

# Passive acoustic telemetry reveals highly variable home range and movement patterns among unicornfish within a marine reserve

A. Marshall · J. S. Mills · K. L. Rhodes ·  
J. McIlwain

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**Abstract** Marine reserves are the primary management tool for Guam's reef fish fishery. While a build-up of fish biomass has occurred inside reserve boundaries, it is unknown whether reserve size matches the scale of movement of target species. Using passive acoustic telemetry, we quantified movement patterns and home range size of two heavily exploited unicornfish *Naso unicornis* and *Naso lituratus*. Fifteen fish (*N. unicornis*:  $n = 7$ ; *N. lituratus*:  $n = 4$  male,  $n = 4$  female) were fitted with internal acoustic tags and tracked continuously over four months within a remote acoustic receiver array located in a decade-old marine reserve. This approach provided robust estimates of unicornfish movement patterns and home range size. The mean home range of 3.2 ha for *N. unicornis* was almost ten times larger than that previously recorded from a three-week tracking study of the species in Hawaii. While *N. lituratus* were smaller in body size, their mean home range (6.8 ha) was over twice that of *N. unicornis*. Both species displayed

strong site fidelity, particularly during nocturnal and crepuscular periods. Although there was some overlap, individual movement patterns and home range size were highly variable within species and between sexes. *N. unicornis* home range increased with body size, and only the three largest fish home ranges extended into the deeper outer reef slope beyond the shallow reef flat. Both *Naso* species favoured habitat dominated by corals. Some individuals made predictable daily crepuscular migrations between different locations or habitat types. There was no evidence of significant spillover from the marine reserve into adjacent fished areas. Strong site fidelity coupled with negligible spillover suggests that small-scale reserves, with natural habitat boundaries to emigration, are effective in protecting localized unicornfish populations.

**Keywords** Acoustic telemetry · Home range · Movement patterns · Marine reserves · Acanthuridae · Guam

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A. Marshall (✉)  
Marine Spatial Ecology Lab, School of Biological Sciences,  
University of Queensland, St. Lucia Campus, Brisbane,  
QLD 4072, Australia  
e-mail: a.marshall@uq.edu.au

A. Marshall · J. S. Mills · J. McIlwain  
Marine Laboratory, University of Guam, Mangilao 96923, Guam

K. L. Rhodes  
College of Agriculture, Forestry and Natural Resource  
Management, University of Hawaii at Hilo, 200 W. Kawili St.,  
Hilo, HI 96720, USA

## Introduction

Marine reserves are being employed more frequently as the principal tool for fishery management, particularly in tropical countries that lack the resources necessary for a more traditional approach (Roberts and Polunin 1991). The effectiveness of a reserve will, however, depend on its placement and size, as well as matching the scale to the movement patterns of target species (Gell and Roberts 2003; Bartholomew et al. 2008). Equally important to reserve size is the length of time since closure in protecting exploited fish stocks (Claudet et al. 2008). As movement is species-specific, the influence of a reserve affects species differently (Botsford et al. 2003) and should be designed

with targeted species in mind (Sale et al. 2005). For example, a mobile species with a large home range and high rates of movement likely spend more time outside the reserve boundary, thereby increasing its exposure to exploitation (Bartholomew et al. 2008) and making a greater contribution to spillover (Chapman and Kramer 2000; Russ 2002; Palumbi 2004). If spillover is excessive, however, the benefits of the reserve are negated (Halpern and Warner 2003). To overcome this problem, reserve size can be increased and would, therefore, protect a greater proportion of mobile fish with large home ranges (Claudet et al. 2008).

The shape and size of reef fish home ranges are highly variable between and within species and can be influenced by habitat heterogeneity, territoriality, resource availability, competitor density and body size (Kramer and Chapman 1999). While it seems logical that large mobile reef fishes might not benefit from small protected areas, biomass build-up does occur for some species of parrotfish, grouper and snapper in marine reserves less than 1 km<sup>2</sup> (Russ and Alcala 1996; Roberts and Hawkins 1997). Such build-up is attributed to intra-specific differences in site fidelity, whereas only a proportion of the population is mobile with the remainder sedentary (Gell and Roberts 2003). For example, in Jamaica, highly variable movement patterns were observed for the stoplight parrotfish, *Sparisoma viride*. Some individuals were recaptured repeatedly at the same site (within 100 s m) whilst others were caught more than 10 kms away (Munro 2000). While the synergistic effects of home range size and mobility, fishing pressure and marine reserve characteristics have the greatest influence on how a species responds to protection (Palumbi 2004), fish mobility is rarely reported in the marine reserve literature (Claudet et al. 2008).

Quantifying movement of reef fishes has benefited from the rapid evolution of acoustic telemetry (Heupel et al. 2006). Before the development of this technology, mark-release-recapture (MRR), using externally visible tags, was the principal method for assessing fish movement (Kramer and Chapman 1999; Samoilys 1997). However, tagging studies can be affected by high tag-loss rates that underestimate total population size, while interpretation of movements is typically limited to a straight-line distance from the point of capture to the point of recapture or resighting (Zeller 1999). In contrast, acoustic telemetry can provide detailed information on movement and behavioural ecology (e.g., home range size, seasonality of behaviour, preferred spawning or foraging areas) measured over multiple temporal and spatial scales (Hocutt et al. 1994; Chateau and Wantiez 2009). The recent move towards using remote hydrophones that passively monitor fish behaviour over months-to-years has brought into question the results of short-term active tracking using boat-based hydrophones,

which underestimate the full extent of a fishes movement and residency times (Palumbi 2004; Meyer et al. 2010). The number of studies utilizing this remote method has increased significantly due to recent developments in the technology, affordability and increased funding opportunities (e.g., Parsons et al. 2003; Meyer and Honebrink 2005; Chateau and Wantiez 2007; Meyer et al. 2007a, b, 2010; Rhodes and Tupper 2008). To date, the majority of published studies focus on large-bodied species with high conservation or commercial interest (e.g., sharks, groupers and tuna). Despite being numerically abundant and contributing to the bulk of the fish biomass on coral reefs, studies on the movement of small and medium-bodied reef fish species are rare (but see Meyer et al. 2010 and Claisse et al. 2011).

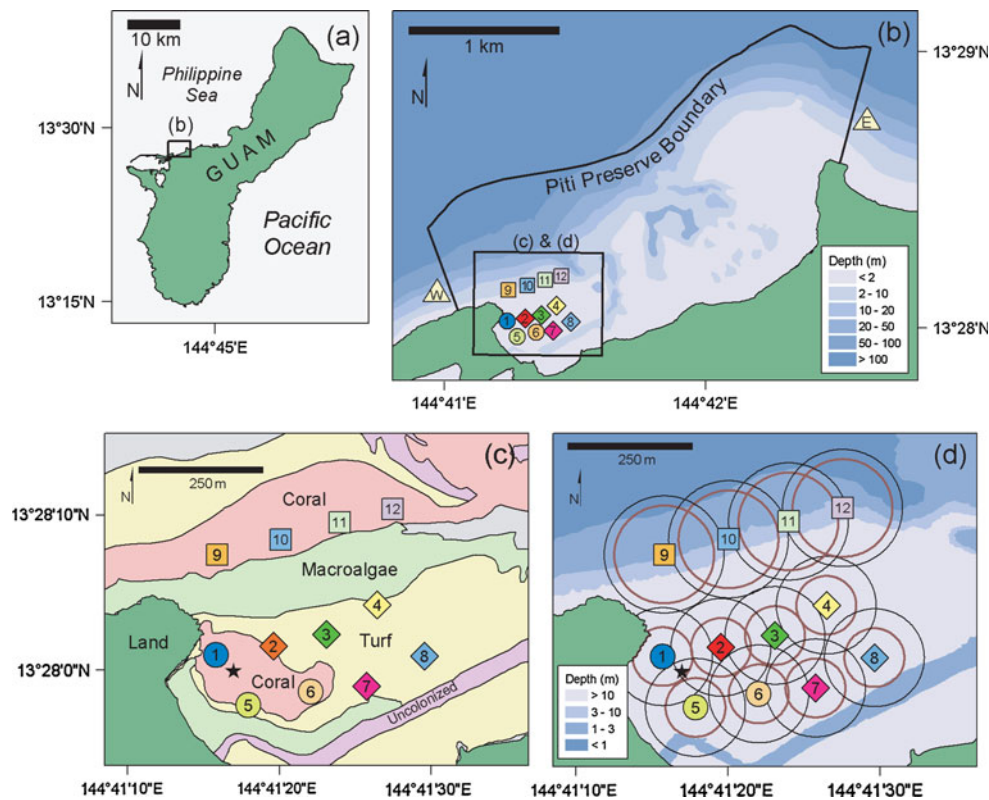
Since the 1970s, Guam's inshore coral reef fisheries have been heavily overfished and the reef habitat degraded from uncontrolled pollution and natural disturbance events (Hensley and Sherwood 1993). A recent reestimate of the official fish landing data for Guam reported that the total catch of coral reef fishes has declined 86% from 1950–2002 (Zeller et al. 2007). The bluespine unicornfish *Naso unicornis* (maximum length 70 cm, Randall 2001), and orangespine unicornfish *Naso lituratus* (maximum length 46 cm, Randall 2001), are major components of reef fisheries throughout much of the Pacific (Gillett and Moy 2006). Both species are heavily targeted by fishers in Guam (Hensley and Sherwood 1993) and in other parts of Micronesia (Rhodes and Tupper 2008).

Marine reserves are the primary management tool for Guam's reef fish fishery. However, their effectiveness as a management strategy for *Naso* is unknown without a clearer understanding of movement patterns and home range size. Therefore, the aim of this study was to use passive acoustic telemetry to determine movement patterns and home range size among individuals (<30 cm maximum length) of *N. lituratus* and *N. unicornis* within a marine reserve in Guam that has been closed to fishing for ten years.

## Materials and methods

### Study site

Guam is the largest and southernmost of the Mariana Islands, located in the north-west Pacific Ocean. This study was conducted between August and December 2008, at Piti Bomb Holes Marine Preserve (13°28'20"N, 144°42'10"E; hereafter, Piti), on the central-west coast of Guam (Fig. 1a). Piti is a semi-enclosed bay, with a total area of 340 ha, encompassing a fringing reef with an extensive shallow (<10 m depth) reef flat of approximately 150 ha (Fig. 1b). Habitats within Piti include shallow seagrass beds, macroalgal and turf covered pavement, expansive



**Fig. 1** **a** The location of Piti Bomb Holes Marine Preserve (black rectangle) on the central-western coast of Guam. **b** The remote acoustic receiver array on the western side of Piti. Receiver positions are indicated by coloured markers (shapes indicate receiver habitat type: circle = reef flat coral, diamond = reef flat turf, square = reef slope coral). The two receivers located outside Piti boundaries are indicated by white triangles (W = West, E = East). **c** Receivers of the array within major habitat types. The major habitat types are delineated by colour and labelled; receiver markers are coded by

habitat type. The black star indicates the centre of the unicornfish capture-and-release site. **d** Receiver positions with average detectable range of transmitters indicated by circles around each receiver (Receivers 1–8: red inner circle = 60-m radius, black outer circle = 100-m radius; Receivers 9–12: red inner circle = 100-m radius, black outer circle = 120-m radius). The black star indicates the centre of the unicornfish capture-and-release site. Bathymetric profiles are provided in the legend

colonies of hard and soft corals, natural and artificial channels, and numerous sink ('bomb') holes, with sandy bottoms (Fig. 1b, c; Burdick 2006). Piti was established in 1997, but regulations prohibiting the removal of marine life were not fully enforced until 2001. Limited seasonal shore fishing of a few culturally important reef fish species is allowed within Piti, but harvesting of *N. lituratus* and *N. unicornis* is prohibited.

#### Acoustic tagging

Passive acoustic telemetry was used to quantify *N. lituratus* and *N. unicornis* home range size and examine movement patterns. The western reef flat of Piti was identified through preliminary surveys as a site of high abundance of both target unicornfish species. In August 2008, *N. lituratus* and *N. unicornis* individuals were captured for tagging over three nights (Fig. 1c). The unicornfish were captured from refuge holes by hand or with nets on snorkel. Captured individuals were held in containers of aerated seawater and

later transported to 10,000-L holding tanks (University of Guam Marine Laboratory). All fish were allowed to acclimate to the tanks and monitored for signs of stress or poor health prior to the surgical tag implantation.

Twenty *N. lituratus* (ten male and ten female) and ten *N. unicornis* were surgically implanted with individually coded acoustic transmitters (V7-4L<sup>®</sup>, 90 s. delay, 197-day battery life, Vemco, Nova Scotia, Canada). The sex of tagged *N. lituratus* individuals was determined by the presence (male) or absence (female) of trailing caudal fin filaments (Randall 2001). The accuracy of this technique was later confirmed by histological gonad assessment in a separate study. As there is no evidence of similar sexual dimorphism in *N. unicornis*, tagged individuals of this species were not assigned a sex. The captured unicornfish, while much smaller than the recorded maximum for these species, were representative of the most abundant and reproductively mature size classes on Guam.

Prior to surgery, individuals were anesthetized in a 1.1 g L<sup>-1</sup> solution of seawater and tricane methanesulfonate, weighed

(total weight, nearest g), and measured (fork length [FL] nearest mm). A sterile transmitter was then surgically placed into the gut cavity through a 1.5-cm incision along the edge of the abdominal wall. The incision was closed with a sterile surgical stapler (3–4 staples) and covered with topical antibiotic cream (Neosporin®). Individuals were also externally tagged between the dorsal pterigiophores with a uniquely numbered T-bar anchor tag (Floy Tag & Mfg Inc., Seattle, WA, USA) imprinted with a phone contact. In addition to topical antibiotic, all fish were injected with oxy-tetracycline (50 mg kg<sup>-1</sup> body weight) to prevent infection. Tagged individuals were returned to the holding tanks and monitored for 10 days prior to release at their capture site. Surgical wounds were monitored, and fish were considered healthy when feeding on macroalgae (*Sargassum* spp.) resumed.

#### Acoustic tracking

The functional range of acoustic tags was measured by conducting in situ range tests among depths and habitats. A V7-4L® equivalent range-test transmitter was strategically placed in stationary positions within the array for fixed periods and also moved gradually away from receivers at fixed distances and times. Detection ranges within the shallow reef flat and shallow reef slope averaged ca. 60 m, with a maximum range of ca. 100 m. In contrast, tag detection in deeper reef slope environments averaged ca. 100 m to a maximum of ca. 120 m (Fig. 1d).

To examine fish habitat use and movement, an array of Vemco VR2 W® omnidirectional acoustic receivers was placed within Piti prior to releasing tagged fish. Data collected in the first week post-release were excluded during analyses to ensure fish behaviour had returned to normal. Twelve receivers were deployed throughout the western end of Piti that included reef flat and reef slope habitats (Fig. 1c, d). In addition, individual receivers were positioned on the reef slope outside each of the eastern and western Piti boundaries to monitor potential spillover (Fig. 1b). The receivers recorded the presence and timing of all tagged fish within range, assuming that the signal was unobstructed. Shallow-water receivers were attached antenna-up, to rebar cemented in a concrete block. In contrast, deep-water (outer fringing reef) receivers were moored to the reef with 3/16" stainless steel cable and suspended in the water column at 3-m depth, antenna-down. Where possible, the receivers were positioned to allow overlap in detection ranges and increase the accuracy of recorded unicornfish positions (Fig. 1d). All receivers were retrieved and downloaded monthly.

In addition, active tracking was conducted biweekly using a portable Vemco VR100® receiver and omnidirectional hydrophone. Active tracking allowed systematic searches in areas not covered by the array, in an effort to relocate fish that were not detected regularly after release.

#### Data analysis

##### Home range size estimation

Minimum convex polygons (MCPs) and kernel utilization distributions (KUDs) based on centre of activity (COA) locations were used to quantify the home range size of unicornfish. The MCP method quantifies the extent of the animal's range, while the KUD estimates the intensity of area use, as a two-dimensional relative frequency distribution of an animal's location over time (Worton 1987).

COA locations were estimated for each individual using the mean position algorithm described by Simpfendorfer et al. (2002). A script was created using the R statistical computing language (R Development Core Team 2009) to calculate COA locations as the mean latitude and longitude of all detections within each sequential two-hour interval during the study period. These COAs were used for all consequent analyses of spatial and temporal unicornfish movement. Receiver locations were collected in WGS84 geographic coordinates, while all spatial analysis was conducted in an Albers equal-area projection.

Home range size and shape for each individual was estimated using both MCPs and KUDs. Both measures were calculated with the *adehabitat* module for R (Calenge 2006), using the *mcp* function for MCPs and the *kernelUD* function for KUDs. The MCPs fitted 95% of COA locations, excluding outlying points by the harmonic mean method. In calculating the KUDs, the *ad hoc* method was used for specifying the smoothing parameter in a 1000 by 1000 cell grid (cells were 1.7 m on a side). Areas where the MCP or KUD isopleths crossed over land were subtracted from home range estimates. We estimated 95% confidence intervals for the KUD and MCP home range estimates using 1000-iteration bootstrapping, sampling from the aggregated COAs (Kern et al. 2003).

##### Analysis of home range size estimates

Home range analyses were performed with log-transformed 95% KUD home range estimates. To investigate the possibility of an ontogenetic shift in home range size, a linear regression model was fitted for each species to test for a relationship between size (FL) and home range size. For *N. lituratus*, a model was also fitted for the same variables but separated by sex.

##### Patterns of movement

To investigate spatial and temporal patterns of movement during the study period, scatter plots (modified from Meyer et al. 2010) of detections of individual fish coded by receiver location were examined. Examined patterns included

(1) short-term and long-term movement patterns, (2) home range shifts, (3) spillover, (4) species-, size- and sex-specific differences, and (5) daily movement patterns: foraging, commuting, or a mixture of both (Meyer and Holland 2005).

## Results

### Acoustic tagging

There were no pre-release mortalities among the 30 acoustically tagged unicornfish, and fish were observed feeding within two days of tagging. Tagged *N. lituratus* females ranged from 165- to 198-mm FL ( $n = 10$ ;  $\bar{x} = 188$  mm), and males from 181- to 204-mm FL ( $n = 10$ ;  $\bar{x} = 196$  mm). The size range for *N. unicornis* sizes was from 228- to 282-mm FL ( $n = 10$ ;  $\bar{x} = 251$  mm).

### Acoustic tracking

Between 30 August and 31 December 2008, 15 of the 30 acoustically tagged unicornfish were successfully tracked within the remote receiver array (Table 1; *N. unicornis* = 7, *N. lituratus* = 4♂, 4♀). None of the remaining 15 tagged individuals were relocated using systematic searches of Piti and adjacent areas throughout the study period and were omitted from analyses.

During passive tracking, we monitored individual *N. lituratus* for periods of 101 to 124 days and *N. unicornis* for 103 to 124 days (Table 1). The majority (73%) of fish (*N. lituratus*  $72 \pm 8.1\%$ ; *N. unicornis*  $62 \pm 11.7\%$ ; mean  $\pm$  SE) were detected during >50% of days monitored, with the number of detections unrelated to body size (fork length vs. logit-transformed % presence: *N. lituratus*:  $F_{[1,6]} = 0.919$ ,  $r^2 = 0.133$ ,  $P = 0.375$ ; *N. unicornis*:  $F_{[1,5]} = 1.969$ ,  $r^2 = 0.283$ ,  $P = 0.219$ ) or species ( $t$  test,  $t_{13} = 0.647$ ,  $P = 0.529$ ) or sex ( $t$  test,  $t_6 = 0.239$ ,  $P = 0.819$ ).

### Home range area estimates

The 95% KUD home range area estimates were significantly larger than the 95% MCP home range area estimates for each fish (paired  $t$  test:  $P = 0.013$ ,  $df = 14$ ). On average, the difference was approximately 3.57 ha (0.88–6.26 ha; 95% CI). Mean home range areas were not statistically significantly different between species or between *N. lituratus* males and females. The mean 95% KUD home range area was  $3.21 \pm 1.53$  ha for *N. unicornis* and  $6.84 \pm 2.77$  ha for *N. lituratus*. The mean 95% KUD home range area of *N. lituratus* females was  $9.62 \pm 4.79$  ha and  $4.06 \pm$

2.76 ha for males. Several fish had 95% MCP home range area estimates of zero if all detections were from only one (NLM02, NU01 and NU02) or two (NLM01, NU03) receivers within the array (Table 1, Fig. 2).

The home range areas of all unicornfish were largely overlapping on the reef flat (Fig. 2). However, for *N. unicornis*, there was an ontogenetic expansion in home range area indicated by a significant positive correlation between home range size (log-transformed 95% KUD) and fork length (Fig. 3,  $r^2 = 0.82$ ,  $P = 0.0052$ ,  $df = 5$ ). The home range areas of the three largest *N. unicornis* included deeper, more exposed areas of the reef slope in addition to shallow sheltered areas of the reef flat. No such relationship was observed for *N. lituratus* (all:  $r^2 = 0.080$ ,  $P = 0.498$ ,  $df = 6$ ; females:  $P = 0.696$ ,  $df = 2$ ; males:  $P = 0.480$ ,  $df = 2$ ).

### Movement patterns and habitat use

Unicornfish displayed strong site fidelity, spending most of their recorded time at few locations within the array (Fig. 2). Overall, unicornfish favoured shallow, sheltered, and structurally complex reef flat coral habitat, with 77.3% of all *N. lituratus* detections and 98% of all *N. unicornis* detections recorded by the receivers ( $n = 3$ ) located there. The receiver at the centre of the capture (and release) location (Fig. 1c, d) recorded 76.82% of all *N. lituratus* detections and 97.6% of all *N. unicornis* detections. The receiver located approximately 240 m away in turf habitat (Fig. 1c, d), recorded the second highest number of all detections (15.19%) of *N. lituratus* individuals.

Home range area estimates among the eight *N. lituratus* tracked ranged extensively from 0.0032 to 23.75 ha (95% KUD, Table 1). Most *N. lituratus* individuals had overlapping home ranges on the shallow, sheltered reef flat. Only one female *N. lituratus* had a home range that extended onto the outer reef slope (NLF02, Fig. 2i). Within the reef flat, the majority of *N. lituratus* detections (77.3%) were in areas of high coral cover, followed by pavement turf (22.6%) habitats.

Home range area estimates among the seven tracked *N. unicornis* individuals ranged widely from 0.005 to 10.82 ha (95% KUD, Table 1), with shallow reef flat receivers recording 98% of all *N. unicornis* detections. Larger individuals utilized more of the reef flat area, but also ventured, albeit rarely (<1% of the total), onto the deeper reef slope (Fig. 2e–g).

### Daily movement patterns

The activity (presented as total number of detections) of both species peaked during daily crepuscular periods

**Table 1** Summary detection data and home range area (hectares) estimates (50 and 95% kernel utilization density [KUD], and 95% minimum convex polygon [MCP]) for four male *Naso lituratus*(NLM), four female *Naso lituratus* (NLF) and seven *Naso unicornis* (NU) tracked within Piti Bomb Holes Marine Preserve from 30 August 2008 until 31 December 2008 (124 days)

Fish ID	Fork length (mm)	Sex	Detection Span (days)	Total days detected	Total detections	MCP 95% home range area (95% CI)	KUD 50% home range area (95% CI)	KUD 95% home range area (95% CI)
NLM01	197	M	123	46	89	0	0.21 (0.12–0.33)	1.15 (0.71–1.52)
NLM02	199	M	123	87	1,072	0	0.0005 (0–0.0016)	0.0032 (0–0.0083)
NLM03	203	M	101	80	967	4.04 (3.15–4.04)	2.28 (2.06–2.46)	12.13 (10.73–13.05)
NLM04	204	M	124	105	10,063	1.28 (0.01–1.28)	0.55 (0.52–0.58)	2.94 (2.82–3.04)
NLF01	188	F	118	97	1,204	0.28 (0.06–0.52)	0.41 (0.28–0.56)	3.25 (2.18–4.26)
NLF02	188	F	103	36	97	5.18 (3.72–5.18)	5.17 (2.6–6.95)	23.75 (17.32–27.78)
NLF03	193	F	124	97	2,476	3.02 (1.84–3.02)	0.59 (0.47–0.73)	4.12 (3.54–4.64)
NLF04	193	F	124	78	402	0.52 (0.04–0.52)	1.74 (1.35–2.08)	7.35 (6.30–8.43)
NU01	228	–	124	104	5,347	0	0.001 (0–0.0025)	0.005 (0–0.011)
NU02	230	–	103	92	780	0	0.001 (0–0.0038)	0.006 (0–0.018)
NU03	244	–	124	95	1,888	0	0.016 (0.009–0.023)	0.104 (0.051–0.16)
NU04	251	–	107	22	33	0.67 (0–0.67)	0.35 (0.10–0.81)	2.67 (0.76–3.61)
NU05	262	–	104	25	52	1.1 (0–3.01)	0.84 (0.34–1.52)	6.28 (2.60–8.51)
NU06	280	–	118	57	219	0.67 (0–1.77)	0.28 (0.13–0.53)	2.58 (1.14–4.23)
NU07	282	–	124	78	469	6.88 (3.85–6.88)	1.38 (0.89–2.02)	10.82 (7.39–13.84)

Using 1000-iteration bootstrapping, 95% confidence intervals (CI) are presented next to each home range estimate in brackets

(Figs. 4, 5). Most activity occurred during the morning (0601–1000 h; 27.2% of detections) and evening (1801–2200 h; 22.4% of detections), while 16.6% of detections occurred in the afternoon (1401–1800 h). Late-night (0201–0600 h, 12.4%), midday (1001–1400 h, 11.1%), and midnight (2200–0200 h, 10.5%) detections were relatively fewer. The peak number of daily detections followed sunrise and sunset (Figs. 4, 5).

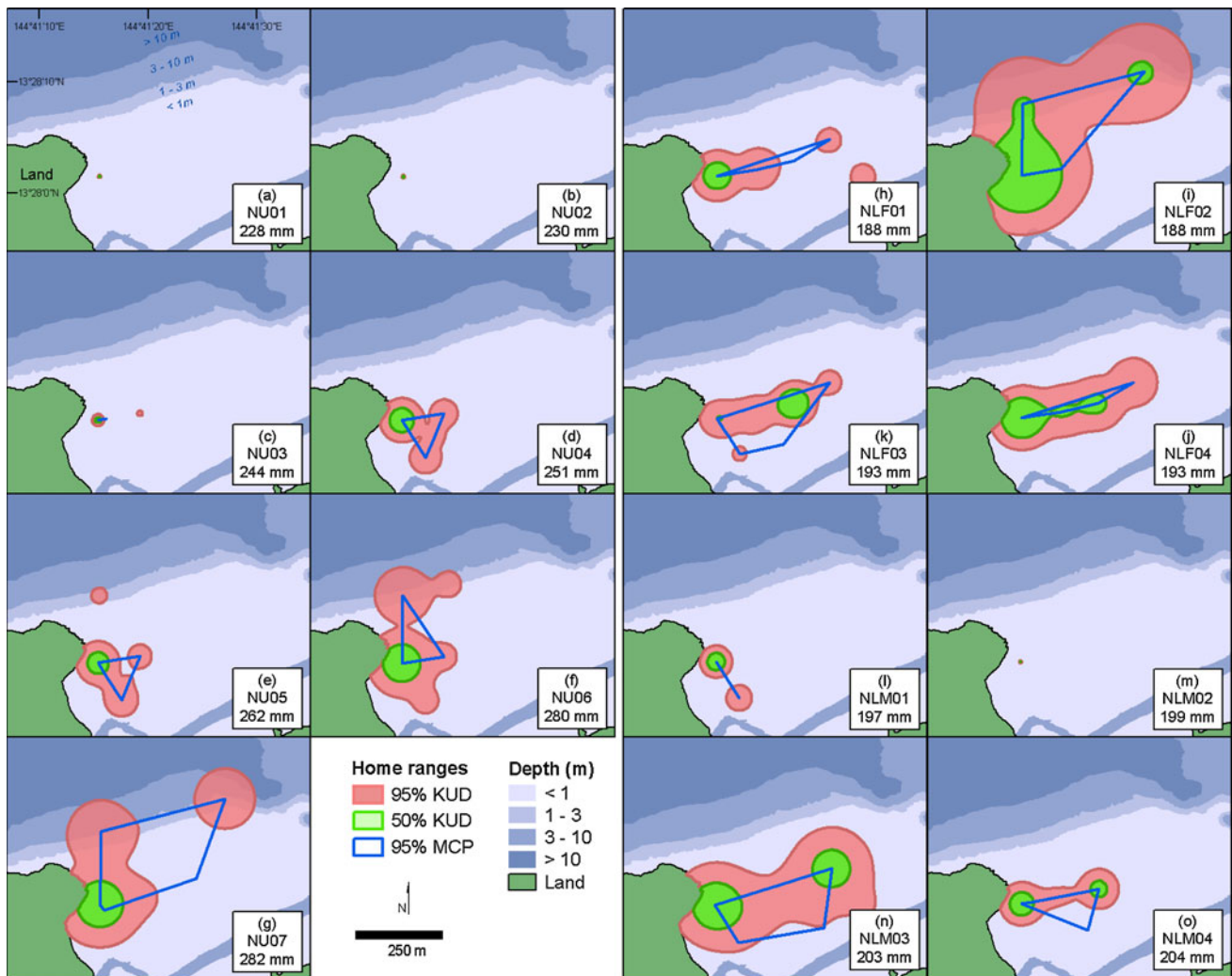
In Piti, three broad daily movement patterns first described in the study by Meyer and Holland (2005) were observed as follows: (1) commuting, (2) foraging and (3) mixed. ‘Commuters’ showed crepuscular shifts in habitat or location between diurnal and nocturnal periods. For example, NLM04 (Fig. 4a) and NLF01 (Fig. 4c) made daily crepuscular migrations of *ca.* 240 m from coral habitat (day) to pavement-turf habitat (night). NLM02, NLF03 (Fig. 4b), NLF04 and NU06 are also examples of ‘commuters’, with detections inside the array only during crepuscular and nocturnal periods before the fish ‘commuted’ outside the array diurnally. ‘Foragers’ occupied the same locations between day and night. For example, NU01 (Fig. 5a), NU03 (Fig. 5b) and NU02 (Fig. 5c) were detected primarily at the capture/release receiver. Some fish showed a mixture of commuter and forager movement patterns, while for a few individuals, the number of detections was insufficient to discern behaviour patterns.

#### Spillover and reserve use

Home range area of *N. lituratus* individuals averaged  $3.79 \pm 1.54\%$  (range = 0.002–13.2%) of the total reef area <5 m deep in Piti (180.2 ha) while *N. unicornis* utilized only  $1.78 \pm 0.85\%$  (range = 0.003–6.0%) of the total. Only one of the fifteen fish (*N. unicornis*, NU06, 280 mm FL) was recorded outside the Piti boundary and only on a single occasion. That fish was recorded *ca.* 600 m from the centre of its home range 15 days after release. The same individual utilized a variety of habitats and was only detected by receivers on 52% of the monitoring days.

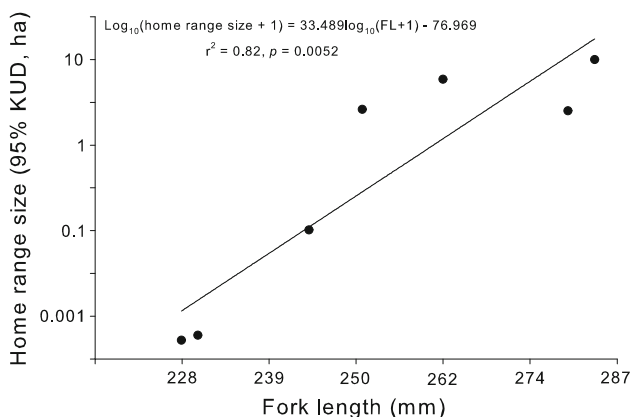
#### Discussion

This study is the first to quantify long-term home range area and movement patterns of *N. lituratus* and *N. unicornis* within a marine reserve in the central Pacific. While the current study supports previous findings of relatively small home range sizes for *N. unicornis* at other locations (Meyer and Holland 2005; Hardman et al. 2010), we add to the understanding of the species by presenting evidence of increasing home range area with body size of individuals less than 30-cm FL. During diurnal and crepuscular periods, both species primarily utilized sheltered, shallow coral habitats, while *N. lituratus* mainly utilized flat pavement



**Fig. 2** Depth-related individual home range area estimates of *Naso unicornis* (a–g) and *Naso lituratus* (females: h–k; males: l–o). Pink bubble contour represents 95% kernel utilization density (KUD),

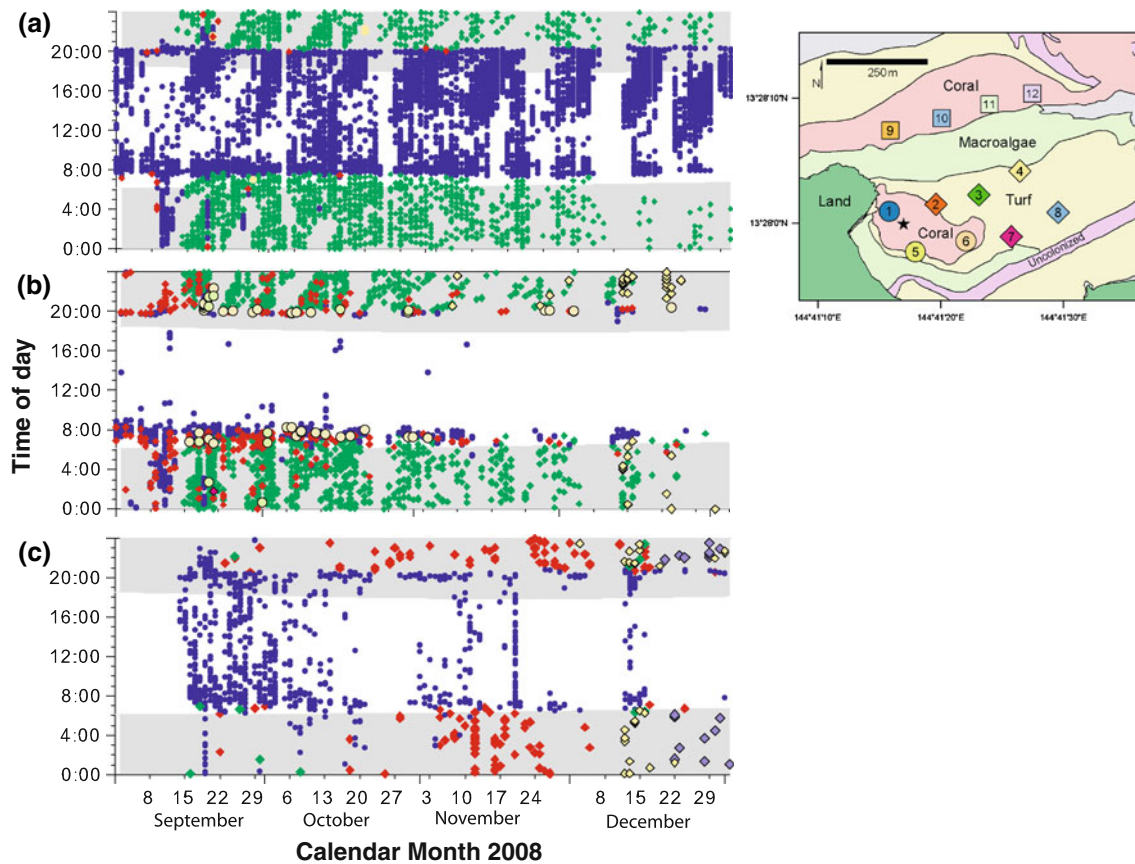
green bubble contour represents 50% KUD, and blue line represents 95% minimum convex polygon (MCP). Bathymetric profiles are shown in the legend



**Fig. 3** The relationship between home range size (95% kernel utilization density, ha) and fork length (mm) of *Naso unicornis* ( $n = 7$ )

algal-turf habitats at night. Overall, most individuals demonstrated strong site fidelity and a preference for rugose habitats that provide protection from predators. Predator avoidance may also have been a factor in the observed activity patterns concentrated around crepuscular periods. Similar to other studies, our findings provide support for the use of small-scale marine reserves for effective management of reef fishes, within the size range of the species examined.

The average body size of unicornfish tagged in this study (*N. lituratus*  $\bar{x} = 192$  mm; *N. unicornis* = 251 mm) is smaller than the maximum lengths recorded for these species (Randall 2001). However, the average size of tagged unicornfish is representative of the most abundant size classes of these species found on Guam, from both fishery-dependent and fishery-independent data (A. Marshall pers.



**Fig. 4** Daily detections of *Naso lituratus* individuals for **a** NLM04 (204 mm male,  $n = 10,063$ ), **b** NLF03 (193-mm female,  $n = 2,476$ ), and **c** NLF01 (188-mm female,  $n = 1,204$ ). The horizontal stripes of grey shading indicate nocturnal periods. Coloured symbols on the

scatter plots correspond to receiver locations (top right of figure). The black star indicates the centre of the unicornfish capture-and-release site

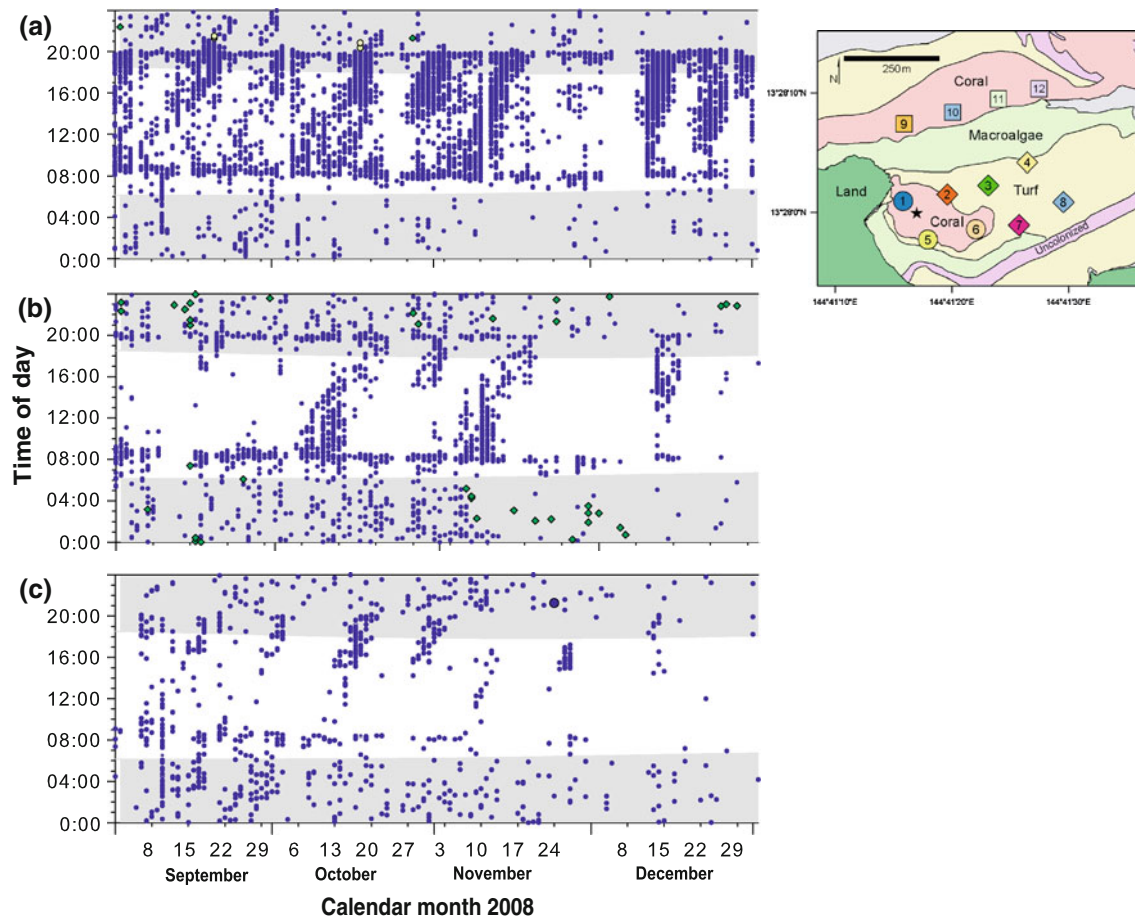
obs.). The tagged unicornfish in this study are also representative of reproductively mature size classes on Guam, where these species mature at a size considerably smaller than elsewhere (A. Marshall pers. obs.). Therefore, Piti is likely protecting reproductively mature unicornfish, with the potential to enhance adjacent fisheries.

During the study period, systematic searches for tagged unicornfish (using a portable receiver and hydrophone from a small boat) were conducted biweekly throughout Piti and adjacent areas. In addition to extensive active tracking searches, underwater visual census surveys were also conducted in Piti and adjacent areas. Furthermore, external tags offered a reward for the return of any fish captured by local fishers. Despite these extensive searches and the offer of a reward, fifteen unicornfish (50% of tagged fish) disappeared and were not relocated after their initial release. Their disappearance could possibly be explained by migration (distant relocation), premature transmitter failure or natural/fishing mortality, although it is not possible to definitively attribute disappearance to any of these causes. Tag-induced mortality cannot be ruled out; however, it is

considered unlikely due to the long captive recovery period of 10 days, which allowed near-complete healing of the surgical wounds. Future movement studies of these species on larger spatial and temporal scales may help to explain the reasons behind the local disappearance of tagged unicornfish in this study.

#### Home range area estimates

Home ranges have been documented for a variety of coral reef fishes (e.g., Bolden 2001; Meyer and Holland 2005; Hutchinson and Rhodes 2010; review see Kramer and Chapman 1999); however, few have quantified home range size of medium-sized benthic species (Eristhee and Oxenford 2001; but see Claisse et al. 2011). For *N. unicornis* and *N. lituratus*, home range areas within Piti varied considerably between individuals. Individual variability in home range size has previously been shown for *N. unicornis* in both Hawaiian (Meyer and Holland 2005) and Rodrigues Is (Indian Ocean) marine reserves (Hardman et al. 2010). For coral reef fishes, home range size and shape are known to



**Fig. 5** Daily detections of *Naso unicornis* individuals for **a** NU01 (228 mm,  $n = 5,347$ ) **b** NU03 (244 mm,  $n = 1,888$ ) and **c** NU02 (230 mm,  $n = 780$ ). The horizontal stripes of grey shading indicate

nocturnal periods. Coloured symbols on the scatter plots correspond to receiver locations (top right of figure). The black star indicates the centre of the unicornfish capture-and-release site

vary in response to environmental and biological factors (Kramer and Chapman 1999). For small, territorial reef fishes, resource availability and competitor density are often primary factors controlling home range area. In comparison, fish with undefended and overlapping home range areas can be influenced by seasonality, sex and habitat availability and composition (Eristhee and Oxenford 2001; Lowe et al. 2003). For *N. lituratus*, the observed variability in individual home range was not shown to be sex-specific. Likewise, the overlap in home range areas does not support influences from fish density or resource availability. A more likely influence on unicornfish movement patterns and home range size is habitat availability and composition. The limited temporal nature of the survey did not provide for an assessment of seasonal influences on home range.

A significant relationship was found between home range area and body size for *N. unicornis*, as has been documented for other coral reef fish (Kramer and Chapman 1999; Nanami and Yamada 2008, 2009). A correlation between home range size and body size can be driven by

underlying ecological processes, such as ontogenetic shifts in habitat preference (Light and Jones 1997; Dahlgren and Eggleston 2000; Nakamura and Tsuchiya 2008). In Hawaii, the size distribution of *N. unicornis* differed among habitats, indicating an ontogenetic habitat shift from shallow, sheltered areas of the reef to deeper, more exposed habitats (Meyer and Holland 2005). In Guam, larger *N. unicornis* used deeper, more exposed reef slope habitat as well as the shallow, sheltered reef flat, resulting in relatively larger home range areas than for the smaller individuals. This expanded home range area could be a behavioural response to foraging optimization in association with reduced predation risk with increased body size (Dahlgren and Eggleston 2000).

#### Movement patterns and habitat use

Habitat preference appeared to have a strong influence on unicornfish movement patterns within Piti, as both species were mostly detected within coral habitat of the shallow, sheltered reef flat throughout the 4-month tracking period.

While these results suggest that unicornfish are relatively sedentary and highly site-attached, extensive movements outside the daily home range from individuals of both species were also recorded. For example, NU06 was recorded up to 1 km from its typical daily home range, while NLF01 moved up to 700 m beyond its home range. *N. lituratus* has previously been recorded with movements of up to 10.9 km beyond its home range (Meyer et al. 2010). Some unicornfish displayed stronger site fidelity than others, although individuals with large variability in daily activity spaces periodically returned to previously occupied habitats. Earlier studies have confirmed that some acanthurids are strongly site-attached (Robertson 1983; Robertson and Gaines 1986; Meyer and Holland 2005), but that home range size and habitat may change with ontogeny. Unicornfish were undetected within the array for an average of 51 out of a total 124 monitoring days, and the degree of site fidelity varied greatly between individuals. Further studies are needed to test the long-term (annual, inter-annual) site fidelity of unicornfish using a larger array of overlapping receivers to increase spatial coverage and the numbers of days detected during the monitoring period.

#### Daily movement patterns

Both unicornfish species displayed the daily movement patterns (commuting, foraging and mixed) first described by Meyer and Holland (2005) for *N. unicornis* in Hawaii. In this study, several individuals made daily crepuscular shifts in habitat or location, presumably ‘commuting’ between different sites used to either feed or rest, while ‘foraging’ fish occupied the same locations between day and night, presumably to stay in proximity of their refuge holes. Many coral reef fish species demonstrate daily crepuscular movement between habitats, with the magnitude of movement varying (metres–kilometres) relative to species and body size (e.g., Holland et al. 1993, 1996; Zeller 1997; Meyer and Holland 2005; Meyer and Honebrink 2005; Meyer et al. 2000, 2007a,b, 2010; Claisse et al. 2011). Unicornfish movements were concentrated around crepuscular periods, but lagged slightly after sunrise and sunset. Based on our results and those from previous studies, these behaviours may be a response to increased predation risk during crepuscular periods (e.g., McFarland et al. 1999; Danilowicz and Sale 1999; Rickel and Genin 2005).

#### Spillover and reserve use

To effectively protect target species, a marine reserve should ideally be an order of magnitude larger than the daily movements of its most wide-ranging residents (Lowe et al. 2003). The home range estimates for *N. lituratus* and

*N. unicornis* were small in relation to the available area of Piti (average of 3.58 and 1.68%, respectively). Additionally, only one fish moved briefly beyond the Piti boundary on a single occasion. Assuming unicornfish tracked in this study are representative of these species, then Piti seems effective in protecting local unicornfish populations. Larger individuals of *N. unicornis* in Hawaii also appeared to have the same level of protection and movement within a small-scale (0.2 km<sup>2</sup>) reserve, with the reserve area several times larger than observed home ranges.

Piti is a semi-enclosed bay with narrow reef flat margins that may limit emigration and short- and long-term movements, as shown in previous studies (e.g., Chapman and Kramer 2000). Additional studies in more open environments may be warranted to verify the utility of small-scale reserves across variable physical settings. Whenever possible, natural habitat boundaries should be considered in designing reserve boundaries and minimizing the exposure of protected fishes to adjacent fisheries (Chapman and Kramer 2000). It is noteworthy that some unicornfish made regular daily migrations of up to 300 metres and that the second largest *N. unicornis* was recorded at receivers located over a kilometre apart within just a few days. It is possible that larger-scale movements of these fish were undetected due to the limited area of our array coverage. Further studies, with increased spatial coverage, are needed to determine home range and movement patterns of larger *N. unicornis* (>30 cm FL) and to establish whether Piti is effective in protecting larger adults of this species.

#### Management and the use of acoustic telemetry

Information on home range size and movement patterns of target species is an important aspect of applied ecology, fisheries and fisheries management and for providing guidance to locally effective marine reserve design and assessment (Bolden 2001). The efficacy of marine reserves as a coral reef fisheries management tool worldwide can be determined by whether they are effective in providing protection for target species (i.e., there is an increase in biomass within reserves), while minimizing negative impacts to local fisheries (Zeller 1997). Consistent with our findings, the movement of target species across reserve boundaries appears to be influenced by reef topography and reserve size, relative to the normal movement patterns and home ranges of target species (Holland et al. 1993, 1996; Meyer and Holland 2005). In this study, passive acoustic telemetry was demonstrated to be a suitable tool for investigating home ranges and movements of small and medium-sized reef fishes on shallow reef flats. However, limitations of this technique have been identified in environments that are structurally complex (Claisse et al. 2011).

On Guam, spillover is highest in areas joined by continuous fringing reef and lowest where headland barriers separate adjacent reefs (Tupper 2007). This study provides further support that reserve boundaries should be placed along natural borders between discrete habitat areas rather than dividing regions of continuous habitat (Chapman and Kramer 2000; Meyer and Holland 2005). Additionally, the large variability in movement observed between individual unicornfish highlights the need to identify general factors that favour or inhibit fish movement and then incorporate these factors into reserve design and assessment. Knowledge of fish home range size and movement patterns provides a basis for assessing the design and effectiveness of marine reserves and will help to achieve effective management of coral reef fisheries throughout the Pacific.

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