

Small home range in southern Australia's largest resident reef fish, the western blue groper (*Achoerodus gouldii*): implications for adequacy of no-take marine protected areas

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Abstract. No-take marine protected areas (MPAs) represent an effective biodiversity conservation tool for a range of species including resident reef fishes that are intrinsically vulnerable to overfishing and other localised impacts. The western blue groper (*Achoerodus gouldii*) is the largest permanent-resident reef teleost in southern Australian waters and has the second-oldest recorded age of any labrid at 70 years. Acoustic telemetry was used to investigate whether adult *A. gouldii* can be effectively protected within adequately sized no-take MPAs. Ten passive acoustic receivers tracked the movements of 15 *A. gouldii* individuals (69–112-cm total length; 7–31-kg weight) at a site off north-western Kangaroo Island, South Australia. Most of the fish displayed high site fidelity (91–100% residence time for 10 of the 11 fish with useful data) for a narrow strip of fringing coastal reef (~1-km length by ~40-m width) throughout a 12-month period. Mean home-range along-shore length and area were estimated at 1076 ± 83 m (s.e.), and $45\,188 \pm 3497$ m², respectively ($n = 11$ fish with useful data). Comparison with other resident temperate-reef teleosts indicated no relationship between fish length and home-range area, and that *A. gouldii* has a relatively small home range. The high site fidelity and small home range of adult *A. gouldii* individuals makes localised populations amenable to a high level of protection within no-take MPAs.

Additional keywords: barotrauma, diel activity, venting.

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Introduction

The implementation of adequately sized and appropriately located no-take marine protected areas (MPAs) is now considered to be an effective biodiversity conservation tool for managing human processes (Lester *et al.* 2009). Previous studies have indicated that there are both ecosystem- and population-scale benefits of spatial protection of marine teleosts through the implementation of restrictions to seascape usage (McClanahan and Arthur 2001; Halpern 2003; Edwards and Plagányi 2011). Reef fishes that have the characteristics of large maximum size, slow growth, high longevity, late maturation and site residency

are intrinsically vulnerable to overfishing (Cheung *et al.* 2007). Adequately sized no-take MPAs can provide a high level of protection from fishing for populations of resident reef fishes (Barrett 1995; Kramer and Chapman 1999; Edgar *et al.* 2004). Indeed, large resident fishes often show a positive response to protection from fishing inside no-take MPAs (e.g. Molloy *et al.* 2009; Russ and Alcala 2011). Such protection from fishing is particularly important for species that also have poor post-release survival rates such that they cannot be adequately protected through conventional fisheries-management regulations that disallow take of selected species in a multi-species fishery,

but which do not remove the risk of incidental capture and therefore fishing mortality, e.g. species-specific spatial closures, non-permanent closures and protected-species status.

The western blue groper (*Achoerodus gouldii*) (Family Labridae) is endemic to southern Australia where it is most abundant on shallow (<60-m depth) reefs along the south coasts of Western Australia (WA) and South Australia (SA) (Shepherd and Brook 2007; Gomon *et al.* 2008). On these temperate reefs, it is the largest teleost that can be considered to be site-attached or a permanent-resident, reaching a maximum size of 175-cm total length (TL) and almost 40 kg (Hutchins and Swainston 2002; Gomon *et al.* 2008). The western blue groper has the second-greatest recorded age of any labrid at 70 years and is a protogynous hermaphrodite, with all individuals starting life as females and some later changing to males (Coulson *et al.* 2009; Cossington *et al.* 2010). Sexual maturation of females occurs at an average age of ~17 years, with sex change to males occurring at ~35 years (Coulson *et al.* 2009). A combination of being long-lived, late-maturing, slow-growing and resident makes *A. gouldii* intrinsically vulnerable to overfishing (see Cheung *et al.* 2007), with protection of the large males being especially important (Coulson *et al.* 2009). Indeed, anecdotal evidence of the disappearance of large males in the central parts of SA during the 1960–1970s from spearfishing (Johnson 1982) led to the subsequent protection of the species in that region under local fisheries legislation. In the remainder of SA, there are currently restrictive regulations on take of western blue groper where relatively small numbers are still harvested by charter and recreational fishers (Jones 2009; Knight 2010). Unquantified levels of non-targeted catch-and-release also occur within the protected zone. In south-western WA, *A. gouldii* contributes to an important local fishery, but is considered to be close to or fully exploited (Coulson *et al.* 2009). Pogonoski *et al.* (2002), in a review of the conservation status of Australian fishes using IUCN criteria, considered *A. gouldii* to be at lower risk (conservation dependent). Reductions in the numbers of large *A. gouldii* may have implications for the ecology of temperate reefs because they have a wide-ranging diet and a variety of feeding modes (Shepherd 2005), and a low natural-mortality rate (Coulson *et al.* 2009).

In addition, *A. gouldii* is highly vulnerable to barotrauma and post-release survival rates may be low (McLeay *et al.* 2002). Thus, post-release mortality is a factor that must be considered in the long-term persistence of *A. gouldii* populations that are subjected to any type of catch-and-release fishing activity, and the current protection status in parts of SA does not actually equate to zero fishing mortality. In contrast, the use of adequately sized and appropriately located no-take MPAs where fishing activity is totally prohibited is likely to be one of the most effective management and conservation tools for adult *A. gouldii* and other species with similar life-history characteristics.

One of the main considerations when designating a no-take MPA to protect resident fishes for biodiversity conservation purposes is the size of the area needed within the context of the extent of movement, migration, philopatry and site fidelity of the species of concern (Kramer and Chapman 1999). Time spent outside these spatially managed areas increases the probability of deleterious impacts at the individual and population scale,

because of anthropogenic impacts including fishing and potentially coastal development and coastal pollution. Within SA, the subadult and adult stages of *A. gouldii* form social groups of one dominant adult male, one to two adult females, and several subadult females. Adults are thought to be permanent residents (Shepherd *et al.* 2002; Shepherd 2005; Shepherd and Brook 2005) and males are considered to be territorial (Shepherd 2005). Thus, the adult stage appears highly amenable to protection from fishing and other localised impacts within no-take MPAs. The outer boundaries of 19 multiple-use marine parks have recently been proclaimed within SA. These marine parks will include numerous no-take zones. At least 12 of the parks overlap the known range of *A. gouldii* in SA. If the no-take zones are adequately sized and appropriately located to include the home ranges of adult *A. gouldii*, it is assumed that a proportion of the spawning stock and recruits would be protected.

Whereas there is already some information on the home-range size of *A. gouldii* (Shepherd *et al.* 2002; Shepherd 2005; Shepherd and Brook 2005), long-term data on home-range size and site fidelity are unavailable, as previous data were collected using scuba observations which are by nature spatially and temporally limited. Acoustic telemetry is a proven methodology for determining the size of reef fish home ranges and site fidelity through tagging and tracking of movements over spatial scales of kilometres and temporal scales of months to years (e.g. Tolimieri *et al.* 2009; Green and Starr 2011; Farmer and Ault 2011). Results obtained with this technology have been used to discuss the effectiveness and performance of MPAs for reef fishes (e.g. Lowe *et al.* 2003; Topping *et al.* 2005; Parsons *et al.* 2010).

In the present study, we used acoustic telemetry to investigate whether adult *A. gouldii* individuals have potential for a high level of protection within adequately sized no-take MPAs. Specific aims of the study were to (1) determine long-term home-range size, (2) determine long-term site fidelity, (3) relate spatial activity patterns to available reef habitat, and (4) compare home-range size with those of other resident temperate-reef teleosts. Specific hypotheses related to the aims were that adult *A. gouldii* would (1) have a well defined home (and core) range, (2) display a high degree of site fidelity, (3) show a strong preference for reef over sand habitat and (4) have a home-range size that is proportional to their large body size.

Materials and methods

Field site

The study was undertaken at Harveys Return on north-western Kangaroo Island, SA (Fig. 1), where *A. gouldii* is protected under local fisheries regulations. The Harveys Return site is characterised by a relatively narrow strip of coastal reef (20–90-m width) that slopes into a sandy bottom with patchy, sparse seagrass (*Posidonia* spp.) at ~12-m depth (Fig. 1). Aerial photography and diver observations indicate that the sand–seagrass habitat extends offshore away from the reef edge for at least 1 km (Fig. 1).

Tracking equipment

Ten VEMCO (VEMCO Division AMIRIX Systems Inc., Nova Scotia, Canada) VR2W receivers were deployed at the field site,

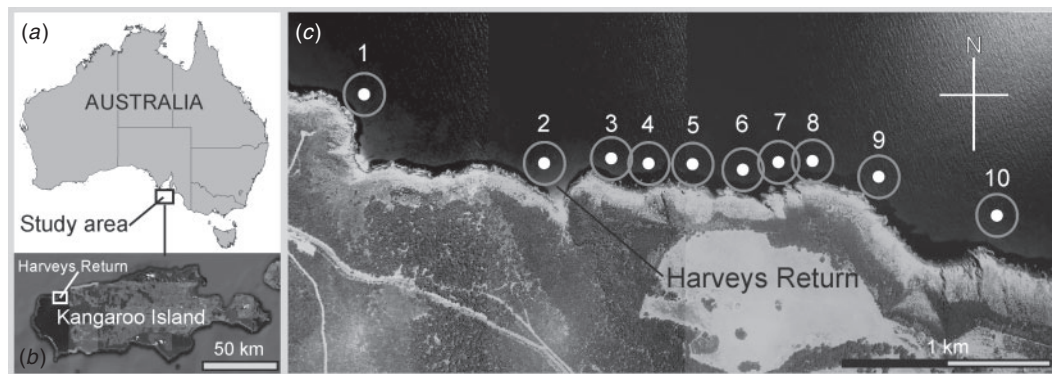


Fig. 1. Maps showing (a) the general location of the study area within Australia, (b) the location of Harveys Return on north-western Kangaroo Island in South Australia, and (c) the locations of the 10 receivers (1–10) along shore adjacent to Harveys Return. Note the dark band of fringing coastal reef and the receivers deployed on the sand adjacent to the reef. The rings around the receivers represent a 100-m detection radius.

Table 1. Details of the 15 *Achoerodus gouldii* individuals tagged within the receiver array at Harveys Return, South Australia

NR = nearest receiver to place of capture, TL = total length. Fish 4 and Fish 7 had pressure-sensor transmitters. Dates are day/month/year. Y = yes, N = no

Fish no.	NR	TL (mm)	Weight (kg)	Sex	Vented (Y/N)	Date tagged	Last day detected	Total no. days detected
1	5	810	11.5	M	Y	20/01/2009	22/01/2009	3
2	3	840	12.8	M	Y	20/01/2009	07/05/2010	472
3	6	740	8.7	F	N	20/01/2009	07/05/2010	472
4	3	710	7.7	F	N	16/02/2009	07/05/2010	445
5	3	810	11.5	F	N	16/02/2009	07/05/2010	441
6	3	715	7.9	F	N	16/02/2009	04/05/2010	401
7	3	970	19.9	M	N	17/02/2009	07/05/2010	445
8	8	690	7.1	M	Y	17/02/2009	07/05/2010	445
9	8	800	11.1	F	Y	17/02/2009	19/11/2009	142
10	8	990	21.1	M	Y	17/02/2009	07/05/2010	445
11	8	1080	27.5	M	Y	17/02/2009	17/02/2009	1
12	5	1120	30.8	M	Y	18/02/2009	25/02/2009	6
13	4	950	18.7	M	N	19/02/2009	07/05/2010	443
14	4	800	11.1	F	Y	19/02/2009	07/05/2010	409
15	4	740	8.7	F	N	19/02/2009	07/05/2010	443

and, in total, 15 individually coded VEMCO transmitters ($n = 13$, V13-1H, $n = 2$, V13P-1H, nominal delay 180 s for both types, estimated tag life 533 and 504 days, respectively, and power output 153 and 158 $1 \mu\text{Pa}$ @ 1 m, respectively) were surgically implanted in 15 *A. gouldii* individuals. The two V13P-1H transmitters were fitted with pressure sensors set for a depth range of 0–50 m, which covered the range of depths found at the study site. The pressure tags were used to monitor whether the fish might move offshore into deeper water, away from the coastal reef.

A V13-1H transmitter with a fixed delay of 5 s was used to determine the effective range of receivers throughout the array. A nominal 200-m inter-receiver spacing was subsequently chosen to ensure significant overlap between receivers during poor acoustic conditions. A ‘sentinel transmitter’ (V9P-S256, nominal delay 120s) was attached ~1 m above R6 to examine changes in detection frequency that would be expected through time (Payne *et al.* 2010).

Acoustic receivers were deployed on sand ~50–100 m offshore from the edge of the coastal reef in 12–18-m depth.

Receivers were coated in anti-fouling paint, and then affixed to a 1.65-m-long steel post that was hammered into the substratum to a depth of at least 0.6–0.8 m. An initial six receivers (R3–R8 deemed the ‘middle part of the array’, Fig. 1) were deployed ~200 m from each other on 19–21 January 2009 and encompassed a total distance of 940 m. Because the initial six receivers were not encompassing the full extent of the tagged-fish home ranges, an additional four receivers (R1–2, R9–10) were deployed on 29 April 2009 at distances of ~400 and ~1200 m from each end of the original array (Fig. 1). Thus, the distance between the two furthest receivers was ~3.2 km, providing an acoustic coverage of ~3.4 km of coastal reef (Fig. 1). Receivers were downloaded periodically on 28 April 2009, 20–21 October 2009 and 7 May 2010, when the study was terminated.

Acoustic tagging

Fish were tagged between 20 January 2009 and 19 February 2009 (Table 1). All fish were captured using baited circle and J-style hooks on monofilament line from depths of <20 m.

Where possible, efforts were made to slowly retrieve the hooked fish to the surface to reduce the degree of barotrauma. Once landed, using a soft rubber sling, each fish was transferred to a steel tub containing an oxygen-enriched solution of 30 ppm eugenol (AQUI-S, AQUIS-S NZ, Wellington, New Zealand) for anaesthetic induction and the sling was also placed on the surface of the solution to reduce visual stimulation during induction, which took 10–20 min. Any fish showing symptoms of barotrauma (bulging eyes, taut body wall, swollen or even prolapsed cloaca) were ‘vented’ (see Wilde 2009); a hypodermic needle (18 gauge, 1.5 inch) was inserted into the swim bladder by using a perpendicular lateral approach ~5–10 cm dorso-cranially to the base of the pectoral fin. Venting was deemed complete and the needle removed once the excess air from the swim bladder had been fully expelled, as seen by the slowing of air bubble production from the needle hub when held under water.

Once surgical anaesthesia had been achieved, as judged by lack of a righting reflex and failure to respond to stimuli, the fish were placed on a padded cradle in dorsal recumbancy. Anaesthesia was maintained using a recirculating pump system (~10 L per minute) from the induction sump tank below, with the eugenol concentration further diluted to 15 ppm. Passage of water over and coverage of gill arches was achieved by regulating the operculum opening and subsequent drainage back into the sump.

Surgical skin preparation was achieved with a light iodine (Betadine, Mundipharma B.V., Hoevelaken, The Netherlands) scrub. The removal of a few scales allowed a small incision (~20-mm length) to be made with a scalpel blade (#10) along the ventral midline, and continued through the linea alba into the coelom, proximal to the cloaca at ~1/4 of the distance from the cloaca to the base of the ventral fins. An antibiotic soaked (Nuflor LA, Florfenicol, Schering-Plough Animal Health, Kenilworth, NJ, USA) transmitter was inserted directly into the coelomic cavity where it became free-floating. Skin and body wall closure was undertaken using 2/0 PDS (polyglactin 910, Ethicon, a monofilament absorbable suture material, Markham, Ontario, Canada) in a simple interrupted suture pattern. Fish were also marked with a pair of external dart tags (Hallprint, Hallprint Pty Ltd, Hindmarsh Valley, South Australia; 85 mm long, 2 mm diameter) that were inserted into the dorsal musculature. The external tags were used to reduce the risk of re-capturing the same fish and to enable scuba divers to observe the post-release behaviour of tagged fish. Fish were then placed into a recovery bath containing clean seawater that was regularly flushed and aerated using a deck hose.

During recovery, the fish were monitored for a return of reflexes and movement of the opercula, fins and body in a coordinated fashion. Total body length was measured to the nearest 5 mm, which allowed weight to be estimated (Coulson *et al.* 2009) and administration of a long-acting antibiotic intramuscularly (Florfenicol, 30 mg kg⁻¹). The likely sex of the fish was also recorded on the basis of body colouration; *A. gouldii* is sexually dichromatic, with adult females usually green in colour and adult males blue (Coulson *et al.* 2009). Once fully recovered after 10–40 min, fish were released at the surface near the location of their capture.

General data analysis

Initially, the entire dataset for all 15 fish and 10 receivers was binned per fish and date. This binned dataset was then used to plot a time-series of detections for each fish throughout the study period. All subsequent analyses were restricted to the 12-month or 374-day period during which we obtained results from the full 10-receiver array (29 April 2009 to 7 May 2010). This excluded Fish 1, Fish 11 and Fish 12 for which no data were received after 22 January 2009, 17 February 2009 and 25 February 2009, respectively.

Home and core ranges

To test the hypothesis that *A. gouldii* has a well defined home range, we needed a measure of activity space. Home range can be defined as the area used by an individual during normal activities and is commonly defined as the area in which an individual spends 95% of its time. The core range is an area of more intense use, often defined as the area in which an individual spends 50% of its time (Tolimieri *et al.* 2009). Because of the linearity of the receiver array along the coast, traditional home-range techniques such as kernel-density estimates could not provide effective area-based home-range estimates. The use of activity centres (Simpfendorfer *et al.* 2002) was also decided against because not all receivers in the array had over-lapping detection ranges (especially for the outermost receivers; Fig. 1), and we lacked control data for weighting mean activity-centre values that account for environmental effects (e.g. depth, rugosity) on detection efficiency across the array (e.g. Farmer and Ault 2011). Instead, as a proxy for activity space, we used the linear extent of the coast utilised by each fish across the entire study period, to calculate two different estimates of home- and core-range size, namely, along-shore length of coast, and area of reef.

Home- and core-range lengths were calculated as the sum of distances (plus 200 m) between the receivers that accounted for 95% and 50% of all detections, respectively. Calculations commenced with the receiver with the greatest number of detections and then progressed to the adjacent receiver with the next highest total, and so on. The additional 200 m was added to account for the distance (i.e. 100 m) at which detection frequency begins to decline significantly (C. Huveneers, unpubl. data). Thus, in the case of a single receiver that accounted for the entire home or core range (i.e. 100% of detections), the range would be 200 m. Home- and core-range areas were calculated by multiplying the range lengths by the mean width of the reef (42 m). The mean width of the reef where all fish had their home range was calculated by measuring the distance between the edge of the reef and the coastline at 10 different locations within the middle part of the array, on the basis of aerial photographs. This approach assumed that individuals utilise the entire width of the reef and do not leave the reef (which seemed appropriate, given our results and data limitations – see Results and Discussion).

To test the hypothesis that *A. gouldii* has a home-range size relative to its large body size, we made a comparison between our home-range estimate and several published values for cases that we believed to be comparable. Selection of published values used the following criteria: published in a mainstream

peer-reviewed international journal; study used acoustic tracking technology; study was on a temperate coastal-reef marine teleost that shows some residency; and mean values of home-range size and fish length were available in the paper.

Site fidelity

To test the hypothesis that *A. gouldii* has a high degree of site fidelity, we needed a measure of residence time. Residence time for each fish was calculated by dividing the total number of days with two or more detections in the middle part of the receiver array, by the total number of days analysed (374 days). A cut-off of two or more detections per day was utilised because this standard has been used in other studies (e.g. Green and Starr 2011) and VEMCO recommends caution with interpretation of single temporally isolated detections.

Diel patterns

Although we did not have any specific hypothesis concerning diel activity patterns, an analysis of this aspect of behaviour was conducted because there is a lack of published behavioural information for *A. gouldii* and acoustic data are amenable to this type of analysis. Nonetheless, Payne *et al.* (2010) demonstrated that caution must be exercised when interpreting diel activity patterns from acoustic detection data. Detections for each individual were summed for each hour of each day throughout the entire array, and mean detection frequency per hourly bin was then calculated for each individual. These detection frequencies were then divided by the grand mean detection frequency for each individual to get standardised detection frequencies that correct for the variable magnitude of detection patterns among individuals. Using data from our fixed-location sentinel transmitter, we employed the approached developed by

Payne *et al.* (2010) to correct for ambient changes in detection frequency. Data from the entire 6 months of deployment for the fixed-location transmitter were used in the correction.

Depth patterns

The percentage of total detections was plotted against depth for the two transmitters with pressure sensors (Fish 4 and Fish 7). The patterns from these two fish were used to infer general patterns of reef-habitat utilisation for the remaining fish without pressure sensors and to inform the calculations of core- and home-range areas.

Results

Capture, fish size and sex

Fifteen fish were tagged, ranging in size from 690 to 1120-mm TL and comprising eight males and seven females (Table 1). On the basis of Shepherd (2005) and Coulson *et al.* (2009), all of these fish were likely to be sexually mature and the five largest fish had a 95% probability of being male ($TL_{95} = 930$ mm, Coulson *et al.* 2009).

General patterns of detection

A total of 983 683 acoustic detections were recorded from the 15 fish during the 15-month study period (Fig. 2). At the time of the final download, 11 of the tagged fish were still being detected within the array (Fig. 2, Table 1). Most fish were detected at least once every day over the 12-month period when all 10 receivers were deployed (Fig. 2). In contrast, Fish 1, Fish 11 and Fish 12 were detected for just 3, 1 and 8 days post-tagging (Fig. 2, Table 1). Fish 9 was detected for 108 days post-release, but was then undetected for a period of 120 days

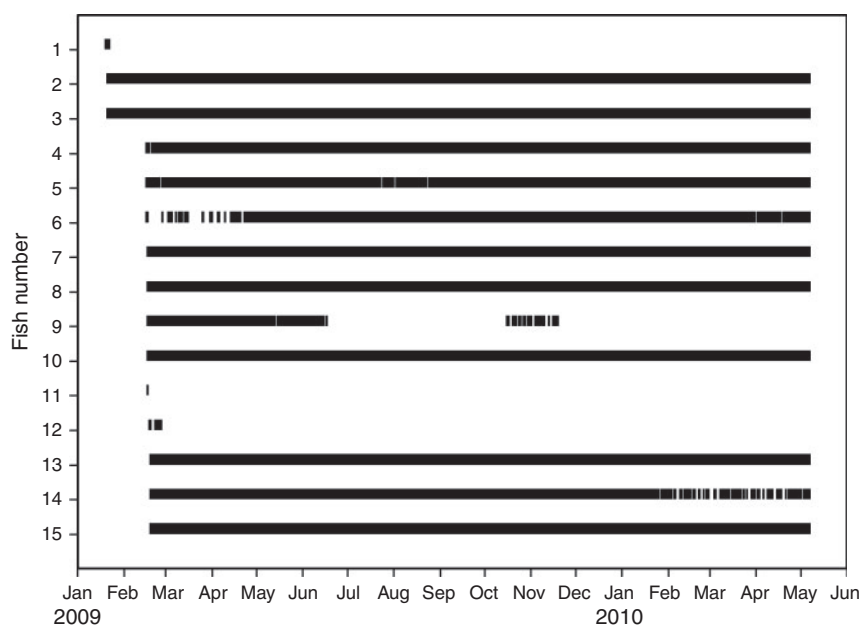


Fig. 2. Time series of all daily detections summed across all 10 receivers for each of 15 *Achoerodus gouldii* individuals tagged at Harveys Return, South Australia, between January 2009 and May 2010. The complete array of 10 receivers was in place from 29 April 2009 to 7 May 2010.

between 17 June 2009 and 16 October 2009. It was then detected again for 34 days between 16 October 2009 and 19 November 2009, after which detections ceased for the remainder of the study (Fig. 2).

Core- and home-range estimates

Spatial usage by individuals across the 10-receiver array was non-uniform (Fig. 3). We observed the following three main patterns: a uni-modal distribution of detections (Fish 2, Fish 3, Fish 4, Fish 14, Fish 15); a uni-modal distribution, but with a skew towards one end of the array (Fish 5, Fish 7, Fish 8, Fish 10); and a relatively uniform distribution across the array (Fish 6, Fish 9, Fish 13). In 75% of the tagged fish, the receiver that logged the most detections was the same as or adjacent to the capture and tagging location (Fig. 3). Estimates of mean core- and home-range along-shore lengths were 436 ± 45 m (\pm s.e., range = 200–662) and 1076 ± 83 m (range = 594–1526), respectively. Mean core- and home-range areas were $18\,308 \pm 1899$ m² (\pm s.e., range = 8400–27 804) and $45\,188 \pm 3497$ m² (range = 24 948–64 092), respectively ($n = 11$, with a mean TL of 822 mm; Table 2). Thus, as hypothesised, most fish had well defined home ranges. There were no significant differences between sexes for any of the parameters of range (all Student's *t*-tests, $P > 0.05$). Fish 6 was excluded from the calculations because most of its detections occurred near the edge of the array (Fig. 3) and it may have been utilising habitat outside of the eastern end of the array. There was no significant linear relationship between home-range length or area and TL ($P > 0.05$).

Site fidelity

As hypothesised, most fish showed a high degree of site fidelity. Apart from Fish 6 and Fish 9, there was minimal evidence that any tagged individuals left the 10-receiver array during the 12-month period that it was in place. The number of detections at the geographical extremes of the array (R1 and R10) was relatively low (<2% of total detections) or completely absent in all fish, except for Fish 6 which had its peak of activity at R10 (46% of detections, Fig. 3). Residence time calculated for the middle of the array (R3–8; excluding Fish 6) was >91% for 10 of the 11 fish, with 100% residence time for seven of these. The main exception to this general pattern was Fish 9 that had a residence time of 15%.

Activity patterns

Diurnal patterns of standardised detection frequencies among individuals were similar, with the relative frequency of detections increasing dramatically at dawn and decreasing quickly at dusk (Fig. 4). Patterns of detection by the sentinel transmitter (data not presented here) showed that the diurnal pattern observed for the fish was accurately described by the receivers and was not due to other environmental factors (see Payne *et al.* 2010). In addition to the diurnal pattern, there was a pattern of total daytime detections related to sex (Fig. 3); during the 12-month period when the entire array was in place, the mean number of detections was significantly greater for males (109 665) than females (44 379) (Student's *t*-test, $t = -2.64$, d.f. = 9, $P < 0.05$).

Depth and habitat utilisation

The two fish with pressure-sensor tags (Fish 4 and Fish 7) showed a distinct uni-modal pattern of detections versus depth (Fig. 5). Fish 4 spent the majority of time (58%) between 4–7-m depth, whereas Fish 7 spent most time (65%) at 8–10-m depth (Fig. 5). Nonetheless, as predicted, it was apparent that most of their time was spent on the reef habitat (which starts above ~12-m depth), with neither fish travelling beyond 20-m depth across the sand–seagrass habitat. Whereas Fish 4 utilised the entire depth range across the reef habitat, Fish 7 did not utilise the shallowest parts of the reef from 0- to 3-m depth.

Discussion

Site fidelity

Patterns of site fidelity among and within temperate-reef teleosts can be complex. For example, some species appear to be permanent residents (Barrett 1995; Lowe *et al.* 2003; Edgar *et al.* 2004), whereas others have a mix of resident and migrant individuals (Parsons *et al.* 2010; Green and Starr 2011). In our study, most fish had high residence times and could therefore be considered as permanent residents for the 12-month study period; a result that supported our prediction. The one exception to the general pattern was Fish 9 which had a residence time of just 15%. The reason for this pattern remains unexplained. Whenever Fish 9 'disappeared' or 'reappeared' for an extended period (Fig. 3), it did so near the middle of the array rather than at the western or eastern extremes of the array. Thus, unless the pattern of detections was due to a faulty transmitter, it appears that Fish 9 moved offshore away from the coastal reef to another location. Fish 9 was a large female (800-mm TL) and it is possible that this fish was seeking to undergo sex change and establish a new territory. Coulson *et al.* (2009) estimated that at 821-mm TL, 50% of *A. gouldii* undergo sex change. Nonetheless, it is likely that social and behavioural factors, rather than just size, mediate the timing of sex change in species such as *A. gouldii* (Gillanders 1999).

Core and home ranges

As predicted, most of the acoustically tagged *A. gouldii* had discrete core and home ranges. Our estimates of home-range length are well aligned with predictions from the regression relationship of home-range length versus fish length as described by Kramer and Chapman (1999) for coral reef fishes ($\log_{10}y = -3.75 + 2.35\log_{10}x$, where y is mean home-range length (m) and x is mean fork length (mm)); for our mean size of 822-mm TL (where TL = fork length), predicted home-range length = 1259 m versus observed = 1076 m). However, attempts by us to determine a similar relationship for temperate-reef teleosts by using published telemetry data from Australia, North America and New Zealand (see Table 3) failed to find any significant relationship between home-range area and fish length ($y = 110129 - 815.74x$, where y is the mean home-range area (m²) and x is fish length (mm), $r^2 = 0.0071$, $P > 0.05$; note that there were insufficient published data on home-range length to test for a relationship between the home-range length and fish length). Nonetheless, it is apparent that the fish we studied were far larger than any others we compared, but that the home-range area was not particularly large (Table 3); the next two largest fish

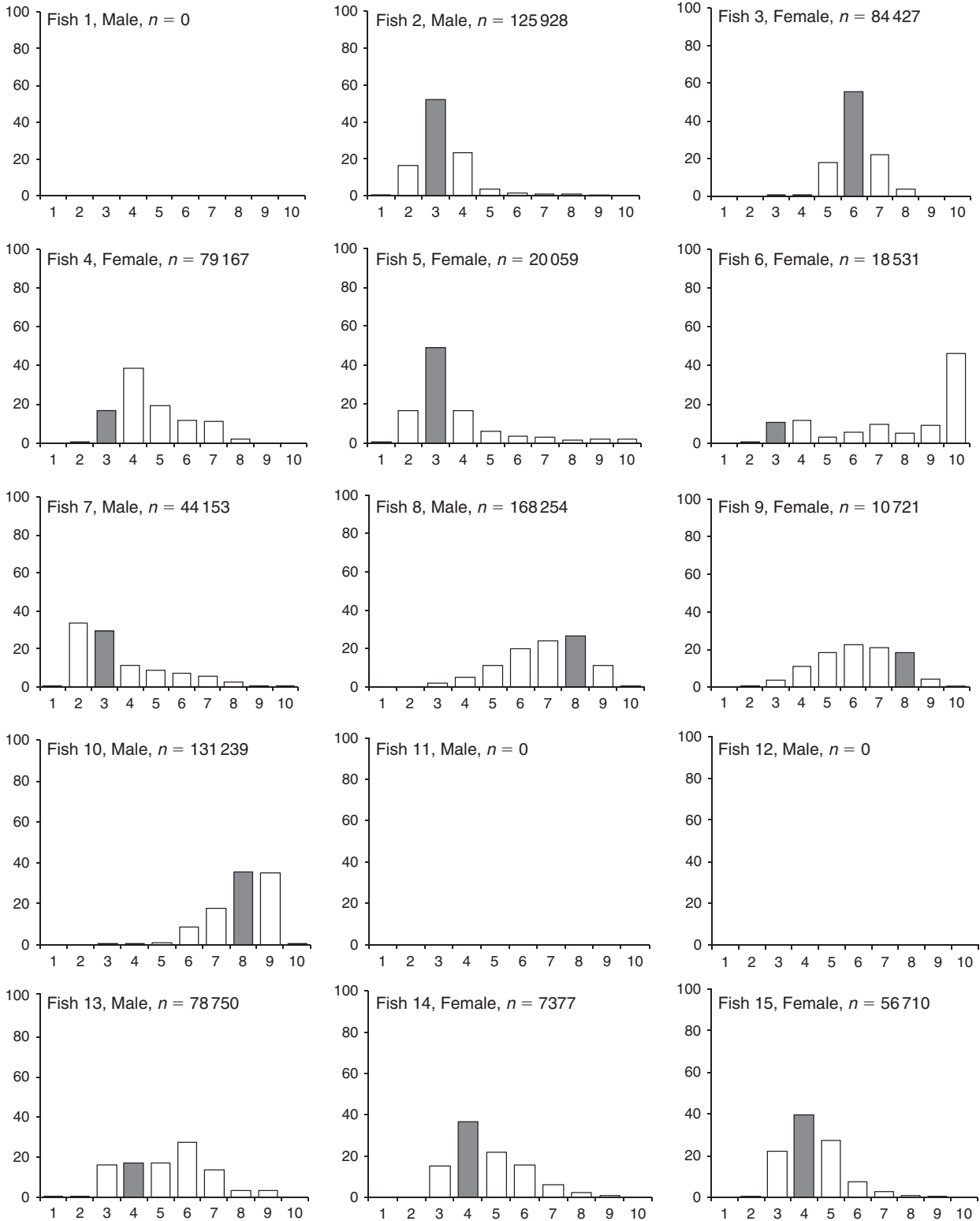
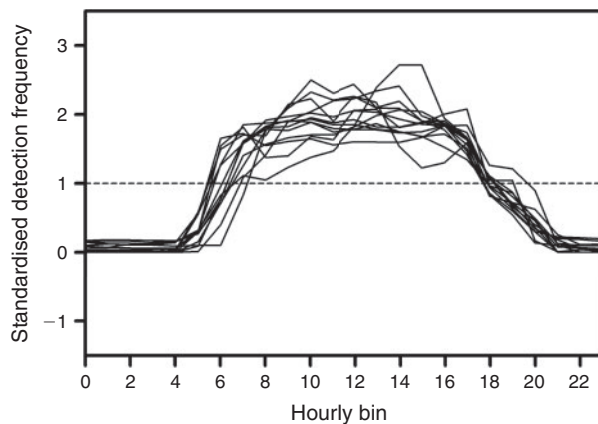


Fig. 3. Distribution of detections for 15 *Achoerodus gouldii* individuals across the 10-receiver array (1–10) at Harveys Return, South Australia, during the period 29 April 2009 to 7 May 2010. Values are the proportions of total detections (shown as n for each fish) at each receiver. Fish 1, Fish 11 and Fish 12 had no detections during the 12-month period used for analysis. Grey columns represent the receiver closest to the location of fish capture. See Table 1 for fish-code details.

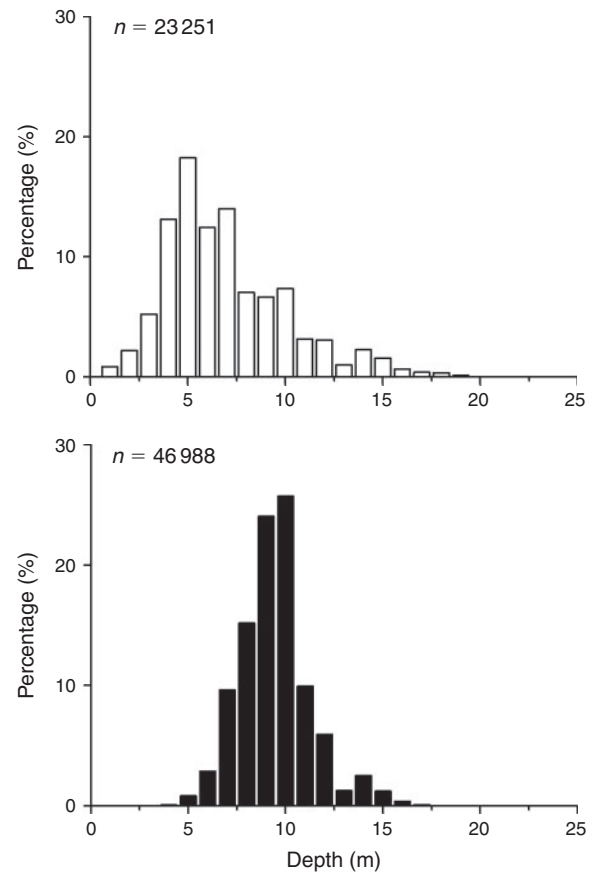
Table 2. Estimates of core- and home-range sizes for *Achoerodus gouldii* at Harveys Return, South Australia

Fish no.	Along-shore length (m)		Area (m ²)	
	Core range 50%	Home range 95%	Core range 50%	Home range 95%
1	—	—	—	—
2	200	946	8400	39 732
3	200	594	8400	24 948
4	386	971	16 212	40 782
5	569	1526	23 898	64 092
6	—	—	—	—
7	569	1340	23 898	56 280
8	386	1313	16 212	55 146
9	504	1313	21 168	55 146
10	547	851	22 974	35 742
11	—	—	—	—
12	—	—	—	—
13	662	1157	27 804	48 594
14	386	971	16 212	40 782
15	386	853	16 212	35 826
Mean	436	1076	18 308	45 188
s.e.	45	83	1899	3497

**Fig. 4.** Diel patterns of standardised detection frequency for *Achoerodus gouldii* at Harveys Return, South Australia, throughout the monitoring period. Each trace represents an individual fish.

values plotted were both *Ophiodon elongatus*, with our fish 1.4 times longer than the largest of these two values and about double the length of most of the other species. Moreover, because our estimates of home range were likely to be overestimates and previous estimates range from 4000 to 78 000 m² (see below), it appears that contrary to our expectations, *A. gouldii* has a relatively small home range for such a large teleost.

Previous studies based on scuba observations indicated that home-range areas of large *A. gouldii* (>600 mm) were 4000–78 000 m² (Shepherd *et al.* 2002; Shepherd 2005; Shepherd and Brook 2005) and therefore our estimates of ~25 000–64 000 m² fall within that range for comparably sized fish. In terms of home-range length, Shepherd *et al.* (2002) reported males occupying ~80–120-m sections of coast at some

**Fig. 5.** Depth utilisation by two *Achoerodus gouldii* individuals at Harveys Return, South Australia. Upper panel = Fish 4, a female of 710-mm TL; lower panel = Fish 7, a male of 970-mm TL. Percentage data are based on the total number of detections at 1-m depth classes.

sites on Kangaroo Island (which were in topographical nature similar to our study site), but the mean home-range area was estimated to be just 4500 m² at these sites and their estimates were based on temporally limited observations. Our estimates of home-range length for coastal-strip reefs were much higher at ~600–1500 m. Unlike Shepherd (2005), we found no evidence of a relationship between home-range size and fish length. However, our range of fish lengths that returned useful data was narrow at 690–990 mm, and because this species can attain 1750 mm, it would be useful to study additional fish of >1000-mm length to estimate their home ranges, and determine whether home range increases with body size.

Our estimates of home range were likely to be over-estimates because of the spatial arrangement of the receiver array, the limitations of the technology used, the limited amount of depth data ($n = 2$ fish) and the calculation methodology used. Because of the close proximity of R3–R8 and the high detection range during suitable conditions (i.e. at least 300 m), simultaneous detections of individual fish would have occurred at two or more receivers (which is actually useful in an evenly spaced and overlapping array, see Simpfendorfer *et al.* 2002). However, in our case this overlap could potentially overstate the outer-range limits of individual fish. For example, some of the detections at

Table 3. Home range-area estimates from published acoustic-tracking data for resident temperate-reef teleosts
 Values for fish length and home-range area are mean values taken only from the fish that contributed to home-range outputs. FL = fork length, SL = standard length, TL = total length

Species name	Common name	Family name	Fish length (cm)	Home-range area (m ²)	Fish length measure	Notes	Habit	Study
<i>Achoerodus gouldii</i>	Western blue groper	Labridae	82.2	45 188	TL	TL = FL	Demersal	Present study
<i>Cheilodactylus fuscus</i>	Red morwong	Cheilodactylidae	28.4	3639	FL	Night	Demersal	Lowry and Suthers (1998)
<i>Cheilodactylus fuscus</i>	Red morwong	Cheilodactylidae	28.4	1865	FL	Day (non-acoustic data)	Demersal	Lowry and Suthers (1998)
<i>Ophiodon elongatus</i>	Lingcod	Hexagrammidae	55.4	2820	SL	Summer	Demersal	Tolimieri <i>et al.</i> (2009)
<i>Ophiodon elongatus</i>	Lingcod	Hexagrammidae	60.4	1139	SL	Winter	Demersal	Tolimieri <i>et al.</i> (2009)
<i>Pagrus auratus</i>	Snapper	Sparidae	34.1	264 934	FL	Non-reserve uni-modal residents	Demersal	Parsons <i>et al.</i> (2010)
<i>Pagrus auratus</i>	Snapper	Sparidae	36.3	454 327	FL	Non-reserve bi-modal residents	Demersal	Parsons <i>et al.</i> (2010)
<i>Pagrus auratus</i>	Snapper	Sparidae	35.9	278 893	FL	Reserve uni-modal residents	Demersal	Parsons <i>et al.</i> (2010)
<i>Pagrus auratus</i>	Snapper	Sparidae	35.9	18 648	FL	Tagged by feeding	Demersal	Parsons <i>et al.</i> (2003)
<i>Pagrus auratus</i>	Snapper	Sparidae	45.8	55 500	FL	Tagged by surgery	Demersal	Parsons <i>et al.</i> (2003)
<i>Paralabrax clathratus</i>	Kelp bass	Serranidae	31.3	3349	SL		Benthopelagic	Lowe <i>et al.</i> (2003)
<i>Sebastes caurinus</i>	Copper rockfish	Sebastidae	33.5	2448	SL	Summer	Demersal	Tolimieri <i>et al.</i> (2009)
<i>Sebastes caurinus</i>	Copper rockfish	Sebastidae	33.5	1868	SL	Winter	Demersal	Tolimieri <i>et al.</i> (2009)
<i>Sebastes maliger</i>	Quillback rockfish	Sebastidae	29.8	1463	SL	Summer	Demersal	Tolimieri <i>et al.</i> (2009)
<i>Sebastes maliger</i>	Quillback rockfish	Sebastidae	29.3	1706	SL	Winter	Demersal	Tolimieri <i>et al.</i> (2009)
<i>Sebastes melanops</i>	Black rockfish	Sebastidae	32.7	250 000	TL		Benthopelagic	Green and Starr (2011)
<i>Sebastes mystinus</i>	Blue rockfish	Sebastidae	35.6	8783	TL		Benthopelagic	Jorgensen <i>et al.</i> (2006)
<i>Semicossyphus pulcher</i>	California sheephead	Labridae	31.0	15 134	SL		Demersal	Topping <i>et al.</i> (2005)

R2 (Fig. 3) may have been from *A. gouldii* that were in fact situated on the reef along the eastern side of the bay at Harveys Return (and not on the western side adjacent to R2; distance was ~200 m from the eastern side to R2), where they could also have been detected by R3; the sandy bay at Harveys Return may have acted as a natural barrier to along-shore fish movement (see Barrett 1995). In addition, it is possible that individuals preferred discrete depth ranges across the reef (Fig. 5), and thus the assumption of a single reef width (= extent of the reef) to calculate home-range area may result in over-estimates of home-range area for some fish. However, given that only two fish had depth data, we had little alternative to the method used.

Hence, our estimates of home range are considered precautionary and suitable for informing processes for setting the maximum dimensions of no-take MPAs to achieve spatially explicit protection of this reef species. Furthermore, our estimates of home-range length are likely to be more accurate than those of home-range area, which integrated a higher degree of uncertainty because of the lack of data on individual depth usage across the reef. To determine more accurate estimates of home-range size and patterns of habitat usage, a triangulation system of receivers is required (e.g. Jorgensen *et al.* 2006; Espinoza *et al.* 2011).

Home-range size can vary between different locations within temperate-reef teleost species (Lowry and Suthers 1998). Our study and other previous work on the home-range size of *A. gouldii* have been conducted on coastal-strip reefs. The home range of this species has not been studied at deeper isolated offshore reefs, where they can occur to at least 50–60-m depth. Such reefs are beyond the capacity of scuba-diver observations or scuba-diver deployment of acoustic receivers. However, acoustic receivers with remote release mechanisms are available and these present a means of collecting movement and site-fidelity data from such locations.

Protection of fish within no-take MPAs

On the basis of our results and previous studies, adult *A. gouldii* fish can generally be considered as permanent residents with well defined home ranges; traits that are also observed in several other temperate labrids (Barrett 1995; Edgar *et al.* 2004; Topping *et al.* 2005). Thus, it should be possible to provide resident adult *A. gouldii* with total protection from localised impacts within adequately shaped and appropriately located no-take MPAs. On the basis of our mean values of home-range length (Table 2), a coastline length of 1.1 km would encompass 95% of activity for all of the tagged fish at our study location. Despite the majority of fish having relatively discrete core and home ranges, there was some variability (Table 2) and some fish displayed much wider movements along the reef system (e.g. Fish 6, Fish 8, Fish 9 and Fish 13), implying that such individuals would require larger no-take MPAs to fully encompass their movements.

Temperate-reef fishes can display considerable variability in home-range size among individuals at the same location (e.g. Lowe *et al.* 2003; Topping *et al.* 2005). An appropriately sized MPA needs to account for variability in home-range size and mode among individuals (Table 2, Fig. 3; see Tolimieri *et al.* 2009), so as to encompass a whole population of individuals or several social groups in species such as *A. gouldii*. A no-take

MPA would also require buffer distances at the edges to account for extremes in home-range movement, emigration and immigration along the reef due to possible changes in social-group structure, possible relocation of home ranges (e.g. Kramer and Chapman 1999; Parsons *et al.* 2003) and the capture of fish at the zone boundaries (e.g. Willis *et al.* 2003). Therefore, in a situation such as Harveys Return, a no-take MPA of several kilometres in length along the shore and several hundred metres in width offshore is likely to be required to protect this particular discrete aggregation of *A. gouldii*. However, this relatively small area alone is not likely to be sufficient to encompass all of the ontogenetically related processes that should be considered at the population level (see below), and the design theory of networking individual no-take areas with neighbouring protected areas needs to be considered in the context of achieving adequacy.

Achoerodus gouldii may undergo ontogenetically related movement from shallow sheltered reefs where juveniles occur to deeper exposed reefs where adults and subadults occur (Shepherd and Brook 2007). These locations can be separated by large distances, depending on the topography of the region (Shepherd and Brook 2007). The Harveys Return site and surrounding coastline is characterised by adult and subadult *A. gouldii*, with relatively few small juveniles (Shepherd and Brook 2007; S. Bryars, unpubl. data for Harveys Return). We do not know the source of juvenile recruits to the Harveys Return site. A no-take MPA at Harveys Return (or other similar locations that are separated from juvenile habitat) will only protect the adult and subadult fish and their associated habitat. Yet it is imperative that the juvenile areas are also protected to ensure a supply of recruits to the adult areas, as connectivity will be a critical factor in the long term effectiveness of any MPA network (Christie *et al.* 2010), including one aimed at protecting *A. gouldii*.

Diel patterns

All tagged *A. gouldii* individuals displayed a distinct diurnal pattern (Fig. 4). Examination of depth data from the two fish with pressure-sensor transmitters indicated that those two fish were not moving into deeper water offshore (and thus out of the receiver array) at night. Nor was there any evidence that fish were moving along shore (east or west) out of the array at night. Thus, it is most likely that the fish were residing in caves and crevices during the night, where they were undetectable to the receivers. The closely related eastern blue groper (*A. viridis*) shelters in caves and crevices at night (Ian Coulson, SARDI, Adelaide, pers. comm.), which may be a mechanism of predator avoidance or to reduce competition with other species that are nocturnal foragers.

Habitat utilisation

Depth-detection distributions showed that (as predicted) the majority of time was spent over the inshore reef habitat at the study site. Although the two depth-tagged fish also spent some time over the adjacent sandy-seagrass habitat, it was apparent that they never ventured >100 m away from the shelter and protection of the reef edge because all of the receivers were in depths of ≤ 18 m at a distance of ≤ 100 m from the reef edge and

no depth detections of >19 m were ever made. Despite only two fish being tagged with depth tags, it was clear that certain depths over the reef were preferred by each fish; Fish 7 (a medium-sized male) did not utilise the shallower parts of the reef, whereas Fish 4 (a large female) did. Large *A. gouldii* individuals appear to follow directed foraging paths within their home ranges (Shepherd 2005) and our observations on depth preferences are likely to be related to such behaviour. Clearly, the inclusion of suitable reef habitat is critical for the protection of adult *A. gouldii* inside no-take MPAs. However, the use of non-preferred sand habitat as a natural boundary for fish movements at the edges of no-take MPAs (see Barrett 1995; Farmer and Ault 2011) could also be employed for adult *A. gouldii*.

Survival of tagged fish

At the completion of our study, detections were no longer occurring for 4 of the 15 fish we tagged and released. Although it is impossible to know why these fish stopped from being detected, there are several possibilities including the following: the transmitters malfunctioned; the fish died as a result of handling stress; the fish died of natural causes; the fish were captured by fishers; or the fish left the acoustic array and did not return. Whereas all explanations are plausible, the sensitivity of *A. gouldii* to barotrauma was readily observed in our study, with half of the fish being vented before release; this was despite our best attempts to minimise stress through slow retrieval rates and capture in shallow water (<20-m depth). Thus, although Fish 9 may have left the array (see earlier), barotrauma could have contributed to the disappearance of Fish 1, Fish 11 and Fish 12, which were all vented (Table 1) but which had detections for just a few days post-release. Although each of these fish displayed external signs of barotrauma, these symptoms may not necessarily be a good indicator of post-release survival (Jarvis and Lowe 2008). Insights into the potentially deleterious effects of barotraumas on *A. gouldii* gained from our study need further consideration and should be the focus of dedicated fishery-dependent studies (see McLeay *et al.* 2002; Jarvis and Lowe 2008).

In summary, our study has provided long-term movement data for one of the largest temperate-reef teleosts so far tracked using acoustic technology. We were able to show that, as predicted, adult *A. gouldii* fish were permanent residents at our study site and that they had well defined home ranges that were strongly associated with the reef habitat. Although no relationship was found between home-range size and fish length across several temperate-reef teleost species, it is apparent that *A. gouldii* does not have a particularly large home range relative to its large size; this is especially so given that our estimates of home range were likely to be over-estimates. The high site fidelity and relatively small home-range size of *A. gouldii* makes it (along with several other southern Australian reef teleosts; see Barrett 1995 and Edgar *et al.* 2004) particularly amenable to protection from fishing and other localised impacts within relatively small no-take MPAs.

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