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Article type : Original articles

Reservoir to river: quantifying fine scale fish movements after translocation

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This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the [Version of Record](#). Please cite this article as [doi: 10.1111/EF12490](https://doi.org/10.1111/EF12490)

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Abstract

Translocation of individuals is a widely used tool in the conservation of threatened species. The movement behaviours of translocated individuals in their new environment is a key factor that can influence translocation success (i.e. survival and reproduction). In this study, eel-tailed catfish (*Tandanus tandanus*) and Murray cod (*Maccullochella peelii*) movements were monitored using fine scale acoustic telemetry over a five-month period in two lowland rivers in eastern Australia. Fine scale movement and habitat selection were compared among translocated lacustrine and resident riverine *T. tandanus*, and between species. We found no difference in fine scale movement behaviours between translocated and resident *T. tandanus*, however there was some variation in movement response to environmental variation between species. In contrast, habitat selection varied not only between the two species, but also between resident and translocated *T. tandanus* individuals. Notably, activity was significantly lower in the first day after release compared to the remainder of the study period. Although *T. tandanus* translocated from a reservoir had never experienced the environmental fluctuations of a riverine system, individuals still responded in the same way as resident riverine fish, suggesting an innate behavioural response. However, this was not the case for habitat selection, where translocated individuals preferred habitats more common in their source population's lacustrine environment. The findings of this study are important in guiding future conservation efforts involving the translocation of wild-caught fish, primarily the importance of the suitable habitat at the release site to ensure the success and persistence of translocated population.

Keywords

Translocation, acoustic telemetry, movement, habitat selection, population source, activity.

Introduction

The translocation of species is an increasingly used conservation strategy to manage and restore populations of threatened fish species (Olden et al. 2011; Schwartz and Martin 2013). Translocations may be to habitats previously occupied or that are novel; however, in both cases, a critical step is evaluating the outcomes of translocated individuals to evaluate the likelihood of long-term population persistence. While survival and reproduction are important short-term indicators of translocation success, there are other indicators that may also be valuable in understanding the translocation outcomes (Brichieri-Colombi and Moehrenschrager 2016). Movement behaviour is one such indicator. Not only is movement a potentially critical process in sustaining species with specific life-history requirements (Dittman and Quinn 1996; Urquhart and Urquhart 1978), it also strongly influences feeding, energy uptake and expenditure (Owen-Smith et al. 2010). Atypical movement behaviours may provide early evidence of potential issues regarding longer-term translocation outcomes, especially if those behaviours persist through time.

Due to the stress of translocation, and inherent differences in source population behaviours, atypical movement behaviours may be observed in translocated individuals (Coombs and Grossman 2006; Kaya 1991). For example, the behavioural activity of translocated bank voles (*Clethrionomys glareolus*) has been found to be dependent on source population, where individuals from one population exhibited consistently higher activity post-release, resulting in increased predation risk and dispersal (Ebenhard 1987). In fish, riverine shoal bass (*Micropterus cataractae*) translocated 50 km downstream to a lacustrine environment all evacuated the impoundment within two to four weeks (Taylor and Peterson 2015). In a similar study, riverine Colorado pikeminnow (*Ptychocheilus lucius*) showed a similar result (Irving and Modde 2000), with all fish translocated into an impoundment moving into riverine environments within a month. All these studies have focussed on relatively coarse-scale movements, rather than examining the influences of translocation on finer-scale movement behaviours such as those associated with foraging or nesting. However, quantifying movement behaviour at such fine scales is challenging due to a range of environmental, logistical and practical constraints (Cooke et al. 2013).

Over the last decade, acoustic telemetry has emerged as an efficient method of tracking aquatic organisms across a range of scales, from broad-scale longitudinal movements of fish (Gilroy 2010; Harding et al. 2017; Walsh et al. 2013), to fine-scale fish movements in two

dimensions within well-defined marine (Furey et al. 2013; Moulton et al. 2017; Zhang et al. 2015) and freshwater systems (especially lakes; Baktoft et al. 2013; Roberts et al. 2017; Yoshida et al. 2014). Both of these scales may be relevant in characterising the movement behaviours of fish, and how movement varies among translocated and resident individuals.

This study focuses on the movement behaviour of two species of freshwater fish, the freshwater catfish (*Tandanus tandanus*; Mitchell, 1838; Family Plotosidae) and Murray cod (*Maccullochella peelii*; Mitchell, 1838; Family Percichthyidae), both of which are endemic to eastern Australia and occur throughout much of the Murray-Darling basin (MDB). These two species have undergone dramatic range contractions and declines in abundance due to the introduction of Common carp (*Cyprinus carpio*), cold water pollution, altered flow regimes and the loss of suitable habitat (Barrett 2004; Koehn et al. 2014). *Maccullochella peelii* are currently listed as critically endangered (Wager 1996) and *T. tandanus* are listed as an endangered population in the MDB in NSW (*NSW Fisheries Management Act 1994*). Both species show relatively restricted movements over much of their life, occupying well defined home ranges (Koehn et al. 2009; Koehn and Nicol 2016; Koster et al. 2015), although both may also undertake occasional long-distance movements during periods of high flow (Koster et al. 2015; Marshall et al. 2016; Reynolds 1983). Such movements may also coincide with the species' breeding activities (Koehn et al. 2009; Koehn and Nicol 2016). For both species, little is known of fine scale movement behaviour. *Tandanus tandanus* are thought to make extensive use of macrophytes and wood structures, with a preference for relatively shallow water (1 m) (Koster et al. 2015). *Maccullochella peelii* utilize demersal main channel habitats dominated by instream wood, selecting areas of overhanging vegetation, deeper water and lower water velocities, closer to the bank (Koehn 2009a).

We aimed to quantify the fine scale movements and habitat selection of *T. tandanus* and *M. peelii* within their nominal home range, and whether *T. tandanus* movement differed between fish translocated from a lacustrine population compared to resident riverine fish. The study examined whether there were differences in movement behaviours (movements outside of the array, rates of movement (ROM) and spatial occupancy) and habitat use between these species. We evaluated differences in short-term movement behavior between species and population sources for 24 hours following tagging and release. We also quantified variation in long term movement behaviour (over a five-month period) in

response to environmental changes and examined variation in habitat use between species and population sources. The new information contributed by this study adds to the growing knowledge of translocated fish movement behaviours and will aid future conservation efforts by offering expected outcomes when translocating adult fish to supplement local populations.

Methods

The study was undertaken in the Gwydir and Mehi rivers in the northern Murray-Darling Basin (MDB), New South Wales, Australia (Figure 1A). The Gwydir and Mehi rivers are semi-intermittent in nature, and typically the river channels do not exceed 25 m in width and 3 m in depth. Both rivers are highly regulated, with a number of weirs and dams throughout both systems. The surrounding catchment of both rivers is used intensively for irrigated-agriculture, stock and domestic use (Southwell et al. 2017). The system receives environmental flows held by the NSW Office of Environment and Heritage (OEH) and the Commonwealth Environmental Water Office (CEWO) on a semi-regular basis, which are released from the main upstream impoundment, Copeton Dam (Figure 1B). The study spanned from late May to early November 2016, where river discharge ranged between 0 and 1968 ML/hr and water temperature ranged between 9.3 and 26.2° C (Figure 2). Channel morphology and microhabitat at the array sites was determined to have remained unchanged throughout the study, through personal observations on multiple trips.

Acoustic telemetry array

Fine scale movement behaviour of resident and translocated fishes was recorded using acoustic telemetry. Array sites were selected based on suitability for a fine scale acoustic array (i.e. river geometry, no obtrusive structures, etc.), whilst maintaining consistency in habitats among sites. A range test was performed (as described in Espinoza et al. 2011) *in situ* to assess signal strength transmitters and spacing of receivers to maximise precision positioning of multiple fish simultaneously. Once maximum ranges were determined, a Vemco positioning system (VPS) array consisting of eight Vemco VR2W 69 KHz receivers arranged in adjacent equilateral triangles was deployed in each river (Figure 1c and d). A

temperature logger (OneTemp, Sydney) was attached to the centre receiver of each array. A terminal receiver was placed approximately 1.5 km both up and downstream of each array, to allow the detection of fish movements beyond the fine scale array range.

Fish collection for acoustic tagging

T. tandanus and *M. peelii* were caught by either electrofishing (Smith-Root GPP 2.5 KVA unit) or gill netting (mesh size = 100 mm). Captured fish were kept in a submerged cage prior to tagging.

Riverine fish collected were composed of five *M. peelii* in each river and three *T. tandanus* in the Gwydir River. The low number of riverine *T. tandanus* tagged reflects the scarcity of these fish within the study rivers. All riverine fish were caught within the boundaries of the fine scale array of their respective river to reduce possible movement outside the array due to homing behaviour. A further 17 *T. tandanus* were collected from Copeton Dam, tagged and translocated to the study rivers (seven fish released into the Gwydir array and ten released into the Mehi array; Table 1). These fish were transported to the study sites in aerated 220 L covered drums, with a maximum of five fish per drum to minimize stress. The transit from Copeton Dam to the study sites took approximately two hours, driving conservatively to minimise stress to the fish.

Acoustic tag implantation, release and recording

Fish were anaesthetised in ambient river water containing 50 mg L⁻¹ benzocaine (ethyl-*p*-aminobenzoate) (Sigma Aldrich, Shanghai) and weighed (g) and measured (mm). Fish were then transferred to an operating cradle, with water containing an equivalent level of anaesthetic (50 mg L⁻¹) continually pumped over the gills to maintain anaesthesia. To access the peritoneal cavity, an incision was made through the body wall of the fish, adjacent to the *linea alba* and anterior of the anal vent. Fish sex was determined visually, as per Lake (1967). Either a Vemco V9 or a V13 69 KHz acoustic telemetry transmitter tag was used as dictated by the weight of the fish, varying to keep under the recommended 2.25% of body weight (Butler et al. 2009; Jepsen et al. 2002; Wagner et al. 2011). Although all fish were large enough to use a larger sized tag, the smaller tags were implanted into the smaller fish. A passive integrated transponder (PIT) tag was also inserted in the peritoneal cavity. The

incision was closed with two or three sutures using 0.3 mm pseudo-monofilament, absorbable thread (Vetafil Bengen; WdT, Garbsen, Germany). After suturing, the fish was given an intramuscular oxytetracycline hydrochloride (0.25 mL kg^{-1}) injection (CCD Animal Health and Nutrition, Toowoomba) and returned to the submerged cage to recover.

All fish were released at the centre of their respective array site within one hour of surgery completion. After 161 days (approximately five months), the data recorded by the receivers were downloaded and sent to the Vemco for processing. Positions for each fish were generated by measuring the differences in transmission detection times at several different time-synchronized receivers. Due to exceptionally high flows over the dates of 04 and 14 - 20 September 2016, no data (neither animal, nor stationary tags) were recorded by the fine scale array in the Gwydir River.

Habitat assessment

A modified version of the in-line transect method, described by Simonson et al. (1994), was used to provide an estimate of aquatic habitat characteristics within each study reach. Transects were taken at 90° to stream flow and were spaced within each study reach at distances of approximately 4% of the total reach length of 450m (26 transects in total, approximately 10 m apart). The first and last transects were placed at a distance of 0% and 100% of the total reach length.

Habitat characteristics were recorded at five points along each lateral transect, placed equidistantly and beginning and ending at each bank. At each point a handheld GPS unit (Garmin Foretrex 601) was used to record the position. Water depth was measured using a collapsible measuring staff. Substrate composition was estimated using a probe (mud, sand, fine gravel, coarse gravel, cobble, rock or bedrock). Submerged microhabitat was visually estimated for 0.5 m^2 around each sample point. Submerged microhabitat was characterised into: aquatic macrophytes, submerged marginal vegetation, submerged overhanging vegetation, emergent vegetation, root masses, undercut banks, large woody debris and small woody debris. Water velocity was recorded with a portable flow meter (Swoffer 2100). Riparian canopy openness was estimated using a spherical densitometer at each transect point.

200 Data Analysis

201 Fish presence and absence within the fine scale arrays were inspected to determine possible
202 transmitter errors and to identify which individuals to include in the analysis. A binary
203 response variable of daily fish presence/absence within the fine scale arrays was generated
204 using the *data.table* package (Dowle and Srinivasan 2017) in R (R Development Core Team;
205 www.r-project.org) and plotted. Individual fish detected at least once within an array on a
206 given day were recorded as '1' and fish not detected were recorded as '0'. Days were used
207 rather than a finer resolution time scale to reduce the chance of erroneously recording a
208 fish as absent from the array that may actually be in an area of the array with poor
209 detection range (within woody debris). First detections at terminal receivers for each
210 individual were also inspected to determine the magnitude, direction and frequency of fish
211 movements outside of the fine scale arrays.

212 Prior to all other analyses, potentially erroneous or uncertain positional records were
213 identified and removed from the dataset using horizontal position error (HPE). The VPS
214 provides an estimate of accuracy for each animal tag position, and these were used to filter
215 the datasets prior to use. For a detailed description of HPE see Smith (2013).

216 *Short-term movement behaviour post-tagging and release*

217 Initial movement in the first 24 hours after release was examined using track maps
218 generated for each individual in the *ggmap* package (Kahle and Wickham 2013) in R.
219 Individuals with less than two positions were excluded.

220 ROM (rate of movement) was generated as a measure of activity for each fish in the first 24
221 hours using the *adehabitatLT* package (Calenge 2006) in R. This was calculated by dividing
222 the step length between two consecutive fish locations by the time taken between the two
223 positions (expressed as m/min). The maximum delay between transmissions of the tags
224 used in this study was of 160 seconds. To avoid underestimating ROM, only consecutive
225 positions less than 160 seconds apart (the maximum time between transmitter pings) were
226 included in this analysis, following the approach of Furey et al. (2013).

227 We compared fish activity (hourly average ROM) immediately post release (day-1) and over
228 the longer term (entire five months) using a linear mixed-effects model (LMM) in the *lme4*

package (Bates et al. 2015) in R. Using Akaike information criterion (AIC), all possible models and interactions were checked, and a best model was selected, which included 'river', 'species', and 'population source' as covariates and 'fish ID' as the random effect. Following the protocol of Zuur et al. (2010), we check for statistical outliers and collinearity among predictor variables was assessed using variance inflation factors (VIF) in R. Model residuals were checked for normality and model fit was assessed by comparing model residuals and fitted values.

The differences between species and population sources in short-term spatial occupancy of fish was tested using permutational analyses of variance (perMANOVA; Anderson 2001). For each river, the mean hourly spatial location (latitude and longitude) of each fish was calculated for the first 24 hours after release. These hourly spatial occupancy data were converted to a euclidean distance matrix for use in the perMANOVA. Species/population source was treated as a fixed factor (with three levels: *M. peeli*, *T. tandanus* riverine and *T. tandanus* lacustrine) and individual fish ID included as a random factor nested within species/population source. The analysis was completed using Primer, ver. 6 (Clarke and Gorley) with the PERMANOVA add-on package (Anderson et al. 2008).

Long-term movement in response to environmental changes

The effect of environmental variation on fish leaving the fine scale arrays was tested using a generalised linear mixed model (GLMM) with a binomial distribution in the *lme4* package (Bates et al. 2015). The binary variable of daily fish presence within the fine arrays generated during preliminary analysis was used as the response variable in the model, including fixed effects of daily river discharges, average daily river temperatures, fish sex and weight, and population source in the case of *T. tandanus*. Individual fish ID was treated as a random effect. Using Akaike information criterion (AIC), all possible models and interactions were checked, and a best model was selected. Species were analyzed separately. Preliminary analyses revealed strong collinearity of fish weight and length, and models including only weight yielded a better fit, so length was dropped as a covariate.

Average hourly rate of movement (ROM) was used to investigate the effect of environmental variation on fish activity. A penalized quasi-likelihood linear mixed model (LMM) with a Gaussian distribution was used to fit hourly ROM data using the *lme4* package

in R. Hourly ROM was log-transformed [$\log(x+1)$] prior to analysis to ensure normality and homogeneity of variances. The model included fixed effects of hourly river discharges, hourly river temperatures, diel period, fish sex and weight, and population source for *T. tandanus*. Individual fish ID was treated as a random effect. Using Akaike information criterion (AIC), all possible models and interactions were checked, and the best model was selected. Model assumptions and fit were assessed following the protocol of Zuur et al. (2010), as earlier described. The first 24 hours after tagging were excluded and each species were analyzed separately.

Habitat selection

Habitat selection was assessed using Euclidean distance-based analysis (EDA) as per Conner and Plowman (2001). This method was chosen as even if habitat classification error occurs, the distance to the correct habitat is reduced (Conner and Plowman 2001; Conner et al. 2003). Firstly, discrete habitat types for the study area were interpolated using universal kriging from sampled transect points within ArcGIS 10.4 Geospatial Analyst extension (ESRI, California). Within the area of detection for each array, 1000 random points were generated and distances between each habitat type and each random point were calculated. A vector of mean distances to each habitat type was then created. For each fish location, the distance to all habitat types was also determined (distance to the habitat occupied by the fish at the time of detection was 0). EDA ratios were calculated as the mean observed distance (from array positions) divided by the mean expected distance (from random points) to each habitat type. A unique EDA ratio was calculated for each habitat type for each fish, retaining the individual as the experimental unit. If habitat use is random, all EDA ratios should equal one, with values >1 indicating positions farther from a habitat type than expected (avoidance) and values <1 indicating positions closer to a habitat type than expected (preference). PerMANOVA was used to evaluate overall difference in habitat use (based on EDA ratios) between rivers and fish population source. For each habitat parameter, differences in EDA ratios between rivers for each species, and population source for *T. tandanus*, were evaluated using non-parametric 1-way analysis of variance (Kruskal-Wallis tests). Individual fish with few detections inside the array ($n < 40$) were excluded from these analyses.

289 Results

290 All 20 tagged *T. tandanus* were detected within their respective fine scale arrays post-
291 release. Resident *T. tandanus* were detected in the array much longer on average than
292 translocated *T. tandanus* (mean 126 days $\pm$ 6 s.e. versus 22 $\pm$ 4, respectively). All 10 *M. peelii*
293 were detected within their respective fine scale arrays at least once a day for 85 $\pm$ 18 days
294 (mean $\pm$ s.e.). We found no evidence of tag failure, or mortality as all individuals were
295 observed making multiple, active bi-directional movements during the study period.

296 All lacustrine *T. tandanus* in the Gwydir River and the majority in the Mehi River were
297 detected by the downstream terminal receiver first, when they left the fine scale array
298 (Figure 3A). Most lacustrine *T. tandanus* were also detected by the terminal upstream
299 receiver in their respective rivers. Only one resident *T. tandanus* was detected by any
300 terminal receiver. Several lacustrine *T. tandanus* were detected by both terminal receivers
301 (approximately 3 km) in their respective river on the same day, as little as two hours apart.
302 *Maccullochella peelii* showed no pattern in first detections at up or downstream terminal
303 receivers (Figure 3B). Two fish (53597 and 535601) were undetected by the fine scale array
304 for over one and two months, respectively, before being detected by a terminal receiver,
305 suggesting they were inhabiting the small length of river between the fine scale array and
306 terminal receiver during the period. All five *M. peelii* in the Gwydir River were first detected
307 by the downstream terminal receiver in either September or October. Most individuals of
308 both species detected by terminal receivers outside of the fine scale arrays were detected
309 re-entering the fine arrays in between and after terminal receiver detections.

310 Short-term movement behaviour post-tagging and release

311 Within the Gwydir River, resident *T. tandanus* remained within the array for the majority of
312 the first 24 hours, and mostly showed limited movement for this period (Figure 4A).
313 Translocated *T. tandanus* displayed varied ranges within the array and most left the
314 detection range of the array several times within the first 24 hours, with two individuals
315 leaving permanently immediately after release. Most translocated *T. tandanus* were
316 detected by the downstream terminal receiver on day-1 (Figure 3A). *Maccullochella peelii*
317 showed varied ranges across day-1, but most remained within the array, with only one
318 individual leaving immediately after release.

In the Mehi River, translocated *T. tandanus* were highly mobile for the first 24 hours, but mostly remained within the array (Figure 4B). *Maccullochella peelii* displayed varied ranges within the array and most individuals left the array at least once, with two individuals permanently leaving immediately after release.

Average hourly ROM was significantly higher over the entire five month period compared to day-1 ($estimate = 1.673 \pm 0.837$, $P < 0.001$; Figure 5). There was also a significant interaction between time period and species, where *T. tandanus* displayed relatively smaller change in average hourly ROM between periods, compared to *M. peelii* ($estimate = -1.526 \pm 0.6$, $P = 0.011$; Figure 5). Permutational multivariate analyses (permANOVA) of variation in spatial occupancy day-1 showed significant differences between individual fish but no significant effect of species/population source for either river (Table 2).

Long-term movements in response to environmental changes

There was considerable variation in the relationships between days detected in array and the environmental predictor variables across the two species (Table 3). Riverine *T. tandanus* remained in the array significantly longer than translocated individuals. *Tandanus tandanus* were more likely to be within the fine scale array in the Mehi River, but *M. peelii* were less likely. River temperature had a significant negative effect on both *T. tandanus* and *M. peelii* for days in array, and for *M. peelii* these effects were stronger in the Mehi River. For *M. peelii*, daily river discharge had a significant negative effect on days detected in array, and this effect was also much stronger in the Mehi River for *M. peelii*. *Maccullochella peelii* spent significantly less time in the array as temperature increased, and this effect was greater in the Mehi River.

There were generally similar patterns in the direction of relationships (either positive or negative) between hourly rate of movement ($\log$ ROM) and environmental variables and morphology for both species (Table 3). Population source was not found to have a significant effect on *T. tandanus* and was excluded from the model. The main effects of river discharge, river temperature and river all had a significant effect on $\log$ ROM for both *T. tandanus* and *M. peelii*. $\log$ ROM was significantly higher in the Mehi River for both species. There was an overall significantly positive main effect of river discharge on both *T. tandanus* and *M. peelii* $\log$ ROM (Figure 6 A and C), but this was significantly lower in the Mehi River

for both species. Similarly, river temperature had an overall significant positive main effect on both *T. tandanus* and *M. peelii* log ROM (Figure 6 B and D) and again this effect was significantly lower in the Mehi River for both species. Both species showed a significant increase in log ROM during the night and dusk diel periods.

Habitat selection

Habitat use analysis based on EDA ratios indicated non-random selection of some habitat types for both species (Figure 7). Permutational multivariate analysis of variance (permANOVA) revealed significant differences in habitat type selection between rivers ($P=0.002$) and fish population sources (riverine and lacustrine *T. tandanus* and riverine *M. peelii*; $P=0.001$). *Maccullochella peelii* tended to actively select deeper areas and lower water velocities and preferred areas with higher riparian canopy cover (Figure 7B). There was also differences between rivers in terms of habitat selection. *Tandanus tandanus* showed significant differences between populations in selection of most habitat types (Figure 7A). For example, lacustrine fish from the Gwydir and Mehi showed greater selection for deeper areas, whereas riverine fish selected shallower areas. All *T. tandanus* showed greater selection for higher riparian canopy cover, submerged over hanging vegetation and the lowest water velocities. However, translocated Gwydir *T. tandanus* showed significantly higher selection for the areas of highest water velocity, compared to resident *T. tandanus*.

Discussion

For both species, average activity was lower for day-1 than for the subsequent five month period. A similar result has been found previously in other fish species (Mulcahy 2003; Thoreau and Baras 1997), and in *T. tandanus* (Butler et al. 2009), where lower activity was reported in post-surgery holding tanks. This change in behaviour is likely due to the stress effects of handling, anaesthesia and surgery. Jepsen et al. (2001) found chinook salmon surgically implanted with telemetry tags possessed elevated cortisol levels, a hormone that is mainly released at times of stress, up to 24 hrs after surgery. In telemetry studies, the current practice for removal of data that may be affected by tag implantation varies from no time omitted (Hannah and Rankin 2011), the first four hours omitted (Furey et al. 2013), or the first 24 hours omitted (Zhang et al. 2015). Given the lower activity rates observed for

day-1 in this study, including data from the first 24 hours post-tagging and release may risk underestimating or misinterpreting fish activity.

Riverine *T. tandanus* and *M. peelii* mostly showed limited movement during day-1, whereas translocated *T. tandanus* were far more mobile. Many left the array and five of the total seventeen were detected over one kilometer downstream. Significantly lower swimming performance has been noted for externally tagged Atlantic salmon smolts (McCleave and Stred 1975) and juvenile white sturgeon (*Acipenser transmontanus*) (Counihan and Frost 1999). Given the lower activity rates found in fish on the first day after tag implantation, it is possible that the translocated lacustrine fish may not be familiar with a riverine environment and are passively following the flow of the rivers downstream. Dispersion of spatial occupancy was significantly different for individuals in day-1, but not among species or population source, suggesting that neither species were aggregating, nor avoiding specific groups. This is an expected result as *T. tandanus* are not known to show intra-specific aggression outside of the nesting period or schooling behaviours (Pusey et al. 2004).

Days detected within the fine scale arrays did vary significantly between population sources in *T. tandanus*, with riverine fish remaining within the array significantly longer than translocated fish. All translocated *T. tandanus* were detected by terminal receivers. Of the total 17 translocated fish, 14 were detected by both upstream and downstream terminal receivers in their respective rivers, showing bi-directional linear movements outside of the array. The increased exploratory behaviour shown by translocated individuals may be due to homing behaviour. Gardner et al. (2015) noted common bream (*Abramis brama*) returning to capture sites from a 35 km downstream translocation within a range of 6 to 24 days, whereas fish released at the capture site showed significantly lower levels of movement. This pattern of translocated fish making long-range homing movements, while resident fish show little movement, is repeatedly supported in the literature (Clough and Beaumont 1998; Crook 2004; Huchzermeyer et al. 2013; Ingram et al. 2013; Irving and Modde 2000). Fish translocated in this study were of lacustrine origin and were translocated over 150 km, which may have contributed to the fish's bi-directional movements, rather than directly to their capture site.

In this study, *M. peelii* were less likely to remain within the a fine scale array as river discharge and temperature increased, and effects of both of these parameters were

stronger in the Mehi River. Changes in river discharge and temperature are known triggers of broad-scale movement for many riverine fish species (Amtstaetter et al. 2016; Harding et al. 2017; Reinfelds et al. 2013; Reynolds 1983). This effect may have been stronger in the Mehi River owing to its intermittent nature. The Mehi River receives far less water than the Gwydir River (Figure 2), and therefore *M. peelii* may have a stronger response to discharge in order to explore or relocate to previously inaccessible stretches of river. *Maccullochella peelii* in the Gwydir River were all detected for the first time by terminal receivers during the species' known breeding period (Koehn and Harrington 2006). As *T. tandanus* are typically a non-migratory fish (Koster et al. 2015; Reynolds 1983), it may be the case that *T. tandanus* spent more time in the fine scale array in the Mehi River for the same reason *M. peelii* spent less time in the array in the same river. The more intermittent nature of the Mehi River may have reduced *T. tandanus* movement outside of the array.

Population source had no effect on *T. tandanus* rates of activity over the entire five months as a whole. Although we know of no other published studies on the fine scale movements of translocated freshwater fish, there are similarities to our findings among studies on broad scale movement of fish after translocation. Gardner et al. (2015) reported that whilst translocated common bream (*Abramis brama*) exhibited higher linear range sizes than resident fish, total distance moved was not significantly different. Given the larger number of detections by terminal receivers for translocated *T. tandanus* (Figure 3A), it appears likely that translocated individuals in this study also have higher linear range sizes than resident individuals. We also showed *T. tandanus* and *M. peelii* were significantly more active at dusk and night compared with other diel periods. Observations of nocturnality for both species have been reported previously (Koehn 2009b; Koster et al. 2015). We found a significant effect of increases in river discharge and temperature on fish activity rates for both species, although the magnitude of this effect varied between rivers, with significantly higher activity rates in the Gwydir River than in the Mehi River. This likely relates to the substantially higher discharge and temperature in the Gwydir River compared with the Mehi (Figure 2) and indicates the important role that both environmental factors have in stimulating movement activity. The overall increase in ROM as river discharge increases may be explained by increased foraging at higher flows, as seen in other fish species (e.g. Smith and Li 1983). The lesser effect noted in the Mehi River may have been due to the generally

narrower channel morphology. Identical river discharge in the Gwydir river would result in a lower water velocity. Given energetic expenditure for fish increases with water velocity (Hinch and Rand 1998; Tudorache et al. 2008) and the recorded preference for lower water velocity in this study, discharge in the Mehi River may sooner reach a critical threshold where the fish find it too energetically demanding to forage. During the study period, river temperatures reached a maximum of approximately 25 ° C. It is well established that for poikilotherms, metabolism and activity increase with ambient temperature (Clarke 2006). In *M. peelii*, Thiem et al. (2018) noted that activity increased up to 20 ° C in river temperature. Significant differences in habitat selection was observed between rivers as well as fish population sources (riverine and lacustrine *T. tandanus* and *M. peelii*). *Maccullochella peelii* tended to select deeper areas, woody structures, and undercut banks. These preferences have been reported previously (Koehn 2009a). *Maccullochella peelii* in both rivers displayed a preference for the highest and lowest areas of water velocity, over intermediate areas. This pattern may have been observed due to the increased foraging potential at higher river flow (Smith and Li 1983). *Maccullochella peelii* may seek the slowest water during non-foraging behaviours and the fastest water while foraging. *Tandanus tandanus* displayed considerable differences between rivers and population sources. Riverine *T. tandanus* actively selected undercut banks and root masses significantly more than translocated fish. Koster et al. (2015) found that riverine and palustrine individuals made extensive use of macrophytes and wood structures. Macrophytes are rare within the Gwydir and Mehi River study reaches, however they were abundant at the lacustrine capture site of the translocated fish (Copeton Dam). Lacustrine individuals may have developed different habitat preferences based on the availability of habitat types in their former range. Similarly, translocated fish preferred deeper water, compared to riverine fish. *Tandanus tandanus* have been observed predominately inhabiting shallow, littorial habitats in previous studies (Koster et al. 2015). Due to the relatively shallow channel morphology of the Gwydir and Mehi rivers, translocated fish may be selecting depths that would be relatively littorial in their original lacustrine environment.

In this study, we demonstrated the utility of acoustic fine scale arrays for quantifying the fine scale movements and habitat use of riverine *M. peelii* and translocated and riverine *T. tandanus* within an Australian lowland river system . Our findings indicate that a period of at

least one day be omitted from studies investigating fine scale movements, to ensure that estimates of movement behaviour are not biased by the short-term effects of fish capture, handling and tag implantation. In terms of fish activity rates, both species responded to environmental variations almost identically and translocated *T. tandanus* responded to environmental variations in the same way as residents *T. tandanus*, even though they had little or no previous exposure to such conditions, such as high flows. However, habitat preferences did vary among species and population sources. We recommend that managers should consider the habitat of sites receiving translocated individuals to ensure maximum retention of the translocated population. There are many complimentary conservation techniques, such as stocking of juvenile fish and habitat restoration, that may also yield positive outcomes for the species, but the information gained from this study also helps to advance conservation efforts by quantifying the expected outcomes of translocating adult fish to supplement local populations.

Acknowledgments

The funding for this project was provided by the Holsworth Wildlife Research Endowment and the Commonwealth Environmental Water Office (CEWO) as part of the Long Term Intervention Monitoring (LTIM) project. H. Pederson provided invaluable advice on the design of VPS arrays within rivers and data processing. We thank D. Roberts for in-kind support and his advice throughout the study, and John St Vincent Welch, Harry Vievers and Ian Wooden for their help with fish collection and surgery. We would also like to thank Brett Parker, Vanessa Reis and Helder Espírito-Santo for their help with deployment and downloading of the acoustic arrays. This study was conducted under ethics permit ENV/06/16/AEC (Griffith University Animal Ethics Committee).

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Author contribution

Conceived and designed the investigation: LCB, GLB, NRB, SEB, MJK

Performed field and/or laboratory work: LCB, GLB, TE, MJK.

Analyzed the data: LCB.

Contributed materials, reagents, and/or analysis tools: LCB, GLB, TE, MJK.

Wrote the paper: LCB, GLB, TE, NRB, SEB, MJK.

Tables

Table 1. Number and source of fish tagged and released in the Gwydir and Mehi rivers.

	Gwydir River	Mehi River
Resident <i>T. tandanus</i>	3	0
Translocated <i>T. tandanus</i>	7	10
Resident <i>M. peelii</i>	5	5

Table 2. PermANOVA testing for differences in spatial occupancy of fish according to species/population source and fish id in each river.

Permutational multivariate analysis of variance			
Source	df	F	P
<i>Gwydir River</i>			
SppPopSource	2	2.379	0.162
FishID(SppPopSource)	10	12.945	0.001
Residual	185		
<i>Mehi River</i>			
SppPopSource	1	4.137	0.082
FishID(SppPopSource)	12	19.369	0.001
Residual	202		

Table 3. Parameter estimates ($\pm$ s.e.) and significance levels from LMMs relating to environmental variables and morphology, and fish movements across two species. Also shown are attributes of the random effects from each LMM, including number of fish IDs in each model, among-fish ID standard deviation and number of observations.

	Days detected in array				log ROM			
	<i>T. tandanus</i>		<i>M. peelii</i>		<i>T. tandanus</i>		<i>M. peelii</i>	
	Estimate	<i>P</i>	Estimate	<i>P</i>	Estimate	<i>P</i>	Estimate	<i>P</i>
Fixed effects								
River discharge	-0.001 $\pm$ 0.001	0.851	-0.001 $\pm$ 0.001	0.002	0.003 $\pm$ 0.001	0.001	0.007 $\pm$ 0.001	<0.001
River temperature	-0.162 $\pm$ 0.035	<0.001	-0.125 $\pm$ 0.047	0.007	0.019 $\pm$ 0.004	<0.001	0.028 $\pm$ 0.003	<0.001
Diel period - day					0.048 $\pm$ 0.032	0.137	-0.378 $\pm$ 0.024	<0.001
Diel period - dusk					0.097 $\pm$ 0.043	0.023	0.106 $\pm$ 0.03	<0.001
Diel period - night					0.097 $\pm$ 0.032	0.003	0.155 $\pm$ 0.023	<0.001
River - Mehi	3.729 $\pm$ 0.734	<0.001	-7.549 $\pm$ 1.22	<0.001	0.659 $\pm$ 0.243	0.01	1.99 $\pm$ 0.4	<0.001
Weight			0.001 $\pm$ 0.001	<0.001				
Sex - male					0.107 $\pm$ 0.225	0.642		
River - Gwydir: Population source - riverine	6.236 $\pm$ 0.489	<0.001						
River discharge: Sex - male			0.001 $\pm$ 0.001	0.003	0.009 $\pm$ 0.001	<0.001		
River discharge: River - Mehi	-0.001 $\pm$ 0.001	0.154	0.001 $\pm$ 0.001	0.008	-0.013 $\pm$ 0.001	<0.001	-0.006 $\pm$ 0.001	<0.001
River temperature: River - Mehi	-0.074 $\pm$ 0.045	0.101	0.162 $\pm$ 0.055	0.003	-0.029 $\pm$ 0.011	0.01	-0.122 $\pm$ 0.01	<0.001
River discharge: Population source - riverine	-0.001 $\pm$ 0.001	0.156						
River temperature: weight			-0.001 $\pm$ 0.001	<0.001				
Random effect (fish ID)								
N (fish ID)		20		10		18		9
Standard deviation		0.496		1.18		0.356		0.54
Observations		3120		1560		5157		9368

Figure captions

Figure 1. (A) Location of Gwydir River system in the MDB (grey), with state borders. (B) Study area and upper catchment of the Gwydir River system, showing Copeton Dam (upstream) and weirs within the study reach (black blocks) and fine scale array locations (grey arrows). Locations of the Gwydir River array (C) and Mehi River (D) array, with acoustic receivers denoted by Δ .

Figure 2. A) Hydrograph and B) water temperatures for Gwydir and Mehi rivers from May to November 2016.

Figure 3 Days detected in array for *T. tandanus* (A) and *M. peelii* (B). Each closed circle represents at least one detection in the VPS array on a given day, and open circles representing detections by terminal receivers. First upstream terminal receiver detection denoted by Δ and first downstream terminal receiver detection denoted by ∇ .

Figure 4. Track maps of average hourly positions for (A) Gwydir and (B) Mehi River fish for first 24 hours after release. Hour 0 – green, hour 24 – red.

Figure 5. Boxplot of hourly mean ROM for day-1 and total duration of study (five months). Median shown as horizontal bar, two hinges at 25th and 75th percentiles and whiskers at max and min.

Figure 6. Partial residual plots of hourly average *log* ROM vs hourly river discharge and hourly river temperature, with lines of best fit across Gwydir and Mehi Rivers for *T. tandanus* (A, B) and *M. Peelii* (C, D), respectively. Shaded band denotes 95 % confidence interval.

Figure 7. Habitat type selection (Mean $\pm$ s.d.) for different population sources (riverine and lacustrine) of (A) *T. tandanus* and (B) *M. peelii* within the Gwydir and Mehi rivers. Habitat type selection was based on Euclidean distance analysis (EDA) ratios of microhabitat types available. Values < 1 indicate increased use relative to availability, while values > 1 indicate avoidance. EDA ratios for each habitat type that were significantly different between rivers and population sources ($p < 0.01$) are indicated by *.

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Title:

Reservoir to river: Quantifying fine-scale fish movements after translocation

Date:

2019-07-26

Citation:

Carpenter-Bundhoo, L., Butler, G. L., Espinoza, T., Bond, N. R., Bunn, S. E. & Kennard, M. J. (2019). Reservoir to river: Quantifying fine-scale fish movements after translocation. *ECOLOGY OF FRESHWATER FISH*, 29 (1), <https://doi.org/10.1111/eff.12490>.

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