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First evidence of spawning migration by goldfish (*Carassius auratus*); implications for control of a globally invasive species

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Abstract

Goldfish (*Carassius auratus*) was one of the first fishes to be domesticated and has been widely introduced across the globe, but is now considered one of the world's worst invasive aquatic species. Surprisingly, there is a dearth of information on its spatial and temporal movement patterns, which hampers the development of effective control programmes. We examined the movement patterns of an introduced population of *C. auratus* in a south-western Australian river using passive acoustic telemetry. The study population had a high residency index within the array (i.e. proportion of all days at liberty that, on average, each fish was detected by a receiver) with fish being detected on 64% of days. The individuals were also reasonably mobile, travelling a mean of 0.30 km (linear river kilometres).day^{-1} within the array, and one fish moved 231.3 km over the 365-day study period (including 5.4 km in a 24 hr period). Importantly, *C. auratus* displayed significant seasonal movement patterns including a clear shift in habitats during its breeding period with most mature individuals being detected in an off-channel wetland during that time. The results of this study strongly suggest that *C. auratus* undertook a spawning migration into a lentic habitat. These results have important implications for developing control programmes for the species, such as targeting connections to off-channel lentic systems during its breeding period.

1 Introduction

Invasive freshwater fishes, defined as alien species that have been introduced and established self-sustaining populations that have spread into new regions, can have fundamental ecological impacts on receiving ecosystems and are a major driver of the decline of aquatic fauna globally (Cucherousset & Olden, 2011; Helfman, 2007). The global rate of alien freshwater fish introductions has increased markedly over the past three decades (Gozlan, 2008; Gozlan, Britton, Cowx, & Copp, 2010) and, like introductions more generally (Myers, Simberloff, Kuris, & Carey, 2000), once they become established, their eradication is often difficult (Britton, Gozlan, & Copp, 2011). Understanding the ecology of alien freshwater fishes is paramount for not only assessing and predicting impacts, but also for developing effective control programmes. As specific stages of the life cycles of freshwater fishes often involve migration between habitats (e.g. for spawning or seeking refuge), understanding the spatial and temporal patterns of movement is a key component of understanding their ecology (Lucas, Baras, Thom, Duncan, & Slavík, 2001; Magoulick & Kobza, 2003; Northcote, 1978). By extension, knowledge of the movement patterns of alien fishes underpins the adoption of risk-based management, which is the most effective approach to managing invasions of alien species (Britton et al., 2011; Copp, Garthwaite, & Gozlan, 2005).

Rivers in Mediterranean climates have been particularly impacted by alien freshwater fishes, with at least 76 species having been introduced into these regions of the world (Marr et al., 2010). South-western Australia is no exception to this trend, with a considerable increase (~63%) in the number of invasive fishes being recorded since the 1970s. Invasive fishes now outnumber the native species found in this region (Beatty & Morgan, 2013). The majority of recent introductions into the region have been of ornamental fishes, and most are climatically mismatched, as they originate from tropical or subtropical regions (Beatty & Morgan, 2013). The increasing water temperatures and reduced flows that are projected for south-western Australian rivers as a result of climate change (Silberstein et al., 2012; Suppiah et al., 2007) are predicted to benefit the many alien fishes, at the likely detriment of native fishes (Beatty & Morgan, 2013).

Indigenous to eastern Asia, the Goldfish (*Carassius auratus* [Linnaeus 1758]) is one such climatically mismatched species now established in numerous rivers in south-western Australia (Morgan & Beatty, 2007; Morgan, Gill, Maddern, & Beatty, 2004). The species is one of the oldest domesticated (Balon, 2004) and most widely introduced freshwater fishes globally (Global Invasive Species Database 2005). *Carassius auratus* was first introduced into Australia in the late 19th century and is now found in almost every state and territory (Britton et al., 2011; Harris, 2013; Koehn, 2004; Morgan et al., 2004). Once introduced, it can rapidly establish and become a dominant species, particularly in still or slow-flowing waterbodies (Lorenzoni, Dolciami, Ghetti, Pedicillo, & Carosi, 2010; Lorenzoni, Ghetti, Pedicillo, & Carosi, 2010; Morgan & Beatty, 2007). While the assessment of its ecological impact is broadly lacking (Corfield et al., 2008), it is a benthic omnivore, and as its feeding activity disrupts the sediment, it can potentially impact aquatic macrophytes, water quality (such as turbidity and the resuspension of nutrients), and may reactivate cyanobacteria through its gut processes (Copp, Tarkan, Godard, Edmonds, & Wesley, 2010; Corfield et al., 2008; Kolmakov & Gladyshev, 2003; Richardson, Whoriskey, & Roy, 1995). It is also known to be a vector for the introduction of parasites and diseases (Corfield et al., 2008; Lymbery, Morine, Kanani, Beatty, & Morgan, 2014; Trust, Khouri, Austen, & Ashburner, 1980).

A population of *C. auratus* has existed in the lower Vasse River, south-western Australia (Fig. 1), for at least the past two decades. This population has the fastest known individual growth rate of this species in the world, with individuals reaching 180 mm total length (TL) at 1 year of age and obtaining a maximum size of ~400 mm TL and weight of ~2 kg (Morgan & Beatty, 2007; Tarkan, Cucherousset, Zieba, Godard, & Copp, 2010). The high growth rate of *C. auratus* in the lower Vasse

River has been attributed to two main factors. The system is highly eutrophic caused by agricultural and urban nutrient inputs (Department of Water 2010) that likely elevates autochthonous productivity and food availability to the species. Moreover, it experiences elevated water temperatures during summer and autumn (up to 30°C) due to the relatively shallow, stagnant habitat of the Vasse River that may also facilitate a faster growth rate (Morgan & Beatty, 2007). The Vasse River population of *C. auratus* has been subjected to an ongoing control programme since 2003; however, no notable decrease in population size had been detected (Beatty et al., 2014).

While there has been much research into the ecology and movement patterns of the ecologically damaging *Cyprinus carpio* Linnaeus 1758 (e.g. Daniel, Hicks, Ling, & David, 2009; Jones & Stuart, 2007; Koehn, 2004; Stuart & Jones, 2006a,b) and a single study into the movement of an introduced population of its congener, *Carassius gibelio* (Bloch 1782) (Slavík & Bartoš, 2004), surprisingly, no published information exists on the annual migration strategy of *C. auratus*. This gap in fundamental ecological knowledge greatly hampers the ability to design and implement effective control and eradication programmes for the species. This study therefore aimed to determine the spatial and temporal patterns of movement of an invasive *C. auratus* population. Given the distribution of *C. auratus* has been quite variable among seasons during past control programmes in the Vasse River (Morgan & Beatty, 2007), it is hypothesised that the species would undergo seasonal migration and elucidating this may enable a more effective control programme to be implemented.

2 Materials and methods

2.1 Study site

The lower Vasse River, in south-western Western Australia (Fig. 1), is a regulated river due to the presence of a drain system that diverts the majority of the annual river flow away from the lower riverine reaches and straight to the ocean (Department of Water 2010). This study examined the movement patterns of *C. auratus* in a ~5.6 river kilometre (rkm) section of the lower Vasse River (i.e.

downstream of the diversion drain, Fig. 1) as it was known to contain a self-maintaining population of the species (Morgan & Beatty, 2007).

2.2 Acoustic array and range testing

Acoustic telemetry is effective in determining the fine and broadscale spatial and temporal movement patterns of freshwater fishes, including alien species (Daniel, Hicks, Ling, & David, 2011; Daniel et al., 2009; Honda, Arai, Kobayashi, Tsuda, & Miyashita, 2012; Jellyman, 2009). Therefore, this study employed this technology to determine the movement patterns of mature *C. auratus*. Eight VR2W (VEMCO) acoustic receivers were deployed within the study site. Receivers were attached to 25-mm-diameter nylon rope and either tied to existing infrastructure (e.g. a bridge or jetty) or suspended below a 200-mm-diameter solid styrene float anchored to the riverbed with a 4.5 kg galvanised sand anchor. Due to very shallow habitat at one site, the receiver was affixed directly to a 1.5-m-long galvanised metal stake driven into the substrate. Seven of the receivers were situated throughout the lower reaches of the river, over a distance of 2.88 km to cover the majority of the region known to be infested by *C. auratus* as detected by Morgan and Beatty (2007). The eighth receiver was positioned at the uppermost point below the Vasse River Diversion Drain to detect more large scale upstream movement (Fig. 1).

V7-4L (VEMCO) 69-kHz acoustic transmitters (i.e. tags) were used as they offered the greatest transmission power while being an appropriate weight for the size of the fish to be tagged (tag weight was ≤0.86% of the weight of individual fish used in the study). The tags were programmed to transmit an acoustic signal at a random interval of between 80 and 160 s (to avoid clashes of detections between transmitters), and the estimated tag life was 388 days. Detection range of the transmissions by the VR2W can vary depending on factors such as depth, flow and substrate type (Whitty, Morgan, Peverell, Thorburn, & Beatty, 2009). Range testing for detections was performed with three of the eight acoustic receivers using a V7-4L range test tag that transmits an acoustic signal every 12 s. A hand-held GPS unit (Garmin eTrex 30) was used to position the range test tag at progressive distance intervals of 10 or 25 m from the acoustic receiver up to a maximum distance of 250 m, and the number of detections by the receiver at each distance was recorded and compared to the expected number (i.e. duration of test multiplied by the transmission interval) over a 5-min period at each station.

2.3 Tagging of experimental fish

Twenty-one individuals of *C. auratus* (mean size = 308 ± 9.77 mm [±*SE*], size range = 260–371 mm TL, weight range = 210–1,105 g; Table 1) were captured from the Vasse River between receivers 1 and 7 (Fig. 1) using a boat-mounted electrofisher (Smith-Root VVP 15-B) on the 5th and 6th December 2012. Fish were placed in an aerated 110-L holding tank at a temporary field laboratory, where each individual fish was anaesthetised by emersion in AQUI-S® solution (dilution rate of 0.125 ml L^{-1} of water). Following the loss of equilibrium and all signs of fin movement, an incision of ~10 mm was made in the abdominal wall, a V7-4L acoustic tag was placed in the peritoneal cavity and the incision was closed with a single suture (glyconate monofilament size 4/0). Each fish was also implanted with a small (12 mm) passive integrated transponder (PIT) tag, which was inserted into the peritoneal cavity via a purpose-built applicator (BioMark HPT12 preloaded tags). Tagged individuals were then placed in oxygenated holding tanks and monitored during recovery (which was deemed to have occurred when individuals maintained equilibrium and resumed full fin movement), after which they were released within ~100 m of the site of capture.

2.4 Data analysis

Tag detections were downloaded from the receivers in January, March and October 2013, and in January 2014, and compiled using the VUE software package (VEMCO). The daily number of detections at each receiver was plotted separately for each fish to examine the spatial and temporal patterns in individual movements within the array. To explore the overall patterns in spatial and temporal movements, the total number of fish detected at each receiver on each day throughout the monitoring period was plotted. Seasonal and diurnal patterns in movements were also explored visually by plotting the average and total number of hits at each receiver in each hour separately for each season.

Distance covered by tagged individuals was calculated by summing the absolute values of the stream distance (in km) between receivers for every consecutive pair of detections for each fish. This yields an estimate of the minimum distance (termed D_{min} for the purpose of this study) that a fish has covered. The actual distance covered is, however, likely to be much greater, as movements outside the detection range of the receivers as well as small-scale movements within the detection range of receivers could not be determined from the passive acoustic telemetry data. The potential relationship between size (TL) of *C. auratus* and D_{min} was explored by fitting a number of regression models to determine whether there was a significant effect ($\alpha = .05$). Residency in the entire array and also at each receiver (Residency Indices [RI]) was calculated as the mean proportions of all days at liberty that each fish was either detected at any receiver or by a specific receiver. Single detections of fish were not included in analyses to eliminate the possible inclusion of 'false detections' (i.e. an erroneous detection of a nonpresent transmitter, which is caused from the collision of acoustic transmissions/codes from two or more tags at a single receiver; Pincock, 2012). The number of fish detected at each receiver, total number of detections and receiver RI were also calculated separately for the breeding period occurring between mid-August and mid-September (Morgan & Beatty, 2007).

A general linear model (GLM) was used to determine the fixed effects of season, receiver, diurnal variation (i.e. detections between 06.00–17.59 hr defined as 'day', and 18.00–05.59 hr defined as 'night') and all their interactions, along with the random effect of fish identity, on the number of acoustic detections at the various receivers during the study. Note that fish size was not included as a factor in the model as the above regression analysis found no significant relationship between D_{min} and the size of the fish. Variance components estimation (ANOVA, Type I) was used to determine the percentage of the random variance attributed to the effect of individual fish. Scheffe's post hoc tests were used to determine the pairwise differences between seasons and receivers. Statistical analyses were undertaken using SigmaPlot (V10.0) and SPSS

3 Results

3.1 Range testing

Range tests demonstrated that 100%, 90% and 50% of tag transmissions could be detected at 50, 100 and 150 m, respectively, by receivers within the main channel of the study area. Thus, the detection radius of receivers in this area was far greater than the width of the river (*c*. 20 m). However, the detection radius within the shallow wetland areas was markedly reduced, with 100% and 0% of transmissions being detected at 12.5 and 25 m, respectively, within the Vasse–Wonnerup Wetland (receiver 1), and 100%, 90% and 50% of transmissions being detected at 25, 50 and 75 m, respectively, within the New River Wetland (receiver 3). Although the ranges of detection of receivers within the two wetlands were small, they were sufficient to record all movement into (and out of) those systems due to the very narrow entrance points (8 and 3 m for receiver 1 and 3, respectively) and the placement of receivers relative to those points.

3.2 Acoustic detections and residency

Five of the 21 fish were excluded from the analyses as they were not recorded after the first 30 days of the 391-day monitoring period, while another individual was also excluded as it appeared at one receiver for an extended and uninterrupted period and was assumed to have either died or to have shed the tag. Although 391 days of monitoring data were collected, the first 10 days following release were excluded to account for any unusual behaviour that fish may have displayed post-tagging. Final days of the study were also excluded to reduce bias from uneven sample sizes of time periods. Data for analysis therefore encompassed a 365-day period from 15/12/2012 to 14/12/2013.

No fish were detected at the upstream-most receiver (i.e. receiver 8 located just downstream of the bypass connection; Fig. 1). The remaining 15 fish were detected a total of 403,728 times over the 365-day monitoring period, with a mean detection frequency per fish of 26,900 ± 4007.3 (±*SE*) and a range of between 4,263 and 63,577 detections (Table 1). The fish spent the majority of their time within the array, with an overall mean RI of 0.64 ± 0.06 (±*SE*; Table 1). There were several notable exceptions of fish that went undetected for long periods (Fig. S1). Of these, all were detected at three receivers on the ‘edge’ of the array, two (receivers 1 and 3) at the entrance points to the two wetlands and the third (receiver 7) that was at the upstream point of the main array (Fig. 1, Fig. S1). Two fish (ID 7585 and 7591) spent extended periods without being detected. This was likely to be in the 3 km stretch of river between receivers 7 and 8, where there were long periods (>3 months) between detections at receiver 7 (Fig. S1). One fish (ID 7582) spent considerable time in the Vasse-Wonnerup Wetlands (downstream of the array) and was last detected at receiver 1 in mid-September (Fig. S1). Two fish (ID 7579 and 7592) spent extended periods in the New River Wetlands (receiver 3).

3.3 Factors affecting acoustic detections

Based on the GLM analysis, the total number of acoustic detections in the array was significantly influenced by receiver ($F = 23.04$, $p = 0.000$), season ($F = 6.84$, $p = 0.000$) and the interaction between receiver and season ($F = 4.36$, $p = 0.000$), but not by time of day or any interactions involving time of day.

3.4 Differences in detections among receivers

Significant pairwise differences existed in the number of detections between receivers, that is between receiver 1 versus all others, receiver 7 versus 2, 4 and 5 and receiver 3 versus 4 (Tables 2 and 3). Receiver 4 (at the boat ramp) had the greatest number of fish visits (86% of fish visited at least once) and the highest mean RI (0.21 ± 0.071 [±*SE*]) over the entire monitoring period (Table 2; Fig. 2; Fig. S1). Five of the other six receivers had similar numbers of fish visiting at least once (between 60% and 80% of fish) and also similar overall RI (0.09–0.13; Table 2). The least visited site (other than receiver 8, which was never visited) was receiver 1 (Vasse-Wonnerup Wetlands); however, this site was still visited by 33% of fish at least once (Table 2; Fig. 2; Fig. S1).

3.5 Differences in movement among individual fish

Differences among individual fish accounted for 9.56% of the variation in number of acoustic detections in the array during the monitoring period ($F = 6.91$, $p = 0.000$).

Mean D_{min} day^{-1} for *C. auratus* over the 365-day period was 0.30 ± 0.05 (±*SE*) linear rkm (Table 2). There was no significant correlation between TL of *C. auratus* and D_{min}. Some individuals had very high levels of mobility over short timeframes. For example, ID 7589 moved back and forth between receivers 2 and 7 over a 24-hr period on 16–17 May 2013, covering a minimum stream distance of at least 5.4 km.

3.6 Seasonal patterns in movement

Season had a significant effect ($F = 6.84$, $p = 0.00$) on the overall mean detections during the study, and there were clear seasonal patterns in movement within the array for most fish. During the period encompassing the known peak spawning period of *C. auratus* in the Vasse River, that is between mid-August and mid-September (Morgan & Beatty, 2007), there were clear preferences for certain sites (Table 2; Fig. 2; Fig. S1). Significant pairwise differences existed in the number of detections between spring versus autumn and spring versus summer (Table 4). A clear decline in the number of fish and detections occurred in the summer/autumn period compared to the winter/spring period for receivers 2, 5 and 6, that is receivers in close proximity to bridges (Fig. 2; Fig. S1). Importantly, a corresponding increase in the number of fish detected and overall detections occurred at receiver 3 (the New River Wetlands) during winter/spring (Fig. 2; Fig. S1).

A temporal shift in site use was also evidenced by changes in the mean RI at receivers during the breeding period compared with the entire monitoring period. There was an increase in the mean RI during the breeding period at receivers 3 (0.17 ± 0.068 [±*SE*] cf 0.11 ± 0.039 [±*SE*] over the entire period) and 4 (0.31 ± 0.092 [±*SE*] cf 0.21 ± 0.071 [±*SE*]). There were also corresponding decreases in the mean RI at most other receivers during the breeding period, most notably receivers 2, 5 and 6 (Table 2). Finally, there was also a large increase (≥100%) in the percentage of the total daily detections at receivers 3 and 4 during the peak breeding period (i.e. 24% and 58% of detections at receivers 3 and 4, respectively) when compared with the entire period (12% and 26% of all detections at receivers 3 and 4, respectively); a corresponding decrease was recorded for all other receivers, most notably receivers 2, 5 and 6 (Table 2).

4 Discussion

Risk-based approaches for the control of invasive freshwater fishes need to be underpinned by a sound understanding of their ecological and life-history traits (Britton, Gozlan, & Copp 2011; Copp, Garthwaite, & Gozlan 2005). As far as the authors are aware, the current study is the first to comprehensively quantify the spatial and temporal movement patterns of *C. auratus*. The only other movement study on the species examined six fish that were translocated and released into a reservoir and passively monitored over a relatively short time period within a South Korean reservoir (Kim et al., 2014). While the current study revealed considerable variability in movement patterns among individual fish, the results demonstrate important commonalities in terms of seasonal movement between habitats that likely indicate the species underwent a spawning migration.

The mean daily movement of *C. auratus* in the current study ($D_{\min}$ day^{-1}) was 0.30 ± 0.05 (±*SE*) km day^{-1}, which was greater than that reported by Jones and Stuart (2007) for *C. carpio* in the eastern Australian Murray River (mean = 0.147 ± 0.238 [±*SE*] km) and slightly less than found by Daniel et al. (2011) for a New Zealand population of *C. carpio* (mean 0.35 ± 0.42 [±*SE*] km). Kim et al. (2014) estimated that *C. auratus* moved ~1.3 km day^{-1} by adding sequential distances between acoustic receivers at which fish were detected. Therefore, along with the hardy and adaptable biology of *C. auratus*, its mobility may add to the challenge of controlling introduced populations of the species. Moreover, because the movement distances were estimated from the cumulative of sequential movements between receivers and did not account for movement within the detection range of each receiver or movement outside of the array, underestimates of the total distance travelled are likely.

4.1 Seasonal movement patterns

In this study, *C. auratus* were found to undertake seasonal movements as evidenced by a notable change in residency from several main channel habitats in the nonbreeding period to receivers 3 (i.e. the New River Wetland) and 4 (i.e. the Boat Ramp) during the breeding period. This movement pattern suggests these sites were the key spawning locations of the fish, given all individuals tagged were mature. The downstream migration in the main channel or lateral migration into wetlands recorded here is comparable with the results of a radio-tracking study undertaken on the closely related *C. gibelio*, introduced into the Czech Republic (Slavík & Bartoš, 2004). Furthermore, although Slavík and Bartoš (2004) found that *C. gibelio* avoided entering fishways, Kim et al. (2014) stated *C. auratus* were frequently recorded in a fishway at the entrance to a major reservoir. These lines of evidence indicate that location-specific investigations of *C. auratus* behaviour in relation to barriers and harvesting structures are advisable for optimising goldfish control.

Considerable intraspecific variation in the movement patterns of individuals is common in telemetry studies, and there remains a dearth of field-based studies examining behavioural syndromes in fishes relative to those in a laboratory setting (Conrad, Weinersmith, Brodin, Saltz, & Sih, 2011). The extent to which the New River Wetland was utilised in this case varied greatly among individual fish, with some being detected there regularly, and others considerably less frequently. Nevertheless, 73% of individuals were detected in the system during the study and 60% during the peak breeding period, with the RI of fish in that habitat also being the second highest. The lower Vasse River, while regulated, is still typical of those in the Mediterranean climatic region having an annual flow period in winter and spring, before ceasing to flow in summer and autumn. The New River Wetland also contracts greatly in size and depth during summer and early autumn. Given the current study occurred in a highly regulated riverine environment, we predict this lateral movement from lotic to lentic habitats may be greater in less regulated systems that undergo a more pronounced seasonal flow regime, including higher peak flows in winter and spring that could provide a stronger cue to migrate for the purpose of spawning. Comparable studies are therefore required in other systems to confirm this hypothesis.

4.2 Implications for an informed control strategy

Control programmes for *C. auratus* in the Vasse River and throughout the world have used a range of techniques, including electrofishing, gill netting and fyke netting (e.g. Morgan & Beatty 2007; Lorenzoni, Ghetti et al., 2010). The current study demonstrates wetlands are important spawning grounds for the species and the narrow entrance to the New River Wetlands or the lentic habitat itself provide candidate sites for direct control action. A recommended management action to control *C. auratus* is to construct a barrier between the Vasse River and the New River Wetland. This barrier could be gated to enable one-way passage of adults into that terminal wetland, which seasonally contracts and even dries out in very low-rainfall years, and could involve trapping at that barrier for inward migrating adults or outward moving juveniles that presumably exit the wetland prior to it contracting in the dry season. Such point source trapping at the channels and inlets of laterally connected wetlands are successful for targeting *C. carpio* (Hillyard, Smith, Conallin, & Gillanders, 2010).

Understanding behavioural syndromes of invasive species may provide a more holistic approach to their management (Conrad et al., 2011). *Carassius auratus* and other cyprinids are known to display well-developed cognitive abilities, including excellent spatial awareness (Braithwaite & de Perera, 2006; Rodriguez, Duran, Vargas, Torres, & Salas, 1994), and are able to learn from each other's foraging behaviour (Bajer, Lim, Travaline, Miller, & Sorensen, 2010). For example, studies of other pest fishes including cyprinids have shown that fish can adapt to management actions and exhibit counter behaviour such as capture avoidance (Hunn & Youngs, 1980; Patil, Purser, & Nicholson, 2015; Stuart, Williams, Mckenzie, & Holt, 2006). Conallin, Smith, Thwaites, Walker, and Gillanders (2012) found that *C. auratus* displayed trap avoidance behaviour with 81% (978 fish) of their captures occurring outside of mesh traps that were deployed at the outlet of a wetland. Conversely, there is also potential to exploit the cognitive and social learning ability of cyprinids in developing control programmes such as attracting them to food sources (Bajer et al., 2010). Therefore, it will be necessary to undertake additional monitoring of the movement of *C. auratus* in response to future control programmes to inform an adaptive management strategy. Recent work on sterile ‘Judas’ *C. carpio* provides a valuable model in this regard (Patil et al., 2015).

4.3 Implications for predicting dispersal

The results of this study have considerable implications for assessing the potential spread and thus the management of this species here and elsewhere. Despite growth being reduced (Altinokand & Grizzle, 2001), *C. auratus* is known to be tolerant of elevated salinities (Schofield, Brown, &

Fuller, 2006), with the Vasse River population recently found to have an acute salinity tolerance of ~11 ppt, and a gradual tolerance of ~21 ppt (authors, unpublished data).

A third of tagged *C. auratus* moved downstream into the upper reaches of the Ramsar-listed Vasse–Wonnerup Estuary at least once during the current study, and recent sampling revealed that juvenile *C. auratus* were present in salinities of up to ~17 ppt in that system (Tweedley, Hallett, & Chambers, 2012; Tweedley, Keleher, Cottingham, Beatty, & Lymbery, 2014), thus justifying their classification as ‘a freshwater straggler species’ in estuaries (Potter, Tweedley, Elliott, & Whitfield, 2015). Salinity in the upper section of that system (i.e. the Vasse-Wonnerup Wetland) remains <1 ppt all year round, while the upper and lower regions of the Vasse Estuary decline to <4 ppt during spring (Tweedley, Keleher, Cottingham, Beatty, & Lymbery, 2014), coinciding with the breeding period of *C. auratus* (Morgan & Beatty, 2007). Therefore, without intervention, it is possibly inevitable that *C. auratus* will eventually spread into other rivers that discharge into those wetland and estuarine habitats. Such potential use of estuarine habitats as ‘saline bridges’ by invasive freshwater species has been noted elsewhere (Brown, Moore, & Quabius, 2001; Brown, Scott, & Wilson, 2007).

The findings of the current study are also timely as there are plans in eastern Australia to introduce the Cyprinid herpesvirus 3 CyHV-3 (widespread in the Northern Hemisphere and parts of Asia), a virus with potential to eradicate many *C. carpio* populations, but has only negligible impact on *C. auratus* (McColl & Crane, 2013). There is potential that *C. auratus*, also widespread in eastern Australia, will expand rapidly to fill the vacant niche left by *C. carpio* in both lentic and lotic habitats. Understanding the movement patterns of *C. auratus* between those systems should contribute to effective control programmes to better target the species. It should also be noted that the current study was limited to a single river with a modest number of individuals being monitored. Therefore, the development of control programmes for this species elsewhere should be also underpinned by similar studies in relevant systems.

Ongoing public education programmes are vital to help prevent future alien fish introductions globally, as are monitoring programmes to increase the chances of early detection to maximise eradication (Britton, Brazier, Davies, & Chare, 2008). Moreover, as the control of introduced fishes is expensive and not always required from an ecological impact perspective (Gozlan, 2008), risk-based control and containment programmes based on sound ecological understanding of invasive species and their receiving environments are needed to understand and mitigate their potential impacts on aquatic ecosystems.

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Figure 1. The location and name of the eight acoustic receivers employed to track goldfish (*Carassius auratus*) in the Lower Vasse River, south-western Australia.

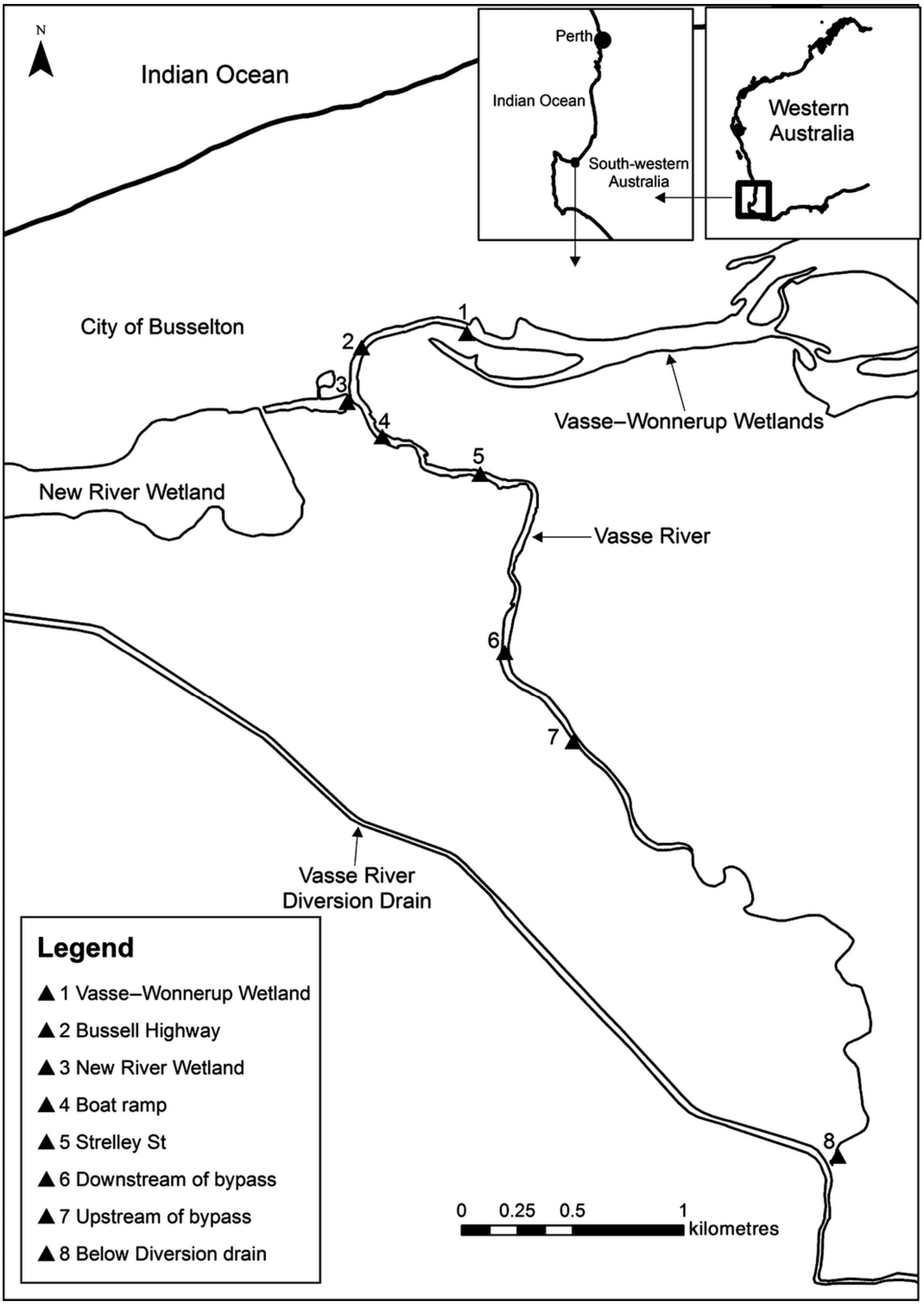

Figure 2. Number of daily acoustic detections (bars) and individual fish (circles) at each of the seven receivers over the 1-year study period in the lower Vasse River, south-western Australia. Note the clear increase in the number of fish detected at receiver 3 (New River Wetland) during winter and spring and concomitant decrease in the fish detected at receivers 2, 5 and 6 during that period. The box indicates the peak spawning period of goldfish (*Carassius auratus*) in the system (Morgan & Beatty, 2007).

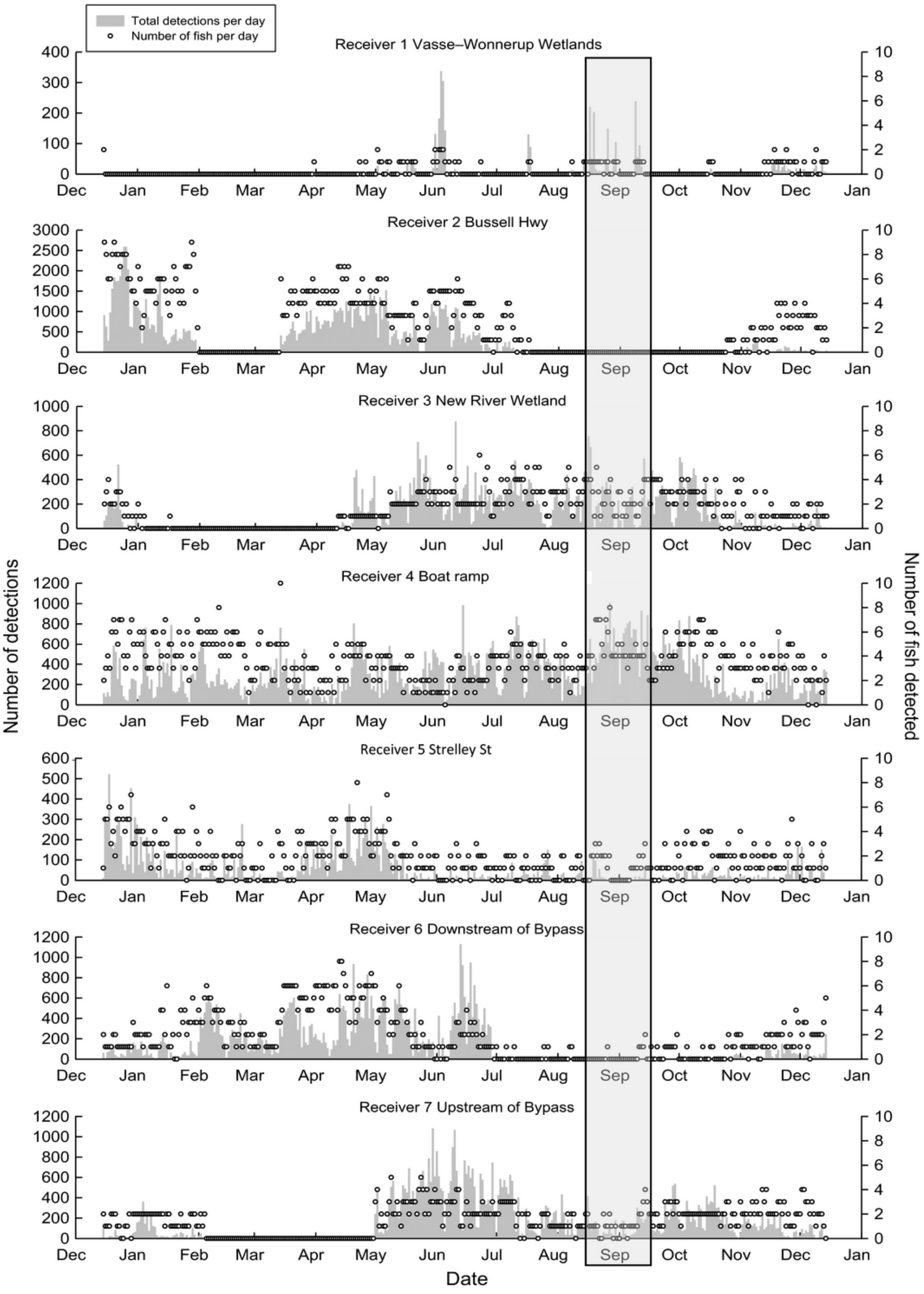

Table 1. Detection data from the 15 *Carassius auratus* acoustically monitored in the lower Vasse River for a 365-day period between 15th December 2013 and 14th December 2014. Residency Index is the proportion of days a tag was detected within the array and $D_{\mathrm{min}}$is the minimum distance travelled for each fish (see text for details)

Fish ID	**TL, mm**	**Tag location**	**No. of detections**	**No. receivers detected at**	**Days detected**	**Residency Index**	**D_{min} (rkm day^{-1})**
7577	355	Boat ramp	63,577	4	343	0.94	0.226
7578	260	Boat ramp	16,022	1	125	0.34	0.02
7579	280	Boat ramp	4,263	6	128	0.35	0.354
7581	294	US of Bypass	30,492	5	258	0.71	0.32
7582	371	US of Bypass	16,167	7	157	0.43	0.227
7584	370	Boat ramp	31,732	6	344	0.94	0.629
7585	290	Boat ramp	7,812	3	84	0.23	0.024
7586	297	US of Bypass	26,986	4	285	0.78	0.453
7587	314	US of Bypass	16,201	6	232	0.64	0.305
7588	265	US of Bypass	44,006	4	341	0.93	0.255
7589	309	US of Bypass	22,616	7	282	0.77	0.634
7591	280	Boat ramp	36,526	5	169	0.46	0.095
7592	357	Boat ramp	42,702	4	214	0.59	0.272
7594	306	US of Bypass	28,055	5	289	0.79	0.447
7595	273	US of Bypass	16,346	5	268	0.73	0.238
Min	260		4,263	1	84	0.23	0.02
Max	371		63,577	7	344	0.94	0.634
Mean	308.1		26900.2	5.06	234.6	0.64	0.3
SE	9.77		4007.31	0.42	21.95	0.06	0.048

Table 2. Acoustic receiver statistics in the Vasse River, including the total number of fish detected and the number of detections at each receiver, and the mean residency index (proportion of daily visits per fish at each receiver) of *Carassius auratus* in the Vasse River. The detection data within the known peak breeding period (i.e. 15th August to 15th September) in the Vasse River are also presented

Receiver information	**Entire period**				**Breeding period**		
Receiver no. and ID	**Distance from receiver 1 (rkm)**	**Number of fish detected (% total)**	**Number of detections (% total)**	**Residency Index (±1 *SE*)**	**Number of fish detected (% total)**	**Number of detections (% total)**	**Residency Index (±1 *SE*)**
1 – Vasse-Wonnerup Wetlands	0	5 (33)	3,450 (0.86)	0.014 (.008)	1 (7)	1,388 (47)	0.04 (.038)
2 – Bussell Hwy	0.42	11 (73)	117,115 (29.1)	0.13 (.038)	0 (0)	0	0
3 – New River Wetland	0.76	11 (73)	48,365 (12.0)	0.11 (.039)	9 (60)	7,013 (24)	0.17 (.068)
4 – Boat Ramp	0.88	13 (86)	104,521 (25.9)	0.21 (.071)	9 (60)	17,275 (58)	0.31 (.092)
5 – Strelley St	1.33	12 (80)	19,347 (4.8)	0.11 (.027)	8 (53)	486 (1.6)	0.07 (.021)
6 – D/S of Bypass	2.27	11 (73)	52,101 (12.9)	0.11 (.033)	3 (20)	35 (0.1)	0.01 (.007)
7 – U/S of Bypass	2.88	9 (60)	58,094 (14.4)	0.09 (.05)	4 (27)	3,519 (12)	0.08 (.052)
Total			402,993			29,716	
Mean (*SE*)		10.3 (.99)	57,570 (15,625)	0.11 (.022)	5.7 (1.4)	4,953 (2,677)	0.10 (.041)

Table 3. Pairwise comparisons (Scheffe's test) of the mean number of detections between receivers from the acoustic array in lower Vasse River between December 2012 and December 2013

(*I*) Receiver	**(*J*) Receiver**	**Mean difference (*I* − *J*)**	***SE***	**Significance**	**95% Confidence interval**	
					Lower bound	**Upper bound**
4	2	0.16	0.144	0.975	−0.354	0.673
	1	1.461	0.144	0.000*	0.947	1.974
	6	0.435	0.144	0.17	−0.079	0.948
	3	0.633	0.144	0.004*	0.12	1.147
	5	0.302	0.144	0.626	−0.212	0.815
	7	0.821	0.144	0.000*	0.308	1.335
2	4	−0.160	0.144	0.975	−0.673	0.354
	1	1.301	0.144	0.000*	0.787	1.814
	6	0.275	0.144	0.726	−0.238	0.789
	3	0.473	0.144	0.098	−0.040	0.987
	5	0.142	0.144	0.987	−0.371	0.656
	7	0.662	0.144	0.002*	0.148	1.175
1	4	−1.461	0.144	0.000*	−1.974	−0.947
	2	−1.301	0.144	0.000*	−1.814	−0.787
	6	−1.026	0.144	0.000*	−1.539	−0.512
	3	−0.827	0.144	0.000*	−1.341	−0.314
	5	−1.159	0.144	0.000*	−1.672	−0.645
	7	−0.639	0.144	0.003*	−1.153	−0.126
6	4	−0.435	0.144	0.17	−0.948	0.079
	2	−0.275	0.144	0.726	−0.789	0.238
	1	1.026	0.144	0.000*	0.512	1.539
	3	0.198	0.144	0.93	−0.315	0.712
	5	−0.133	0.144	0.991	−0.647	0.38
	7	0.386	0.144	0.307	−0.127	0.9
3	4	−0.633	0.144	0.004*	−1.147	−0.120
	2	−0.473	0.144	0.098	−0.987	0.04
	1	0.827	0.144	0.000*	0.314	1.341
	6	−0.198	0.144	0.93	−0.712	0.315
	5	−0.331	0.144	0.51	−0.845	0.182
	7	0.188	0.144	0.945	−0.325	0.702
5	4	−0.302	0.144	0.626	−0.815	0.212
	2	−0.142	0.144	0.987	−0.656	0.371
	1	1.159	0.144	0.000*	0.645	1.672
	6	0.133	0.144	0.991	−0.380	0.647
	3	0.331	0.144	0.51	−0.182	0.845
	7	0.519	0.144	0.045	0.006	1.033
7	4	−0.821	0.144	0.000*	−1.335	−0.308
	2	−0.662	0.144	0.002*	−1.175	−0.148
	1	0.639	0.144	0.003*	0.126	1.153
	6	−0.386	0.144	0.307	−0.900	0.127
	3	−0.188	0.144	0.945	−0.702	0.325
	5	−0.519	0.144	0.045	−1.033	−0.006

The number of detections were $\log_{10+1}$ transformed prior to analysis.

[a] Significant differences at α = .01.

Table 4. Pairwise comparisons (Scheffe's test) in the mean number of detections between seasons from the acoustic array in the lower Vasse River between December 2012 and December 2013

(*I*) Season	**(*J*) Season**	**Mean difference (*I* − *J*)**	***SE***	**Significance**	**95% Confidence interval**	
					Lower bound	**Upper bound**
	Spring	0.376	0.109	0.008a	0.07	0.681
Autumn	Summer	−0.046	0.109	0.981	−0.351	0.26
	Winter	0.252	0.109	0.149	−0.053	0.558
	Autumn	−0.376	0.109	0.008a	−0.681	−0.070
Spring	Summer	−0.422	0.109	0.002a	−0.727	−0.116
	Winter	−0.123	0.109	0.735	−0.429	0.182
	Autumn	0.046	0.109	0.981	−0.260	0.351
Summer	Spring	0.421	0.109	0.002a	0.116	0.727
	Winter	0.298	0.109	0.059	−0.007	0.604
	Autumn	−0.252	0.109	0.149	−0.558	0.053
Winter	Spring	0.123	0.109	0.735	−0.182	0.429
	Summer	−0.298	0.109	0.059	−0.604	0.007

Number of detections were $\log_{10+1}$ transformed prior to analysis.

[a] Significant differences at α = .01.

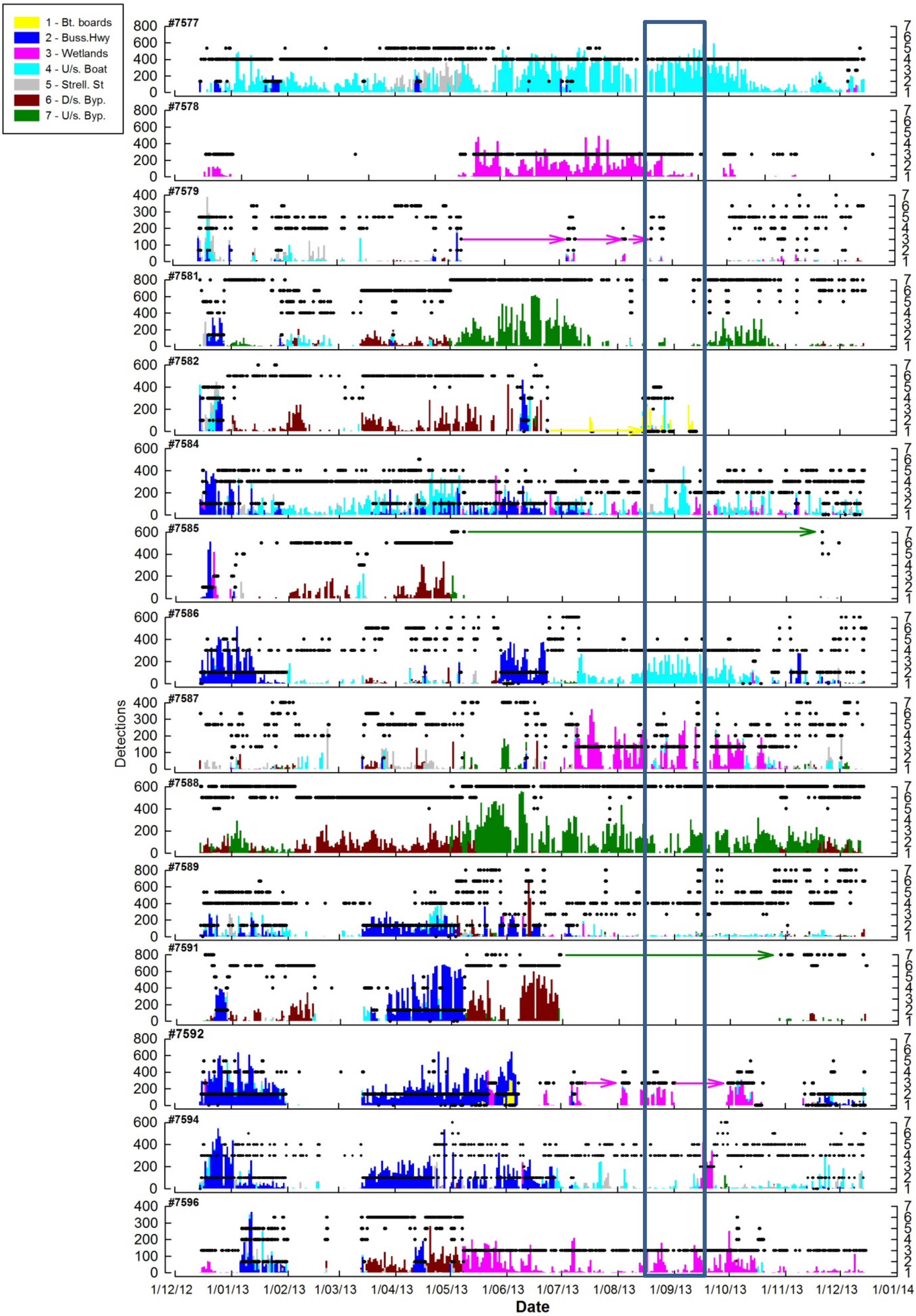

Fig. S1. Detections at seven receivers for 15 *C. auratus* tracked for a year in the lower Vasse River. N.B. total detections per day for each fish are displayed as colour coded bars (corresponding to each receiver). Dots are actual individual detections corresponding to the receivers (coded 1-7 on the right hand axes). Horizontal coloured arrows indicate a fish left a receiver for an extended period but was again subsequently detected at that receiver (see text for details). The box indicates the peak spawning period of goldfish (*Carassius auratus*) in the lower Vasse River (Morgan & Beatty 2007).