Final Report

“Spatial assessment, sex-specific habitat use and vulnerability of spawning populations of squaretail coralgrouper, *Plectropomus areolatus*, in Pohnpei, FSM”

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Project summary

Pohnpei is one of only two Pacific island nations to include specific fish spawning aggregation (FSA) conservation protocols into fisheries management. These actions include area protection of the largest recorded multi-species FSA site (Kehpara Marine Sanctuary, KMS) in the Indo-Pacific and a two-month sales ban on serranids during a portion of the presumed reproductive season for three species. Three other known (and likely several unknown) multi-species FSA remain vulnerable to fishing and have not been assessed for fishing impacts, spawning population area distribution or reproductive season. To determine reproductive times for serranids at KMS to improve the effectiveness of the commercial ban, the state marine resource agency and a local NGO conducted monthly underwater site monitoring from 2000-2005. Results were presented to the state marine resources committee in May 2005 and include recommendations to match the sales ban to the observed reproductive season and include a concomitant subsistence fishing ban. In 2005, a NOAA-funded vulnerability assessment of squaretail coralgrouper was initiated at KMS (PI) to show the effects of fishing on reproductively active individuals within the spawning season. Results show that subsistence fishing during the current sales ban period (February-March) is substantial, with 25% of recaptured (tagged) squaretail coralgrouper (January-September) taken during the sales ban period and 61% of recaptures coming from areas presumed to be migratory pathways and feeding and resting areas within the spawning season. Perhaps more importantly, catch reportedly came from a 7-10 km area proximate to the tag location, suggesting that (1) movement is limited for reproductively active individuals between spawning months, (2) spawning populations reside year-round within a small area relative to the FSA, and/or (3) fishing is highly concentrated in areas proximate to the FSA. Regardless, as this study shows, reproductively (or recently) active fish are highly vulnerable to overfishing and FSA loss is possible from fishing proximate to spawning sites. If spawning populations are spatially limited (e.g. < 50-100 km^2), FSA loss could impart heavy socio-economic pressures on fishing communities dependent on them, or whose access is restricted to certain reef areas (e.g. marine tenured areas). A complimentary NOAA-funded market survey of the impacts to reproductively active squaretail coralgrouper during non-commercial ban periods was completed in 2006 (Rhodes and Tupper 2007). To complete one of

two remaining informational needs[1] for comprehensive management of Pohnpei FSA (that can also serve as a regional blueprint), an in-depth analysis of essential fish habitat, including FSA migratory pathways, feeding areas and home range was warranted. The project employed active tracking of 15 acoustically tagged individuals from two adjacent FSA sites separated by ~ 20 km. Fish were tagged in Month 3 of 5 of the reproductive season and tracked over two reproductive and two non-reproductive months. The project determined individual sex-specific spatial habitat requirements, the possibility of distinct FSA-specific spawning population areas (and overlap) and the relationship between FSA size and non-reproductive spatial distribution. These findings will increase scientific knowledge of reproductive dynamics to improve FSA management needs and raise community awareness of the vulnerability of both FSA and the effects of FSA loss on their own socio-economic stability.

The specific activities and timelines for this project were:

	Task	Initiation	Completion	Duration	Milestone
1	Technical and conceptual training in tracking instrumentation and techniques to all participants	Month 1	Month 1	1 month	Trained dive and tracking assistant to assess EFH
2	Deployment of VR2	Month 1	Month 1	1 month	All 7 VR2s deployed
3	Development and initiation of classroom instruction on fisheries management techniques and the use of tag-recapture in decision-making	Month 1	Month 4	4 months	Completed internship for COM interns in indepent marine studies coursework; ability of students to grasp key concepts in marine conservation and the use of mark-recapture in marine resource management
4	Tagging of 20 coralgrouper at KMS	Month 1	Month 2	3-5 d within 2 months	20 coralgrouper tagged and released
5	Acoustic tracking and mapping	Month 1	Month 4	4 months	Tracking and mapping of 20 coralgrouper from the KMS FSA, defining home range, including reproductive home range
6	Analysis and final mapping	Month 5	Month 6	1 month	Complete mapping of maximum area of FSA and home range for formulation of recommendations and comparison
7	Development of recommendations and presentation of findings to the state	Month 7	Month 7	1 month	All data analyzed, report and Powerpoint presentation prepared for and delivered to the state legislature and marine resources committe
8	Manuscript preparation	Month 8	Month 9	1 month	A minimum of 1 manuscript prepared and submitted to a peer reviewed journal of fish and fisheries management

Progress to date:

Task 1: Technical and conceptual training in tracking instrumentation and techniques **Complete**

- Since the beginning of the project we have provided basic technical and conceptual training to several Division of Marine Resources and Development (DMRD) conservation officers who accompany me in the field on a daily basis. I have provided more in-depth training for one intern from the College of Micronesia (COM), who is now able to search for and manually track fish with the Vemco VR100 acoustic receiver.

[1] A temporal and spatial assessment of other known FSA sites is necessary before recommendations for a seasonal (species-specific or blanket) sales and catch can be made.

Task 2: Deployment of VR2 **Complete**

- Due to problems with equipment malfunction and loss, data from VR2s was limited and is not being used in the manuscript.

Task 3: Development and initiation of classroom instruction. **Complete**

- Prior to his departure from Pohnpei, K.L. Rhodes talked to students and the public at COM. In addition to supervising an intern student, N. Hutchinson gave a presentation on the project and the use of tagging in relation to marine conservation and resource management in late July. He has subsequently provided information since leaving FSM to the intern student, who is presenting a talk on his experience to his classmates.

Task 4: Tagging of 20 coralgrouper at KMS. **Complete (15/20 tagged)**

- 16th – 18th April: 10 individuals were tagged on the spawning aggregation (5 males : 5 females). One of the females did not recover from anaesthesia and no further individuals were caught.
- 15th – 19th May: Reduced numbers of aggregating fish resulted in a catch of only 6 individuals during this period (5 males: 1 female)
- 14th June: Diver observations indicate that spawning ended in May, with no aggregation present at Kehpara Marine Sanctuary.
- 20th July: Final positions of fish recorded. 7 fish were found overall after they had left the spawning aggregation.

Task 5: Acoustic tracking and mapping. **Complete**

- A systematic series of searches was carried out to pinpoint the position of fish after spawning, along the outside and inside of the barrier reef, around coral patches within the lagoon and around the fringing reef. The positions of 7 out of the total of 15 tagged fish were recorded. These include 3 females,2 located on the spawning aggregation site and in the far North of Pohnpei and 4 males, 3 that are resident in areas close to the aggregation site and 1 that is located adjacent to a patch reef inside Pehleng Channel to the North of the aggregation. The positions of these fish were checked every 2-3 days at minimum in order to provide details related to movement patterns and home range (Figs 1, 2)
- Problems with boats and man-power in May meant that nocturnal tracking was not possible around assumed staging areas. While tracking was conducted in these areas during the day, no tagged fish were recorded.
- The area between Nalap Channel and Dawak Channels was covered twice since the beginning of the study, with searches conducted every 100 - 200m along reef edges and around all known coral patches in the lagoon. The total area covered was along the west of the island between Sokehs channel (7.0°N, 158.180°E) and Pelian channel (6.78044°N, 158.27618°E).

Task 6: Analysis & final mapping. **Complete**

- All positions were mapped onto georeferenced photographs and data was analysed to determine distances travelled, areas bounded by tracks and estimates of home ranges were calculated (see materials & methods plus results attached from the draft manuscript, attached to this report.

Task 7: Development of recommendations and presentation of findings to the state. **Complete**

- K.L. Rhodes presented initial findings to the state in April 2008 and provided a summary of findings and recommendations to state officials during a visit in April 2009.

Task 8: Manuscript preparation. **Complete**

- See attached draft manuscript, submitted Dec. 2008 to Journal of Fish Biology.

Appendix 1: Manuscript submitted to Journal of Fish Biology

Spatial management needs of squaretail coralgrouper, *Plectropomus areolatus* (Rüppell 1830), based on active and passive acoustic telemetry

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Abstract. The aim of the current study was to determine for adult squaretail coralgrouper (*Plectropomus areolatus*) spatial requirements for effective and biologically meaningful marine protected area (MPA) design, based on reproductive and non-reproductive habitat use. To determine movement relative to spawning sites and identify non-reproductive home range areas, *P. areolatus* were re-located or tracked following acoustic tagging at a fish spawning aggregation (FSA) site within a small-scale MPA. Active tracking over 75 days showed variability in both the distance and timing of movement from FSA sites following spawning. Tagged *P. areolatus* used highly confined non-reproductive home range habitats, with individuals attached to specific coral reef areas outside and inside the barrier reef. No sex-specific variations in distance of movement or home range habitat were apparent. Six of the seven individuals that were re-located were found within 2-8 km of the FSA. Results support previous findings of small catchment areas for reproductive populations of *P. areolatus* relative to FSA sites and suggest that FSA loss could negatively impact local fish and fishing communities. To adequately protect adult populations of *P. areolatus*, large-scale, biologically meaningful MPAs are needed that include both reproductive and non-reproductive habitats.

Introduction

The formation and use of fish spawning aggregations (FSA) to reproduce characterizes a substantial number of commercially important fishes, including groupers (Epinephelidae) (Thresher 1984; Sadovy 1996; Domeier and Colin 1997; Sadovy de Mitcheson et al. 2008).

These aggregations are highly attractive to fishers, since they are often spatially and temporally predicable, encompass large numbers of individuals, and can produce substantial catch volumes over relatively brief time periods. For many groupers, FSA formation is seasonally brief, with FSA persisting for around two weeks within a reproductive month (e.g. Rhodes and Sadovy 2002). Within FSA, spawning often occurs near the end of the aggregation period and may last no more than 1-3 days within each reproductive month (e.g. Rhodes and Sadovy 2002) in contrast to fishing, which often persists throughout the aggregation period (e.g. Graham et al. 2008). As a result, FSA and associated populations are highly vulnerable to overfishing (Sadovy and Domeier 2005) through both direct removal of adults and concomitant reductions to reproductive output (e.g. Coleman et al. 1996). Declines in abundance through FSA fishing are often masked by relatively stable catch-per-unit effort giving fishers a false sense of population stability (Sadovy and Domeier 2005). Sex-specific temporal variability in residency and catch is also common (e.g. Rhodes and Sadovy 2002), increasing the potential for altered reproductive behavior and skewed operational (spawning) sex ratio (e.g. Coleman et al. 1996; Nemeth et al. 2007; Rhodes and Tupper 2008).

Globally, the effects of aggregation fishing have been manifested as FSA loss and diminution of population abundance, reductions in individual size within populations, and alterations in sex ratio within affected FSA (e.g. Johannes et al. 1999; Sadovy and Domeier 2005; Aguilar-Perera 2007; Sadovy de Mitcheson et al. 2008). All of these effects impact adult populations by diminishing reproductive output, which in turn has the potential to catalyze continued population declines (Roberts and Hawkins 1999). Such patterns of decline have, however, been reversed where aggregations have been protected, albeit only where effective management and enforcement practices occur (Beets and Friedlander 1998; Nemeth 2005).

Among the groupers that have been examined in detail, evidence suggests that most individuals within FSA are derived from relatively small catchment areas (the areas from which fish are drawn) (e.g. Zeller 1998; Nemeth et al. 2007; Starr et al. 2007; Rhodes and Tupper 2008). Thus, overfishing and loss of FSA may be felt as localized population declines and concomitant reductions in food security and income to fishing communities (Bell et al. 2009). Recent tag-recapture surveys also suggest that reproductive adults may utilize migratory corridors to reach FSA sites to further increase the vulnerability of FSA to overfishing when these are targeted (e.g. Starr et al. 2007; Rhodes and Tupper 2008).

Among transient aggregation-forming epinephelids, the squaretail coralgrouper, *Plectropomus areolatus*, is a widely distributed, highly valued Indo-Pacific species (Heemstra and Randall 1986). The species is locally (e.g. Rhodes and Tupper 2007) and regionally important to fisheries, including the large-scale live reef food fish trade (LRFFT) emanating from Southeast Asia (Sadovy et al. 2003). Squaretail coralgrouper are described as monandric, protogynous hermaphrodites (Rhodes *unpublished data*) and form relatively large (100s-1000s of individuals) seasonal spawning aggregations in most locales surveyed (e.g. Rhodes and Tupper 2008; Robinson et al. 2008; Golbuu Y, Palau International Coral Reef Center *personal communication*). In other locales, smaller aggregations may form monthly, with seasonal peaks in abundance over a few months (Pet et al. 2005; Hamilton R, The Nature Conservancy *personal communication*). In Pohnpei, Micronesia, for example, *P. areolatus* form FSA over a 5-month period, but form monthly FSA at some sites, such as in Roviana Lagoon, Solomon Islands. It is currently unclear whether all aggregations that form monthly throughout the year are reproductive. Regardless of the location, FSA typically persist over approximately two weeks per reproductive month and disperse following spawning.

In areas where aggregation fishing is active, reports and observations of squaretail coralgrouper FSA loss or reductions in abundance have been reported (Pet et al. 2005; Golbuu Y, Palau International Coral Reef Center *personal communication*). In Pohnpei, Micronesia, *P. areolatus* has been shown to utilize reproductive migratory corridors, which along with other co-aggregating grouper are targeted by fishers (Rhodes and Tupper 2008). Regionally, interest in management of the species and its FSA is growing because of widespread FSA loss and population declines. The species was recently assessed as Vulnerable (A2d) owing to these reported and perceived changes (IUCN 2008) and there is thus a need to produce effective regional management options, including the use of MPAs (marine protected areas).

Marine protected areas have been promoted by resource managers as a useful management tool to protect spawning aggregations (Bohnsack 1998; Sadovy and Domeier 2005). However, few FSA have been adequately assessed to determine spatial needs to effectively protect reproductive adults, including catchment areas (areas from which adults are drawn to FSA) or habitat use within and between reproductive periods. As a result, few existing MPAs are biologically meaningful and most are likely of insufficient scale to maintain or grow populations (e.g. Fulton et al. 1999; Sala et al. 2001; Starr et al. 2007). None has adequately incorporated migratory corridors into MPA design. As a result, declines in abundance within FSA have been noted even following MPA protection (Golbuu Y, Palau International Coral Reef Center *personal communication*). Thus, the level of vulnerability and potential for reductions in spawning stock during aggregation periods remains high.

Regionally within the western and central Pacific, only two countries have implemented management directed at squaretail coralgrouper. In each instance, small-scale MPAs (Palau and Pohnpei, Micronesia) and seasonal sales (Pohnpei) or combination sales-catch bans (Palau) have been implemented. These measures have shown mixed results, with reductions in aggregation size continuing at some protected sites, most likely a result of a lack of MPA enforcement, unregulated fishing outside reproductive periods and fishing along reproductive migratory corridors.

The objective of the current study was to assess for *P. areolatus,* distance of movement between reproductive and non-reproductive habitats and examine spatial requirements for biologically meaningful MPA design. To accomplish this goal, the study utilized active tracking of acoustically tagged *P. areolatus*. A second objective was to assess home range size and residency within and outside the spawning season. Both objectives were undertaken to improve regional management for the species.

Materials and Methods

Study Site

To assess area management requirements for *P. areolatus*, the study was conducted in and around the Kehpara Marine Sanctuary (KMS) in Pohnpei, Federated States of Micronesia (6°55'N, 158°15'E) (Fig. 1; see Rhodes and Sadovy 2002 for additional site details). This small

(1.46 km^2) protected area encompasses a multi-species (epinephelids and other coral reef fishes) fish spawning aggregation (FSA) site. During peak reproductive months, *P. areolatus*, brown-marbled grouper, *Epinephelus fuscoguttatus*, and camouflage grouper, *Epinephelus polyphekadion*, co-aggregate at the KMS to spawn, with aggregations spatially segregated but temporally overlapping in some months (Rhodes and Sadovy 2002; Rhodes et al. 2005; Rhodes and Tupper 2008).

Fish capture, catch per unit of effort, and acoustic tagging

To capture *P. areolatus* for tagging, two local fishers, targeted individuals at the FSA from the surface with mask, snorkel and hook-and-line, using live *Myripristis* sp. as bait. To determine monthly variations in site visitation frequency, tagging was conducted during what are typically the two final months of the 5-month spawning season (April-May). Tracking was also conducted during non-reproductive months (June-July) to an accurate assessment of home range use. Fish were captured in April (18 April) and May 2008 (16-19 May) in the week prior to full moon. Upon capture, fish were brought on-board and anaesthetized in a 0.75 g L^{-1} solution of seawater and 99.5% pure tricane methanesulfonate until fish lost equilibrium (*ca.* 2-5 min). Following anaesthesia and air bladder deflation, all individuals were weighed (±1 g body weight), measured (±1 mm total length [TL]) and sexed macroscopically using a 1-mm bore nylon cannula (Rhodes and Sadovy 2002). Sex designations and maturity stages followed criteria previously used for *E. polyphekadion* (Rhodes and Sadovy 2002), with oocyte stages determined under 10X magnification using a handheld eyepiece. A 2-cm surgical incision was then made through the gut wall just anterior to the vent for insertion of a uniquely identifiable Vemco V13-1L® (AMIRIX Systems, Halifax, Nova Scotia) coded acoustic tag (69.0 kHz, 40 sec delay). Incisions were closed using a surgical skin stapler (Conmed Reflex 35W, Conmed Endosurgery, Utica, NY) and coated with topical antibiotic. Fish were recovered on-board in aerated seawater. After recovery (*ca.* 10-15 minutes), fish were released adjacent to the FSA in shallow water (5-10 m) areas of the reef flat, with the goal of reducing the risk of predation.

Acoustic tracking

In order to determine distance of movement and essential fish habitat during both reproductive and non-reproductive periods, initial positions were recorded for fish at the point of release following tagging. Tracking of fish was conducted in the immediate release area until fish disappeared from the FSA.

In total, active tracking of acoustically tagged *P. areolatus* was conducted daily over 75 of 90 days (18 April to 18 July) using a Vemco VR100® on-board acoustic receiver to determine fish locations (Table 1). Tracking was conducted over an 8-10-hr period daily to maximize the potential number of detected individuals. Initial tracking utilized an omni-directional hydrophone (Vemco VH165-5M®) to determine fish presence and general location. Once a signal was detected, exact positions of individuals were identified with a directional hydrophone (Vemco VH110-10M®). Specific fish location is determined when signal strength is equal within a 360° radius of the boat position. Positions were then recorded with a handheld Garmin GPS Model 72 receiver (Garmin, Olathe, KS) for subsequent analysis of spatial habitat use. Prior to tracking, range testing was conducted to determine maximum detection distances of tagged fish.

Between monthly fish tagging, searches were concentrated in areas between Nahlap Channel and Dawahk Channel (Fig. 1). Searches followed both the inside and outside of the barrier reef, targeting submerged lagoon patch reefs and the inner and outer edges of the fringing reef. After tagging in May, the search area was expanded northward to Sokehs Channel and east to Pelian Channel (Fig. 1). Searches were performed over 100-200 m tracks perpendicular to the reef and start and stop points were recorded using the handheld GPS. For each transect, the boat was allowed to drift slowly for *ca.* 5-10 minutes to maximize area coverage and increase the likelihood of signal detection. For patch reefs, searches included the entire patch perimeter. Since motor noise interfered with signal detection and because movement was often dependent on drift from currents of wind, straight-line movement along transects was not always possible, thus, area coverage may have been incomplete and non-overlapping in some instances, and some fish positions may have been missed.

In an effort to verify the use of Kehpara and Pehleng Channels as staging areas or entryways into the lagoon, tracking was concentrated in these areas prior to and after spawning. Tracking also focused on lagoon areas adjacent to the KMS FSA to assess whether fish moved across the reef crest into the lagoon after spawning. Although some tracking was done nocturnally, efforts focused primarily on diurnal periods, when coralgrouper are generally most active (Zeller 1998; Rhodes *personal observation*; R. Hamilton *personal communication*).

Identification of essential fish habitat (EFH): Analysis of tag data

All tracks were mapped onto geo-referenced aerial images and the straight-line distance between areas of reproductive (i.e. FSA) and non-reproductive EFH was determined. Spatial dimensions of essential non-reproductive fish habitat, i.e. home ranges, were calculated by laying polygons over areas where fish were present during tracking, with area estimates performed by Imagetool 3.00 (Wilcox et al. 2002). Home range estimates were determined where more than five tag positions were recorded, by calculating fixed-kernel estimates with smoothing done by least-squares cross-validation using Homeranger software (Hovey 1999). For tracks where small sample sizes were used, results should be interpreted with caution, as these are known to produce poor estimates of home range (Seaman et al. 1999; Blundell et al. 2001)

Results

Range testing

Range testing indicated that detection rates for tags varied depending on fish location in relation to the reef. In open water with no obstructions between the tag and hydrophone, signals could be detected at ranges of up to *ca.* 250 m. However, as tagged fish tended to be associated with the reef, detection distances were generally reduced to *ca.* 100 m. Finally, when tagged fish were surrounded by spatially complex coral, reception distances dropped to under 40 m, with the worst case detection scenario less than 10-20 m of fish position.

Coralgrouper abundance patterns

A total of 15 individuals were tagged with Vemco V13-1L® acoustic tags during April and May that included 5 females and 10 males. Five males were acoustically tagged in each month, with an additional two males Floy tagged in May (n = 12). Four females were tagged during a single day in April and two females were captured in May during five days of fishing (n = 6). No aggregation was observed to form in June. Based on cannulation of captured individuals, all fish were reproductively mature and active, with late stage vitellogenic oocytes (females) and free-running milt (males). Size range was comparable to that of adults caught at the FSA during research in previous years (Rhodes and Tupper 2008) and ranged from 410.5 ± 182.1 mm (± SD, hereafter) TL for females and 552.9 ± 33.3 mm TL for males.

Movement, residency and home range habitat

Following tagging and release, all fish were tracked to determine post-tag departure times (Table 1). In April, all males and the majority of females left the FSA site within the first 48 hours post-tagging, whereas in May two newly tagged males remained in the immediate area for 4-10 days prior to dispersing away from the FSA.

Out of the total 15 acoustic tag deployments, one female died post-release in May, as indicated by a constant signal in one position for 42 days. Efforts to locate the latter female (and/or tag) using SCUBA were unsuccessful. Seven individuals (four males and three females) were subsequently relocated within their non-reproductive home range habitats. One female, tagged during April, was found in a small area adjacent to the FSA throughout the study and appeared to be resident. Eight individuals were not relocated following tagging either on the FSA or within areas covered during tracking.

Of the total number of fish tagged, only one male tagged in April returned to the FSA in May (1 of 9 tagged fish), where it remained for 7 days until presumed spawning on or before the full moon. Subsequent tracking over a 10-hr period following its departure from the FSA showed movement to a home range area only 1441 m to the south of the FSA (Fig. 2). Of the remaining six fish successfully re-located, four individuals (3 ♂, 1 ♀) were found in areas immediate adjacent to the FSA (within 1.5 km), while the remaining two fish (1 ♂, 1 ♀) were located away *ca.* 6 and 23 km, respectively, from the FSA (Figs. 1 and 2). No individuals were successfully tracked in real time from the FSA to home range habitats, thus no additional information on reproductive migration corridors or rates of movement was gathered.

Movement of fish in reproductive and non-reproductive areas

Of the six fish that were re-located away from the FSA (Fig. 1), four (3 males = T1, T2, T6; 1 female = T3,) were found in outer reef areas at 10–50 m depth and within 22-1441 m of the FSA (Fig. 1b). One additional male (T5) was located inside the lagoon on a patch reef (*ca.* 25 m diameter) 6 km northeast of the FSA near Pehleng Channel (Fig. 1c). During the final days of tracking, one additional female (T4) was located 23 km north of the FSA in Behnemen Channel (Fig. 1d) and traversed the barrier reef through the channel at *ca.* 11.5 m depth during tracking. Few positions were taken of the latter female prior to the conclusion of the project owing to logistic constraints.

Analyses of polygons indicated that fish maintained individual home ranges of 0.004-0.12 km^2 (95 % fixed-kernel estimate; Fig. 3). On several occasions, more intensive tracking (i.e. positions every 30-60 minutes) was performed to examine short-scale movement patterns of male T1 (Fig. 1b). Over a period of several hours, this individual utilized the whole of its home range, moving distances of up to 200 m over a 1-hr period. In contrast, male T5 tended to move shorter distances 10–50 m and moved into adjacent areas nearby only every few days (Fig. 1b). There were no apparent differences in depth or area of home range for males or females.

Discussion

Spawning aggregations (FSA) are critical life history events for a number of coral reef fishes (e.g. Thresher 1984; Sadovy and Domeier 2005). For most epinephelids studied to date, FSA are shown to be highly susceptible to overfishing and typically can withstand only low levels of fishing pressure, including that for subsistence use. Nonetheless, FSA have been widely targeted by fishing interests, primarily by commercial fishers, resulting in aggregation loss, population declines, altered spawning (operational) sex ratios, changes to reproductive behaviour and reductions in mean fish size, among others (Beets and Friedlander 1998; Coleman et al. 2000; Sadovy and Domeier 2005). Less well understood, however, is the spatial scale over which FSA fishing impacts reproductive populations, and how management should be designed to minimize or eliminate these impacts. For biologically meaningful management to be instituted critical reproductive and non-reproductive habitats must be identified and characterized, and included in area management strategies at spatial and temporal scales sufficient to sustain populations.

Habitat association and site fidelity

In Pohnpei, acoustic tag-recapture and tracking surveys of adult *P. areolatus* have provided the first evidence of non-reproductive essential fish habitat association and size. From these surveys, *P. areolatus* appear highly site attached and inhabit relatively small home ranges (0.004-0.12 km^2) in seaward and lagoonal coral-rich areas of moderate to high reef complexity. The spatial extent of home range areas appear similar to many other epinephelids studies to date, including the con-specific leopard coralgrouper (*P. leopardus*) that utilizes home ranges less than 0.16 km^2 (size range = 38-67 cm FL) (Zeller 1998). Similarly, gag grouper (*Mycteroperca microlepis*) were shown to inhabit home range areas of 0.003 to 0.26 km^2 (Kiel 2004), while graysby (*Cephalopholis cruentata*) home ranges were considerably smaller (0.0012 to 0.0024 km^2) (Popple and Hunte 2005).

During the current study, *P. areolatus* showed high site fidelity to home range habitats. For other epinephelids, both site fidelity and homing has been demonstrated for (*Epinephelus marginatus*) (Lembo et al. 1999), graysby *(Epinephelus cruentatus*) and coney (*Epinephelus *fulvus*) (Corless et al. 1997), and mutton hamlet (*Epinephelus afer*) and Nassau grouper (Beets and Hixon 1994). Gag grouper (*M. microlepis*) has demonstrated site fidelity following translocation over distances of 1-8 km (Keil 2004). FSA site fidelity by *P. areolatus* was shown during previous tagging studies (Rhodes and Tupper 2008) and movement between home range and the FSA was demonstrated for one acoustically tagged male in the current study. FSA site fidelity has been reported previously for both *E. striatus* and *P. leopardus* (Zeller 1998; Starr et al. 2007). Thus, site attachment during both reproductive and non-reproductive periods appears to characterize a number of epinephelids, including *P. areolatus* and lends supports for protection of both reproductive and non-reproductive habitats.

Distance of movement and catchment areas

The number of tag-recapture studies examining epinephelid movement is growing and provides the basis for spatial management requirements of reproductive populations. Included among the findings is the potential for long-distance movement between reproductive and non-reproductive habitats for some individuals. Nassau grouper, for example, have been found to travel between 110 and 240 km relative to FSA prior to capture (e.g. Colin 1992; Bolden 2000). For *P. areolatus*, the potential for long distance movement comes both from the current study and from a 2005 tag-recapture survey when two individuals (combined studies) moved 23 km from the FSA. In both instances, the fish moved past other known (or reported) *P. areolatus* FSA sites to reach home range (current study) or recapture locations (2005 study). In contrast to long distance movement is an increasing number of tag-recapture studies reporting short-distance movement between FSA and home range habitats or recapture locations. For example, six individuals from the current study and > 90% of recaptures from the 2005 study were located or recaptured 1.5 to less than 10 km of the Kehpara FSA (Rhodes and Tupper 2008). In both studies, year-round residency at or near the FSA site was observed among a few individuals. Similarly, in Belize (Glover's Reef), recaptured (Floy-tagged) Nassau grouper appeared to be clustered within *ca.* 15 km the FSA, while acoustically tagged fish were spread rather evenly around the atoll (max. distance *ca.* 30 km) (Starr et al. 2007). For tagged *E. guttatus* in the US Virgin Islands, Nemeth et al. (2007) reported recaptures primarily within 10 to 15 km, respectively, of two separate FSA sites. While results from other areas may reflect fishing effort focused on particular areas adjacent to FSA, this was not the case in Pohnpei, where fishing effort did not correspond strictly with recapture locales. These latter finding show that fish and not merely fishing effort are concentrated near FSA (Rhodes and Tupper 2008). Further support for small catchment areas is provided by Zeller (1998) who, using freeze-brand tagging techniques, recorded travel distances from 220 m to 5 km for *P. leopardus* between home range and FSA sites. For these combined species in their respective locales, preliminary evidence suggests that catchment areas are basically similar in size, and relatively small in comparison to the extensive reef area surrounding each respective FSA.

While there is clear overlap among reproductive populations utilizing different spawning sites, the information presented here and elsewhere suggests that FSA overfishing or loss could disproportionally affect localized areas surrounding FSA. Where multi-species grouper spawning aggregations occur, FSA loss could have more substantial impacts to reef community structure, for example, by altering trophic webs. For local fishing communities, these changes could also produce economic hardship and create food insecurity (Bell et al. 2009). Finally, where selfrecruitment is high, FSA loss could produce longer lasting effects, with recovery of populations and their respective FSA perhaps taking years to decades (e.g. Colin et al. 2003; *but see* Burton et al. 2005)

Mortality and the limitations to acoustic surveys in coral reef environments

During the current study, tracking detected only 7 of 15 (known) surviving individuals, with the fate of the additional 8 fish unknown. The loss of these 8 individuals is likely the result of one or more of the following factors: tag-induced mortality, predation, long-distance movement outside of surveyed areas, or detection failure during tracking. As previously mentioned, long-distance movement is clearly possible for *P. areolatus*. Of the three possible fates listed, however, long-distance movement for this percentage of tagged fish appears the least likely explanation, based on past results showing small catchment areas (Rhodes and Tupper 2008). A more likely cause is tag detection failure, particularly given the range limitations inherent in coral reef environments (20-100 m). While methods to improve tag detection in reef environments are limited, one possible improvement is the use of continuous acoustic tags with shorter ping rates. The trade-off to this method is the limit in the number of frequencies that can be simultaneously monitored. A second possible explanation for missed tags is tag mortality. Tag mortality is an inherent problem in acoustic studies involving reproductively active individuals already under metabolic stress. During the current study, reductions in tag mortality may have been possible from additional recovery and observation times. This typically requires removing animals from the natural environment over for prolonged periods, thereby potentially altering reproductive and social behavior. The current study chose to minimize time outside the normal reproductive and social setting and opted instead to release fish within the FSA shortly after capture and tagging, usually within 30 minutes. Using this method, minimal changes to behavior following tagging were observed, with tagged fish demonstrating normal reproductive interactions shortly after release (e.g. Rhodes and Tupper 2008). A trade-off to this method is a potential increase in predation, since stressed fish are known to attract predators, such as grey reef (*Carcharinus amblyrhynchos*), white (*Triaenodon obesus*) and blacktip (*Carcharhinus melanopterus*) sharks that actively patrol the FSA. While no tagged fish were observed being preyed upon during this or prior studies, the possibility of tag loss to predation remains. It is likely that each of these factors contributed to the failure to detect all of the fish tagged. Future research may wish to examine these factors in greater detail, including the trade-offs of prolonged recovery under varying conditions, particularly changes in social and reproductive behavior following tagging.

Designing area management with acoustic surveys

The number of studies examining home range use and movement of groupers relative to FSA is currently limited. Nonetheless, these combined studies show remarkably similar results, with limited spatial use during non-reproductive periods and reproductive migrations typically less than 20 km. While it is still too early to generalize spatial guidelines for FSA-based MPA based on home range size and migration patterns, these combined findings clearly show that most if not all FSA-based MPA currently in use are too small spatially to be biologically meaningful and must be expanded to include migratory corridors (where known) and adjacent reef areas where home rage habitats occur. Since many known FSA sites are multi-species in nature (e.g. Rhodes and Sadovy 2002, Heyman et al. 2005), expanded area coverage would also enhance protection for other highly vulnerable species, such as humphead wrasse (*Cheilinus undulatus*) (Chateau and Wantiez 2007) and other highly site attached fishes (e.g. Kaunda-Arara and Rose 2004). For *P. areolatus* in Pohnpei, past and current findings suggest that most of the reproductive population utilizing Kehpara (KMS) could be protected with a 200-300 km^2 MPA. While politically difficult to achieve, the current area of the KMS MPA at only 1.46 km^2 obviously provides little protection to the reproductive population outside the immediate aggregation area. Without further area improvements or other additional management to reduce fishing pressure on reproductive adults, the potential for negative impacts to reproductive populations (and fishing communities) associated with the KMS *P. areolatus* remains high.

Future research

To support the recent findings on catchment areas and migratory corridors, future research should focus tagging efforts not only on reproductive, but also on non-reproductive habitat to determine how these two essential fish habitats are related and what impacts on populations their inclusion (or exclusion) would have. These types of studies could provide further insight into how FSA loss from fishing impacts local fish and fisher communities, and would assist in the development of biologically meaningful and locally effective marine protected are design.

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References

Aguilar-Perera A (2007) Disappearance of a Nassau grouper spawning aggregation off the southern Mexican coast. Mar Ecol Prog Ser 327:289-296

Beets J, Hixon M (1994) Distribution, persistence, and growth of groupers (Pisces: Serranidae) on artificial and natural patch reefs in the Virgin Islands. Bull Mar Sci 55:470-483

Beets J, Friedlander A (1998) Evaluation of a conservation strategy: a spawning aggregation closure for red hind, *Epinephelus guttatus,* in the U.S. Virgin Islands. Environ Biol Fish 55:91-98

Bell JD, Kronen M, Vunisea A, Nash WJ, Keeble G, Demmke A, Pontifex S, Andréfouët S (2009) Planning the Use of Fish for Food Security in the Pacific. Mar Policy 33:64-76

Blundell GM, Maier JAK, Debevec EM (2001) Linear home ranges: Effects of smoothing, sample size, and autocorrelation on kernel estimates. Ecol Monogr 71:469-489

Bohnsack JA (1989) Protection of grouper spawning aggregations. NOAA/NMFS Southeast Fisheries Center Coastal Resource Division Contribution Number CRD-88/89-06, 8 p

Bolden SK (2000) Long distance movement of a Nassau grouper (*Epinephelus striatus*) to a spawning aggregation in the central Bahamas. Fish Bull 98:642-645

Burton ML, Brenna KJ, Muñoz RC, Parker RO (2005) Preliminary evidence of increased spawning aggregations of mutton snapper (*Lutjanus analis*) at Riley's Hump two years after establishment of the Tortugas South Ecological Reserve. Fish Bull 103:404-410

Chateau O, Wantiez L (2007) Site fidelity and activity patterns of a humphead wrasse, *Cheilinus undulatus* (Labridae), as determined by acoustic telemetry. Environ Biol Fish 80:503-508

Coleman FC, Koenig CC, Collins, LA (1996) Reproductive styles of shallow-water grouper (Pisces: Serranidae) in the eastern Gulf of Mexico and the consequences of fishing spawning aggregations. Environ Biol Fish 47:129-141

Coleman FC, Koenig CC, Huntsman GR, Musick JA, Eklund A-M, McGovern JC, Chapman RW, Sedberry GR, Grimes CB (2000) Long-lived reef fishes: the grouper-snapper complex. Fisheries 25:14-21

Colin PL (1992) Reproduction in the Nassau grouper, *Epinephelus striatus* (Pisces: Serranidae) and its relationship to environmental conditions. Environ Biol Fish 34:357-377

Colin PL, Sadovy YJ, Domeier ML (2003) Manual for the study and conservation of reef fish spawning aggregations. Society for the Conservation of Reef Fish Aggregations (SCRFA) Special Publication No. 1 (version 1.0), 98 + iii p, www.scrfa.org

Domeier ML, Colin PL (1997) Tropical reef fish spawning aggregations: defined and reviewed. Bull Mar Sci 60:698-726

Fulton E, Kault D, Mapstone B, Sheaves M (1999) Spawning season influences on commercial catch rates: computer simulations and *Plectropomus leopardus*, a case in point. Can J Fish Aquat Sci 56:1096-1108

Heemstra PL, Randall JE (1993) FAO Species Catalogue, vol 19. Groupers of the World Family Serranidae, Subfamily Epinephelinae. An annotated and illustrated catalogue of the grouper, rockcod, hind coral grouper and lyretail species known to date. FAO Fish Synop No 125, vol 16. FAO, Rome

Heyman HD, Kjerfve B, Graham RT, Rhodes KL, Garbutt L (2005) Spawning aggregations of cubera snapper, *Lutjanus cyanopterus* (Cuvier), in the Belize Barrier Reef over a 6-yr period. J Fish Biol 67:83-101

IUCN (2008) IUCN Redlist of Threatened Species, www.iucnredlist.org

Johannes RE, Squire L, Graham T, Sadovy Y, Renguul H (1999) Spawning aggregations of groupers (Serranidae) in Palau. Marine Research Series Publication No. 1. The Nature Conservancy, Arlington

Kaunda-Arara B, Rose GA (2004). Long-distance movements of coral reef fishes. Coral Reefs 23:410-412

Kiel BL (2004) Homing and spatial use of gag grouper, *Mycteroperca microlepis*. M.Sc. thesis, University of Florida, p79

Lembo G, Fleming IA, Økland F, Carbonara P, Spedicato MT (1999) Homing behaviour and site fidelity of *Epinephelus marginatus* (Lowe, 1834) around the Island of Ustica: Preliminary results from a telemetry study. Biol Mar Medit 6:90-99

Nemeth RS (2005) Population characteristics of a recovering US Virgin Islands red hnd spawning aggregation following protection. Mar Ecol Prog Ser 286:81-97

Nemeth RS, Blondeau J, Herzlieb, Kadison E (2007) Spatial and temporal patterns of movement and migration at spawning aggregations of red hind, *Epinephelus guttatus*, in the U.S. Virgin Islands. Environ Biol Fish 78:365-381

Pet JS, Mous PJ, Muljadi AH, Sadovy YJ, Squire L. (2005). Aggregations of *Plectropomus areolatus* and *Epinephelus fuscoguttatus* (grouper, Serranidae) in the Komodo National Park, Indonesia: monitoring and the implications for management. Environ. Biol. Fish 74:209-218

Popple ID, Hunte W (2005) Movement patterns of *Cephalopholis cruentata* in a marine reserve in St. Lucia, W.I., obtained from ultrasonic telemetry. J Fish Biol 67A:981-992

Rhodes KL, Sadovy Y (2002) Temporal and spatial trends in spawning aggregations of camouflage grouper, *Epinephelus polyphekadion* (Bleeker 1849) in Pohnpei, Micronesia. Environ Biol Fish 63:27−39

Rhodes KL, Tupper MH (2007) A preliminary market-based analysis of the Pohnpei, Micronesia, grouper (Serranidae: Epinepheline) fishery reveals unsustainable fishing practices. Coral Reefs 26:335−344

Rhodes KL, Tupper MH (2008) The vulnerability of reproductively active squaretail coralgrouper (*Plectropomus areolatus*) to fishing. 2008. Fish Bull 106:194-203

Rhodes KL, Tupper MH, Wichilmel CB (2008) Characterization and management of the commercial sector of the Pohnpei coral reef fishery, Micronesia. 2007. Coral Reefs 27:443–454

Roberts CM, Hawkins JP (1999) Extinction risk in the sea. Trends Ecol Evol 14:241-246

Robinson J, Aumeeruddy R, Jörgensen TL, Öhmann MC (2008) Dynamics of camouflage (*Epinephelus polyphekadion*) and brown marbled grouper (*Epinephelus fuscoguttatus*) spawning aggregations at a remote reef site, Seychelles. Bull Mar Sci 83(2):415-431

Sadovy Y (1996) Reproduction of reef fishery species. In: Polunin NVC, Roberts, CM (eds) Reef fisheries. Chapman and Hall, London, pp15-60

Sadovy YJ, Donaldson TJ, Graham TR, McGilvray F, Muldoon GJ, Phillips MJ, Rimmer MA, Smith A, Yeeting B (2003) While Stocks Last. The Live Reef Food Fish Trade. Asian Development Bank, Manila

Sadovy de Mitcheson Y, Cornish A, Domeier M, Colin PL, Russell M, Lindeman KC (2008) A global baseline for spawning aggregations of reef fishes. Conserv Biol 22:1233-1244

Sala E, Ballasteros E, Starr RM (2001) Rapid decline of Nassau grouper spawning aggregations in Belize: fishery management and conservation needs Fisheries 26:23-30

Seaman DE, Millspaugh JJ, Kernohan BJ, Brundige GC, Raedeke KJ, Gitzen RA (1999) Effects of sample size on kernel home range estimates. J Wildl Manag 63:739-747

Starr RM, Sala E, Ballasteros E, Zabala M (2007) Spatial dynamics of the Nassau grouper *Epinephelus striatus* in a Caribbean atoll. Mar Ecol Prog Ser 343:239-249

Thresher RE (1984) Reproduction in reef fishes. TFH Publication, Neptune City

Zeller DC (1998) Spawning aggregations: patterns of movement of the coral trout *Plectropomus leopardus* (Serranidae) as determined by ultrasonic telemetry. Mar Ecol Prog Ser 162:253-26

Figure legends

Fig. 1 Map of Pohnpei (a) showing the spatial extent to tracking and the initial tag locations and recapture sites (letters). Main channel locations are numbered consecutively from north to south: 1-Sokehs, 2-Behnemen; 3-Dawahk, 4-Pehleng, 5-Kehpara, 6-Nahlap, 7-Pelian. Map inserts (b-d) show the initial positions that tagged fish (T1-6) were recorded at following release (b; numbered points) in the Kehpara Marine Sanctuary, and subsequent positions where they were recorded during non-reproductive periods (black polygons). Figs. 1b-d correspond to the geometric areas highlighted in Fig. 1a. Dark shading = land; medium shading = reef flat; light shading = reef slope

Fig. 2 Straight-line distances traveled by *Plectropomus areolatus* from FSA to non-reproductive sites. Note the scale change

Fig. 3 Non-reproductive home ranges for *Plectropomus areolatus* as recorded by direct measurements of polygons overlaid on tracks and calculated with Homeranger software

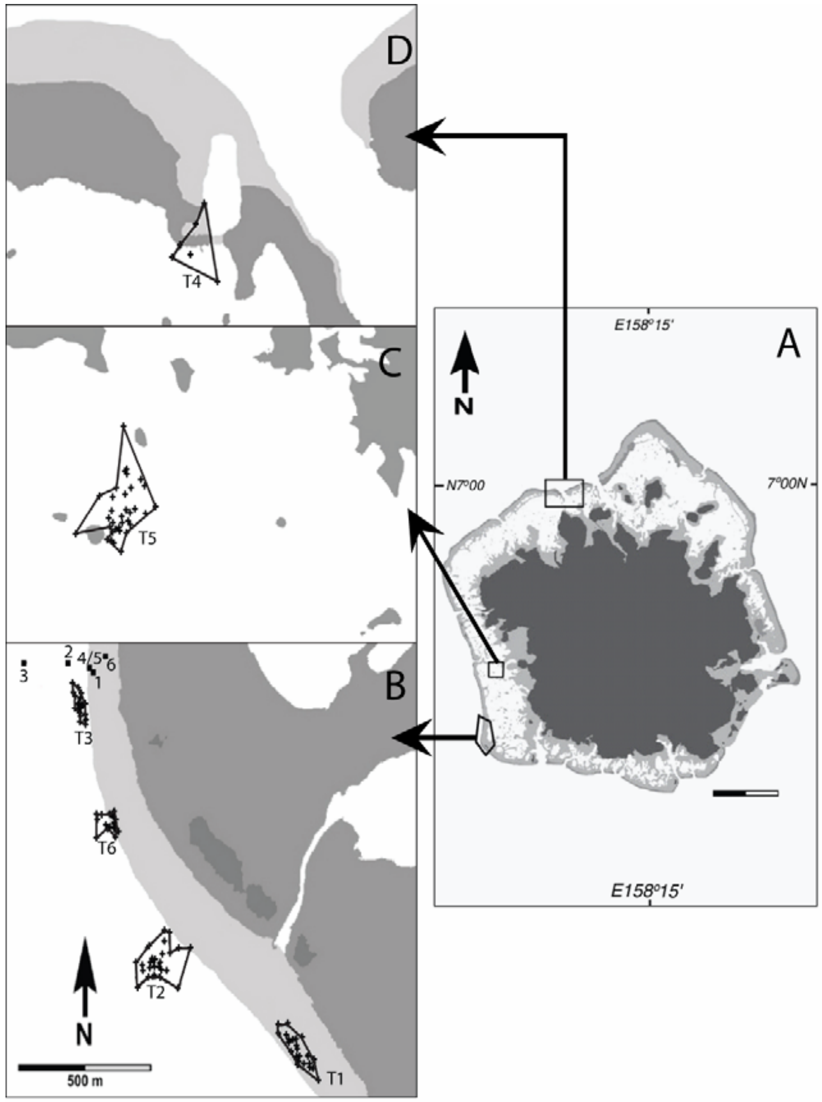


Figure 1

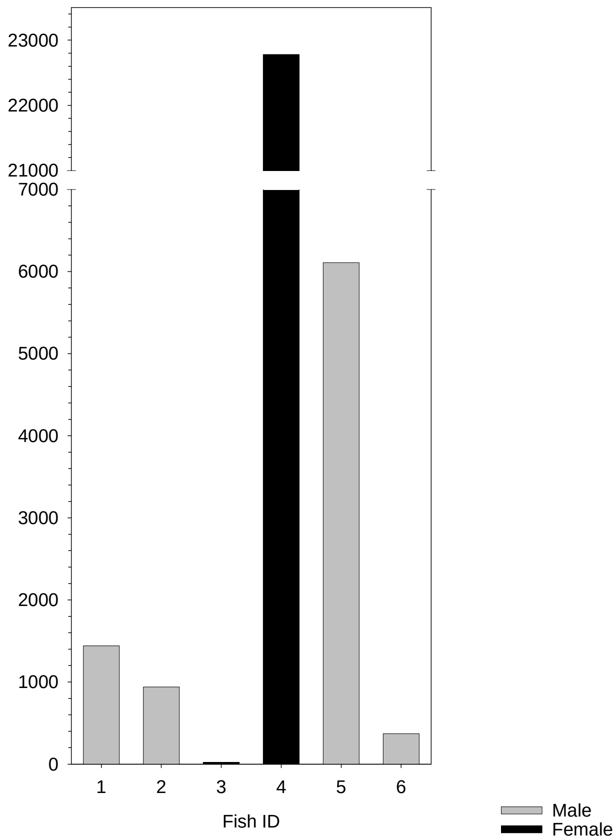
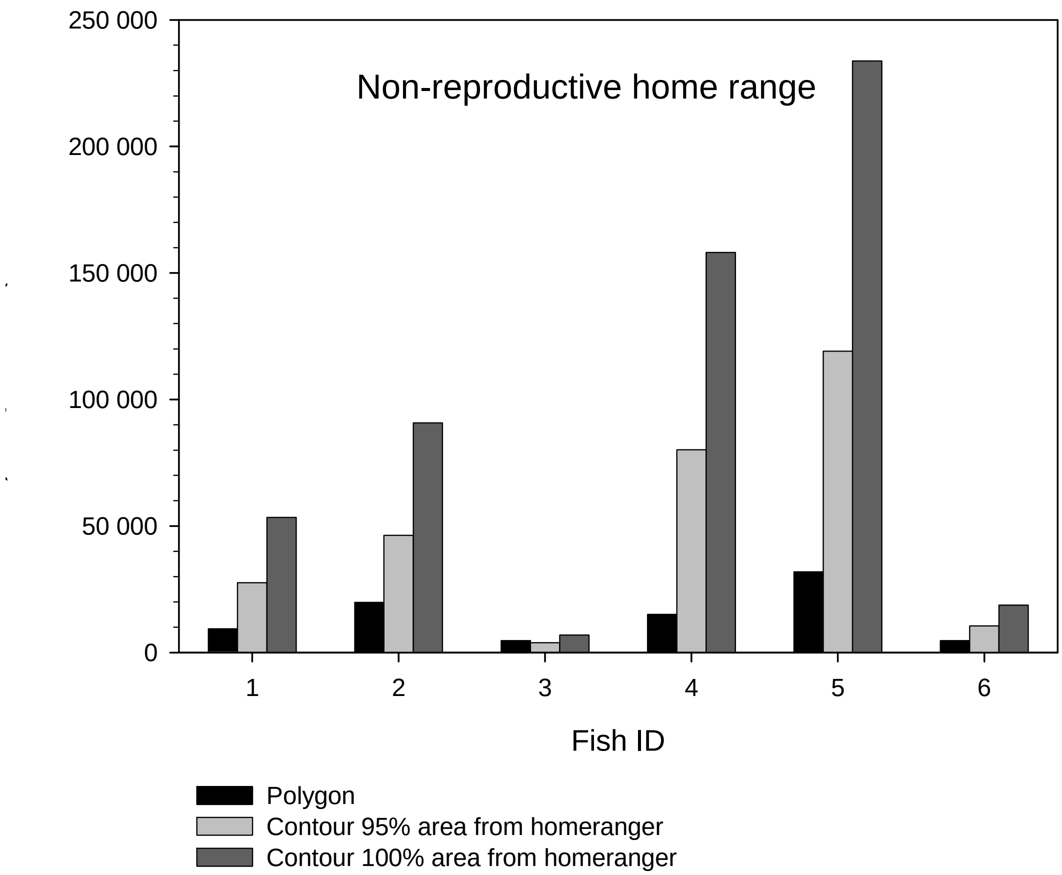

23000
22000
21000
7000
6000
5000
4000
3000
2000
1000
0
1
2
3
4
5
6
Fish ID
Male
Female

Figure 2



250 000
200 000
150 000
100 000
50 000
0
Non-reproductive home range
1
2
3
4
5
6
Fish ID
Polygon
Contour 95% area from homeranger
Contour 100% area from homeranger

Figure 3

Table 1: Summary of post-tag departure times. Individuals in **bold** are those detected during tracking after they had left the FSA. N/A indicates that a tagged individual did not recover from anaesthesia.

Month	Fish ID	Sex	Day tagged (before full moon)	Days present on FSA (Post-tagging)	Fate
		♀	3	1	Unknown
April	**T1**	♂	**3**	**0**	Tracked
		♀	3	0	Unknown
	T2	♂	3	0	Tracked
	T3	♀	**3**	**90**	Tracked
	T4	♀	**3**	**1**	Tracked
		♂	3	1	Unknown
	T5	♂	**3**	**1**	Tracked
		♂	3	0	Unknown
		♀	N/A	N/A	Dead
May		♂	4	0	Unknown
	T6	♂	**4**	**10**	Tracked
		♂	4	4	Unknown
		♂	4	0	Unknown
		♀	3	42	Dead
		♂	3	1	Unknown