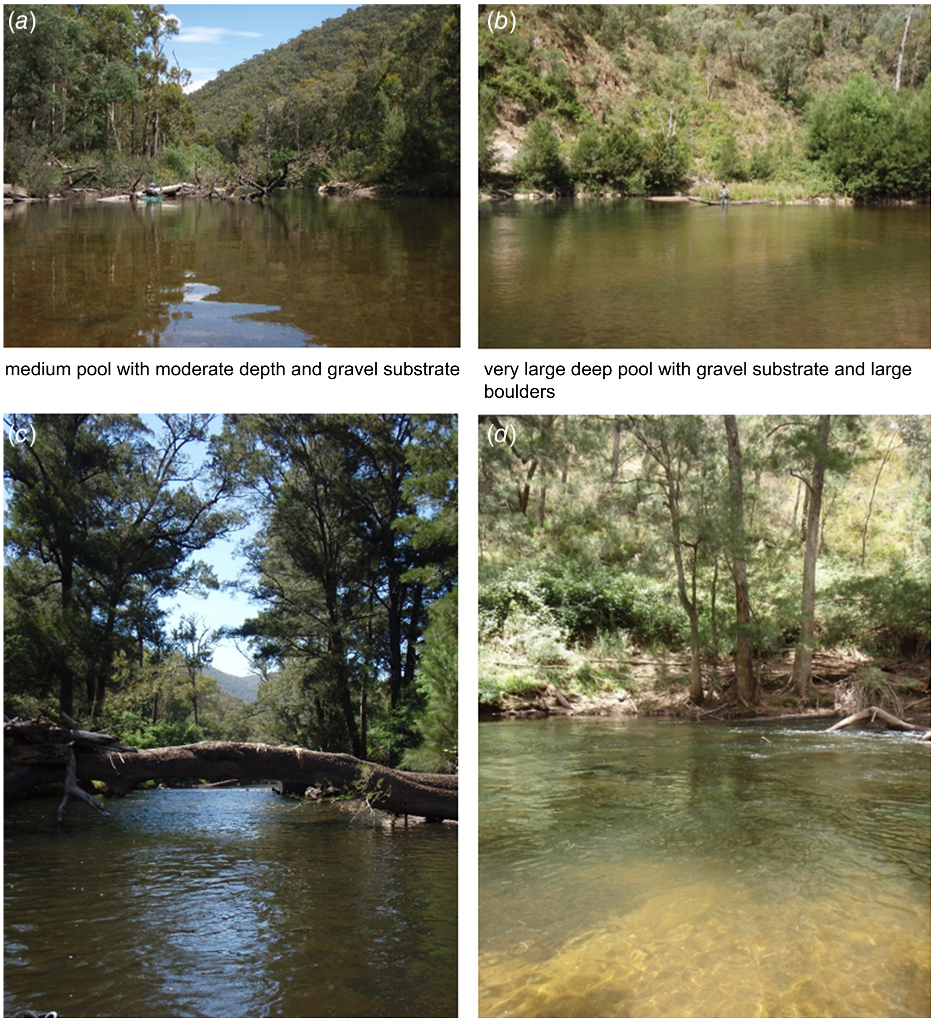
These findings call into question the dominant narrative that habitat degradation and river regulation are the primary causes of native fish decline and localised extinction, particularly for large-bodied species. Rather, this study, drawing on historical and contemporary ecological information, strongly supports a hypothesis that alien fish species, and in many cases their continual stocking – as with alien trout species in the Goodradigbee – are a primary cause of native fish decline and localised extinction, including large-bodied species, and particularly in montane and upland streams.

Alternative explanations discounted

Any theories positing habitat degradation as the cause of native fish decline and extinction in the Lower Goodradigbee should be examined critically through the lens of environmental conditions in the river itself (i.e. instream environmental condition), as opposed to an excessive focus on disturbance of any kind occurring anywhere in the Lower Goodradigbee's catchment. The evidence, observations and photos presented in this paper demonstrate the Lower Goodradigbee River is in excellent instream environmental condition over the great majority of its 32.2 km course, and rules out explanations such as habitat degradation or spawning site siltation for the decline and extinction of native fish in the great majority of the river's course.

A number of factors contribute to the excellent instream environmental condition of the Lower Goodradigbee:

a. the river borders Brindabella National Park for the first 25.7 km of its course
b. widespread clearing in its valley (western bank) does not occur until 21.5 km into its course
c. cattle grazing does not commence until ~21.5 km into its course
d. cattle grazing is light in pressure and grazed areas are well vegetated by native pasture



medium pool with moderate depth and gravel substrate

very large deep pool with gravel substrate and large boulders

deep run with cobble substrate and woody debris

head of deep pool with submerged woody debris and gravel substrate

Fig. 7. High quality former native fish habitats in the Lower Goodradigbee River. With the exception of (*a*), no native fish were caught or sighted in any of these habitats. (*a*) Medium pool with moderate depth and gravel substrate. (*b*) Very large deep pool with gravel substrate and large boulders. (*c*) Deep run with cobble substrate and woody debris. (*d*) Head of deep pool with submerged woody debris and gravel substrate. (e) Deep run with rock faces and large boulders. (*f*) Very large deep pool abutting rocky cliff. (*g*) Large log jam with deep plunge pools and boulders. (*h*) large deep pool with submerged woody debris. Images: Simon Kaminskas.

e. forestry in the western portion of the catchment does not abut or come close to the river at any point
f. a healthy native riparian vegetation corridor is present for the first 27.4 km and present in some form for 30.8 km.

Further evidence supporting the excellent instream environmental condition of the great majority of the Lower Goodradigbee's course comes from upstream studies. The Upper Goodradigbee is regularly used as a reference site for studies on the regulated, impacted Cotter River, indicating it is in excellent instream environmental condition (e.g. Chester and Norris 2006; Peat and Norris 2007; Harrison and Broadhurst 2015; Broadhurst *et al.* 2016, 2021).

Furthermore, macroinvertebrate sampling sites in the lower section of the Upper Goodradigbee, including a site immediately before the river enters the Cascade Zone (Bramina Creek confluence), typically record Band A scores ('SIMILAR TO REFERENCE')[3] and occasional Band X scores

[3]Macroinverbrate samples are similar in species diversity and number to those predicted by reference sites with water quality and/or habitat in good condition.

Fig. 7. (*Continued*).

('MORE BIOLOGICALLY DIVERSE THAN REFERENCE')[4] across seasons under the macroinvertebrate-based AUSRIVAS predictive stream health assessment system (Peat and Norris 2007; Harrison and Broadhurst 2015; Broadhurst *et al.* 2016, 2021). These typically high scores are despite the lower section of the Upper Goodradigbee flowing through the 15.2 km long, largely cleared Brindabella Valley, which no doubt contributes to some rare, atypical Band B scores (SIGNFICANTLY IMPACTED)[5]. The latter references include underwater photos of the Goodradigbee stream bed that show high water clarity, cobble substrate and lack of siltation, with Broadhurst *et al.* (2021) also finding a clear pattern of consistently better biological condition in Goodradigbee River sites compared to other upland rivers in the region (Cotter and Queanbeyan).

Thus the Upper Goodradigbee is in demonstrably good to excellent instream environmental condition where it enters the 9.5 km Cascade Zone demarcating the Upper and Lower River. As both the 9.5 km Cascade Zone and the first ~20 km of the Lower Goodradigbee represent a considerable *improvement* in valley condition and riparian vegetation over the Brindabella Valley – with both sections largely forested (Fig. 8) – it can be concluded that the Lower Goodradigbee starts its course in good to excellent instream environmental condition, and at minimum maintains, and probably improves, that condition for at least the first 20 km of its course. Excellent instream environmental condition in effect persists for the first 27.4 km of its course, where the first significant thinning of riparian vegetation occurs.

[4]Macroinvertebrate samples exceed species diversity and number to those predicted by reference sites.
[5]Macroinvertebrate samples have reduced species diversity and numbers to those predicted by reference sites.

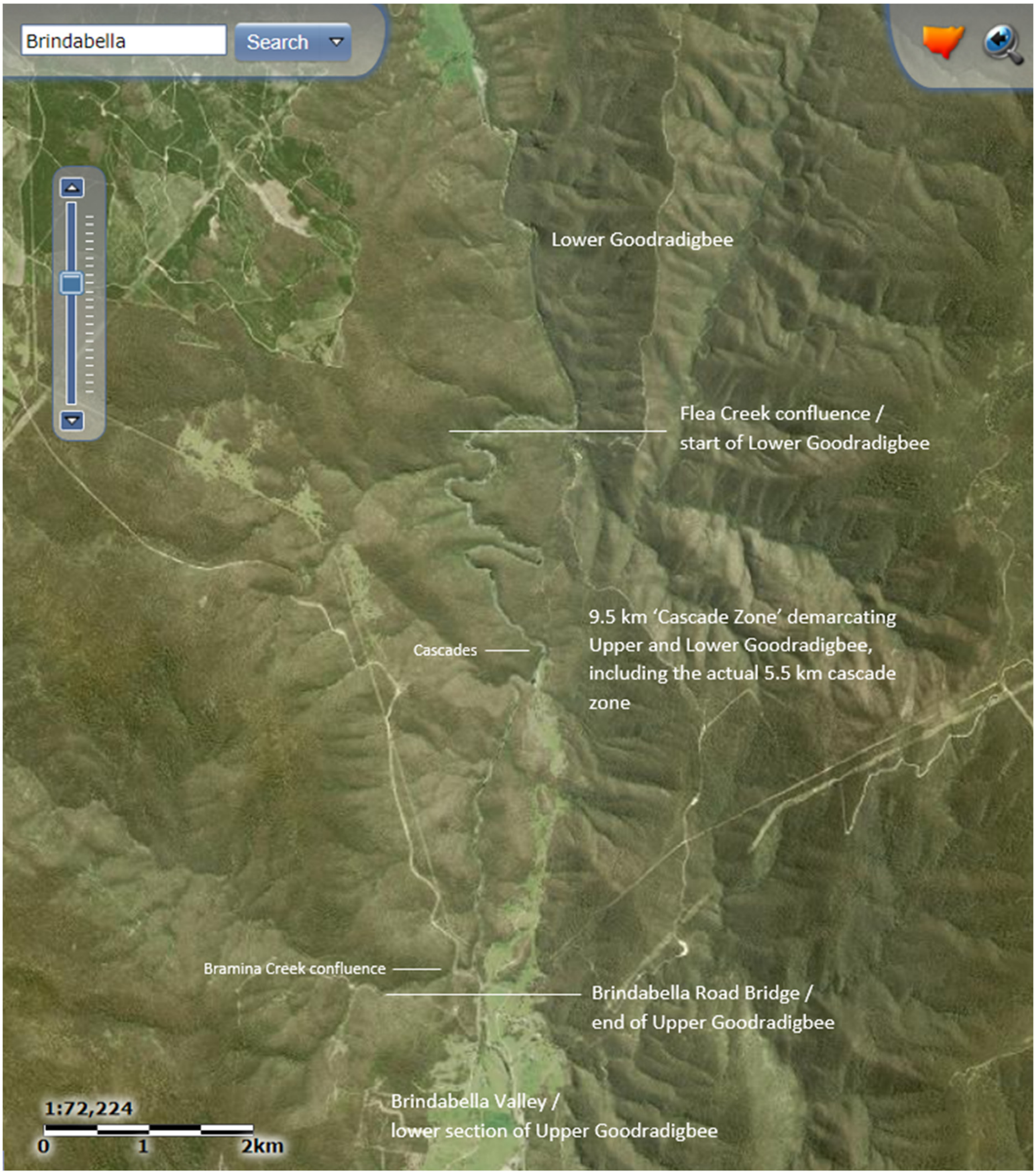


Fig. 8. Aerial image showing significant improvement in catchment and riparian vegetation as the river transitions from the Upper Goodradigbee to the Cascade Zone and Lower Goodradigbee.

The nature of the great majority of Lower Goodradigbee's course also rules out overfishing as a plausible cause of native fish decline and extinction. In particular, the numerous remote areas and limited access points of the Lower Goodradigbee mean large sections of its course experience little human access or fishing pressure, a point made by Pratt (1979). Indeed, Pratt (1979), as a keen trout angler and then-Director of the Conservation and Agriculture Division in the Federal Department of the Capital Territory, provides arguably the most succinct summary of the excellent instream environmental condition of the Lower Goodradigbee, albeit from an alien trout angling perspective. It also provides another line of evidence discounting habitat degradation or spawning site siltation as a cause of decline and extinction of native fish in the Lower Goodradigbee:

> 'The Goodradigbee River is regarded as the major breeding area for the trout population of Burrinjuck Reservoir. The river is relatively short, with a turbulent flow through granite and limestone country. The bed of the stream is commonly rocky and there are numerous rapids, thus the water is highly oxygenated. The river drains a mountainous catchment, much of it protected against disturbance or development within the Kosciusko National Park, thus the water is of high quality. Snowfields in the upper part of the catchment ensure a reliable flow of cold water at spawning time. Heavy shading of the river and most tributary creeks by eucalypt forest, *Acacia* spp., *Casuarina* sp., and native grasses helps maintain low water temperatures and provides cover for migrating fish. There are numerous creeks with extensive gravel beds relatively free from siltation throughout their length, and similar gravel beds throughout much of the main river. A major feature of the catchment is that most of it has been only lightly disturbed by man, and much of it is uninhabited. The remainder is only sparsely populated, with few roads or tracks, thus erosion, turbidity, siltation and other forms of pollution are not major problems. Consequently, there are excellent spawning facilities for trout throughout the length of the river, from slightly upstream of Wee Jasper to the headwaters, and in the numerous creeks draining into the river.'

Alien trout and trout stocking impacts on large-bodied native fish in the Australian scientific literature

Acknowledgement or examination of alien trout impacts and alien trout stocking impacts on native fish species other than small-bodied galaxiids are strikingly rare in the scientific and management literature generated in Australia after the 1980s. A rare exception is Gilligan (2005), who noted:

> 'Given their long history of release, it at first appears that [alien] rainbow trout stocking could not have resulted in the distinct declines of Macquarie perch in the upper [Murrumbidgee] catchment observed between 1979 and 1985 as reported by Lintermans (2000*a*). However 1980 was the first year when very large numbers of rainbow trout were released ... Therefore, increases in the stocking rate of rainbow trout, more than any other factor, coincide with the decline of the threatened Macquarie perch in the upper Murrumbidgee.'

Other rare exceptions include Lintermans (2006), who recorded a potentially significant dietary overlap between Macquarie perch and alien trout species in the Queanbeyan River using Schoener's index of niche overlap; Ebner *et al.* (2007), who examined alien trout for Macquarie perch predation in the pre-enlargement Cotter Dam; and the National Recovery Plan for Macquarie perch (Department of Environment and Energy (DoEE) 2018), which presents multiple lines of evidence strongly implicating alien trout and alien trout stocking in the loss of Macquarie perch from most montane and upland stream habitats in the southern Murray–Darling Basin.

In contrast to recent literature, older literature commonly noted that alien trout species (*O. mykiss* and *S. trutta*) and alien trout stockings were having serious impacts on native fish species and had suspected involvement in the declines and localised extinctions of many populations of large-bodied native fish species (e.g. Whitley 1955; Butcher 1967; Cadwallader 1977, 1978, 1979, 1996; Cadwallader and Rogan 1977; Jackson 1978, 1981; Jackson and Williams 1980; Cadwallader and Backhouse 1983; Cadwallader and Gooley 1984).

In particular, Butcher (1967) noted that both alien trout species 'eat and compete with' Macquarie perch, trout cod and blackfish species and 'may have a significant effect on small trout-cod, very small Macquarie perch and small blackfish'; Cadwallader and Rogan (1977) suggest a link between the collapse of the Lake Eildon Macquarie perch population and the stocking of more than 1 million alien trout (*O. mykiss* and *S. trutta*) between 1958 and 1967; Cadwallader (1979) links the disappearance of trout cod from a suitable stretch of upstream habitat they formerly occurred in in Seven Creeks to decades of heavy alien trout stocking (primarily *S. trutta*); and Cadwallader and Gooley (1984) stated:

> '.. in general a 'good trout stream' is also a good trout cod stream. Perhaps it is more than coincidence that the areas formerly occupied by trout cod in north eastern Victoria, from where the species appears to have been almost eliminated, are areas which have been heavily stocked with trout.'

Tilzey (1980) reveals there were two schools of thought during this period; one that maintained the effect of alien fish had been minimal, with essentially all blame on habitat and hydrological changes, and another that maintained that alien fish themselves had had considerable impact. While the 'habitat' school appears to have dominated the debate at that time and since, this study's analysis and observations, and the observations and results of many other studies, particularly Townsend and Crowl (1991), McDowall (2006) and Raadik (2014), suggest it is time for a reassessment.

In a more historical vein, Trueman (2007, 2011) provides a number of oral histories that document declines and collapses of montane/upland populations of large-bodied native fish after alien trout introduction and stocking, and Rowland (2020) links the loss of many Murray cod populations in montane/upland streams of the northern NSW tablelands to alien trout introduction and stocking (primarily *O. mykiss*). Importantly, Murray cod populations have been re-established in many of these northern tableland streams since the 1970s, after their re-introduction via stocking, aided by a concomitant waning of alien trout dominance in these streams (Rowland 2020). This is likely due to a warming thermal regime under anthropogenic climate change.

The recognised phenomena of shifting baselines (e.g. Pauly 1995; Pinnegar and Engelhard 2008; Humphries and Winemiller 2009; McClenachan *et al.* 2012) and intergenerational amnesia (e.g. Alleway and Connell 2015) have seen the issue of assisted alien trout invasion, and concomitant loss of montane/upland populations of large-bodied native fish, largely fade from public and scientific consciousness. However, in the 1910s, 1920s and 1930s, native fish anglers were in no doubt that alien trout and alien trout stockings were driving the declines and localised extinctions of large-bodied native fish that they were witnessing in many montane, upland and slope streams (Supplementary material). Amongst these historical articles are some that presciently raised concerns about the persistence of the Lower Goodradigbee Murray cod population in the face of alien trout domination (e.g. Yass Tribune-Courier 1929, 1938). Collectively these articles, along with the oral history evidence of Rhodes (1999) and Trueman (2007, 2011) and the analyses of Minard (2015), reveal a strong and credible counter-narrative of alien trout impacts in south-eastern Australia, extant at that time but now lapsed. This counter-narrative strongly challenges the narrative that has been dominant in Australia for many decades now – an ecologically implausible narrative that:

1. claims a relative benignity in alien trout introductions and alien trout stockings
2. downplays or denies the former occurrence of large-bodied native fish in montane/upland streams
3. rejects all historical evidence of alien trout impacts and alien trout stocking impacts
4. places all blame on habitat degradation and hydrological changes for large-bodied native fish declines and localised extinctions, particularly in montane/upland streams
5. where alien fish impacts are acknowledged, focuses almost exclusively on alien carp and redfin impacts.

This dominant narrative is clearly reflected in documents that purport to regulate the environmental impacts of alien trout stocking in NSW (New South Wales Fisheries (NSW Fisheries) 2003; New South Wales Department of Primary Industries (NSW DPI) 2005).

Current assumptions, stocking practices and management practices with alien trout

Historical precedence means there is a place for alien trout and alien trout fishing in southern-eastern Australia nowadays. However, the current long-standing assumption by state fishery agencies, acclimatisation societies and most trout anglers – that all sizeable upland/montane rivers and streams in south-eastern Australia exist solely for alien trout, alien trout stocking and alien trout fishing – is manifestly unreasonable and needs to change.

This assumption is clearly demonstrated by:

1. the historical evidence presented in this paper (Supplementary material)
2. the extreme alien trout dominance in these streams as quantified by sampling (Llewellyn 1983; Harris *et al.* 1996; Harris and Gehrke 1997; Gilligan 2005; Davies *et al.* 2008, 2012; Murray–Darling Basin Authority (MDBA) 2021)
3. mass annual stockings of alien trout into these streams, including streams where endangered native Macquarie perch are found (NSW: upper Murrumbidgee; Victoria: Holland Creek) (New South Wales Department of Primary Industry (NSW DPI) 2020, 2021*a*; Victorian Fisheries Authority (VFA) 2021*a*)
4. the listing of all of these streams as 'trout waters' in state fishing guides and regulations (New South Wales Department of Primary Industry (NSW DPI) 2021*b*; Victorian Fisheries Authority (VFA) 2021*b*)
5. the findings of the federal overview on the impacts of alien salmonids on native fauna (Cadwallader 1996).

Current trout stocking and management practices benefit only a tiny proportion of the general population (i.e. keen trout anglers). It takes place to the exclusion of all other community values and perspectives, including those of Indigenous people, native fish anglers, naturalists, and those who simply wish to see an upland/montane stream in its natural state, with its natural fish, frog and invertebrate fauna intact (Noble *et al.* 2018). The current trout stocking and management practices also take place to the exclusion of any serious conservation or recovery efforts with gravely threatened native fish and other aquatic fauna in our larger upland/montane streams.

Examples include:

- a near-complete lack of dedicated trout-free montane and upland stream habitat for conservation of threatened aquatic fauna (Cadwallader 1996);
- numerous alien trout management and stocking impediments to the conservation of threatened aquatic fauna (Jackson *et al.* 2004);
- a lack of trout-free habitat for critically endangered (federal EPBC Act) spotted tree frogs (*Litoria spenceri*) (Gillespie 2001);
- an inability to find upland stream habitats free of trout or trout stocking for critically endangered (state legislation) purple-spotted gudgeon (*Mogurnda adspersa*) and threatened southern pygmy perch (*Nannoperca australis*)

(federal EPBC Act: vulnerable) reintroduction projects in the Murrumbidgee catchment (Gilligan 2005);
- the release of 173 500 alien rainbow trout between 2009–2010 and 2019–2020 (with more ongoing) in the upper Murrumbidgee River (New South Wales Department of Primary Industry (NSW DPI) 2021*a*), where the larger of NSW's two viable populations of endangered Murray–Darling Macquarie perch persist (cf. Abercrombie River: Pearce 2013); and
- the blocking of a translocation of endangered Macquarie perch above a population-constraining set of falls on the Upper Queanbeyan River in favour of trout fishing and trout stocking interests, with the subsequent collapse and loss of that Macquarie perch population (Lintermans 2013).

In summary, the current trout stocking and management practices are manifestly inequitable socially and community-wise, and cannot be defended environmentally and ecologically.

Potential mechanisms for historical and current alien trout impacts

Mechanisms for such historical alien-trout-driven declines and extirpations include:

1. competitive and predation driven displacement from optimal food and habitat resources (McKeown 1934; Age 1935; Butcher 1945; Cadwallader 1978, 1996; Ault and White 1994; Hayes 1996; McDowall 2003, 2006; Lintermans 2006; Pardo *et al.* 2009; Rogosch and Olden 2020; Vidal *et al.* 2020)
2. predation, including the often-overlooked predation on and even between larval and early stage juvenile fish (Blinn *et al.* 1993; Cadwallader 1996; Marsh and Douglas 1997; Lintermans 1998; McDowall 2003, 2006; Rikardsen and Sandring 2006; Schooley *et al.* 2008; Raadik *et al.* 2010; Raadik 2014; Lhendup *et al.* 2019).

Records demonstrate that alien rainbow trout predation specifically was a key impact mechanism in Canberra and the surrounding region historically, and arguably remains so today. Lintermans (1998) reports heavy alien rainbow trout predation on two-spined blackfish in the upper reaches of the neighbouring Cotter River, with up to 21.4% of backpack-electrofished, non-juvenile rainbow trout containing two-spined blackfish in their stomachs. The author has similarly seen a number of instances of alien rainbow trout predation on two-spined blackfish in the Cotter River system over 26 years (Fig. 9*a*, *b*). Both Ebner *et al.* (2008) and Lintermans *et al.* (2013) found two-spined blackfish to be at very low abundances in the Cotter River immediately downstream of Bendora Dam, where alien trout abundances – almost exclusively rainbow trout – were highest. The latter acknowledge the large abundances of alien [rainbow] trout present as a possible cause, by way of predation and competition for food. The author is also aware of numerous unpublished records of rainbow trout predation on two-spined blackfish in Corin and Bendora Reservoirs on the Cotter River, made by various governmental agencies in the course of monitoring and sampling, and two unpublished records from the Lower Goodradigbee River and tributary Micalong Creek respectively.

Studies in the mainstem and tributaries of the Colorado River, USA also provide useful insights into the extent and impacts of such alien trout predation, as well as providing perspective on past, largely unsuccessful, small-scale conservation stockings of native species such as trout cod and Macquarie perch into alien trout dominated montane and upland streams.

- Healy *et al.* (2020) recorded a 480% increase in native fish numbers including federally endangered humpback chub

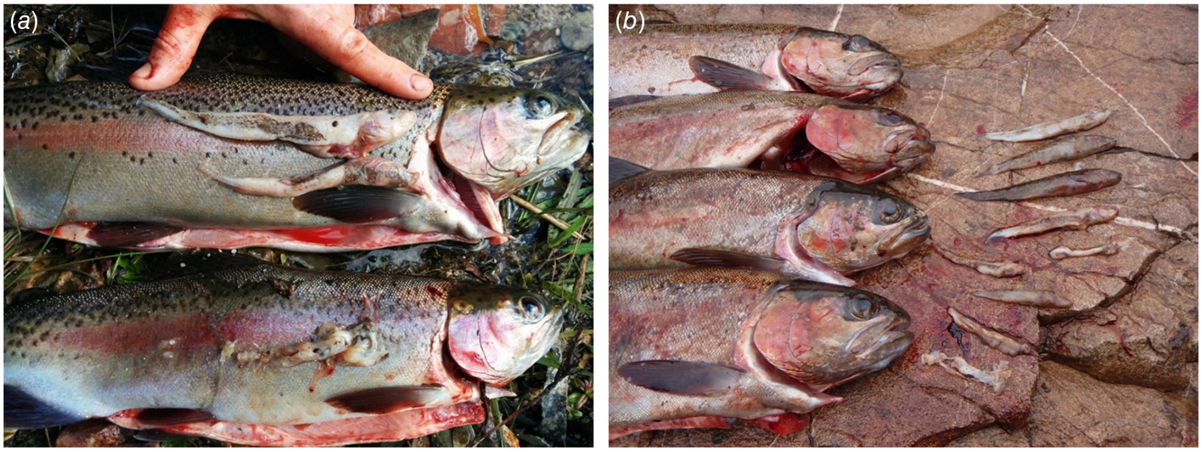


Fig. 9. (*a*) Alien rainbow trout (*Oncorhynchus mykiss*) predation on native two-spined blackfish (*Gadopsis bispinosus*). Cotter system, 2015. (*b*) Alien rainbow trout (*O. mykiss*) predation on native two-spined blackfish (*G. bispinosus*). Cotter system, 2017. Images: Simon Kaminskas.

(*Gila cypha*) over 6 years in a mountain stream tributary of the Colorado River once management suppression of alien trout species surpassed 60%.
- Spurgeon *et al.* (2015) studied trophic niche and dietary interactions between translocated [reintroduced] federally endangered humpback chub in a Colorado River tributary dominated by alien rainbow trout. An ontogenetic shift to piscivory in alien rainbow trout was observed at 120 mm TL, and the incidence of piscivory in rainbow trout was 5.3%.
- Yard *et al.* (2011) found on average alien rainbow trout and brown trout ingested 85% more native fish including the federally endangered humpback chub than alien fish in the mainstem Colorado River. This is in spite of the fact that native fish constituted less than 30% of the small fish available in the study area. Rainbow trout incidence of piscivory was 0.5–3.3% and brown trout incidence of piscivory was 8–70%. Alien rainbow trout as small as 100 mm TL were recorded consuming fish.
- Marsh and Douglas (1997) provided context on the impact on seemingly low levels of predation by five alien fish species including rainbow trout on federally endangered humpback chub in the Little Colorado River. They state 'Our data indicate that on average about 3% of rainbow trout and channel catfish ate an average of 2.3 humpback chubs. If our estimated average meal of 2.3 prey is taken once a week, a predator population of 1000 would annually consume 3588 humpback chub. Predatory fishes probably number in the thousands.'

A final consideration is that local studies and observations on alien trout predation are based on visual searches for the remains of juvenile to adult native fish in trout stomachs. Alien rainbow trout and brown trout predation on native fish larvae remains unexplored and unquantified across south-eastern Australia. This is an urgent priority in regards to Macquarie perch conservation, with the behaviour of Macquarie perch larvae as recorded in the Cotter River – schooling in small groups (~5–30), along steep rock faces in deep sections of pools, in areas of low or no flow (Broadhurst *et al.* 2012) – suggesting they may be extremely susceptible to predation by fast, agile alien rainbow trout of all age classes.

Larval fish predation is particularly difficult to identify and record due to extremely rapid digestion rates, with a 50% reduction in identification of larvae after only 30 min and a 97% reduction after 60 min (Schooley *et al.* 2008). DNA assays of stomach contents are essential to detect and quantify such predation on larvae. Significant predation on threatened native fish larvae by alien fish species has been demonstrated in the USA through DNA assays (e.g. Ley *et al.* 2014; Hereford *et al.* 2016) and proof-of-concept for the technique has been demonstrated in Australia (Hardy *et al.* 2014).

Low numbers of observed crayfish in the Lower Goodradigbee River

Based on previous surveys (e.g. Fulton *et al.* 2012; Starrs *et al.* 2015), our casual visual surveys using polaroid sunglasses and slow moving kayaks in the very clear waters of the Lower Goodradigbee was probably a relatively efficient way of sighting Murray crays – superior to baited hoop nets albeit not as efficient as snorkelling. Our experience is that the white chelae of even small Murray cray individuals stand out and make the species extremely visible in clear water.

The relatively low numbers of Murray crays sighted over the course of this observational kayak journey on the Lower Goodradigbee was surprising. Due to its substantially forested catchment, riparian vegetation and remoteness, the great majority of the Lower Goodradigbee River is effectively free of both instream habitat degradation and human take, which are the usual causes of *Euastacus* species decline (e.g. Horwitz 1990, 1995; Furse and Coughran 2011*a*, 2011*b*; McCormack 2012) (some illegal take possibly occurs in the Lower Goodradigbee at access points, but these are few). Our tally of eight Murray crays is significantly less than other studies (e.g. Starrs *et al.* 2015), and very low considering the 32.2 km of river traversed. It is also noteworthy that our last sighting of a Murray cray was made at the base of Swinging Bridge Reserve, in contrast to the 1951 specimen sampled much further downstream at Coodravale (Australian Museum 2021*b*).

Possible explanations include effects of 2012 flooding and possible predation on juvenile crayfish by alien fish species. A 91% decline of *E. armatus* over 6 years was recorded in the nearby upland Goobaragandra River following extreme flooding in 2012, which resulted in significant siltation and significant loss of fringing streamside vegetation and boulder habitat (Fulton and Noble 2016; Noble and Fulton 2017). The Lower Goodradigbee River also experienced heavy flooding in 2012 but is not damaged as per the Goobaragandra River; overhanging riparian vegetation and boulder habitats are still common and siltation is very low except in the very lowest reaches of the river.

Alien trout species are known to predate on juveniles of *Euastacus* species (Sydney Morning Herald (SMH) 1937; Pigeon 1981; Horwitz 1990, 1995; Furse and Coughran 2011*a*; McCormack 2012) and alien trout predation is noted as a specific conservation concern for the Orbost spiny cray (*Euastacus diversus*) (Murray 2003; Lieschke *et al.* 2014), the alpine cray (*Euastacus crassus*) (van Praagh 2003) and the West Australian marron (*Cherax cainii*) (Tay *et al.* 2007). The impact of alien fish predation on juvenile *Euastacus*, particularly predation by alien trout species, has scarcely been researched and is in need of urgent investigation and quantification. Predation by alien carp, now the dominant alien fish in the Lower Goodradigbee, similarly requires research. One carp was observed grubbing repeatedly for unknown prey in the gravel substrate of a deep 'boulder pocket' in a fast-flowing run at the base of a pool; *Euastacus* juveniles may have been one of the targets of this foraging behaviour.

Finally, seasonal effects may be influential; *Euastacus* species are typically more active in cooler months (Gilligan *et al.* 2007; Furse and Coughran 2011*b*). However, our observations indicate that summer conditions at the time were not limiting activity.

Recent declines of alien trout species in the Lower Goodradigbee River

Despite its long domination by strong breeding populations of alien trout species (*O. mykiss* and *S. trutta*), it is becoming increasingly apparent that a warming thermal regime, driven by anthropogenic climate change (CSIRO and Bureau of Meteorology (BOM) 2020; IPCC 2021), is making the Goodradigbee River below the Brindabella Valley (i.e. the Cascade Zone and the Lower Goodradigbee) marginal for alien trout species. This is in agreement with anecdotal reports from local anglers, contemporary fish sampling data, and the observational kayak journey undertaken on the Lower Goodradigbee for this study. Only four alien rainbow trout were sighted and one rainbow trout caught on this observational kayak journey; in contrast, rainbow trout were still somewhat common in this stretch of river in the mid-1990s (S. Kaminskas, pers. obs.).

Given the remarkable recovery of endangered and threatened native fish recorded in a mountain stream in the USA once alien trout were strongly suppressed (Healy *et al.* 2020), one might expect a similar response in the Lower Goodradigbee River now that alien trout species are being strongly suppressed by anthropogenic climate change (continual stockings notwithstanding). Unfortunately, little ecological benefit has derived from the loss of alien trout species from the Lower Goodradigbee as alien carp have opportunistically and rapidly occupied their vacated niche. While this ecological shift from one invasive fish species to another invasive fish species may be unusual because of the intermediary role played by anthropogenic climate change and warming thermal regimes, it is worth noting it is not the first such ecological shift in Murray–Darling waterways. Alien redfin perch were dominant in lowland rivers of the southern Murray–Darling Basin in the 1950s and 1960s until rapidly displaced by invading alien carp (Rowland 2005, 2020); alien tench (*Tinca tinca*) were abundant in Lake Mulwala on the Murray River until rapidly displaced by invading alien carp between 1979 and 1983 (Rowland 2020); and vast shoals of alien goldfish in Lake Burley-Griffin in Canberra rapidly disappeared upon the invasion of alien carp in the late 1970s (Pratt 1979).

Historical and scientific literature indicate thermally-driven declines in alien trout species have occurred in the nearby Upper Murrumbidgee River and other Australian Capital Territory rivers as well (e.g. Canberra Times (CT) 1973; Greenham 1981) but commenced earlier (i.e. late 1960s). Rising stream thermal regimes, as a consequence of anthropogenic climate change, are increasingly recognised in Australia (e.g. Bond *et al.* 2011; Booth *et al.* 2011; Koehn *et al.* 2011; Morrongiello *et al.* 2011) as well as overseas (e.g. van Vliet *et al.* 2013*a*, 2013*b*). Declines in invasive coolwater alien species such as rainbow trout (Rahel and Olden 2008) and their supplantation by invasive warmwater alien species such as carp (Britton *et al.* 2010) are predicted. Thermally-driven declines in alien trout distribution in Australia are increasingly recognised by anglers targeting alien trout (e.g. Flylife 2017) and alien-trout-focussed state fishery agencies (Douglas *et al.* 2018; New South Wales Department of Primary Industries (NSW DPI) 2020).

Curiously, the decline of alien trout species in the mid and lower reaches of many Murray–Darling Basin rivers was arguably one of the first clear biological signals of anthropogenic global warming in south-eastern Australia, and aligns neatly with the first anthropogenic climate change signal detected in Australian climatic records (i.e. 1930s) (King *et al.* 2016). It is important in present day contemplations of alien trout impacts to recall that their dominance and attendant impacts once extended to the middle and even lower reaches of rivers in past decades. At its greatest extent, this phenomenon saw situations such as the aforementioned dominance of Burrinjuck Reservoir and all tributaries by rainbow trout in the 1930s, with its attendant native fish predation; large brown trout hunting southern pygmy perch in the lowland Barmah Forests in the 1940s (Cadwallader 1977); brown trout displacing native fish in the middle and lower reaches of the King River in the 1920s (Argus 1928); brown trout displacing native fish in the Ovens River as far downstream as Wangaratta between the 1920s and 1940s (Cadwallader 1977); and speculation – based on increasing trout captures – on whether alien trout species would take over the lowland reaches of southern Murray–Darling rivers in the 1930s (Sydney Morning Herald (SMH) 1928; Advertiser 1933; Riverine Herald 1933; Shepparton Advertiser 1933). Finally, despite recent rainbow trout declines, the Lower Goodradigbee River remains dominated by alien fish, now in the form of carp, and rainbow trout and brown trout continue to dominate the Upper Goodradigbee River (Murray–Darling Basin Authority (MDBA) 2021).

Potential native fish recovery in the Lower Goodradigbee River

In the present ecological situation, and given the functional and actual extinctions of Macquarie perch and silver perch respectively, Murray cod are the only remaining large-bodied native fish species that could potentially recover in the Lower Goodradigbee River. It is not clear, therefore, why Murray cod have mostly failed to recolonise the Lower

Goodradigbee River now that alien trout species are effectively absent. Burrinjuck Reservoir, which just intercepts the lowest reaches of Goodradigbee River, has a reasonable Murray cod population derived from natural recruitment in the Murrumbidgee River and stocking (Forbes *et al.* 2016).

Inhibition by alien fish, including stocked alien trout

One possibility is that the significant numbers of alien rainbow trout fingerlings still being released into the Lower Goodradigbee River are having an inhibitory effect through predation and competition, despite sampling, observations and anecdotal reports indicating almost none are surviving to adulthood. It is also possible the extremely high numbers of alien carp and increasing numbers of alien redfin perch in the Lower Goodradigbee River are now having a similar inhibitory effect on recolonisation of Murray cod to what alien trout species are hypothesised to have had in the past. Dietary competition between carp and Murray cod larvae is indicated (Tonkin *et al.* 2006). Redfin perch are predators of small and juvenile native fish (e.g. Morgan *et al.* 2002; Hammer 2004; Barrett *et al.* 2014; Lintermans *et al.* 2014; Wedderburn *et al.* 2014; Brown and Morgan 2015; Wedderburn and Barnes 2016) and have been linked to past declines of Murray cod in the southern Murray–Darling Basin (Rowland 2005, 2020). Redfin perch are also the main vector of the alien pathogen Epizootic Haematopoietic Necrosis Virus (EHNV) (Langdon *et al.* 1986; Langdon and Humphrey 1987; Langdon 1989; Whittington *et al.* 1996, 2010), which is a serious threat to some native fish species, although rainbow trout can vector EHNV as well (Langdon *et al.* 1988; Langdon 1989; Whittington *et al.* 1994, 1999; Becker *et al.* 2013; Kaminskas 2021).

Loss or diminution of migratory behaviours

Another possibility is that Murray cod in the Burrinjuck Reservoir population have lost some of their upstream migration instincts, via severe declines in wild populations (Murray–Darling Basin Commission (MDBC) 2004; Rowland 2005; Murray–Darling Basin Authority (MDBA) 2020; Rowland 2020), impoundment effects (Koster *et al.* 2020), and stocked fish losing behavioural acuity (Mittelbach *et al.* 2014). This could be a factor contributing to the current findings. However, observations by anglers suggest upstream migration instincts – often spawning related – are still present to some degree in Murray cod populations across the Murray–Darling Basin, even in stocking-derived impoundment populations. Even so, Murray cod populations today appear to lack the more aggressive upstream migration instincts that populations of yesteryear displayed, which were triggered by flow events or by seasonal cues, both of which are still present in the Goodradigbee River (e.g. Goulburn Post 1885; Tumut Advocate and Farmers and Settlers' Adviser 1904; Sunday Sun 1907; National Advocate [Bathurst] 1925; Trueman and Luker 1992; Trueman 2007, 2011).

Stocking of hatchery-reared fish results in the loss of many appropriate behaviours and localised adaptations in riverine populations (e.g. Brown and Laland 2001; Hutchison *et al.* 2012; Mittelbach *et al.* 2014), which can include movement patterns. Studies have already identified localised adaptations in allopatric native fish populations (i.e. temperature tolerance) (Harrisson *et al.* 2016; Pavlova *et al.* 2017; Svozil *et al.* 2019). In the closely related trout cod, stocked fish demonstrated strikingly different movement patterns to wild fish in lowland rivers (Ebner *et al.* 2006; Ebner and Thiem 2009). Impoundments may also alter movement patterns in *Maccullochella* species. Koster *et al.* (2020) found that radio-tracked Murray cod in weir pools differed from riverine populations previously studied, with an absence of longer-distance (10–100 km) movements. Such effects are likely occurring in the Murray cod population of Burrinjuck Reservoir and make the case for assisted recovery of Murray cod via conservation stockings directly into the Lower Goodradigbee River at multiple points along its length, commencing at the Flea Creek confluence. It is probable that a Murray cod population established in the Lower Goodradigbee through a long-term conservation stocking program would become self-sustaining and, through natural selection, redevelop more appropriate localised migratory/movement behaviours (e.g. Hutchings 2014).

Ulcerated carp – possible atypical *Aeromonas salmonicida* in the Lower Goodradigbee River and impacts

A review of relevant scientific literature and diagnostic photographs strongly suggest the ulcerated alien carp observed were suffering from infections of the alien pathogen atypical *A. salmonicida* (Wiklund and Dalsgaard 1998; Goodwin and Merry 2009; Department of Agriculture, Water and Environment (DAWE) 2019). This bacterial pathogen is common in goldfish, where it takes the form of the Goldfish Ulcer Disease (GUD) (Department of Agriculture, Water and Environment (DAWE) 2019). Atypical *A. salmonicida* entered Australia via imports of infected alien goldfish in 1974 (Whittington *et al.* 1987; Humphrey and Ashburner 1993; Whittington *et al.* 1995) and it is now indicated as being endemic (i.e. permanently established in an epidemiological sense) in south-eastern Australia (Department of Agriculture, Water and Environment (DAWE) 2019). Field records of this alien pathogen in wild fish populations in south-eastern Australian rivers are sparse (Whittington *et al.* 1987; Rowland and Ingram 1991; Department of Agriculture, Water and Environment (DAWE) 2019); therefore, these new observations of suspected atypical *A. salmonicida* in numerous wild alien carp are valuable.

Atypical *A. salmonicida* was presumably brought into the Lower Goodradigbee River by alien carp immigrating from

Burrinjuck Reservoir. Other possibilities include an origin from contaminated alien trout stockings (Whittington and Cullis 1988; Whittington 1989; Kaminskas 2021), or from contaminated carp or goldfish in an outdoor pond somewhere in the Goodradigbee catchment. It is noteworthy one pool with particularly high numbers of ulcerated carp (Fig. 6*b*) is only 1.3 km upstream of a site where 26 500 alien rainbow trout fingerlings have been released over the previous 10 years (Table 4*a*). Assuming the first scenario, entry of atypical *A. salmonicida* into Burrinjuck Reservoir was probably due to the propensity of anglers in past decades to use goldfish (as well as juvenile carp) as bait for Murray cod. This is well documented and considered a key factor in the spread of both alien species across the Murray–Darling Basin, particularly carp (Koehn 2004; Rowland 2005, 2020).

Of great concern is that silver perch individuals have been recorded with atypical *A. salmonicida* infection in aquaculture settings (Whittington *et al.* 1995; Read *et al.* 2007; Department of Agriculture, Water and Environment (DAWE) 2019). Conversely, Murray cod individuals are seemingly unaffected or symptomless carriers (Rowland and Ingram 1991; Ingram *et al.* 2005; Read *et al.* 2007). The implication, therefore, is that this alien fish pathogen is another potential factor in the collapse of the silver perch population in Burrinjuck Reservoir and tributaries, including the Lower Goodradigbee River. This reminds us that alien fish impacts frequently extend to alien pathogen and parasite impacts (Kaminskas 2021), in addition to predation, competition and displacement impacts. Other alien pathogens (e.g. EHNV and other alien iridoviruses) are already implicated in recent declines of two native fish species (silver perch, Macquarie perch). Specifically, an abundant silver perch population in Burrinjuck Reservoir and inflowing tributaries – primarily the Murrumbidgee River but extending to the lowest reaches of the Lower Goodradigbee River – crashed unnaturally rapidly (less than one generation) over a several year period in the mid-1980s (Kaminskas 2021).

Conclusions

Historical evidence from printed media combined with contemporary fish sampling data, scientific literature and field observations confirm a once-abundant assemblage of large-bodied native fish species, comprising Murray cod, Macquarie perch and silver perch, as well as the intermediately sized two-spined blackfish and the small-bodied mountain galaxias species and carp gudgeon species, is almost wholly extinct in the Lower Goodradigbee River. These multiple lines of evidence suggest this is due to the impacts of alien fish on native fish – in particular alien trout domination and alien trout stockings – as well as relatively recent alien carp invasion.

Similar questions regarding alien fish impacts and alien fish stocking impacts should be asked of a number of other montane and upland streams or stream reaches in the Murray–Darling Basin that offer excellent instream environments, habitats and hydrological conditions, but for which sampling shows are almost entirely dominated by alien fish numerically and biomass-wise – primarily strong breeding populations of alien trout species – and have mostly or entirely lost their large-bodied native fish assemblages (e.g. Llewellyn 1983; Harris and Gehrke 1997; Davies *et al.* 2008, 2012). These include the upper Murray River and unregulated tributaries, inflowing tributaries of Eildon Dam including the Goulburn, Big, Delegate, Howqua and Jamieson Rivers, the upper Ovens River and tributaries including the Buffalo River, and the long tract of the upper Mitta Mitta River and tributaries above Dartmouth Dam, as well as many smaller streams in south-eastern NSW and north-eastern Victoria.

The impacts of alien fish and alien fish stocking in Australia require major re-evaluation and dedicated research. The example of the Lower Goodradigbee River strongly cautions us that such alien fish impacts alone (i.e. rather than instream habitat degradation or river regulation) can result in extinctions of large-bodied native fish in montane, upland and slope stream habitats. Specifically, the domination of such stream habitats by strong wild breeding populations of alien trout (both species), and the continual stocking of such stream habitats with alien trout (both species), are both indicated to be incompatible with the survival of large-bodied native fish species in such stream habitats over long, multi-decadal timeframes. Of these two threatening processes, alien trout stockings are discretionary and unnecessary. At minimum, they should cease in any stream habitats where endangered or otherwise threatened large-bodied native fish still occur, e.g. Macquarie perch in the Upper Murrumbidgee River and Holland Creek.

Field observations of ulcerated carp observed in the Lower Goodradigbee River underscore the need for these specific fish to be captured and screened for atypical *A. salmonicida*, and underscore the need to establish better processes to capture and investigate observations of pathogen-affected fish generally (the GPS coordinates for one pool with ulcerated carp (Fig. 6*a*, *b*) can be provided by the author). Field observations also suggest there is a need to consistently monitor Murray cray numbers in the Goodradigbee River; to ensure 'no take' regulations for Murray crays in this waterway are being observed; and to investigate potential levels of predation by alien fish on juvenile Murray crays in this and other rivers.

Based on the discussion in this paper, it is strongly recommended that stocking of alien rainbow trout into the Lower Goodradigbee River for angling be ceased. These are now largely ineffectual in creating populations of adult alien trout in this section of the river; however, released trout may still have damaging ecological effects for the duration that they persist, as well as posing disease transmission risks. Such a cessation should be part of a broader conversation on alien trout stocking practices and management practices in south-eastern Australia.

Conversely, conservation stockings of native Murray cod, silver perch or Macquarie perch should be initiated in the Lower Goodradigbee River. Murray cod is probably the most suitable species, considering the superb habitat that is highly suited to the species (Tumut Advocate and Farmers and Settlers' Adviser 1904; Age 1907*b*; Trueman and Luker 1992; Rhodes 1999; Trueman 2007, 2011; Kaminskas 2018; Hutchison *et al*. 2019; S. Kaminskas, pers. obs.) and the ideal hydraulic regime (i.e. Mallen-Cooper and Zampatti 2018; Stuart *et al*. 2019; Tonkin *et al*. 2021), which still supports some relictual Murray cod spawning (Peterson 2003). The Lower Goodradigbee River has enormous potential to support a healthy self-sustaining Murray cod population again.

Murray cod also have the advantages of well-established hatchery breeding techniques that produce large numbers of fingerlings, recent advances in behavioural training, resistance to alien pathogens known and suspected to be present in the system (e.g. ENHV, atypical *A. salmonicida*), and avoidance of the emerging hybridisation problems being caused by trout cod stockings (e.g. Couch *et al*. 2016). As the apex predators of the Murray–Darling Basin (Ebner 2006; Rowland 2020) adult Murray cod also have the greatest capacity to exert predatory pressure on the currently abundant alien carp and redfin population. Any such Murray cod stockings should have a strong conservation emphasis and be focussed on quietly re-establishing at least one functional native fish population in the Lower Goodradigbee River, one of the few unregulated and undegraded large rivers remaining in Australia's Murray–Darling Basin.

Supplementary material

Supplementary material is available online.

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Data availability. Sustainable River Audit data is available on request from the Murray–Darling Basin Authority, in their role as Data Manager for these projects. Some Sustainable River Audit data is available for download from the Australian Government's data.gov.au website, and some Sustainable River Audit data and records are available online through the Atlas of Living Australia website. Hard copy historical records are available in the National Library of Australia's collection. Electronic historical records are available through the National Library of Australia's online TROVE archive. Data used for the catchment land use map is from ABARES (2021) Catchment Scale Land Use of Australia – Update December 2020, ABARES, Canberra, February CC BY 4.0., which is available at https://doi.org/10.25814/aqjw-rq15.

Ethics approval. An ethics approval was not needed nor possible to obtain for this study as it was an independent study and was not conducted under the auspices of a university or a research agency. Sampling for this study took the form of standard recreational fishing conducted in accordance with NSW DPI fishing regulations (made under the *Fisheries Management Act 1994*) and responsible fishing guidelines published by NSW DPI (https://www.dpi.nsw.gov.au/fishing/recreational/fishing-skills/responsible-fishing-guidelines). Similarly, best practice guidelines published by NSW DPI were followed for both the catch-and-release fishing (the Murray cod) (https://www.dpi.nsw.gov.au/fishing/recreational/fishing-skills/catch-and-release) and for the fish euthanasia (the rainbow trout) (https://www.dpi.nsw.gov.au/animals-and-livestock/animal-welfare/animal-care-and-welfare/other/companion-animal-files/humane-harvesting-of-fish-and-crustaceans).

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