Tilapia Incursion – Mitchell River catchment

Reporting the ecology and movement patterns of new tilapia (*Pelmatolapia mariae* and *Oreochromis mossambicus*) populations in the Mitchell River catchment to identify priority areas and actions to mitigate their impacts

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Queensland Government

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Foreword

This report follows the establishment of two species of invasive tilapia fishes in a tropical wet-dry river catchment following new sightings in 2017.

This report provides a comprehensive overview of the ecology of the current tilapia population in the Walsh River, including the use of new techniques to study movement over their entire lifetime. It also outlines the likely current extent of the tilapia population in the broader Mitchell River catchment using data from field surveys and previous sightings.

This report will inform decision making and on-ground action by i) identifying priority areas for local eradication efforts and ii) identifying areas for regular monitoring to determine if tilapia have further expanded their range.

While complete local eradication of these invasive fishes from the Mitchell catchment may be difficult, we hope that the new information on their ecology and movement provided in this report will inform strategies to mitigate their impacts on the Mitchell River ecosystems and prevent the spread of tilapia into other river systems.

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Executive summary

Scope and purpose

This study explored the geographical extent, biology, ecology (including feeding habits), and movement patterns of newly established tilapia populations (populations refers to spatially separated populations – the genetics of tilapia in the Mitchell catchment are currently unknown) in the Mitchell River catchment to inform on-ground actions for control and local eradication by identifying priority areas for local eradication and control efforts and high-risk areas for monitoring of future invasion.

Key messages and findings

- During the study tilapia were found only in the upper Walsh River catchment, upstream of Eureka Creek.
- Population progression is apparent in existing populations, with increases in abundance and body size of spotted tilapia *Pelmatolapia mariae* in both Bruce and Leafgold weirs and increase in abundance in Bruce Weir and spread to Leafgold Weir of Mozambique tilapia *Oreochromis mossambicus* observed in field surveys over the course of the study.
- Spotted tilapia populations in Bruce and Leafgold weirs are likely to grow rapidly in the coming years as larger individuals produce more offspring than their smaller counterparts did in previous years.
- Currently, tilapia populations in the Mitchell catchment show strong habitat preferences to areas with abundant macrophytes and deeper (>1 m) pools, however, increases in population abundance may lead to other habitats being exploited.
- Estimated movement patterns based on strontium isotope analyses varied between the three sites containing tilapia, with the Eureka Creek population found to be highly resident.
- Both species showed evidence of movement and age did not appear to influence movement of tilapia, with some juveniles and some adults from Bruce Weir showing evidence for movement during their lifetime.
- All tilapia caught in Leafgold Weir in 2019 showed evidence of movement to the weir from elsewhere, most likely originating from Eureka Creek.
- From our data we cannot rule out the Mareeba-Dimbulah Water Supply Scheme (MDWSS) as a source of the tilapia incursion as several tilapia had strontium isotope profiles that match mussels from Tinaroo Dam. However, more sampling is needed to better capture the Eureka Creek strontium isotope range which is influenced by inflowing water from the MDWSS. We also suggest reviewing the efficiency of fish screens and conducting population genetic analyses on tilapia in the Mitchell and Barron catchments, as well as other potential source populations.

- Plant material (macrophytes and filamentous algae) was the main food source supporting the growth and reproduction of both Mozambique and spotted tilapia.

Priority areas for monitoring include downstream reaches of the Walsh River, as well as wetlands and creeks on the floodplain. Priority areas for tilapia control should be the three sites where tilapia are currently established (Bruce Weir, Leafgold Weir, Eureka Creek), particularly Bruce Weir which has the most established populations of both Mozambique and spotted tilapia.

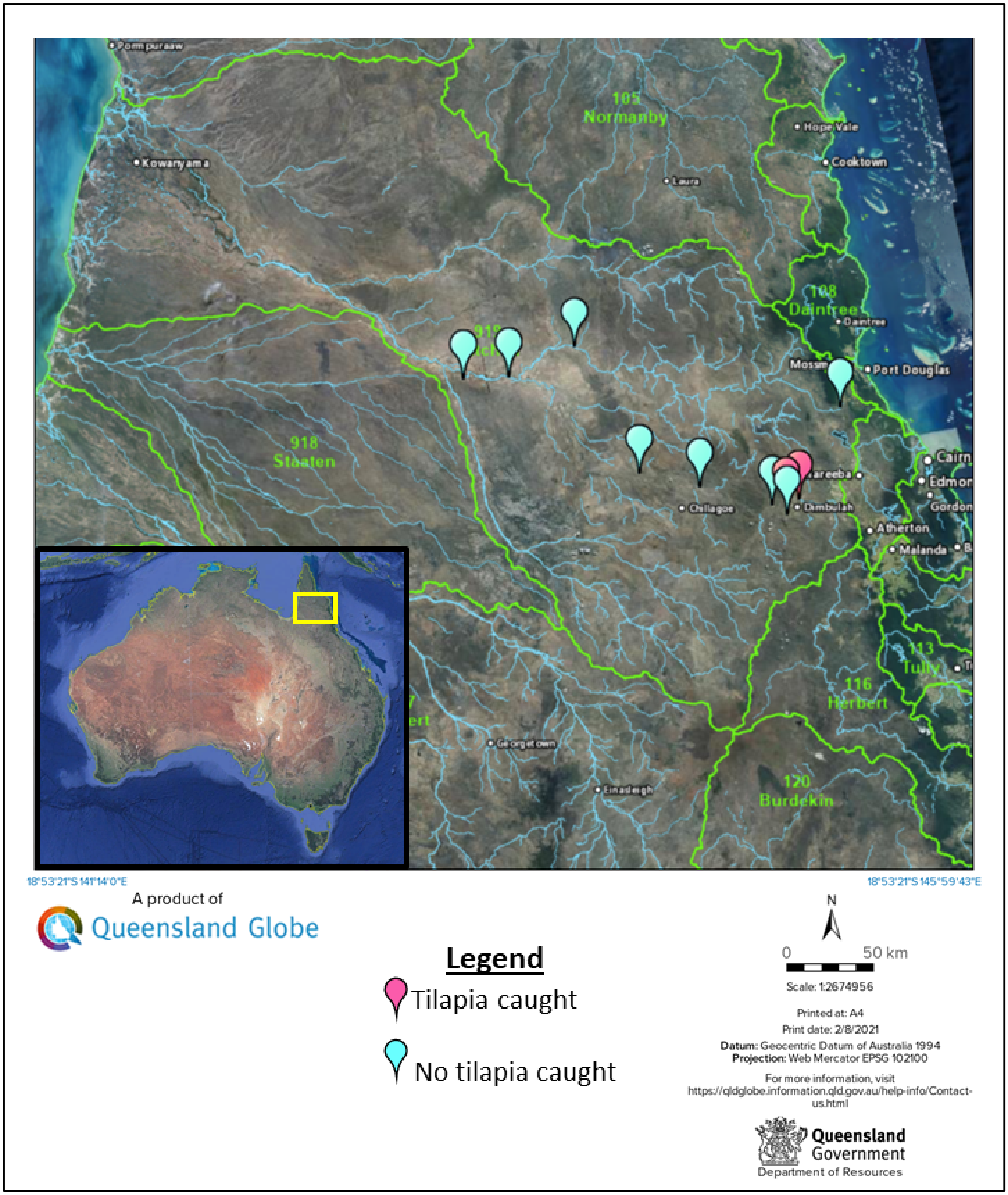

Figure 1. 2020 and 2021 electrofishing survey sites in the Mitchell River catchment

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Introduction: Invasive tilapia in Australian rivers

In October 2017, invasive tilapia were reported in the Walsh River, downstream from Rookwood Crossing. Biosecurity Queensland convened the Rapid Response team consisting of researchers, stakeholders and Natural Resource Management (NRM) groups. Following initial surveys by Biosecurity Queensland, researchers from Griffith University secured funding from the Department of Agriculture, Water and Energy to determine the extent of the incursion, the movement patterns and important food sources for the invasive populations. This report documents the findings following analyses of fish caught in multiple survey trips.

Tilapia – invasive freshwater tropical fish

Tilapia are a tropical freshwater fish from the Cichlidae family, native to Africa and the southwestern Middle East (Skelton, 2012). While Nile tilapia *Oreochromis niloticus* (L.) have been a large component of inland aquaculture fisheries in Asia and South America over the past 50 years (Attayde et al., 2011), there are also several species of ornamental tilapia that have been introduced to non-native waterways around the world (Deines et al., 2016). In many countries the introduction of tilapia has benefited ecosystem services including the provision of high protein food (Deines et al., 2016). However, tilapia have the potential to negatively impact ecosystems through competition with native species (via aggressive behaviour), reduction of water quality, and damage to habitat (Arthington and Blühdorn, 1994; Greiner and Gregg, 2008).

Tilapia are successful competitors because they are able to survive in low oxygen conditions, are successful breeders by mouthbrooding or nest protecting, and are generalist feeders that often consume aquatic plants as part of their diet (Canonico et al., 2005; Doupe et al., 2010; Skelton, 2012). Tilapia can adapt their reproductive strategies to suit environmental conditions (Reardon and Chapman, 2008) and can be aggressive towards native fish during nesting (Bradford et al., 2011). The reproductive success of native fish may also be reduced by the consumption of eggs and larvae by tilapia (Canonico et al., 2005; Doupé et al., 2009). Additionally, while established tilapia populations are often found in waterbodies with poor water quality, they can also contribute to eutrophication (i.e. harmful algal blooms) through excretion of waste and bioturbation during the consumption of benthic algae (Greiner and Gregg, 2008). These feeding habits, along with nest building, can reduce habitat quality through substrate damage (Arthington and Blühdorn, 1994; Greiner and Gregg, 2008). Globally there are reported ecological changes associated with tilapia introductions, including a reduction in the CPUE of river fisheries (Gu et al., 2015), but the harm to ecosystems is not clearly documented (Deines et al., 2016). Despite a lack of documented ecosystem impacts, the risks of tilapia invasion associated with their feeding and reproductive traits are recognised globally and they are known to be difficult to eradicate once established in a new catchment. Therefore, understanding the ecology of populations at the beginning of colonisation is important for informing monitoring, prevention, and eradication strategies.

Tilapia in Australian rivers

Before European settlement, Australian rivers did not contain any salmonid, cyprinid or cichlid fish species (Unmack, 2001). Native Australian freshwater fish are presumably well adapted to the harsh climatic and seasonal changes of drought, floods and bushfire runoff (Olden et al., 2008). However, many species are declining in numbers due to river fragmentation and poor water and habitat quality (Koehn and Lintermans, 2012; Lintermans et al., 2020). Many of these issues are caused by anthropogenic pressures such as river regulation, runoff and increased erosion caused by clearing of vegetation and poor land management (Vörösmarty et al., 2010). Additional pressures occur when invasive species are also present because native Australian species lack the specialization and plasticity seen in many freshwater species from other continents (Dudgeon et al., 2006; Olden et al., 2008).

Tilapia are strictly prohibited in Australia due to the risks associated with their invasion in Australian rivers and waterbodies (Greiner and Gregg, 2008). Despite strict regulations, heavy penalties and expensive education and eradication efforts (mostly by government), tilapia continue to spread to new waterbodies and river systems in Australia. Tilapia are kept illegally in aquaria and stocked dams, and the intentional release of tilapia into waterways and overflow of flooded dams are some of the main causes of new introductions (Ovenden et al., 2015). There are two tilapia species currently found in Australia, Mozambique tilapia *Oreochromis mossambicus* and spotted tilapia *Pelmatolapia mariae*. The introduction of Mozambique tilapia to Australian waterways occurred in the 1970's, and while spotted tilapia were seen in some lakes and ponds in the 1970's, it wasn't until the early 1990's that it became well established in some streams (Russell et al., 2012).

The Mozambique tilapia grows to 33 (females) – 44 cm (males), and is the only cichlid on the IUCN world's worst 100 invasive alien species list ("Global Invasive Species Database," 2020). The spotted tilapia, a slightly smaller species growing to 25-30 cm, is highly flexible in terms of habitat selection, and is known to inhabit brackish waters (Webb et al., 2007a). The growth of these tilapia species in both body size and population size can be rapid. For example, 12.5 ton of tilapia were removed from a pond in Cairns after it was stocked with 6-8 individuals 18 months prior (Lintermans et al., 2014). In ideal water temperatures (above 23°C for Mozambique tilapia and between 25°C and 33°C for spotted tilapia) these tilapia can reproduce year round with multiple broods each year, facilitating fast population growth of both species in river systems in northern Queensland (Webb et al., 2007b, 2007a). The reproductive strategies of tilapia are a key component of their success in establishing new populations, with mouthbrooding by Mozambique tilapia and nest building and defending by spotted tilapia ensuring their brood have a high survival rate compared to many native species (Webb et al., 2007b, 2007a).

The Mitchell River catchment and its recent tilapia incursion

The Mitchell River catchment is situated in the wet-dry tropics of northern Queensland, Australia, and covers an area of approximately 72 000 km^2 (Petheram et al., 2018). The westward flowing main channel of the Mitchell River stretches from the headwaters in the Daintree rainforest in the east to the river mouth in the Gulf of Carpentaria in the west. Major tributaries that flow into the Mitchell River include the Walsh, Lynd, Alice and Palmer rivers. Bedrock dominates headwaters in the eastern third of the catchment before elevation drops and an alluvial delta megafan spreads west from the confluence of the Mitchell and Palmer Rivers, producing a network of braided channels, creeks and wetlands on the floodplain (Batlle-Aguilar et al., 2014; Rustomji et al., 2010).

Rainfall in the Mitchell catchment is highly seasonal, with only 4 % of annual rainfall (on average) falling across the catchment during the dry season, from May to October (Petheram et al., 2018). Historical flow data shows that the main channel of the Mitchell River experiences perennial flow most years, while the Palmer and Walsh rivers experience cease to flow conditions in most years (an average of 45 and 33 zero flow days per year, respectively). With mostly unmodified flow, the Mitchell River catchment has a high diversity of fish, with 46 species recorded (including two species of tilapia), many of which move between habitats in the catchment (Jardine et al., 2017, 2012; Pusey et al., 2004). Fish movement is influenced by flow-mediated connectivity and few barriers to fish movement currently exist within the catchment (O'Mara et al., 2021). Factors affecting fish movement are important to consider when assessing tilapia dispersal potential throughout the Mitchell catchment. Existing barriers include a natural rock cascade on the Mitchell River ~32 km upstream from the confluence of the Walsh and Mitchell Rivers, and one dam in the headwaters of the Mitchell which is considered to have a hydrological impact (Southedge Dam at Lake Mitchell; Marshall, 2016). Several weirs also exist on the upper Walsh River that aid in irrigating a small area of agriculture.

The irrigated agricultural area along the upper Walsh River comprises only 0.3% of the catchment area and is dominated by sugarcane and horticulture (Watson et al., 2018). However, the Mitchell River catchment has received considerable attention for expansion of irrigated agriculture that would require new water infrastructure development (Commonwealth of Australia, 2015). Understanding the current impacts of existing water resource infrastructure in terms of habitat and water quality, and risk of pest introduction, is important for identifying risks of further water resource development in the Mitchell catchment. The Mareeba–Dimbulah Water Supply Scheme (MDWSS) irrigates crops along the upper Walsh River by supplementing water from an inter-basin transfer via an irrigation channel from the eastern draining Barron River (Webster et al., 2009). Part of the MDWSS also extends into the upper reaches of the Mitchell catchment (Lyons et al., 2018).

Tilapia were first detected in the Mitchell River catchment in 2008 in Eureka Creek (a tributary of the upper Walsh River) and were eradicated soon after discovery with rotenone poisoning (DAF, 2011a). In 2017, tilapia were sighted in the Walsh River around 85 km downstream from the Eureka Creek and Walsh River confluence (www.daf.qld.gov.au). Biosecurity Queensland surveys in 2019 caught spotted tilapia in Eureka Creek and at the Leafgold and Bruce weirs on the Walsh River. Mozambique tilapia were also found in Bruce Weir during these surveys, though in fewer numbers than spotted tilapia.

While sources for introduction into Eureka Creek and the Walsh River are unknown, the presence of one of the outlets of the MDWSS irrigation channel in Eureka Creek upstream of the incursion site has raised suspicions as to whether the tilapia originated from the Barron catchment. The Barron River, including Tinaroo dam, has substantial populations of both Mozambique and spotted tilapia, which were first detected in the Barron catchment in the 1980's and 90's (Greiner and

Gregg, 2008). Expensive fish exclusion screens were placed at the beginning of the channel in 2004 to prevent the spread of tilapia into the Mitchell catchment (https://pestsmart.org.au/case_studies/pest-fish-exclusion-screens/). Part of this study will explore the possibility of tilapia in the Mitchell catchment originating from Tinaroo Dam via the MDWSS.

Project aims and scope

Spotted and Mozambique tilapia (hereafter tilapia) have the potential to spread rapidly across northern Australia, which could have serious negative impacts on environmental, economic, social and cultural values in the region (Greiner and Gregg, 2008). To mitigate the impacts of this threat, managers and other decision-makers urgently need more information on tilapia in the Mitchell River. Thus, researchers from Griffith University have collaborated with Biosecurity Queensland, Queensland Department of Environment and Science, and the Mitchell River Traditional Custodian Advisory Group (MRTCAG) to study tilapia in the Mitchell River to address the following aims:

1. Determine current extent of tilapia in the Mitchell catchment and examine habitat preferences to identify risk areas for further colonisation
2. Determine migration patterns and timeframes for migration within established populations
3. Identify food sources that support tilapia growth and reproduction
4. Assess impacts for biodiversity and fisheries throughout the Mitchell River and northern Australia

These aims were addressed using a combination of fieldwork, laboratory analyses, and expert review. The results of each aim are presented as separate chapters in this report.

1 Current distribution and habitat preferences of tilapia in the Mitchell River catchment

The first step in managing invasive species is understanding their present distribution. This information can be used to identify areas to target for local eradication and control efforts. Understanding the habitat preferences of the invasive species helps to identify which currently uninvaded habitats may be vulnerable to invasion, and thus require protection (defensive control measures). In this chapter we report the locations tilapia were captured at during the study and identify their preferred habitat and potential vulnerable habitats elsewhere in the Mitchell catchment.

1.1 Methods

Field surveys

In 2019, Biosecurity Queensland and Tropical Water Consulting (Terry Vallance) conducted an electrofishing survey of the upper Walsh River. Tilapia caught during these field trips were measured and given to Griffith University for otolith microchemistry analysis. Environmental DNA (eDNA) surveys conducted by TropWATER James Cook University (Cecilia Villacorta-Rath) detected tilapia eDNA within the Mitchell catchment outside of the range of the study sites of the 2019 electrofishing survey. To determine if tilapia were in fact inhabiting parts of the river outside of this range, we conducted an exploratory field trip in September-October 2020 with Terry Vallance from Tropical River Consulting and members of the Mitchell River Traditional Custodian Advisory Group (MRTCAG). During this field trip we sampled sites of varying habitat type in the lower Walsh and mid-upper Mitchell sub-catchments. Since no tilapia were sighted or caught during this trip, we conducted a further field trip with Terry Vallance in June 2021 to three sites on the upper Walsh River to determine the persistence of the populations sampled in 2019 and collect tilapia specimens for stomach contents analysis (Chapter 3). While we intended to resample the sites in which tilapia were caught during the 2019 electrofishing trips (Eureka Creek, Leafgold Weir, Bruce Weir), boat access was impossible at the Eureka Creek site due to recent excavation of the riverbank by the landholder. We sampled a pool on the upstream side of the Eureka Creek and Walsh River confluence after a quick investigation of a shallower accessible section of Eureka Creek with the boat electrofisher that yielded no tilapia. After capture tilapia were euthanised and measured for standard length.

Habitat assessment

Habitat assessments were performed at each site surveyed during our 2020 and 2021 field trips, recording water physicochemistry (oxygen, temperature, conductivity), maximum depth, and habitat characteristics (recorded as percentages averaged across left bank, right bank and open water observations: mud, sand, bedrock, macrophyte, small woody debris, large woody debris, and overhanging vegetation coverage, and percentage of steep and undercut banks). Habitat assessment data from previous studies we conducted in the Mitchell catchment in 2018 and 2019 was combined with the 2020 and 2021 habitat assessment data to identify macrohabitats and sites with similar habitat characteristics to the weir sites currently invaded by tilapia. This was achieved using multivariate statistical analyses in PRIMER, including principal components analysis and SIMPER (using Euclidean distances). Before these analyses were performed variables were log (continuous measured variables) or arcsine square root (percentage variables) transformed to adjust for skewness and variables were standardized to place them on the same scale.

1.2 Results

Tilapia extent

Tilapia were not caught outside of their previously known range during 2020 and 2021 field trips (known range determined during 2017 and 2019 Biosecurity Queensland electrofishing surveys), indicating that the sites sampled by helicopter in 2017 near Rookwood on the Walsh River are the most downstream record of tilapia in the Mitchell catchment (Fig. 1 & 2). Population sizes at the downstream limits of the range are unknown due to sampling difficulty in the lower Walsh River because of limited accessibility and suitable electrofishing habitat. Within their range, tilapia populations appear to be quite condensed, with established populations in Bruce Weir and Leafgold Weir, and likely in Eureka Creek. The Bruce Weir population extends from around 400 m upstream of the weir to the lower reaches of Leadingham Creek and both Mozambique and spotted tilapia were present in this population. In 2021 we caught six Mozambique and 23 spotted tilapia in Bruce Weir, and observed five others (one Mozambique, three spotted, and one juvenile tilapia of unknown species). The Leafgold Weir population appears to be condensed in the area between the weir and 300 m upstream. During the 2021 survey of Leafgold Weir we caught one Mozambique and 12 spotted tilapia and observed another three spotted tilapia. The 2021 survey was the first to detect Mozambique tilapia in Leafgold Weir. Tilapia were not caught downstream of Leafgold Weir at the confluence of the Walsh River and Eureka Creek, and 2019 Biosecurity Queensland surveys did not catch any tilapia upstream of the Bruce Weir population. No tilapia were caught at a site further downstream on the Walsh River near Chillagoe (Fisherman's Hole), though low water in the late dry season (2020) and slippery bedrock substrate affected electrofishing efficiency. However, future monitoring of this site may be required in response to reported tilapia sightings by Chillagoe locals.

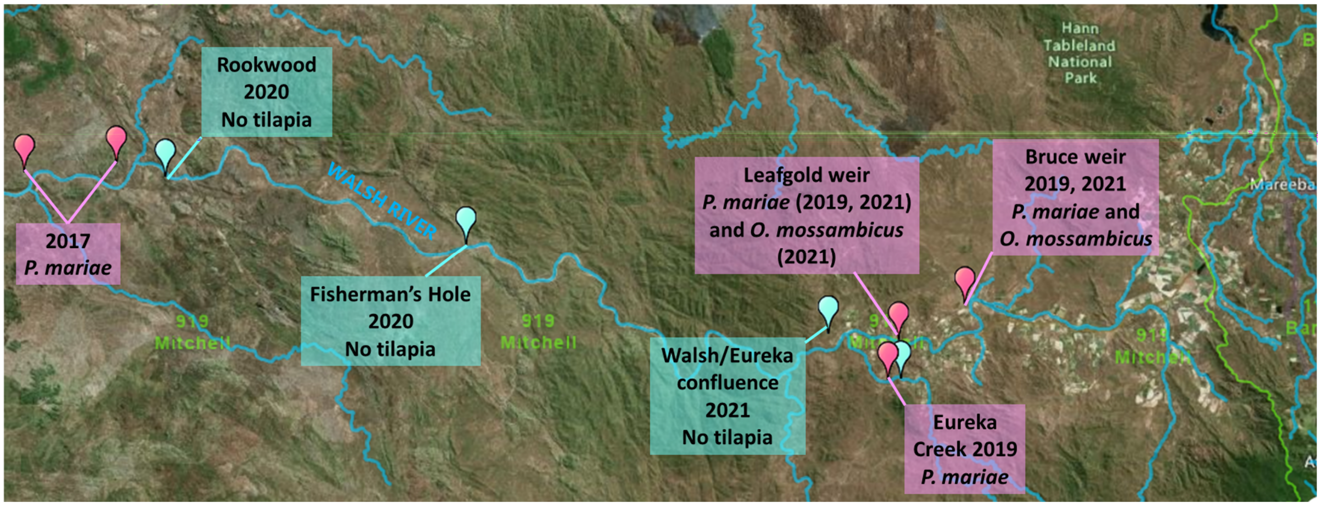


Figure 2. Walsh river electrofishing survey results from this study and known Mozambique *O. mossambicus* and spotted *P. mariae* tilapia capture locations from 2017 and 2019 Biosecurity Queensland surveys. Eureka Creek sampling in 2021 was not performed in the same location as the 2019 surveys, due to accessibility. Pink markers represent sites where tilapia have been caught, while blue markers represent sites where no tilapia were caught.

Fish lengths and weir population sizes

Increases in both tilapia numbers and sizes in Bruce and Leafgold weirs were observed between the 2019 Biosecurity Queensland survey and our 2021 survey, indicating progression of population establishment (Fig. 3). Given that spotted tilapia can reach sexual maturity at around 11-12 cm (Bradford et al., 2011, field dissections confirmed most individuals sampled in 2021 were mature at 11-12 cm and above), 91% of spotted tilapia caught in Bruce Weir and ~67% of spotted tilapia caught in Leafgold Weir were likely able to reproduce.

Bruce Weir contains the most established population of both tilapia species in the Mitchell catchment.

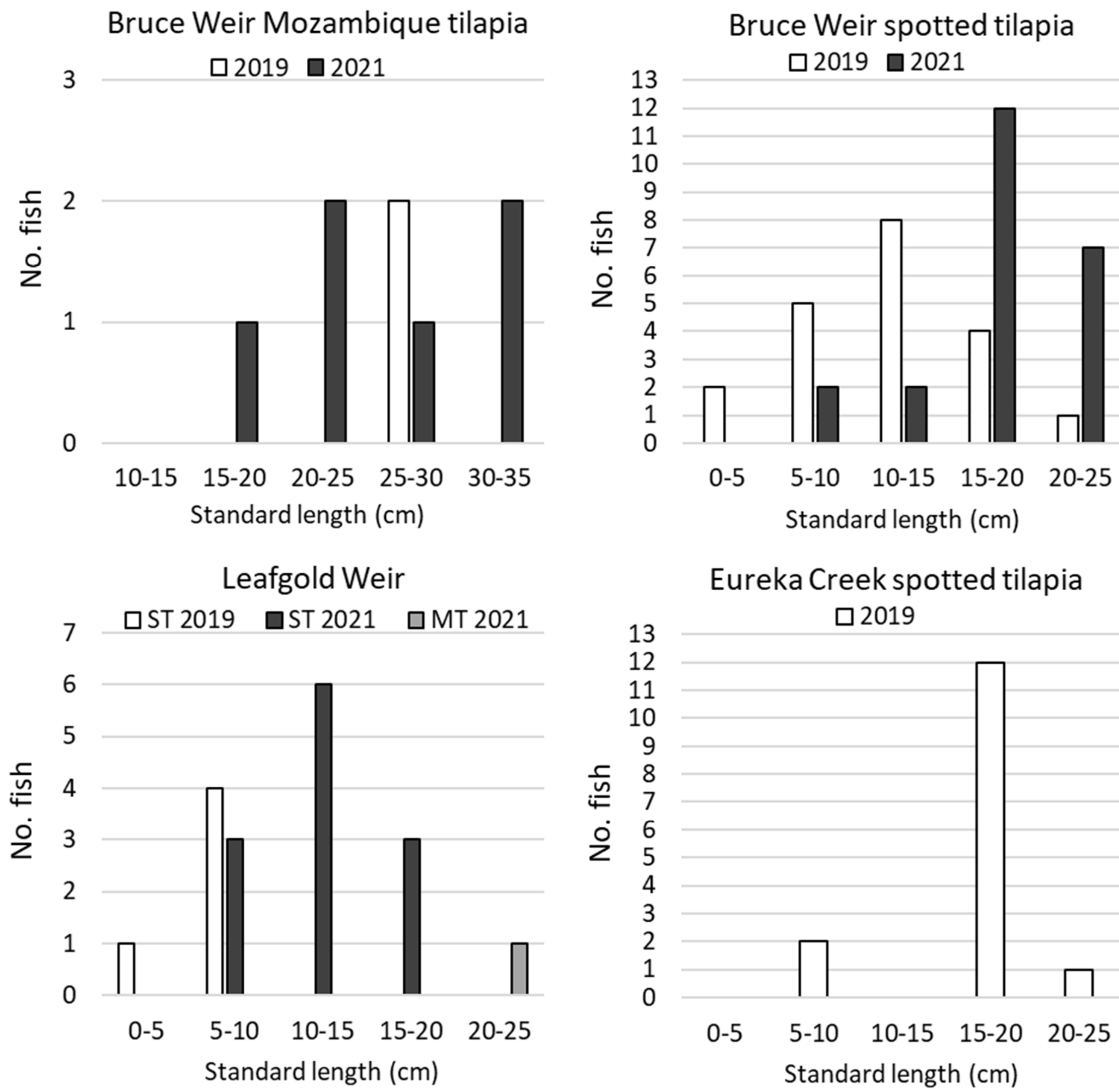


Figure 3. Lengths of tilapia caught in Bruce Weir, Leafgold Weir and Eureka Creek. ST = spotted tilapia, MT = Mozambique tilapia.

Habitat

Current tilapia populations showed clear habitat preferences to deeper areas with high macrophyte coverage. Bruce and Leafgold weirs have variable depths (0.5 - >2 m) and have submerged, emergent and floating macrophytes present in high densities, including a proliferation of Hymenachne weeds (Fig. 4). In Bruce Weir, Mozambique tilapia were mostly caught along the edges of the Hymenachne, while spotted tilapia were mostly caught in submerged macrophyte beds in open water. In Leafgold weir this habitat preference also occurred, and an additional school of smaller spotted tilapia were caught along Hymenachne in a small backwater close to the weir on the northern bank. Macrophytes are also present along Eureka Creek.

Figure 4. Bruce weir (a)(b), Kaitlyn O'Mara with a spotted tilapia in Bruce Weir (c), tilapia catch from Leafgold Weir (d), and Leafgold Weir (e)(f). Photos K.O'Mara.

Weir habitats, which appear to be favoured by tilapia in the Walsh River, were most similar to other deeper, muddy habitats with macrophytes present (Fig. 5). These characteristics were present in many creeks and wetlands down on the floodplain, and a SIMPER analysis confirmed that these sites were more similar to weir habitats than most river channel sites (SIMPER averaged squared distances (squared standard deviations): weir-wetland = 15.7, weir - floodplain creek = 15.9, weir – river channel = 24.5).

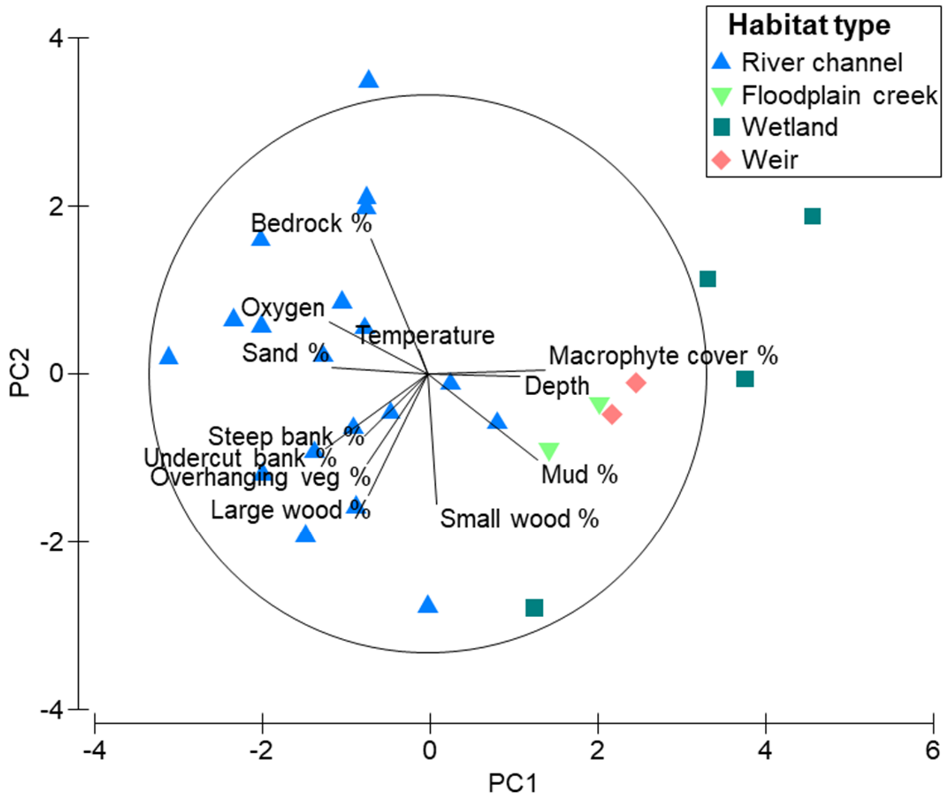


Figure 5. Principal components analysis plot of multivariate water physicochemistry and habitat characteristics across sites in the Mitchell River catchment, labelled by macrohabitat. Vector lengths show direction and contribution to separation of sites by principal components. Tilapia were caught in weir sites.

A SIMPER analysis between individual sites and weir habitats showed that some sites were more likely to provide favourable tilapia habitat than others (Fig. 6). Sites with environmental characteristics that were more similar to weir habitats are more likely to provide ideal tilapia habitat and may be at high risk of tilapia invasion if tilapia reach those areas of the catchment. Creek and wetland sites, and Rifle Creek in the headwaters of the Mitchell had the most similar habitat characteristics to weir sites. However, the strong affinity of tilapia for macrophyte beds suggests that anywhere macrophytes are present may be at higher risk of tilapia colonisation. A GIS satellite imagery assessment of locations with high densities of macrophytes in the Mitchell catchment would provide a more detailed assessment of likely invasion sites for targeted risk management strategies.

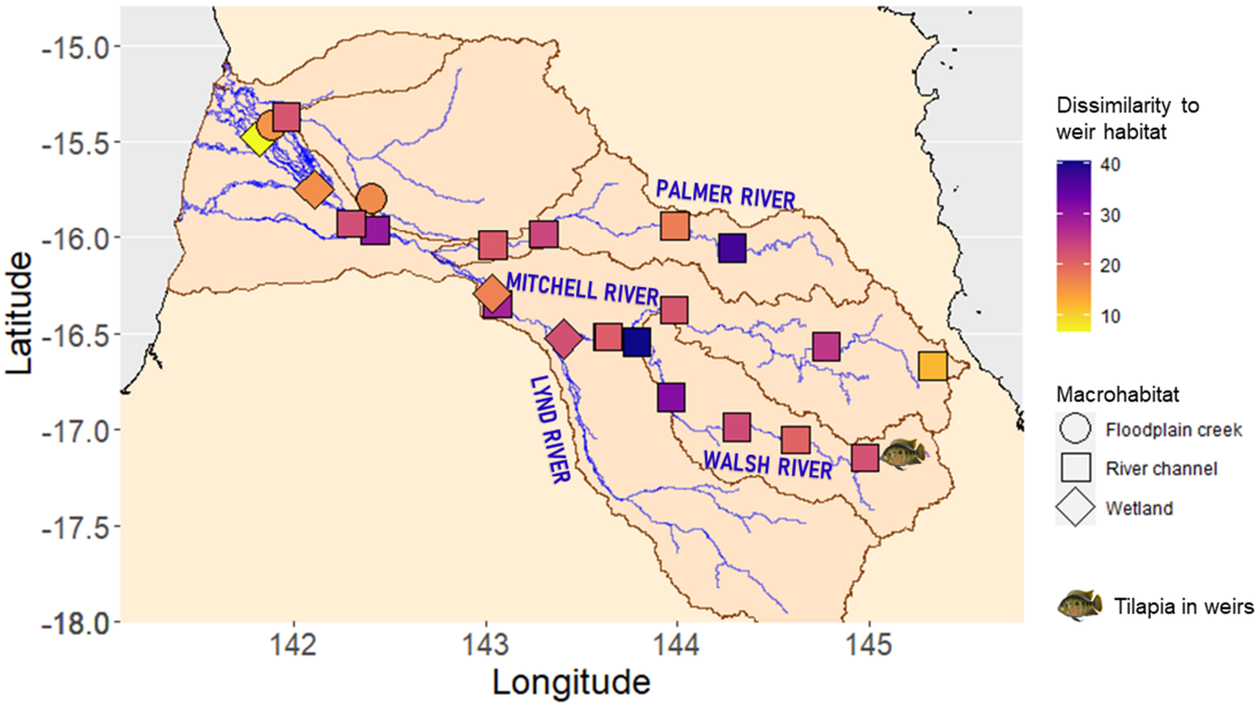


Figure 6. Map of Mitchell River catchment sites surveyed for habitat between 2017 and 2020. Symbol shape depicts macrohabitat type and colour scale shows average squared distances from weir habitats from SIMPER analysis. The distances given in the 0-40 scale are equal to the square of the number of standard deviations of each site away from weir habitat sites. Sites with lower values have habitat characteristics that are more similar to weir habitats than sites with higher values.

2 Migration patterns and timeframes within established tilapia populations

The spread of invasive species can occur via introductions by humans, flooding of illegally stocked dams, and dispersal from established populations in other water bodies. Understanding the movement patterns of an invasive population can help identify likely source locations and the potential for future spread. This information can be used to guide the location of control measures to limit the ongoing incursion and to develop an understanding of the potential rate of dispersal to new locations. In this chapter we report analyses of fish ear bones (otoliths) to understand the movement patterns of tilapia caught during the study.

2.1 Methods

Fish integrate strontium isotopes (the ratio of ^{87}Sr to ^{86}Sr) in the surrounding water into their sagittal otoliths (ear bones) and the concentric growth of otoliths ensures that results of the cross-sectional laser ablation analysis reflect the $^{87}Sr/^{86}Sr$ isotope ratios in the surrounding water from birth to death. As such, comparisons between strontium isotope ratios within the otolith and those in the waters of a catchment can be used to estimate where a fish has been throughout its life (Fig. 7). Sagittal otoliths were dissected from 42 tilapia (two Mozambique and 20 spotted tilapia from Bruce Weir, five spotted tilapia from Leafgold Weir, and 15 spotted tilapia from Eureka Creek) collected by Terry Vallance during the 2019 Biosecurity Queensland electrofishing surveys. Standard length of each fish was recorded. Following dissection, otoliths were cleaned of adhering tissue and stored to dry. One otolith from each fish was embedded in a two-part epoxy resin and sectioned transversely (320 µm section) for laser ablation analysis.

To create an isoscape for determining movement patterns of the tilapia, water samples and/or mussel shells were collected from multiple sites along the Walsh River, including multiple side creeks in the Upper Walsh catchment (Emu Creek being the most downstream Creek sampled), and from Tinaroo Dam in 2020 and 2021. Mussel shells reflect the surrounding water $^{87}Sr/^{86}Sr$ isotope ratios and record fluctuations in water $^{87}Sr/^{86}Sr$ over their lifetime. This provides a useful tool for determining the range of water $^{87}Sr/^{86}Sr$ in each region. However, mussels prefer specific habitats and may therefore be absent or difficult to find at some sites. Indigenous knowledge shared by Traditional Owners (from MRTCAG) on the 2020 field trip was critical to the collection of mussels for this project. They demonstrated how to locate mussel habitat by looking for specific features of the substrate and water flow which indicate the likely location of the animals. Using the knowledge provided by the Traditional Owners, project research assistant, Chantal Saint Ange, was able to successfully locate and collect mussels.

The mussel shell was embedded in resin and sectioned for laser ablation analysis. Water $^{87}Sr/^{86}Sr$ isotope ratios were used for sites where mussels were not found, using the water $^{87}Sr/^{86}Sr$ value as the mean, and the minimum and maximum values were assigned using the average standard deviation of mussel $^{87}Sr/^{86}Sr$ values for upper Walsh River catchment sites (excluding Eureka Creek for which the range was used because it is heavily influenced by inflowing water from the MDWSS and therefore has a skewed distribution). Sites that were sampled for water and mussel $^{87}Sr/^{86}Sr$ previously (2017,2018) matched our 2020/2021 $^{87}Sr/^{86}Sr$ water and mussel data.

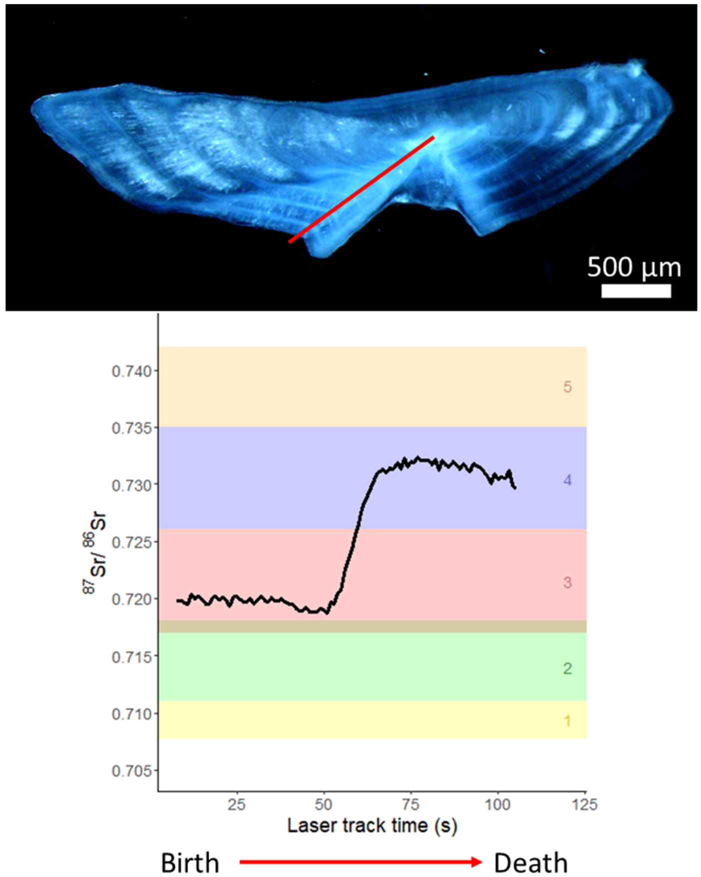


Figure 7. Conceptual illustration how likely fish movements are identified from strontium isotope ratios in an otolith. As a fish ages, it grows its otolith in concentric rings from its core. A laser scan of the otolith from core to edge (red line on top image) shows the strontium ratios from birth to death (depicted in the line plot at the bottom). These are compared with the strontium ratios from different regions to identify movement (coloured bars on plots represent separate regions). In this example, the fish was likely born in Region 3 and moved to Region 4.

Separate isoscape regions were identified using a cluster analysis of the mean and standard deviation of $^{87}Sr/^{86}Sr$ mussel/water values for each site (Fig. 8, Table 1). Density plots of the site distributions were produced and minimum and maximum values for each isoscape region were defined as the values that separated each cluster (where there was the least amount of overlap between site clusters). The spatial variation that creates an isoscape is generally linked to the underlying geology of the catchment. We visually matched the data from the laser ablation analyses to the isoscape to make predictions as to whether each fish was captured in a different location from its birth. For fish that showed evidence of movement, we assigned them to parts of the river at different points in their life based on the closest (in physical river distance) isoscape regions that their $^{87}Sr/^{86}Sr$ isotope ratios matched.

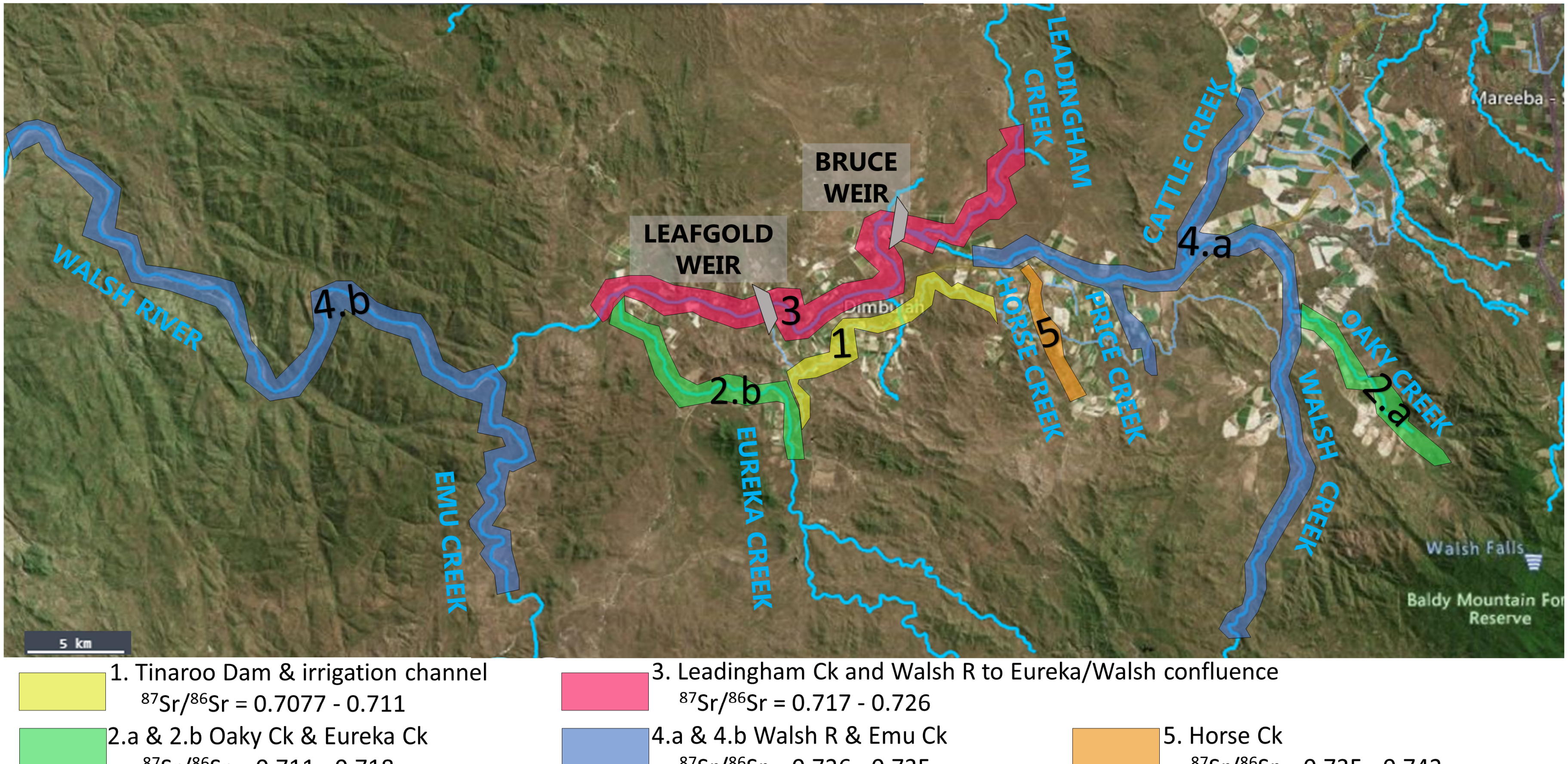


Figure 8. Strontium isoscape. Regions were defined from water and mussel shell $^{87}Sr/^{86}Sr$ distributions. Polygons that are the same colour have the same defined $^{87}Sr/^{86}Sr$ isotope range. Region boundaries are approximate and should be used as a guide only.

Table 1. $^{87}Sr/^{86}Sr$ value ranges for each isotope region of the upper Walsh River, assigned from the $^{87}Sr/^{86}Sr$ values of water and mussel shell samples collected throughout the upper Walsh catchment.

ISOTOPE REGION	$^{87}SR/^{86}SR$ RANGE
1	0.7077-0.711
2	0.711-0.718
3	0.717-0.726
4	0.726-0.735
5	0.735-0.742

2.2 Results

Unique movement and residency patterns were observed for tilapia caught in each location. Evidence for movement outside of the region of capture was found in 12 out of 22 fish caught in Bruce Weir (including both of the Mozambique tilapia), all five fish caught in Leafgold Weir, and zero out of 14 fish caught in Eureka Creek.

Table 2. Number of fish from each site born in their region of capture or elsewhere.

		BORN IN		
		Region 1 or 2 **Eureka Ck or MDWSS**	**Region 3** **Walsh River weirs/Leadingham Creek section**	**Region 4a** **upstream Walsh River**
CAUGHT IN	**Eureka Creek**	**14**	**0**	**0**
	Bruce Weir	**0**	**20**	**2**
	Leafgold Weir	**5**	**0**	**0**

The otolith $^{87}Sr/^{86}Sr$ transects of all fish caught in Eureka Creek were stable which indicated that the tilapia caught there were highly resident to Eureka Creek (Fig. 9a & A1, Table 2). Strontium isotopes of otoliths from all fish caught in Eureka Creek and one fish from Leafgold Weir matched the Tinaroo Dam Sr isotope signal (Fig. 9a & 9b). While more sampling needs to be done to capture the full Eureka Creek strontium isotope signal range, it is most likely that these fish were residing close to the MDWSS outlet in Eureka Creek (water from Tinaroo Dam/Barron River flows into Eureka Creek from this outlet). However, from this data we cannot rule out the possibility that tilapia in Eureka Creek may have come from the irrigation channel of the MDWSS.

Otolith $^{87}Sr/^{86}Sr$ isotope ratios indicated that all tilapia caught in Leafgold Weir in 2019 most likely originated from Eureka Creek.

It appeared that some individuals caught in Leafgold Weir probably moved up and down the stretch of the Walsh River below the weir near the Walsh-Eureka confluence, or moved in and out of Eureka Creek, before moving upstream past the weir wall into Leafgold Weir (Fig. A2). While the results are based on subjective interpretations of the transects and other movement histories are possible, we have identified the most likely movements based on shortest swimming distance, weir locations, and $^{87}Sr/^{86}Sr$ isotope ratios of different regions. It is unlikely the Leafgold Weir population was seeded from the more established Bruce Weir population because we would expect the $^{87}Sr/^{86}Sr$ isotope ratios of the earliest period of life to match the $^{87}Sr/^{86}Sr$ isotope ratios of tilapia caught in Bruce Weir not Eureka Creek.

Upstream movement of fish past Leafgold Weir is thought to be possible because Leafgold Weir can drown out (Mackay and Fulton-Brown, 2021). Weir drown out occurs when the downstream water level rises above the height of the weir and the weir becomes submerged (Keller, 2010). The Leafgold Weir tilapia were all juveniles and sub-adults (<13 cm) and were smaller than 87% of tilapia caught in Eureka Creek, indicating that movement is not limited to adult tilapia, and substantial movements can be made by younger tilapia. For example, a 2.3 cm spotted tilapia caught in Leafgold Weir likely swam there from Eureka Creek before being captured (Fig. 9c).

A 13 cm spotted tilapia caught in Leafgold Weir had a unique movement pattern that was unlike any other fish caught in 2019. The $^{87}Sr/^{86}Sr$ isotope ratios during the earliest period of life for this tilapia (Fig. 9b) were a strong match to the Tinaroo dam (and irrigation channel) $^{87}Sr/^{86}Sr$ and were lower than the $^{87}Sr/^{86}Sr$ isotope ratios of fish caught in Eureka Creek, whereas the remaining four Leafgold Weir tilapia had early periods matching Eureka Creek $^{87}Sr/^{86}Sr$ isotope ratios. There could be several reasons for explaining why one fish had a different $^{87}Sr/^{86}Sr$ isotope ratio in its early life to the others caught in the same location, including this individual inhabiting an area of Eureka Creek closer to the irrigation channel outlet than the others. Alternatively, it is possible that this fish was born in the Barron catchment or the MDWSS irrigation channel. There is a discrepancy in available information on required mesh sizes, with a case study on the MDWSS by the Centre for Invasive Species Solutions (DAF, 2014) stating that 0.5 mm mesh will exclude all tilapia life forms and DAF (2011b) stating that a 50 µm mesh is required, which is 10 times smaller than the mesh size on the exclusion screens used in the MDWSS. Up to date information on the effectiveness of the screens, along with studies into the population genetics of the two regions, is needed to rule out the possibility of the Barron catchment as the source population.

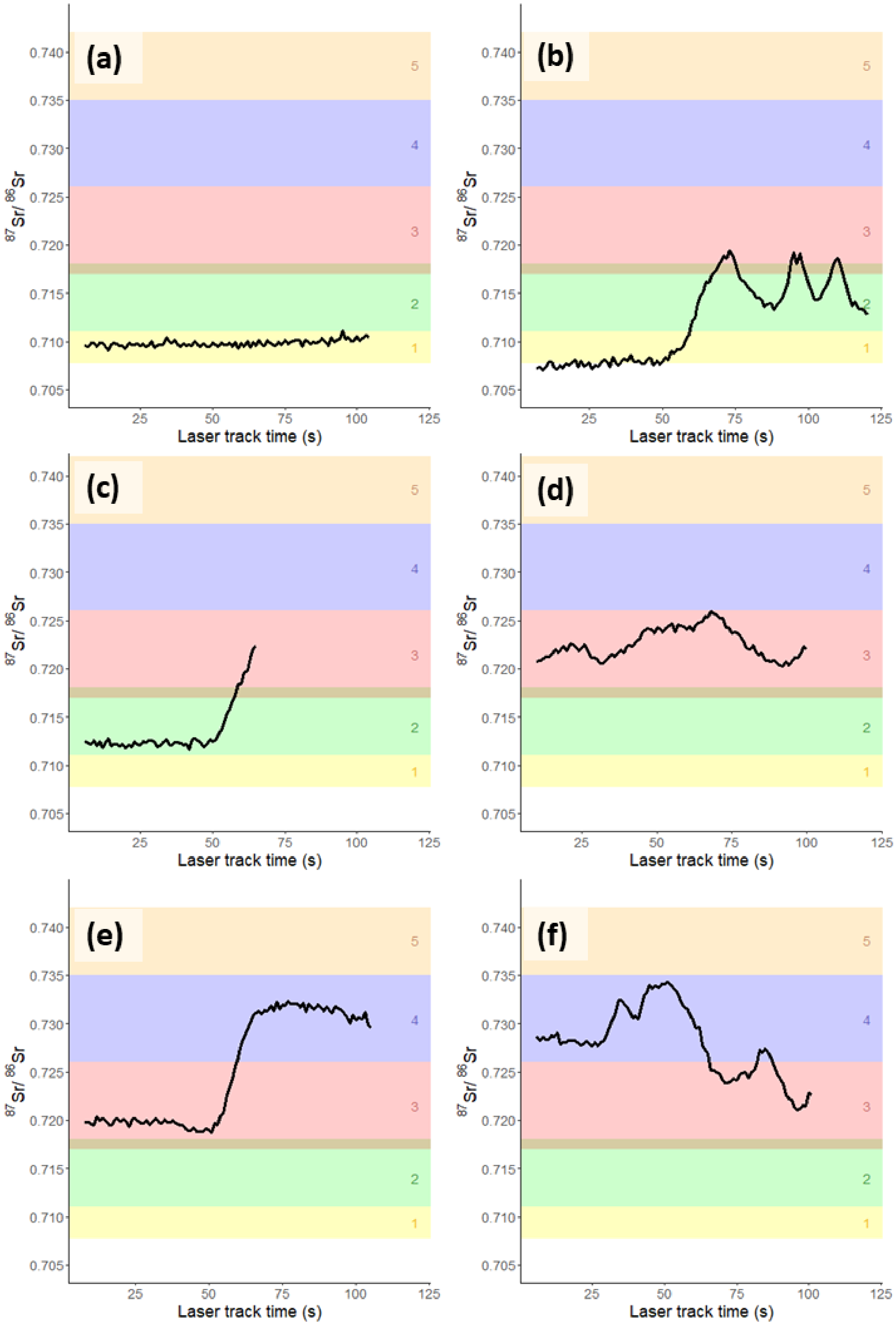


Figure 9. Example otolith laser ablation tracks for a spotted tilapia born and caught in Eureka Creek (all Eureka Creek fish had the same stable Sr isotope track pattern)(a), a 13 cm spotted tilapia born in region 1 or 2 and caught in Leafgold Weir (b), a 2.3 cm spotted tilapia most likely born in Eureka Creek and caught in Leafgold Weir (c), a 16.2 cm spotted tilapia born and caught in Bruce Weir (d), a 7.9 cm spotted tilapia born in Bruce Weir, moved upstream, and caught back in Bruce Weir (e), and a 27.5 cm Mozambique tilapia caught in Bruce Weir but born upstream (f). Strontium isotope region values are depicted by coloured and numbered bands. Some transects do not end at the corresponding region that they were captured in because the fish likely recently migrated to the site of capture and/or the data smoothing process has removed the last values of the transect.

In contrast to Leafgold Weir, fish migration upstream past Bruce Weir is unlikely because Bruce Weir is 2.5 m higher than Leafgold Weir and is unlikely to drown out (Mackay and Fulton-Brown, 2021). The otolith $^{87}Sr/^{86}Sr$ isotope ratios of fish from Bruce Weir support this, with no values matching regions 1 or 2 (Fig. A3). Instead, fish caught in Bruce Weir were either residents in Bruce Weir/Leadingham Creek their entire life or moved between this region and further up the Walsh River (Fig. 9d-9f). Both of the Mozambique tilapia caught in Bruce Weir appear to have been born further upstream in region 4a, whereas most spotted tilapia caught in Bruce Weir appear to have been born in Bruce Weir (Table 2). While three spotted tilapia had birth $^{87}Sr/^{86}Sr$ isotope ratios matching the highest values of region 2a (upstream of the weir), the birth $^{87}Sr/^{86}Sr$ values were within the full range of $^{87}Sr/^{86}Sr$ values measured in mussels from Bruce Weir and these individuals were therefore assigned Bruce Weir as their birth location. There was no clear size related (and therefore age related) movement patterns observed in the Bruce Weir spotted tilapia population. While spotted tilapia caught in Bruce Weir that showed evidence of movement were all less than 15 cm long, around half of the total number of individuals less than 15 cm long showed no evidence of movement.

Across all populations there were two additional insights into the Walsh River tilapia revealed by otolith $^{87}Sr/^{86}Sr$ isotope ratios. Firstly, the Bruce Weir and Eureka Creek populations may have resulted from separate incursion locations, since fish likely cannot swim upstream past Bruce Weir and the Eureka Creek tilapia appear to have never been elsewhere in the catchment. It is unlikely that unsampled fish swam to Eureka Creek from Bruce Weir since Eureka Creek was the original incursion site where tilapia were found in 2007. Secondly, the tilapia otolith $^{87}Sr/^{86}Sr$ isotope ratios suggest that there was no downstream movement past Emu Creek by any of the tilapia caught during the 2019 survey. Therefore, there was either no exploratory movements to downstream areas by fish from current established sites or tilapia that made exploratory movements did not return to upstream established tilapia sites. Upper Walsh tilapia populations should therefore be targeted for local population control/eradication, and monitoring of sites downstream of Eureka Creek should continue to ensure any newly established populations are quickly identified.

3 Food sources supporting tilapia growth and reproduction

A key step in predicting impacts of invasive species on native biodiversity is understanding their diet and position in the food web. Food web collapse can occur when competition for food or over exploitation of a single trophic level is exhibited by invasive species. Understanding the diet preferences of the invasive species helps to identify which resources may become depleted in invaded areas and predict how aquatic food webs may be impacted by tilapia invasion. In this chapter we report the stomach contents of tilapia captured during the study to identify the food sources supporting growth and reproduction.

3.1 Methods

Tilapia caught during the 2021 field survey were placed in an ice slurry after capture to preserve the structure and consistency of stomach contents. Stomachs were dissected in the field and placed in sample bags before being frozen and transported to Griffith University for stomach contents analysis. Stomach content analyses were performed on 39 tilapia stomachs using a microscope and petri dish. Stomachs were cut open and stomach fullness (0 (empty) - 100 (full) %) was recorded before emptying the stomach contents onto a petri dish and balance and the total contents were weighed (to the nearest 0.01 g). Stomach contents were separated with water and examined under a microscope to determine the objects present within the stomachs. Prey items were identified, and a percentage of the total contents was assigned to each item using a grid under the petri dish.

3.2 Results

Most tilapia stomachs contained food items, with only five stomachs out of 39 found to be empty (Fig. 10), suggesting fairly constant feeding occurs. Plant material was found in all stomachs that were not empty, sediment/detritus was found in most stomachs, any other very small food items were found in some stomachs (Fig. 11). However, plant material made up a much greater portion of the contents of each stomach than sediment/detritus and other food items (Fig. 12).

The stomach contents analysis clearly demonstrated that the primary prey item for tilapia from the Leafgold and Bruce weirs in the Mitchell Catchment was plant material, including macrophytes, filamentous algae, and epiphyton.

Macrophytes and filamentous algae were the dominant plant types present in tilapia stomachs, with most stomachs containing a mix of filamentous algae and macrophytes. The ratio of filamentous algae to macrophytes varied between stomachs. While several other prey items, such as atyid shrimp and fish eggs, were found in some stomachs (Fig. 11 & 13), these items were all small (most were less than 0.5 mm, with the largest items (atyid shrimp and fish eggs) less than 2 mm in size; Fig. 12), suggesting that they may have been incidentally ingested when consuming macrophytes. Sediment and detritus can accumulate in weirs as water flow is slowed and inflowing particles become trapped. It is therefore possible that sediment and detritus may have also been incidentally ingested by tilapia when consuming macrophytes.

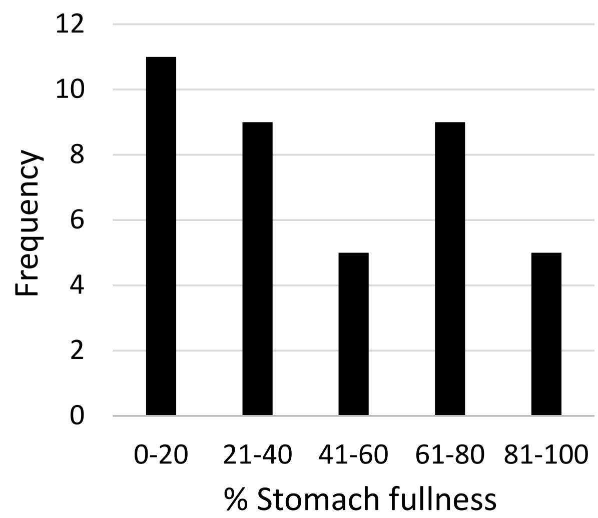


Figure 10. Stomach fullness percentage class frequency of occurrence.

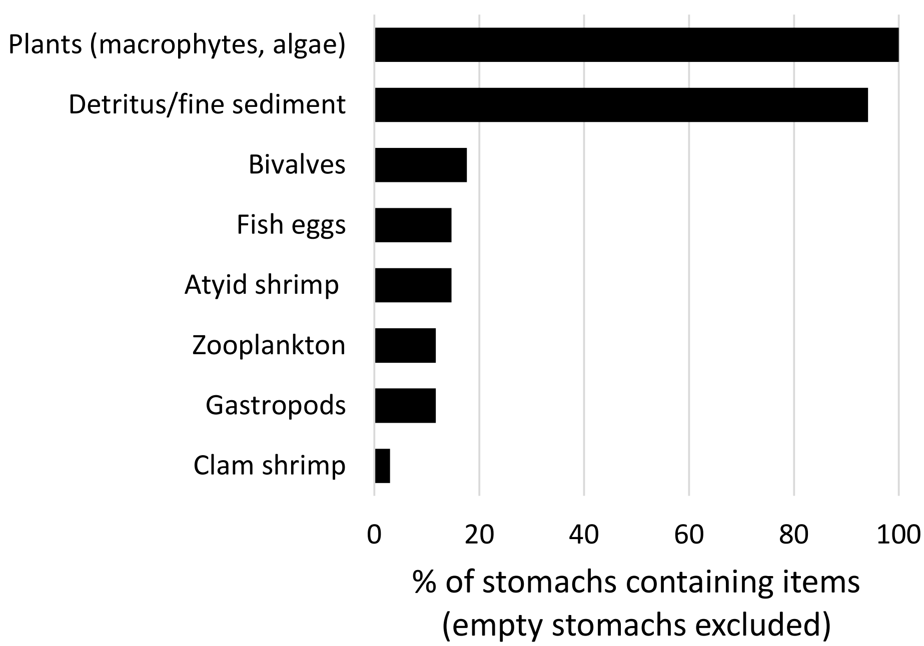


Figure 11. Prescence/absence of food items shown as the percentage of stomachs (excluding empty stomachs) in which each prey item was found.

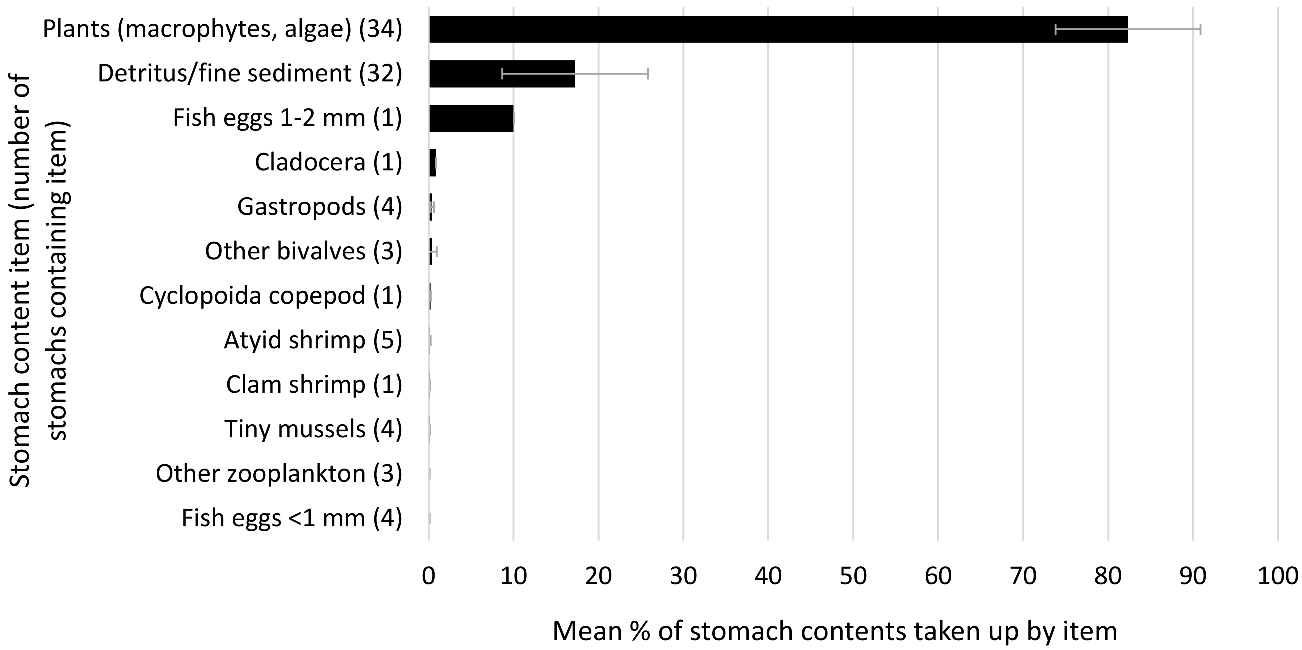


Figure 12. Mean percentage of stomach contents taken up by each stomach content item.

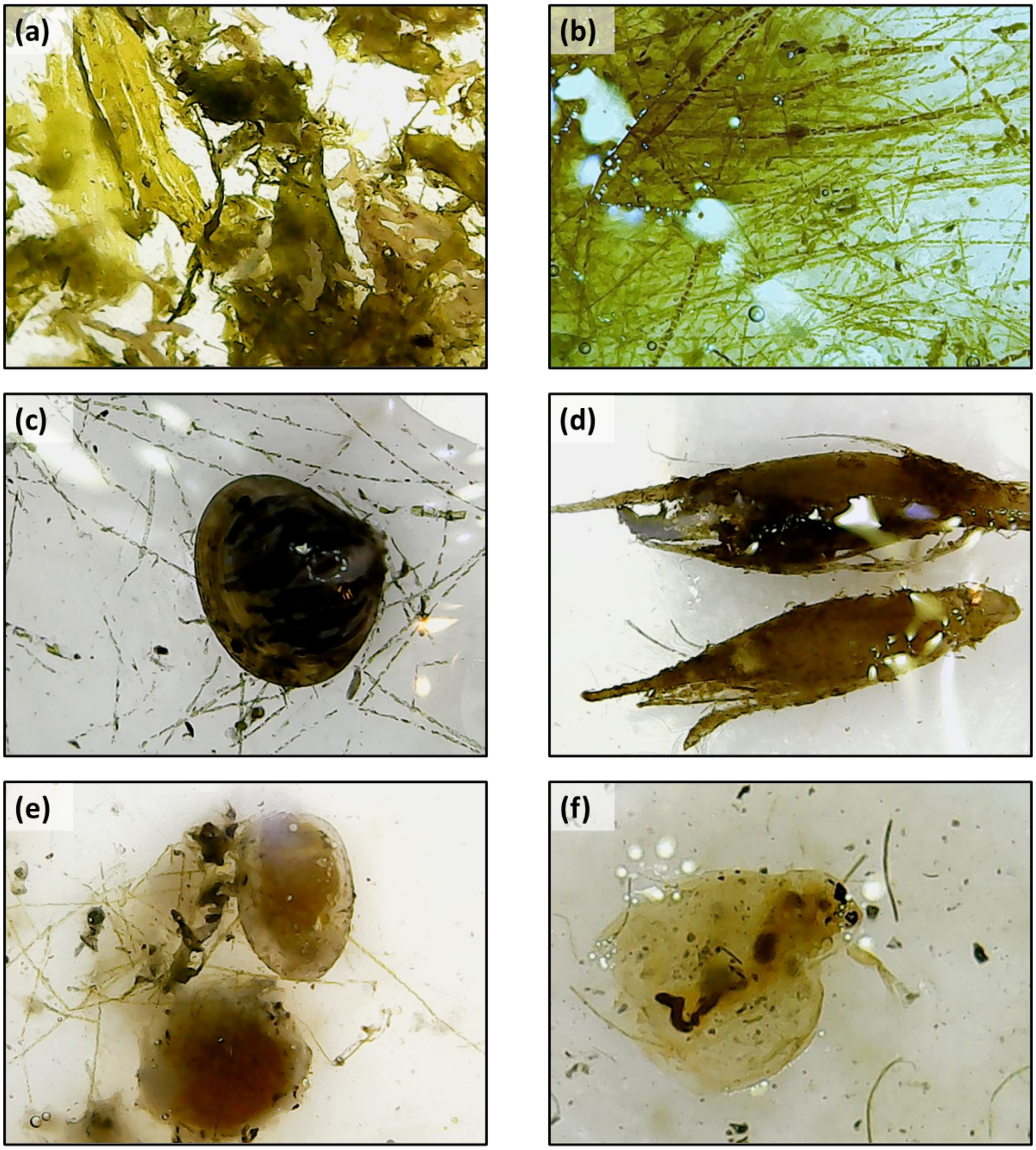


Figure 13. Microscope photos of tilapia stomach contents. (a) Aquatic plants, mostly macrophytes, (b) aquatic plants, mostly filamentous algae, (c) bivalve, (d) atyid shrimp carcasses, (e) fish eggs, (f) zooplankton, Cladocera.

4 Possible impacts of tilapia on biodiversity and fisheries throughout the Mitchell River catchment and northern Australia

This study showed that tilapia are becoming increasingly established in the Mitchell catchment. Population progression appears to be following a trend of growing populations in favourable habitats (such as the Bruce and Leafgold weirs), and occasional sightings further downstream. The increase in both numbers and size classes of spotted tilapia in the weirs indicates that the rate of population growth will increase rapidly in years to come as larger adults are expected to produce more eggs than their smaller counterparts did in previous years. While the established populations are currently restricted to the upper Walsh River, sightings further downstream in 2017 are cause for concern of spread to other areas of the catchment. The absence of deeper pools with macrophyte beds in the Walsh River below Eureka Creek may help limit the speed of population dispersal, however, this is not certain.

Off-channel creeks and wetlands were identified as high-risk areas of tilapia invasion (using a habitat similarity analysis), indicating that fast establishment of populations in creeks and wetlands on the floodplain may occur if tilapia reach the lower part of the Mitchell catchment. Tilapia are known to thrive in dam and weir environments, and rapid population growth is likely to occur when they invade new wetlands (Lintermans et al., 2014). Wetlands serve as aquatic refugia for many fish and other wildlife during the dry season and the impacts on biodiversity in these wetlands may be devastating (Waltham et al., 2014). Destructive feeding and nesting behaviour can stir up bottom sediments and may negatively affect water quality, including increasing turbidity (Greiner and Gregg, 2008). Aggressive mating behaviour is also likely to impact native fish. As numbers of tilapia increase in wetlands, native fish will be left with little space to escape aggressive attacks and the time and energy spent evading aggressive attacks may decrease their overall fitness and reproductive success (Martin et al., 2010). Lintermans et al., (2020) identified small bodied fish with isolated populations as being most at risk of imminent extinction, with one of the main causes being alien fish. Therefore, fish species that primarily inhabit wetlands, such as the rare pennyfish *Denariusa australis*, may be most at risk of local extinction in the Mitchell River and other northern Australian rivers where tilapia exist. Kroon et al., (2011) reported that the presence of tilapia and two other invasive fish species reduced the abundance of five native fish species, including three endemic species, in another catchment in northern Australia. While current tilapia populations in the Mitchell catchment have shown strong habitat affinity, spotted tilapia are known to be highly adaptable to different environments, including brackish mangrove habitats (Webb et al., 2007a). Therefore, habitats found to be lower risk in our habitat similarity assessment, such as those along the lower Walsh River, may still become invasion sites for tilapia and should be monitored.

If tilapia spread around the Mitchell catchment and establish additional populations the upstream reach of the Mitchell River may become an important refuge for local native species that are vulnerable to tilapia invasion. The Mitchell Falls, a natural rock barrier ~32 km upstream of the Walsh Mitchell confluence is likely to prevent upstream migration of tilapia. Ensuring tilapia are not transferred to this reach is therefore important for maintaining biodiversity in the Mitchell catchment, where the severity of possible impacts upon tilapia population expansion is largely unknown. The headwaters of the Mitchell River were also environmentally similar to weir habitats, though our study sites in the Mitchell headwaters contained fewer macrophytes. The preference of tilapia in the Walsh River for habitats with abundant macrophytes is closely linked to their feeding behaviour.

Tilapia are known to be highly herbivorous, with grinding teeth and long digestive tracts that aid in the breakdown of macrophytes and other plant material (Bradford et al., 2011). Occupying a low trophic level, tilapia in the Mitchell catchment are primary consumers, feeding on mostly macrophytes, filamentous algae and detritus. These stomach contents were found in similar proportions to those measured in tilapia in another northern Australian catchment, the Mulgrave River (Rayner et al., 2009). Fish feeding at lower trophic levels are known to have higher invasion success because there are more resources available at the bottom of the food web (Gido and Franssen, 2007). Direct competition for resources is unlikely to be a problem for most native fish species in the Mitchell catchment, with few herbivorous native species present. The success of tilapia invasion at various locations throughout the catchment is likely to be influenced by the availability of basal food sources, and the number of herbivorous, omnivorous and piscivorous species present, which can change with connectivity (Baiser et al., 2010). Food webs may be most impacted by tilapia presence through changes in macroinvertebrates and epiphytic algae. Macroinvertebrates are a major source of energy and polyunsaturated fatty acids for native fish in the Mitchell catchment (O'Mara et al., *In review*) and changes to the abundance and trophic relationships of macroinvertebrates could have severe effects on Mitchell River food webs. Macrophytes house high densities of macroinvertebrates and epiphytic algal species, and macrophyte rich wetlands are the main source of primary production in the Mitchell catchment (Molinari et al., 2021; Thomaz et al., 2008). A reduction in macrophyte coverage via consumption by tilapia could therefore impact the productivity of the system and may cause a shift in the diet of omnivorous fish from a mix of plant and animal sources to a primarily animal diet (David et al., 2017). Understanding the trophic interactions of tilapia is important for informing targeted control strategies. In a review on the impacts of invasive species on food webs, David et al., (2017) suggested that invasion management strategies based on bottom-up control should mainly be used to control invasive species at lower trophic levels.

While this study revealed important findings on the biology, ecology and movement patterns of a newly established tilapia population and identified high priority areas for monitoring and management, there is still much to be learnt on the ecological impacts of tilapia on biodiversity in rivers in northern Australia. Further south, the impacts of invasive carp on native fish biomass and food webs has received more research attention (Kopf et al., 2019; Marshall et al., 2019). Kopf et al. (2019) found that both carp biomass and flow alterations affected native fish biomass in the Murray-Darling Basin, with higher carp biomass and reduced flows significantly reducing native fish biodiversity. With no current figures on the scale of impacts relating to biomass of tilapia, the effectiveness of tilapia population control strategies cannot be assessed. Further, it is unclear exactly what the impacts of tilapia presence are, highlighting a major gap in knowledge that is needed to inform tilapia management strategies. Understanding movement patterns, interactions with other species, and feeding habits is crucial for effectively controlling or eradicating populations of invasive fish in Australian rivers (Kopf et al., 2019; Marshall et al., 2019; Taylor et al., 2012).

Conclusions and recommendations

We studied the biology, ecology, and movement patterns of newly established tilapia populations in the Mitchell catchment, with the following key findings:

- Tilapia were not found outside of their known populations (Bruce Weir, Leafgold Weir, Eureka Creek).
- Two weirs were sampled for tilapia in 2019 and 2021 and spotted tilapia increased in both size and numbers in both weirs between sampling years.
- One Mozambique tilapia was caught in Leafgold Weir in 2021. This was the first detection of this species downstream of Bruce Weir.
- Tilapia populations in the Mitchell catchment show strong habitat preferences to areas with deeper (>1 m) pools and abundant macrophytes.
- A habitat similarity analysis showed that creek and wetland habitats were most similar to favoured tilapia habitats and may be at risk of future invasion if current populations spread throughout the catchment.
- Both species showed evidence of movement.
- Movement patterns varied between the three tilapia populations, with the Eureka Creek population found to be highly resident.
- Age did not appear to influence movement of tilapia, with some juveniles and some adults from Bruce Weir showing evidence for movement during their lifetime.
- All spotted tilapia caught in Leafgold Weir in 2019 showed evidence of movement from elsewhere, most likely originating from Eureka Creek.
- Both Mozambique and spotted tilapia consume predominately plant material as their diet.

After reviewing these findings, we make the following recommendations:

- Review the fish screens between Tinaroo Dam and outlets into the Walsh subcatchment and conduct population genetics analyses on tilapia in the Walsh River, Barron River/Tinaroo Dam, and other possible source populations.
- Implement control programs for the three currently established populations (Bruce Weir, Leafgold Weir, Eureka Creek), particularly Bruce Weir which has the most established populations of both Mozambique and spotted tilapia.
- Monitor downstream reaches of the Walsh River, as well as wetlands and creeks on the floodplain and if possible, implement strategies that help to control the spread of tilapia.
- Install widespread signage and implement an education program to develop community support for tilapia control and encourage fishers to remove any individuals they catch.

Appendix A Strontium isotope laser ablation plots for individual fish

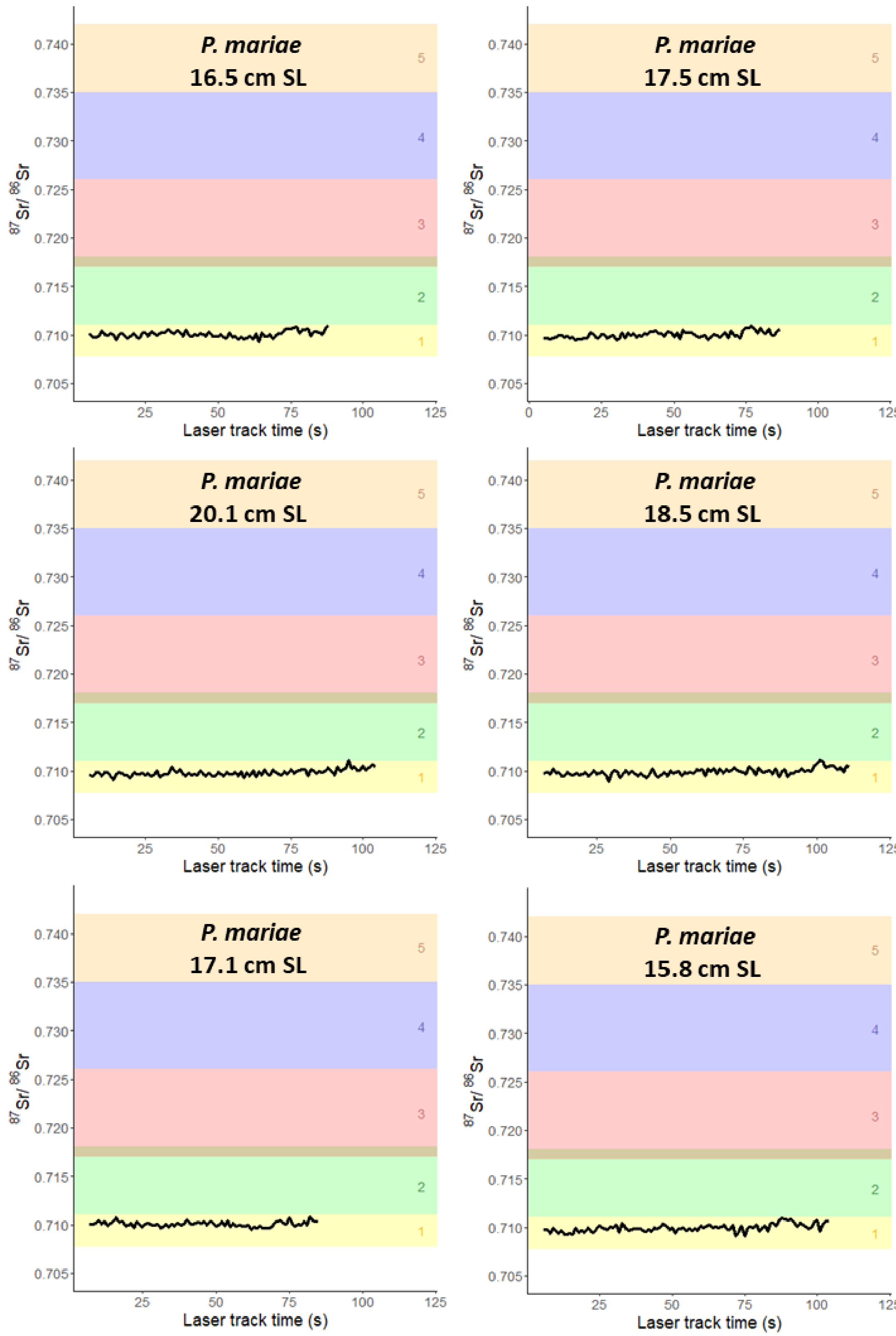
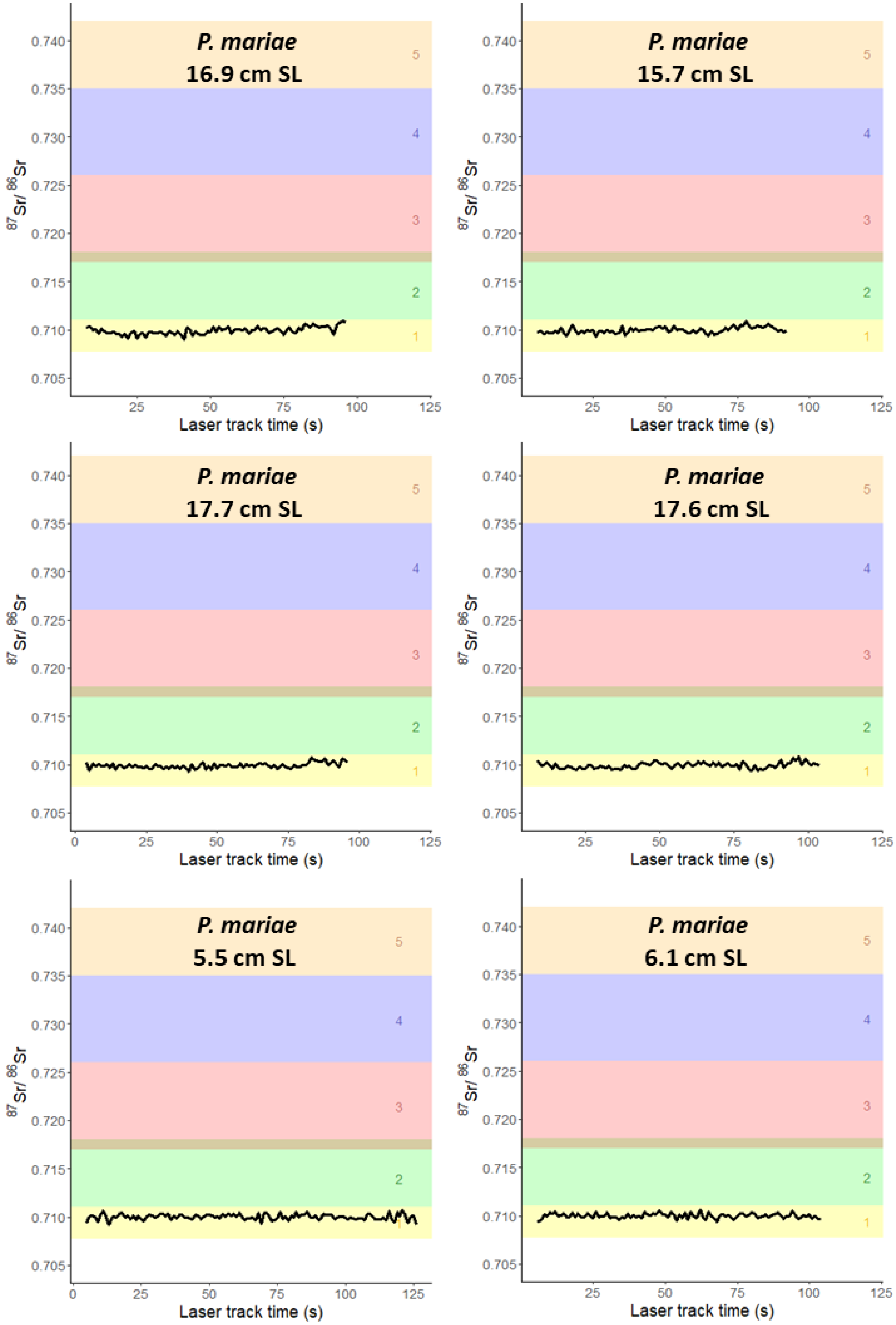


Figure A1. $^{87}Sr/^{86}Sr$ **isotope ratio laser ablation transects of tilapia collected from Eureka Creek in 2019. Coloured bars represent different regions (described in Fig. 7).**



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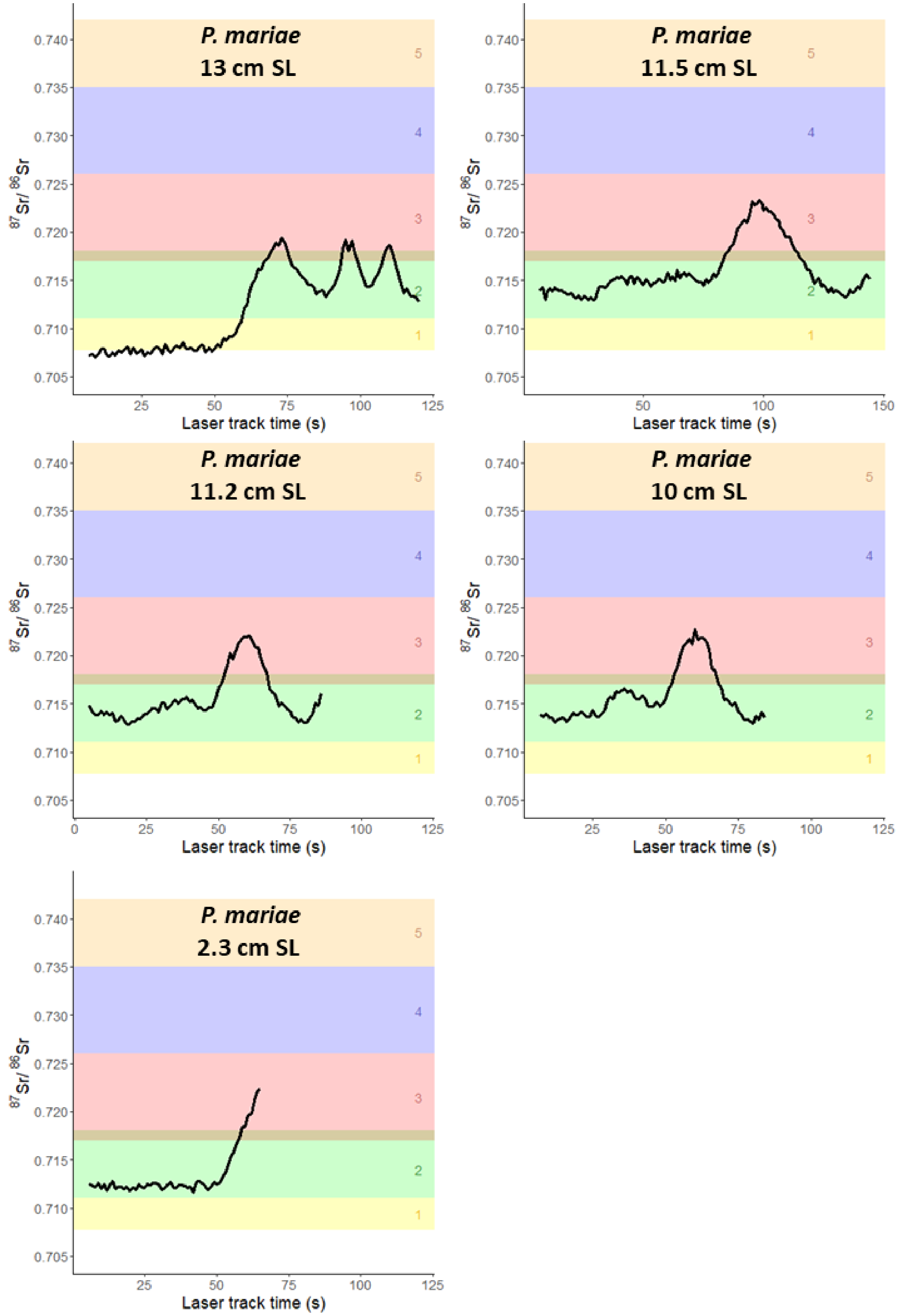


Figure A2. $^{87}Sr/^{86}Sr$ **isotope ratio laser ablation transects of tilapia collected from Leafgold Weir in 2019. Coloured bars represent different regions (described in Fig. 7).**

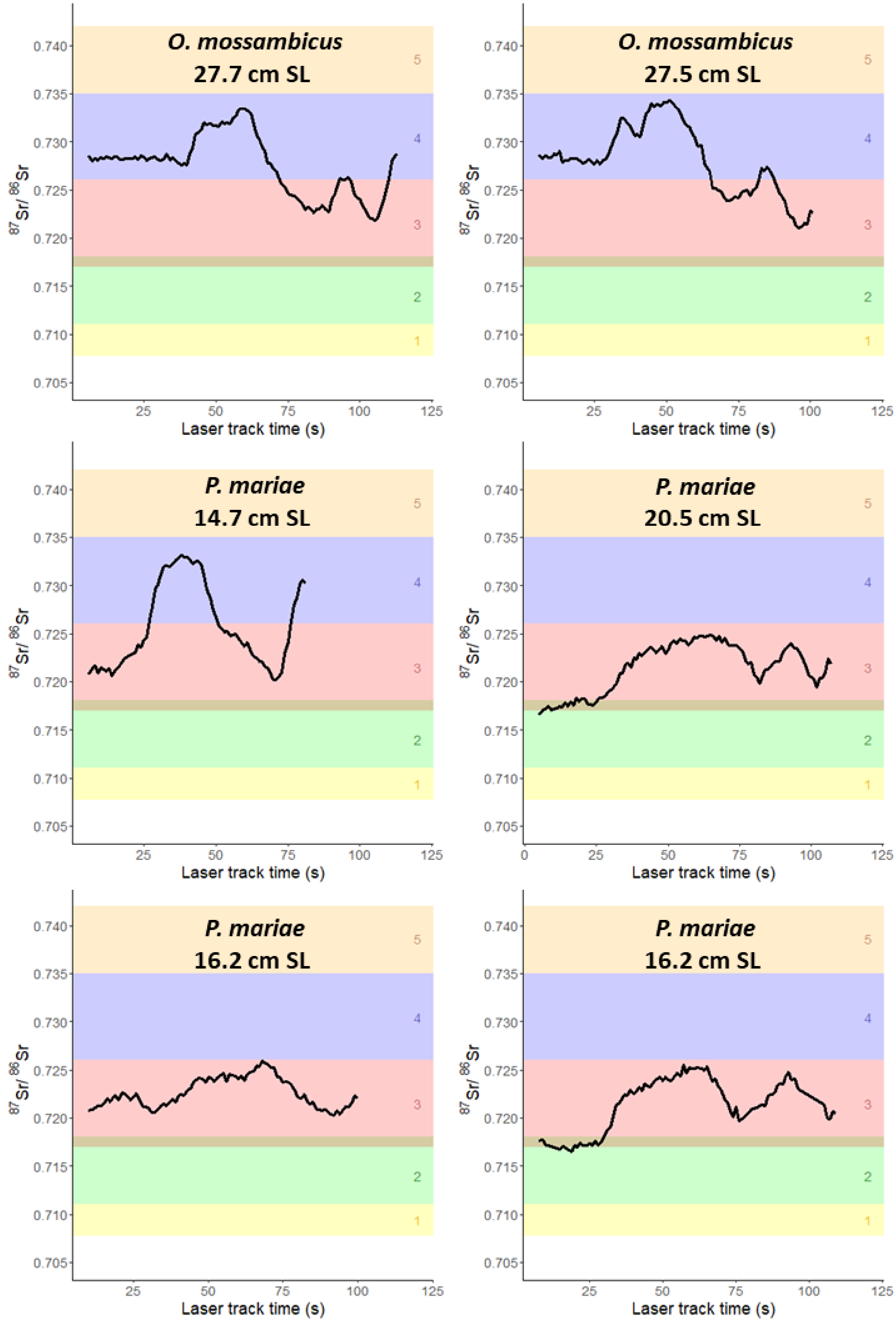
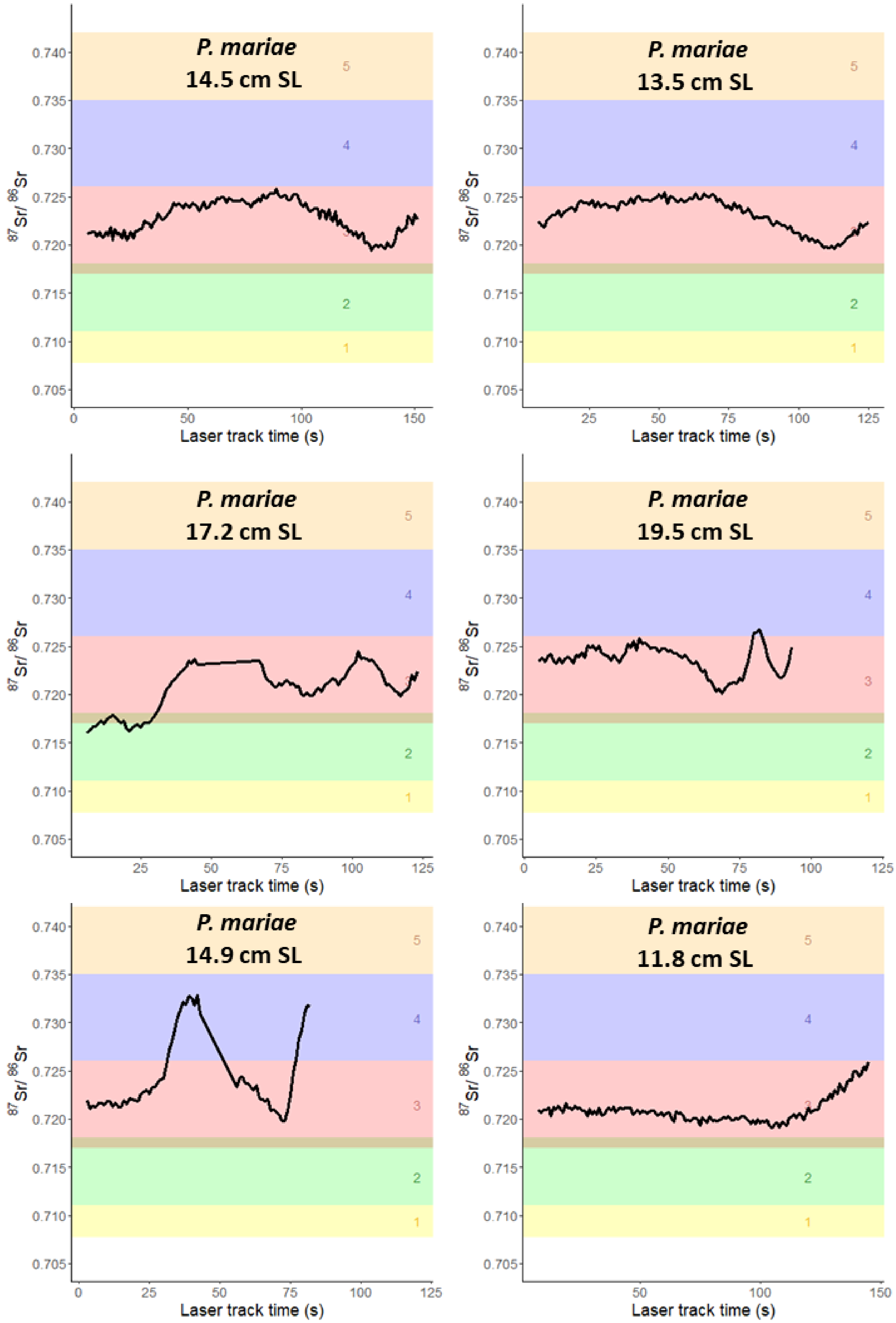


Figure A3. $^{87}Sr/^{86}Sr$ isotope ratio laser ablation transects of tilapia collected from Bruce Weir in 2019. Coloured bars represent different regions (described in Fig. 7).



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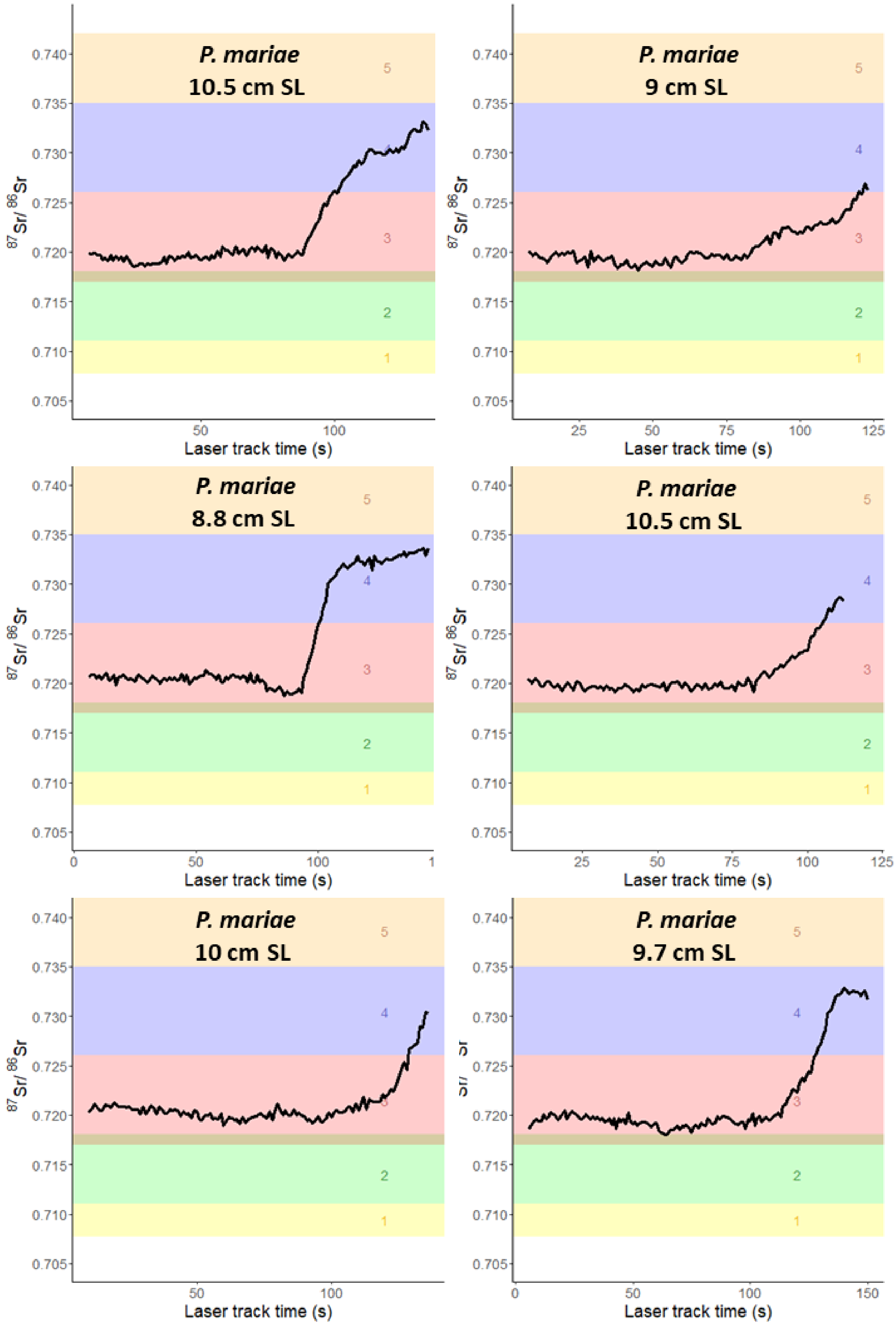

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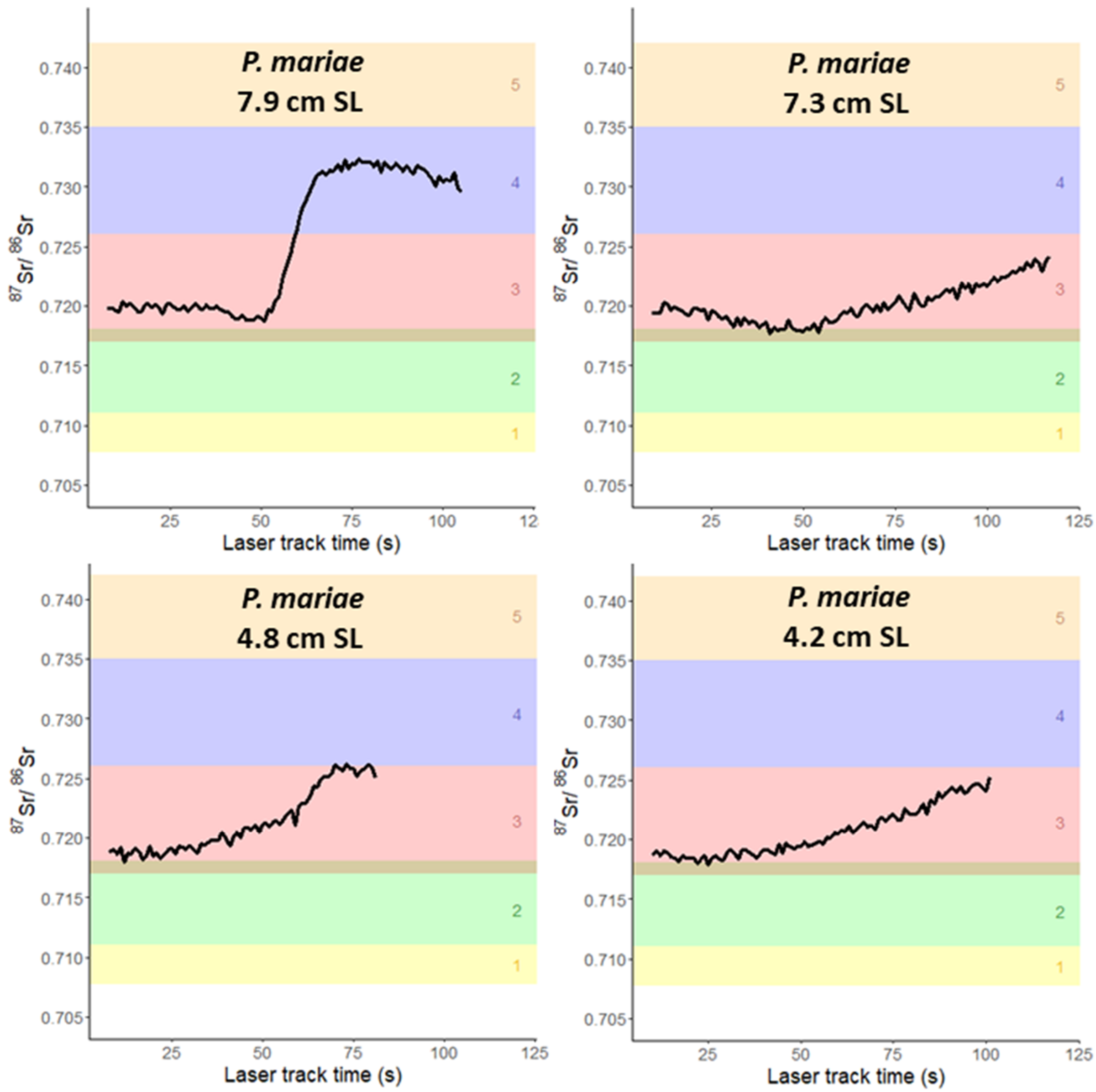

Figure A3 continued.

Appendix B References and further information

B.1 Supporting documents and materials

The study design and results presented in this report are supported by technical reports of previous surveys (electrofishing and eDNA) conducted by key partners.

Reports and Summaries	Notes
Vallance, T. (2017) Tilapia Delimitation Survey, Walsh River 07 November 2017. Tropical River Consulting.	2017 lower Walsh River helicopter electrofishing survey report
Edmunds, R.C., Cooper, M., Huerlimann, R., Robson, H., and Burrows, D. (2019). Environmental DNA survey of Eureka Creek, Upper Mitchell, and Walsh River for invasive *Oreochromis mossambicus* and *Tilapia mariae* (November 2017). Report 19/06, Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER), James Cook University, Townsville.	eDNA survey report

B.2 Figures and tables in this report

Figures in this report

Tables in this report

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B.4 Glossary of key terms

TERM	DEFINITION
Drown out	Refers to weir water levels. Drown out occurs when the downstream water level rises above the height of the weir and the weir becomes submerged.
Eradication	Complete removal of tilapia from a water body that is not directly connected to another water body with established tilapia populations.
Electrofishing	Electrofishing is a fishing technique that uses direct current electricity flowing between a submerged cathode and anode. This affects the movements of nearby fish so that they swim toward the anode, where they can be caught or stunned.
Epiphyton	Biofilm (periphyton) growing on other plants.
Filamentous algae	Algae cells that form long visible chains, threads, or filaments, which intertwine and form a mat, generally growing near shore and sometimes growing on the bottom or on rooted aquatic plants.
Floodplain	An area of low-lying ground adjacent to a river, formed mainly of river sediments and subject to flooding.
Irrigation channel	An open 176 km gravity-fed channel that takes water from Tinaroo Dam through Mareeba, Walkamin, East Barron, Mutchilba and Dimbulah, with another 189 km of subsidiary channels and pipelines. At capacity, the main channel carries 1710 ML a day, supplying about 225,000 ML to irrigators annually.
Isoscape	A map of defined regions of a particular isotope.
Region	A stretch of river with similar water isotope values.
Laser ablation	LA-ICP-MS (Laser Ablation Inductively Coupled Plasma Mass Spectrometry) is an elemental and isotopic analysis technique performed directly on solid samples. It begins with a laser beam focused on the sample surface to generate fine particles. The ablated particles are then transported to the secondary excitation source of the ICP-MS instrument for digestion and ionization of the sampled mass. The excited ions in the plasma torch are subsequently introduced to a mass spectrometer detector for both elemental and isotopic analysis.
Macrophytes	Aquatic plants that grow in or near water and are either emergent, submergent, or floating.

TERM	DEFINITION
PRIMER	Plymouth Routines In Multivariate Ecological Research is a statistical package that is a collection of specialist univariate, multivariate, and graphical routines for analysing species sampling data for community ecology.
Sagittal otoliths	Sagittal otoliths are primary hearing structures in the inner ear of all teleost (bony) fishes and are normally composed of aragonite.
SIMPER	The similarity percentages routine analysis in PRIMER software. Used to identify variables that contribute most to the difference between two groups. Euclidean distance can be applied for environmental variables.

B.5 Acronyms

CPUE	Catch Per Unit Effort
eDNA	Environmental DNA
GIS	Geographic Information System
MDWSS	Mareeba Dimbulah Water Supply Scheme
MRTCAG	Mitchell River Traditional Custodian Advisory Group
PRIMER	Plymouth Routines In Multivariate Ecological Research
SIMPER	Similarity Percentages
SL	Standard length
Sr	Strontium

B.6 Research users

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