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# Fine-scale acoustic telemetry in a riverine environment: movement and habitat use of the endangered Mary River cod *Maccullochella mariensis*

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ABSTRACT: Understanding movement and habitat requirements of endangered species is critical to conservation management. We evaluate fine-scale acoustic telemetry to study breeding-related movement and habitat use of the endangered Mary River cod *Maccullochella mariensis* in a riverine environment and, in relation to key environmental variables, to inform management. Movement activity varied significantly in relation to water temperature and diel period, and spatial occupancy and habitat selection varied substantially in relation to the nesting behaviour of Mary River cod. Important nesting habitat included a large hollow log mid-channel and well-shaded logs and log jams adjacent to the river bank. Extrapolating this information to the general population was inhibited by relatively small sample sizes, due in part to the restricted spatial scale of the hydrophone arrays and longitudinal movements of tagged fish beyond the acoustic range of our array. Notwithstanding this, our results demonstrate that (1) fine-scale acoustic telemetry can quantify complex biological behaviours in riverine environments; (2) Mary River cod require specific environmental stimuli and habitat to support the reproductive cycle; and (3) changing environmental conditions may influence Mary River cod behaviour, and understanding this response is necessary for sustainable management. Findings from this study can inform future applications of this methodology in riverine environments and contribute to the development of management strategies and habitat restoration activities supporting the recovery of Mary River cod populations.

KEY WORDS: Native fish · Mary River cod · Endangered species · Conservation management · Acoustic telemetry · Fish habitat

## 1. INTRODUCTION

Understanding movement and habitat use of endangered species is necessary for conservation management (Cooke et al. 2016). The interaction of habitats and environmental conditions provides a matrix of opportunities for biota, with the quality and availability of specific habitats dictating movement, condition, growth and reproductive success (Lucas & Baras 2001). Loss of these key habitats can affect the long-term viability of populations; therefore, quantitative knowledge regarding habitat use and move-

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ment behaviour of endangered species is critical for conservation managers (Crook et al. 2015).

The development of acoustic telemetry has provided researchers with the opportunity to quantify animal movements in aquatic ecosystems (Espinoza et al. 2011, Ellis et al. 2019). In riverine environments, this technology has primarily been used to quantify broad-scale movements, where hydrophone arrays are deployed at fixed intervals over long stretches of river. Less commonly, fine-scale acoustic telemetry involving deployment of multiple hydrophones in arrays within shorter river reaches (typically <1 km; hereafter termed fine-scale array) enables the triangulation of acoustic tag transmissions to determine the precise position of animals within 2- or 3-dimensional space (Roberts et al. 2017, Carpenter-Bundhoo et al. 2020). Spatio-temporal positioning of wild animals in natural environments provides unprecedented ecological information on habitat use and movement behaviour in response to environmental stimuli.

Potential trade-offs involved in the application of coarse- versus fine-scale acoustic telemetry arrays in riverine environments require consideration. Although the potential for information gain is high, the cost and consequent limited extent of fine-scale arrays increase the likelihood that animals will exit arrays, precluding the location of animal positions. The risk that tagged animals move outside of the detection range of a fine-scale array may depend on multiple factors, including time of year, flow-related hydrological connectivity and species-specific traits such as home range extent, life-history, age and size. These are important considerations when designing telemetry studies on endangered aquatic species, given the costs involved in establishing fine-scale arrays and the potential stress to animals associated with capture, tagging and release (Cooke et al. 2013).

Accelerated declines in biodiversity observed within freshwater environments (Tickner et al. 2020) highlight the need to address key knowledge gaps for freshwater species at risk. The Mary River cod *Maccullochella mariensis* is a large freshwater fish endemic to the Mary River in South East Queensland, one of the fastest urban growth areas in Australia. Flow alteration, habitat degradation, introduced fishes and overfishing have contributed to the listing of Mary River cod as Endangered under the Australian Government's Environmental Protection and Biodiversity Conservation Act 1999 and the IUCN Red List of Threatened Species (Brooks et al. 2019). These anthropogenic impacts threaten the viability of Mary River cod by fragmenting populations and reducing the availability of spawning habitat and reproductive opportunities.

This study evaluated the utility of fine-scale acoustic telemetry in a riverine setting to quantify movement and habitat use of the Mary River cod during its breeding period. Movements and habitat use were quantified over 2 breeding seasons and assessed in relation to environmental conditions. Key findings from this research will inform the potential application and trade-offs involved in using fine-scale acoustic telemetry in research programs for endangered aquatic species, including the conservation management of Mary River cod.

## 2. MATERIALS AND METHODS

This study focused on one of the major tributaries of the Mary River, Obi Obi Creek, which has a 61 000 Ml storage (Baroon Pocket Dam) in the upper reach (Fig. S1 in the Supplement at www.int-res.com/articles/suppl/n042p125_supp.pdf). Twenty-four Mary River cod (335–850 mm total length, 568 ± 168 mm [mean ± SD]) were captured from Obi Obi Creek in June 2013 and surgically implanted with Vemco V13-1x transmitters.

Fine-scale movements of Mary River cod were quantified using Vemco VR2W hydrophone arrays established at 2 sites (Fig. S1) over 2 consecutive years (2014 and 2015). For Site 1, 6 hydrophones were deployed in a grid pattern over a 150 m reach of Obi Obi Creek. For Site 2, 13 hydrophones were deployed in an array over a 350 m reach of the creek. Hydrophones located upstream and downstream of fine-scale arrays (hereafter termed terminal hydrophones) were also used to determine the presence of Mary River cod in areas immediately surrounding each array over the study period.

TD-Diver dataloggers (Van Essen Instruments) were installed in Obi Obi Creek to monitor water levels and water temperature over the study period (Fig. S2). Rainfall observations were sourced from the Bureau of Meteorology's Climate Data Online website (http://www.bom.gov.au/climate/data/) for the Kenilworth Township station (040106). Diel period was calculated using the insol package in R (Corripio 2014).

Bathymetry and habitat data for Site 2 were collected using a boat mounted with a Brookhouse NMEA 0183 datalogger coupled to a Garmin® GPS and depth sounder. Data for Site 1 were collected using a Leica TCR1205+ total station and corner cube prism attached to a levelling staff, due to lack of GPS reception at this site. Water depth and habitat features were recorded along bank-to-bank cross-sections for the entire array areas.

Raw acoustic data downloaded from fine-scale arrays were provided to Vemco for processing with the Vemco positioning system (VPS) algorithm (Espinoza et al. 2011); detections of Mary River cod within hydrophone arrays, and at terminal hydrophones, were also assessed to determine occupancy of individuals within the fine-scale arrays and in the immediate surrounding areas.

Rate of movement (ROM, m min$^{-1}$) was calculated for individual fish as a measure of activity within the arrays using the adehabitatLT package (Calenge 2006) in R version 3.6.0 (www.r-project.org). ROM responses to environmental factors including river height, water temperature and diel period were assessed using a mixed-effects linear regression model, using the lme4 package in R (Bates et al. 2015).

Spatial occupancy of Mary River cod was examined using kernel utilisation distributions (KUDs) in the adehabitatHR package (Calenge 2006) in R. For each cod, 95 and 50% KUDs were produced from VPS positions, and data were displayed for 3 time periods related to potential cod nesting behaviour, defined based on prior knowledge of timing and temperature required for the onset of nesting, and on inspection of changes in movement activity of tagged fish. The 3 time periods were specified as pre-nesting (22 August–25 September 2014 and 19 August–2 October 2015), nesting (25 September–14 October 2014 and 2–21 October 2015) and post-nesting (14 October–21 December 2014 and 21 October–18 December 2015).

Variation in habitat selection before, during and after the potential nesting period was assessed using Euclidean distance-based analysis (EDA) (Conner & Plowman 2001). Discrete habitat features within fine-scale arrays were interpolated using universal kriging from sampled transect points within the ArcGIS 10.4 Geospatial Analyst extension (ESRI). EDA ratios were calculated as the mean observed distance (from VPS positions) divided by the mean expected distance (from random points) to each habitat type, 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).

For more detailed methodology, refer to Text S1 in the Supplement.

## 3. RESULTS

### 3.1. Movement behaviour

Seventeen of 24 tagged Mary River cod were detected within 2.5 km of hydrophone arrays across both study sites (Fig. S3). Of these, fine-scale movement behaviour of 4 fish was quantified for the breeding seasons of 2014 and 2015 (Fig. S3). Two tagged cod (ID 29388 and ID 29405) were detected within the Site 2 fine-scale array over the study period (Fig. S3); however, due to high site fidelity within complex habitat (undercut bank and log jam) and detection on receivers with unsatisfactory triangulation, positioning was not possible through the VPS system. Manual tracking with the VR100, however, indicated movement activity of these cod within the complex habitat.

ROM (m min$^{-1}$) analyses indicated distinct patterns of movement activity among the 4 cod within the fine-scale arrays. Cod 29385 (535 mm) exhibited no distinct temporal changes in ROM over the study period (Fig. 1A), and Cod 29391 (535 mm) showed similar activity from 22 August to 11 September 2014 before leaving the array for the remainder of the study period (Fig. 1B, Fig. S3). Cod 29413 (850 mm) and Cod 29408 (490 mm) demonstrated periods of high ROM in September followed by a marked reduction throughout October (Fig. 1C,D). Reduced ROM coincided with a post-winter increase in water temperature to approximately 19°C, followed by a relative increase in ROM by November.

Regression analysis of the effects of environmental variables on ROM for all 4 cod revealed significant effects of water temperature and diel period, whereas river height was not selected in the best model (Table 1). ROM decreased significantly ($p < 0.01$) with increasing water temperature (Fig. 2A) and during the day diel period (Fig. 2B).

### 3.2. Spatial occupancy and habitat selection

KUD analysis of fish positions (Fig. 3) and EDA of habitat selection (Fig. S4) for 3 Mary River cod revealed different spatio-temporal patterns of occupancy and habitat use. Cod 29385 exhibited relatively broad spatial occupancy patterns (Fig. 3A–C) and active selection of logs and rocks in shallow water (Fig. S4A), with relatively little variation over the study period. In contrast, spatial occupancy and habitat selection for Cod 29413 and Cod 29408 changed substantially between the 3 time periods

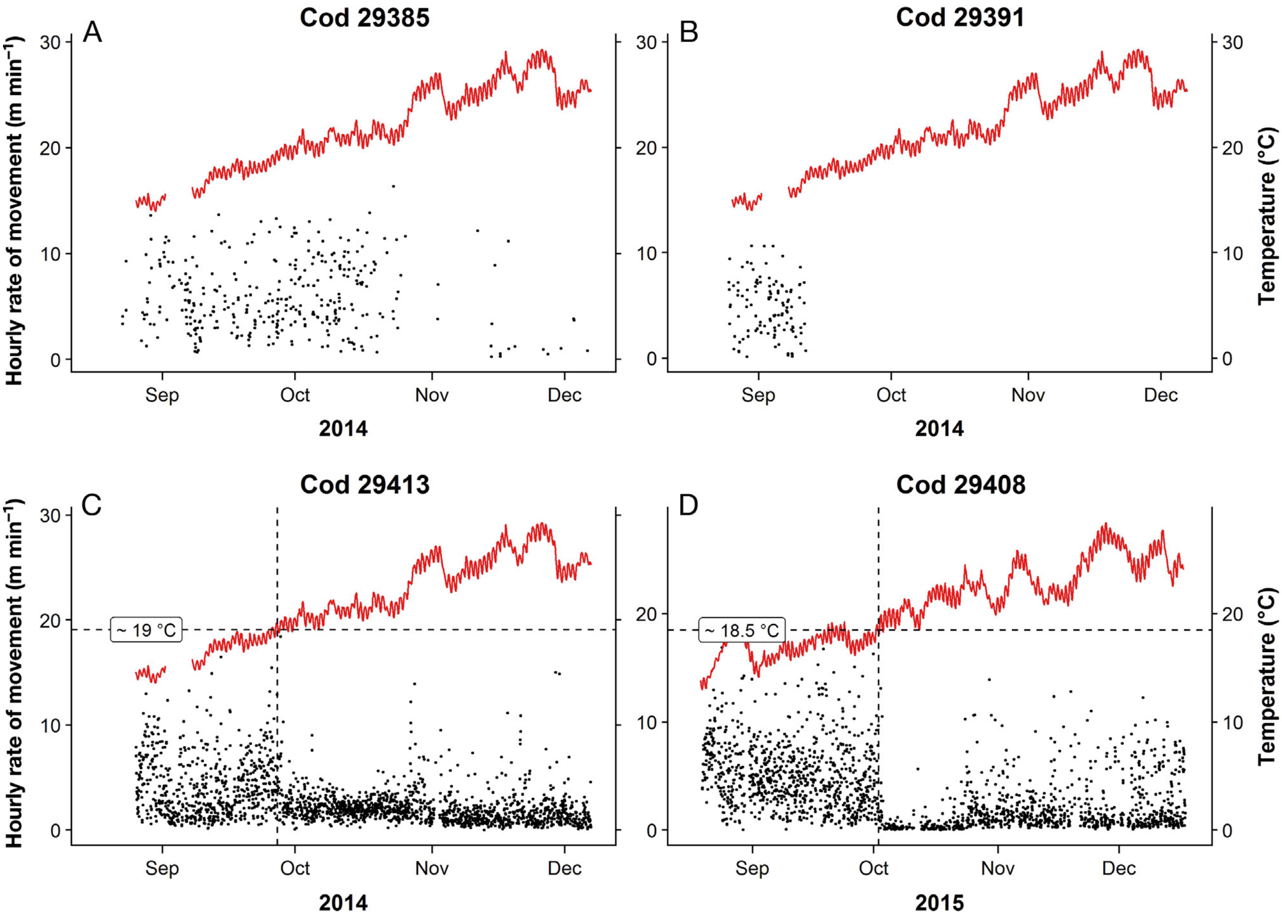


Fig. 1. Hourly average rate of movement for (A) Cod 29385, (B) Cod 29391 and (C) Cod 29413 from the Site 1 (adopted middle thread distance [AMTD] 18 km) array from August to December 2014 and for (D) Cod 29408 from the Site 2 (AMTD 13 km) array from August to December 2015. Dashed lines indicate water temperature (text box) at commencement of presumed nesting period

Table 1. Coefficients of linear mixed model (family = Gaussian) relating environmental variables to Mary River cod activity (log rate of movement, m min$^{-1}$) within the Obi Obi Creek fine-scale array. **Bold**: significance ($p < 0.01$)

| Effect | Estimate ± SE | p |
|---|---|---|
| Fixed | | |
| Water temperature | −0.11 ± 0.01 | **<0.01** |
| Day | −0.47 ± 0.05 | **<0.01** |
| Dusk | −0.11 ± 0.06 | 0.08 |
| Night | −0.02 ± 0.05 | 0.72 |
| Random (fish ID) | | |
| N (fish ID) | 4 | |
| SD | 0.28 | |
| Observations | 4339 | |

related to potential nesting behaviour. Cod 29413 demonstrated very restricted spatial occupancy (Fig. 3D–F) and close affinity with a large submerged hollow log mid-channel, particularly during the nesting period (Fig. S4B). Cod 29408 demonstrated broad use of surrounding habitat in the pre- and post-nesting period (Fig. 3G,I, respectively). During the nesting period, however, this cod occupied a small area (Fig. 3H) of shallow littoral habitat in the waterhole, in close association with logs, log jams and overhanging riparian vegetation (Fig. S4C).

## 4. DISCUSSION

In this study, we validate fine-scale acoustic telemetry as a viable technique for quantifying movement behaviour and habitat use of an endangered fish in a riverine environment. The ability to generalise this information to populations over larger spatio-temporal scales was, however, inhibited by rela-

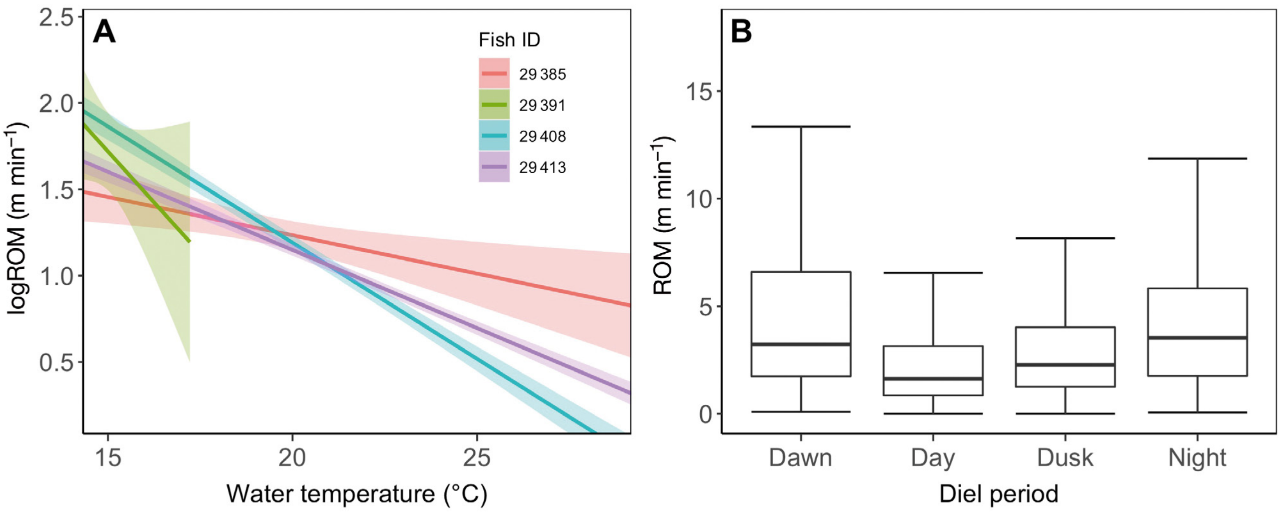


Fig. 2. Variation in hourly average rate of movement (ROM) of Mary River cod in response to environmental changes in Obi Obi Creek over the study period. (A) Partial residual plot based on the mixed-effects model of log hourly average ROM as a function of water temperature, showing regression lines and 95% CIs for each fish ID (random effect levels) for sampled temperatures. (B) Box and whisker plots of hourly average ROM of fish during diel periods. Solid lines in boxes are medians, box ends are 25$^{th}$ and 75$^{th}$ quartiles and whiskers show maximum and minimum values

tively small sample sizes. This was due in part to the restricted spatial extent and detection efficiency of the hydrophone arrays in confined and complex riverine habitats and the unanticipated longitudinal movements of tagged fish outside of the array detection areas.

We initially tagged and released 24 individual cod, 17 of which were detected within close proximity of the 2 fine-scale arrays; however, many of these individuals were not detected within the fine-scale arrays. Extended dry periods as observed prior to the 2014 breeding season (DNRME unpubl. data) likely reduced foraging opportunities and fish condition, and also inhibited access to critical habitats. Furthermore, the extended dry period with minimal baseflows at Site 2 in 2015 (DNRME unpubl. data) may have physically prevented tagged cod residing in adjacent habitats from accessing our fine-scale array. This highlights the challenges involved in using fine-scale acoustic telemetry in riverine environments.

Our study demonstrated that movement activity of Mary River cod varied significantly in relation to water temperature and diel period, and differences in activity, spatial occupancy and habitat selection observed may be related to nesting behaviour of this species. Relatively high movement activity observed at the start of the breeding period (August and September) may be driven by increased feeding, territoriality and nesting habitat selection. This movement behaviour has also been observed in other Australian freshwater cod and attributed to competition for limited nesting sites (Simpson & Mapleston 2002, Butler & Rowland 2009). We also found significant decreases in movement activity and discrete spatial occupancy, indicative of nesting behaviour, coinciding with post-winter water temperatures rising to approximately 19°C. This observation is supported by previous studies indicating that temperature is a key breeding trigger for Australian freshwater cod (Cadwallader & Gooley 1985, Rowland 1993, Simpson & Mapleston 2002, Humphries 2005, Koehn & Harrington 2006, Butler & Rowland 2009).

Movement activity was significantly lower during the day due to the nocturnal foraging strategies of Australian percichthyids, including Mary River cod (Simpson & Mapleston 2002). All Australian freshwater cod species are apex predators that utilise ambush strategies to capture their prey. Preference for complex habitats (e.g. submerged boulders, logs and undercut banks) that provide cover support this predation strategy. Habitats selected by Mary River cod in this study included deep water, undercut banks, riparian overhangs and large woody debris. During the nesting period, 2 Mary River cod (29413 and 29408) showed close affinities for a large hollow log mid-channel and for well-shaded logs and log jams adjacent to the river bank, respectively. These fish likely established nests in these habitats as they offer hard surfaces for the deposition of eggs that are easier to maintain and provide protection from potential predators of eggs and larvae (Butler & Rowland 2009).

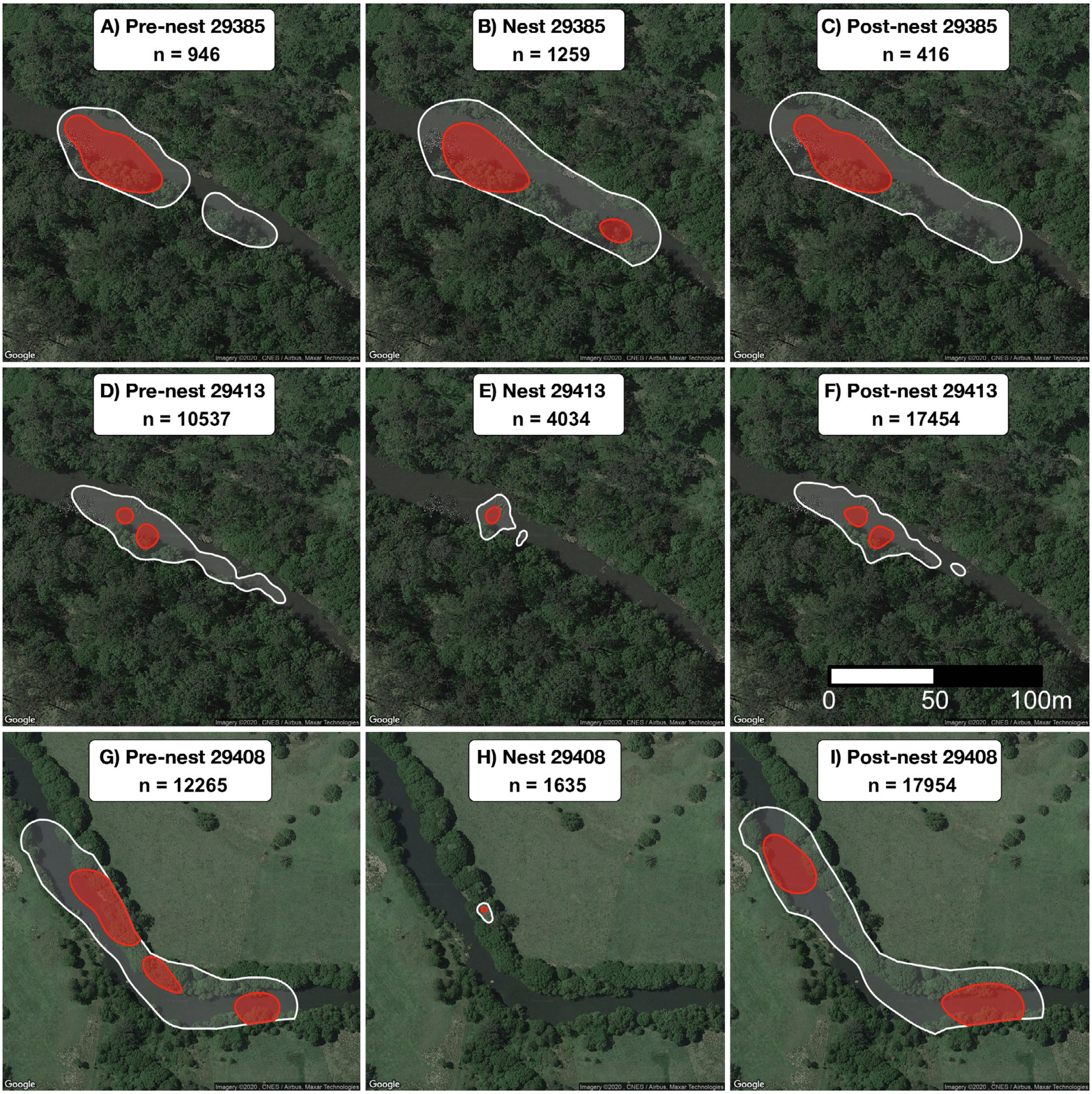


Fig. 3. Kernel utilisation distributions (KUDs) for (A–C) Cod 29385, (D–F) Cod 29413 and (G–I) Cod 29408. The pre-nesting, nesting and post-nesting periods are shown left to right for each fish, with the number of detections in each period also shown. White and red polygons represent 95 and 50% KUDs, respectively

## 5. CONCLUSIONS

Knowledge of animal movement and habitat use is critical to inform natural resource management strategies that balance human and environmental needs. This study demonstrated fine-scale acoustic telemetry as a viable technique for studying movement and habitat use of an endangered fish. However, our study also highlighted some of the potential challenges involved. These were related to the high probability of fish moving beyond the detection zones of the fine-scale arrays and the difficulty in accurately triangulating some fish positions within complex instream structures. These findings can inform future applications of fine-scale acoustic telemetry in riverine environments and contribute to the development of management strategies and habitat restoration activities for Mary River cod.

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