FINAL REPORT

NOAA Coral Reef Conservation Program – General Coral Reef Conservation

NOAA Grant NA16FZ2958 "Testing the effectiveness of MPAs and other reef fish management strategies using agent-based models."

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Introduction

The management of a marine fishery is a difficult task (Costanza 2000) and in tropical nations such as Guam, where ecologically complex ecosystems are under heavy pressure from rapidly increasing anthropogenic stress, the problem is exacerbated. In Guam, the desire of local fishers to continue traditional fishing activities involving the harvest of juvenile fish further impedes management efforts. Over the past 15 years, CPUE of reef fish in Guam has declined by 70% (G. Davis, Guam Department of Agriculture, personal communication). Marine Protected Areas (MPAs) have received much attention in recent years as an alternative approach to traditional fisheries management. The primary goals of MPAs are to protect critical habitat and biodiversity, and to sustain or enhance fisheries by preventing spawning stock collapse and providing recruitment to fished areas. Recently, MPAs have become a major component of the U.S. Pacific Islands' coral reef conservation strategies.

In May of 1997, the Guam Department of Aquatic and Wildlife Resources (DAWR) established a network of five MPAs, termed "marine preserves", around the island, accounting for 11.8% of Guam's shoreline and 15.3% of Guam's reef area. Fishing within these MPAs is restricted to shore-based cast netting and hook and line fishing for select reef species, and trolling seaward of the reef margin for pelagic fish. These MPAs became fully enforced on January 1, 2001. The Republic of Palau also has a system of MPAs designed to protect their coral reefs, which support the local economy through both fisheries and marine-based tourism.

The ultimate objective of this research is to develop agent-based models (ABMs) to compare the effectiveness of MPAs versus alternative management strategies (e.g., commercial trade bans) and more "traditional" approaches to regulating catch and effort (e.g. quotas, gear restrictions, size limits, etc.). Traditional fisheries science models can be used to set aggregate total allowable catch (TAC) for reef fish in the Western Pacific Islands, but they provide little insight into the effects of alternative management approaches when species are heterogeneously distributed among habitats. The recent development of powerful object-oriented programming languages and geographic information systems has created opportunities for alternative approaches to fisheries modeling. Agent-based models are new modeling tools that incorporate individual agents into a spatially and temporally explicit "bottom-up" model. The model can be parameterized by quantification of habitat-specific settlement, growth, movement, mortality, and spawning, so habitat cells within the model simulate the ecological processes and events occurring in each habitat type. The advantage of such models is that they can be used as a computer-generated artificial fisheries management laboratory, in which managers can compare the outcomes of various fishery management policies. Fishery managers can be modeled as agents who modify fisher incentives, and hence spatially explicit ecological outcomes, through policy instruments.

Among the most desirable and most vulnerable nearshore reef fishes in the U.S. Western Pacific Islands are the larger species such as humphead or Napoleon wrasse (*Cheilinus undulatus*) and large groupers (*Epinephelus spp.*, *Plectropomus spp.*, and *Variola spp.*). The humphead wrasse is listed as Management Unit Species in the draft Coral Reef Ecosystems Fisheries Management Plan (Western Pacific Fisheries Management Council 2000). This species is slow growing and long-lived, with delayed reproduction in resident aggregations (P.L. Colin, Coral Reef Research Foundation, unpublished data) and low replenishment rates (Myers 1999). These life history traits render it particularly susceptible to overexploitation (Donaldson and Sadovy 2001). The humphead wrasse is a major component of the live reef fish trade and is subject to intense fishing pressure. Catches have declined dramatically over the past few decades (Myers 1999). It has been listed as "vulnerable" by the International Union for the Conservation of Nature (IUCN) and is currently under consideration for CITES II listing. In addition to their fishery value, large reef fishes are important to divers and have high tourism value (Rudd and Tupper 2002).

In order to create the environmental base for our ABM, we require information on habitat utilization patterns of the species being modeled. Thus, the first objective of our proposed research is to identify essential spawning, foraging and nursery habitat and ontogenetic habitat shifts for humphead wrasse and groupers Palau.

In our original proposal, we had originally planned to include the bumphead parrotfish (*Bolbometopon muricatum*) as a study species. However, it quickly became apparent that bumphead parrotfish did not occur in high enough densities in Guam or Palau to provide sufficient data for robust analyses. Moreover, bumphead parrotfish proved to be very fragile, with mortality rates due to marking of nearly 50%, which we considered unacceptable. The bumphead parrotfish was therefore dropped from this research, and replaced with two large, vulnerable, commercially important groupers, the camouflage grouper (*Epinephelus polyphekadion*), and the squaretail coral trout (*Plectropomus areolatus*).

In addition, although this work was originally proposed for both Guam and Palau, we have gotten little data from Guam except for the juvenile phases of humphead wrasse. This is due to the unfortunate fact that most large, vulnerable reef fishes (particularly groupers) no longer occur in Guam in densities sufficient to support this research and modeling effort. Therefore, the project is focused on Palau, and we present the research results from Palau in this report.

Methods

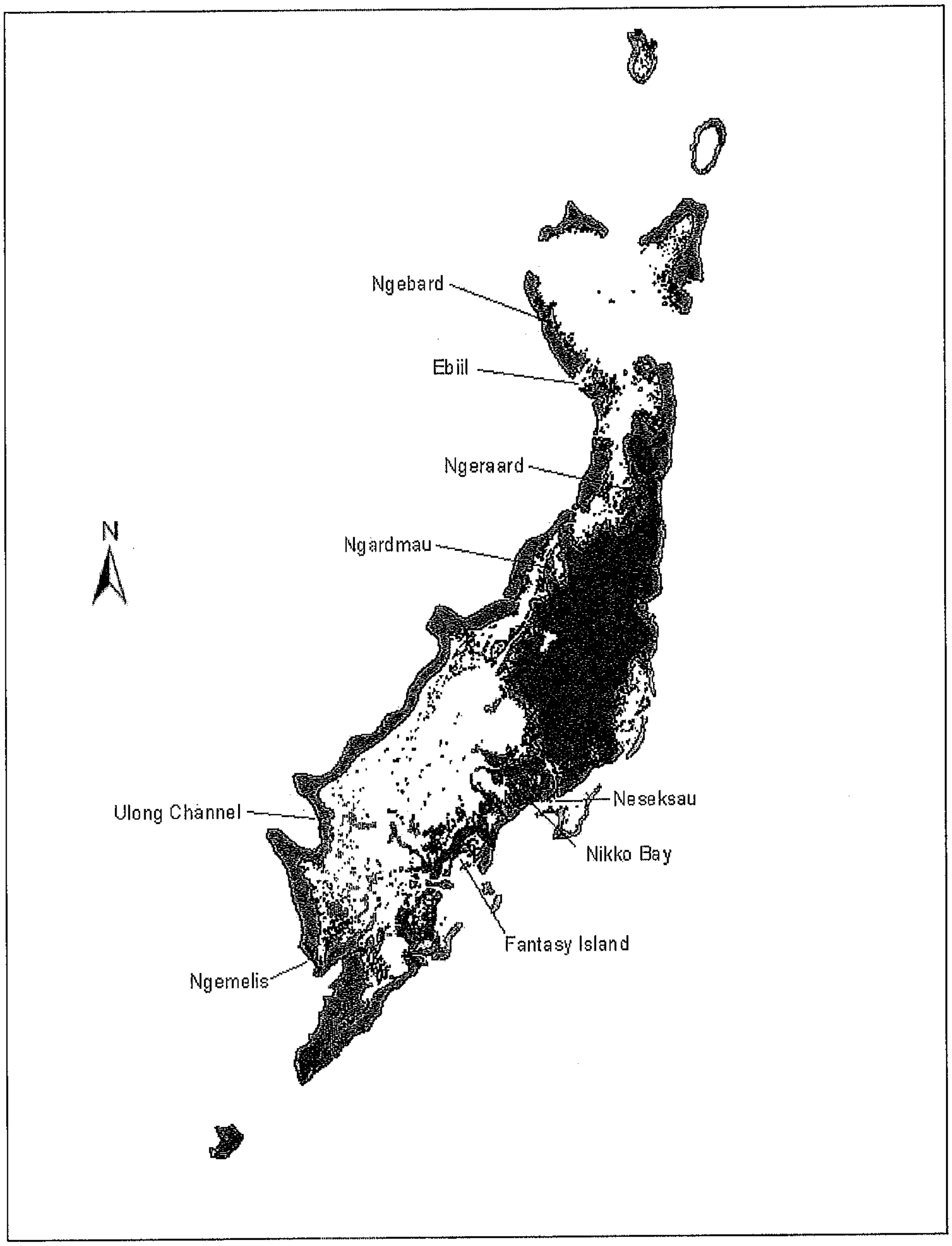
Fish habitat utilization

The study was conducted at selected sites in the main Palau archipelago (Figure 1). Shallow nearshore habitats were broadly classified as mangroves, seagrasses, patch reefs, fringing reefs, offshore bank or barrier reefs, sand/algal plains, tidal channels. Reef habitats were further subdivided into zones (reef flat, reef crest, submarine terrace, reef slope, etc.). These categories were further defined to microhabitat level based on species composition and percent cover of coral, algae, sponges and other epifauna. In each habitat, the abundance and size of humphead wrasse and groupers was quantified and a sample of the population marked and released to determine movements between habitats and habitat-specific growth and mortality rates. Specific methodology is detailed below.

Table 1. Study sites in Palau and Guam.

Site	Macrohabitats	Fishing Pressure	Anthropogenic Impacts*
PALAU			
Ngeraard	Lagoon (seagrass, sand/algal plain, patch reefs, cut by tidal channel)	Light	Moderate
Ngardmau	Lagoon (seagrass, sand/algal plain, patch reefs)	None (MPA)	Light
Ulong Channel	Barrier reef cut by partial channel (reef flat, reef crest, submarine terrace, deep reef slope)	None (MPA)	Light
Ngebard Channel	Barrier reef cut by complete channel (reef flat, reef crest, submarine terrace, deep reef slope)	Moderate	Minimal
Ebiil Channel	Barrier reef cut by partial channel (reef flat, reef crest, submarine terrace, deep reef slope)	None (MPA)	Minimal
Ngemelis	Barrier reef (reef flat, reef crest, submarine terrace, deep reef slope)	None (MPA)	Light
Fantasy Island	Lagoon (seagrass, sand/algal plain, patch reefs, cut by tidal channel)	Moderate	Moderate
Ngeseksau	Lagoon (seagrass, sand/algal plain, patch reefs, cut by tidal channel)	Light/Moderate	Minimal
Nikko Bay	Lagoon (seagrass, sand/algal plain, patch reefs)	Light/Moderate	Moderate

Figure 1. Map of Palau showing location of study sites.



i. Among-habitat variation in settlement

At each site, newly settled humphead wrasse (≤ 15 mm total length)and groupers (≤ 25 mm total length) were visually censused by SCUBA diving or snorkeling along five haphazardly placed 25 m x 2 m belt transects. Divers recorded the microhabitat (coral or seagrass species, sediment type, grain size, etc.) in which each newly settled individual is found. Due to the large number of zero values involved in settlement surveys, all settlement data were log(x+1) transformed where assumptions of parametric analysis are not met. Analysis of variance (ANOVA) was used to test the null hypothesis that settlement does not differ among habitat types.

ii. Among-habitat variation in abundance, growth, survival and movement

Humphead wrasse settle at a size of 8-15 mm TL, with a mode of about 12 mm TL (M. Tupper, unpublished data). This small size makes newly settled individuals inappropriate for mark-recapture studies, as the mortality associated with the marking process is unacceptably high (e.g. 28% in haemulids 11-15 mm TL, Tupper and Juanes 1999). The principal investigator (M. Tupper) has extensive experience (>3500 fish tagged) with this technique in temperate and tropical labrids, haemulids, and gadids. Mortality associated with this technique is typically 8-10% for fishes 20-30 mm TL (Tupper and Boutilier 1995, 1997; Tupper and Juanes 1999). Pilot marking trials indicated that individuals 35 mm TL and larger could be marked with < 10% mortality (2 deaths in 22 trials). Thus, only individuals larger than 35 mm TL (about 2-3 weeks post-settlement) were marked. In each habitat type, early juveniles 35-50 mm TL were captured using a 10% solution of the anesthetic Quinaldine sulfate. Groupers settle at a size of roughly 25 mm and can be marked successfully within a few days to a week of settlement. All captured fish were measured to the nearest mm TL and marked *in situ* with subcutaneous injections of visible implant elastomer (Northwest Technologies, Inc.), using a different pattern of colored dots for each site/habitat. Marked fish were released immediately at their point of capture. A detailed habitat description was made at each capture point, and the location was recorded using a hand-held GPS unit. Natural mortality was calculated as the field estimate of mortality minus the mortality due to the marking procedure.

In Palau, 250 newly-settled humphead wrasse were tagged with elastomer injection (100 at Ngeraard and 50 each at Ngardmau, Nikko Bay, and Fantasy Island). Tags were divided among habitat types as follows: 80 in branching coral/macroalgae, 50 in branching coral, 50 in bushy macroalgae, 35 in sea grass and 35 in coral rubble. Following initial tagging of the fish, growth and mortality/emigration of juveniles was estimated by 12 successive censuses and recaptures of marked individuals, performed twice each week for six weeks along the same transects. At each successive census, all recaptured individuals were measured to the nearest mm TL, and their location recorded by GPS as above. Cumulative percent survival of released fish was estimated as (number in census/total number released) x 100%. The null hypotheses that neither growth nor survival vary among habitats was tested using ANOVA. Survival data is proportional and was therefore arcsin-transformed prior to analysis. As with settlement data, the effects of habitat characteristics on growth and mortality will be determined by multiple regression techniques.

Abundance of subadult and adult fishes was determined in each habitat type using timed long-swim underwater visual censuses. In two or more 15-minute increments per site, fishes were counted within 10m either side of an imaginary line in front of the diver as he/she swam at a constant rate along a fixed depth interval. If there was a habitat limitation, such as a wall or steep slope along one side of the transect, the width of the transect was adjusted accordingly. (e.g., 10 m on the left and 2 m on the right, etc.). Start/stop points were marked with small surface buoys and the distance traveled determined by GPS fixes at those points. The area surveyed was calculated from these measurements. This method is more appropriate than standard line transects or point counts for counting these species (T.J. Donaldson, University of Guam Marine Lab, unpublished data; J.H. Choat, James Cook University, personal communication).

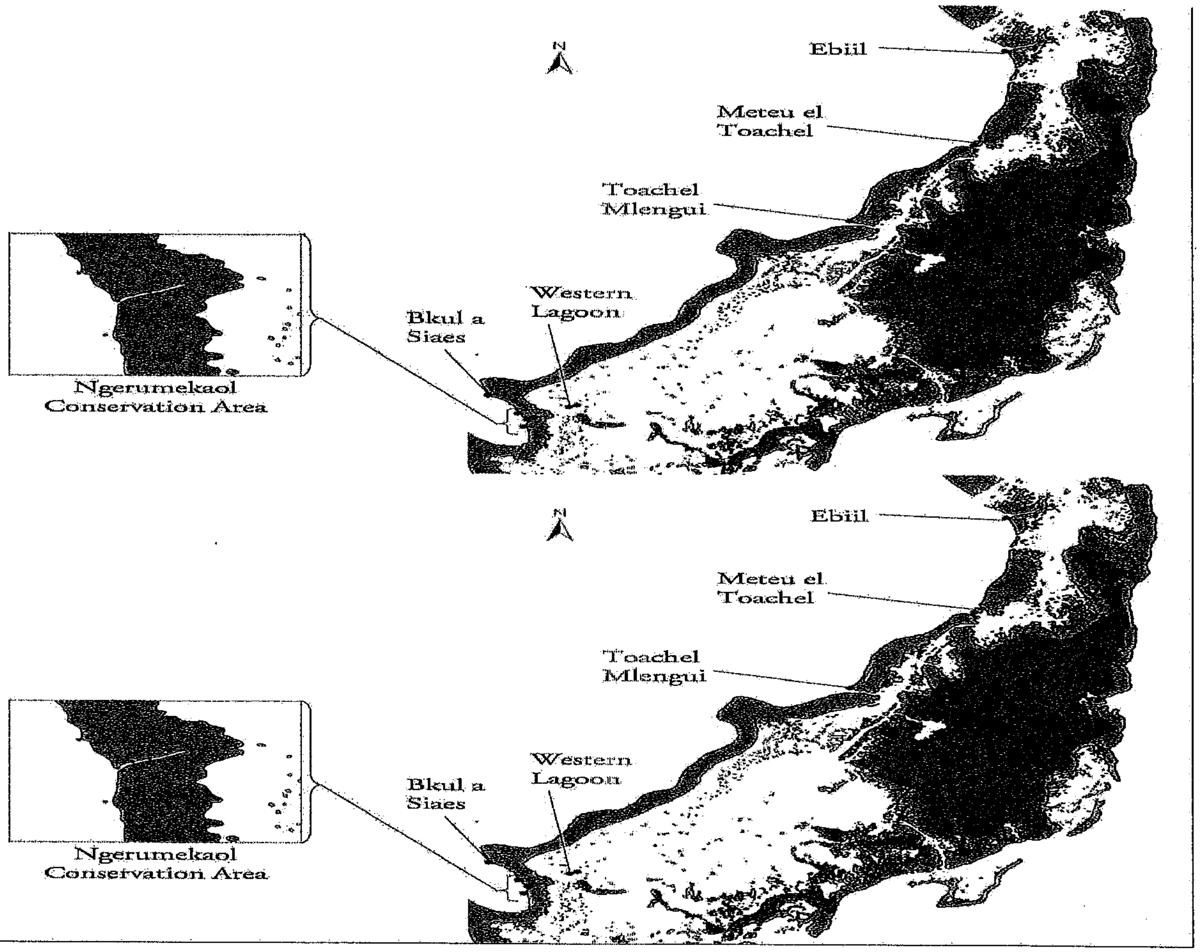
Movement of spawning camouflage groupers and squaretail coral groupers

Our initial intent for this project was to tag humphead wrasse and bumphead parrotfish with internal acoustic transmitters, but both species suffered high mortality from the procedure, particularly the bumphead parrotfish. However, Dr. Pat Colin of the Coral Reef Research Foundation has been following the movements and spawning habits of humphead wrasse in Palau for the past several years, and he has offered to help us parameterize the agent-based model with regards to humphead wrasse spawning-related movements. We therefore decided to concentrate our acoustic tagging studies on groupers, which are easy to catch and tag and do not suffer high mortality from the implantation procedure.

We implanted Vemco™ V16 sonic transmitters in 26 camouflage grouper and 4 squaretail coralgroupers in July 2004, and another 50 squaretail coral groupers in May 2005. All fish were caught on hook and line at Ulong Channel (Ngerumekaol Conservation Area). Transmitters were 16 mm in diameter. An array of 14 Vemco™ VR2 submersible hydrophones (receiver/loggers) was set up along the western barrier reef of Palau (Figure 2). The array included 3 hydrophones in Ulong Channel (mouth, mid-channel, and lagoon side), 1 hydrophone each on the north and south sides of the channel, in shallow (3 m) lagoon waters, 2 hydrophones on deeper (14 m) lagoon patch reefs near Ulong Island, 1 hydrophone each at 1 km north and south of Ulong Channel entrance, on the barrier reef at a depth of 15 m, 1 hydrophone 3 km southwest of Ulong Channel entrance at Shark City (this unit was lost and is not included in the analysis), 1 hydrophone 3 km north of Ulong Channel entrance at Siaes Corner, and 1 hydrophone each at the channel entrances to Western Passage, Devilfish City, and Ebiil Channel.

Hydrophones were attached to eye bolts driven into dead coral substrate, and suspended approximately 1 m above the substrate with plastic floats. Hydrophones were retrieved and downloaded at roughly 60 day intervals, generally 4-5 days after a new moon.

Figure 2. Map of the western barrier reef and lagoon of Palau, showing locations of hydrophones.



Results

Among-habitat variation in settlement and survival of humphead wrasse

Twelve microhabitat types were identified as potential habitats for juvenile humphead wrasse. Newly settled humphead wrasse were found in 6 of these 12 habitat types (Figure 3). Humphead wrasse were found at all sites except Fantasy Island. Levels of settlement were low in seagrass, soft coral and coral rubble habitats, moderate in branching coral and bushy macroalgae, and highest in combinations of branching coral (primarily *Porites cylindrica* and *Seriatopora spp.*) and bushy algae. The among-habitat differences in settlement were statistically significant (ANOVA, $p < 0.0001$). Post-hoc comparison tests (Tukey's Honestly Significant Difference) indicated that habitats fell into four groups with respect to settlement strength: 6 habitats had zero settlement; seagrass, soft coral and rubble had low settlement and did not differ from each other; branching coral and bushy macroalgae had significantly higher settlement than the previous groups but did not differ from each other, and the combination of branching coral and bushy macroalgae had significantly higher settlement than all other habitats. This last habitat type was found primarily in shallow bank areas on the northwest coast of Babeldoab. This appears to be the most important settlement habitat for humphead wrasse in both areas.

A total of 112 tagged individuals were recaptured. Post-settlement survival (Figure 4) was also significantly higher in combined branching coral and bushy macroalgae than in all other habitats (ANOVA, $p < 0.0001$). However, survival did not differ among the remaining 5 habitats in which settlement occurred (Tukey's HSD). The pattern of settlement and post-settlement survival indicates that shallow inshore areas with abundant branched coral interspersed with bushy macroalgae are likely to be essential nursery areas for humphead wrasse. Interestingly, this type of nursery habitat is nearly identical to that utilized by the Nassau grouper (*Epinephelus striatus*) in the tropical western Atlantic Ocean (Eggleston 1995).

Growth of newly-settled humphead wrasse (Figure 5) was again highest in combined branching coral and bushy macroalgae than in all other habitats (ANOVA, $p < 0.001$). However, there was no difference in growth rate between branching coral and bushy macroalgae as separate habitats. Survival was zero in all other habitats in which settlement occurred.

We recorded no movement of tagged humphead wrasse settlers from their initial tagging sites. All tagged individuals < were found within 5 m of their initial tagging site. This suggests that newly settled humphead wrasse display strong site fidelity while in smaller size classes. This has been demonstrated for other young-of-year labrids and haemulids in tropical and temperate waters (Tupper and Boutilier 1995, 1997; Tupper and Juanes 1999).

Size and abundance of humphead wrasse in various macrohabitats

In order to better understand the life history cycle of the humphead wrasse, it is important to know the general habitat associations of different life history stages. We divided the available habitats in Palau and Guam into five broad categories: (1) shallow inshore banks and reef flats, (2) shallow fringing reefs and lagoonal patch reefs, (3) shallow backreef sections of the barrier reef, (4) deep lagoon reefs and shoreward ends of reef channels, and (5) seaward ends of reef channels and outer barrier reef slopes.

In shallow inshore banks and reef flats, the only humphead wrasse observed were young-of year less than 10 cm total length (Figure 6). This is consistent with our observations that shallow coral/algal habitats serve as nursery areas for humphead wrasse. Interestingly, no humphead wrasse were found on the backreef area of the barrier reef. This emphasizes the importance of shallow inshore nurseries for this species, as similar stands of branched coral and macroalgae occurred on the back side of the barrier reef, but these were occupied by the tripletail wrasse *Cheilinus trilobatus*, rather than humphead wrasse. After reaching about 10 cm total length, most humphead wrasse appeared to move to shallow lagoon patch reefs. The modal length in this habitat was about 15 cm (Figure 7). On deeper lagoon reefs and at the shoreward entrances of reef channels, humphead wrasse ranged from 18 to 66 cm long (Figure 8). The largest of these were found at the shoreward entrances to barrier reef channels.

The largest humphead wrasse (65 to 120 cm) were found on the outer barrier reef, particularly at the seaward edges of reef channels and around reef promontories (Figure 9). Spawning was observed within these habitats. Thus, it appears that humphead wrasse undergo ontogenetic migrations from shallow inshore areas to deeper lagoon reefs and then to channels in the barrier reef, finally moving to the outer barrier reef after reaching sexual maturity.

Figure 3. Among-habitat variation in settlement of humphead wrasse, *Cheilinus undulatus*, at 4 sites in Palau.

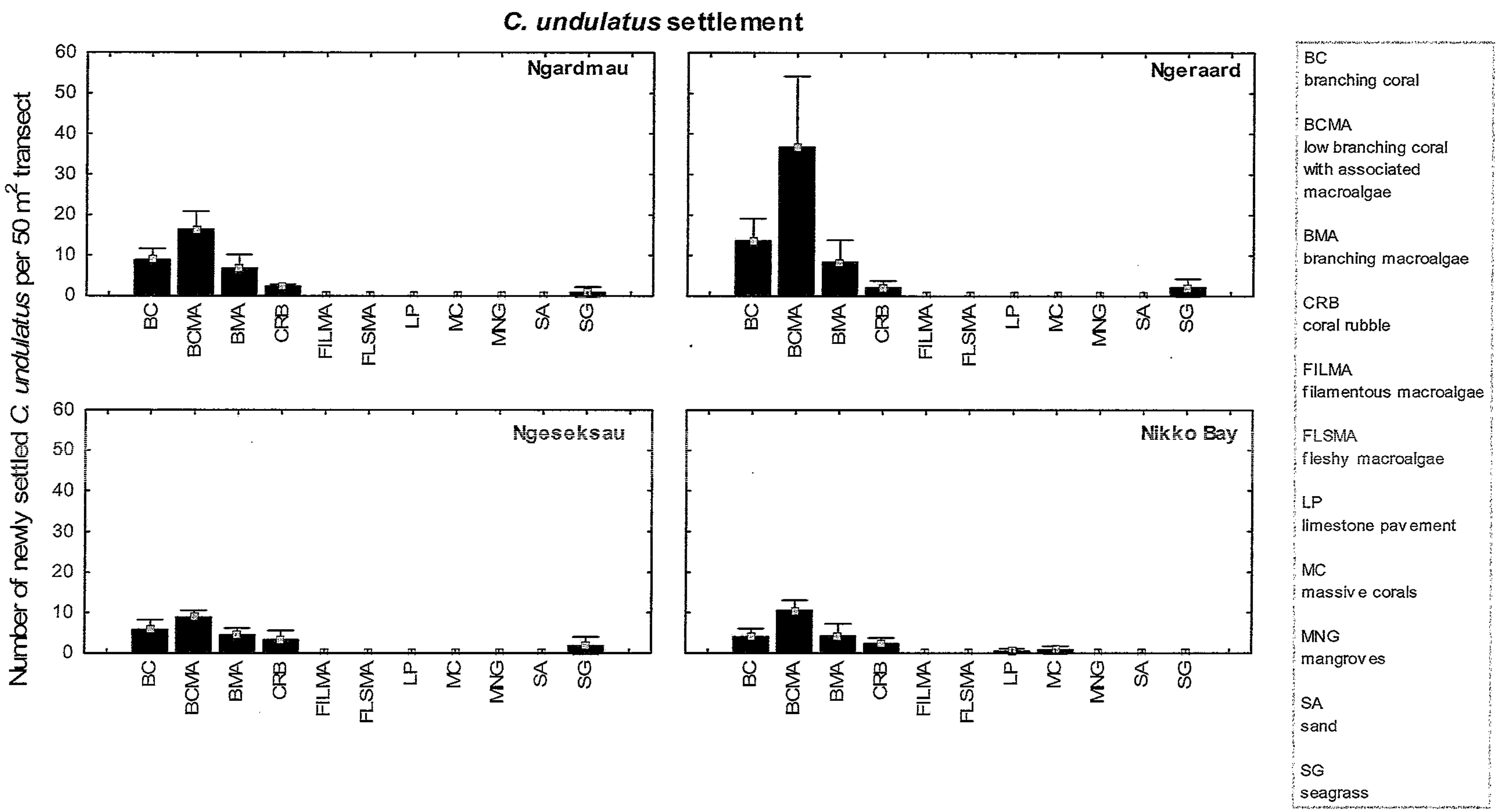


Figure 4. Among-habitat variation in survival of humphead wrasse, *Cheilinus undulatus*, at 4 sites in Palau.

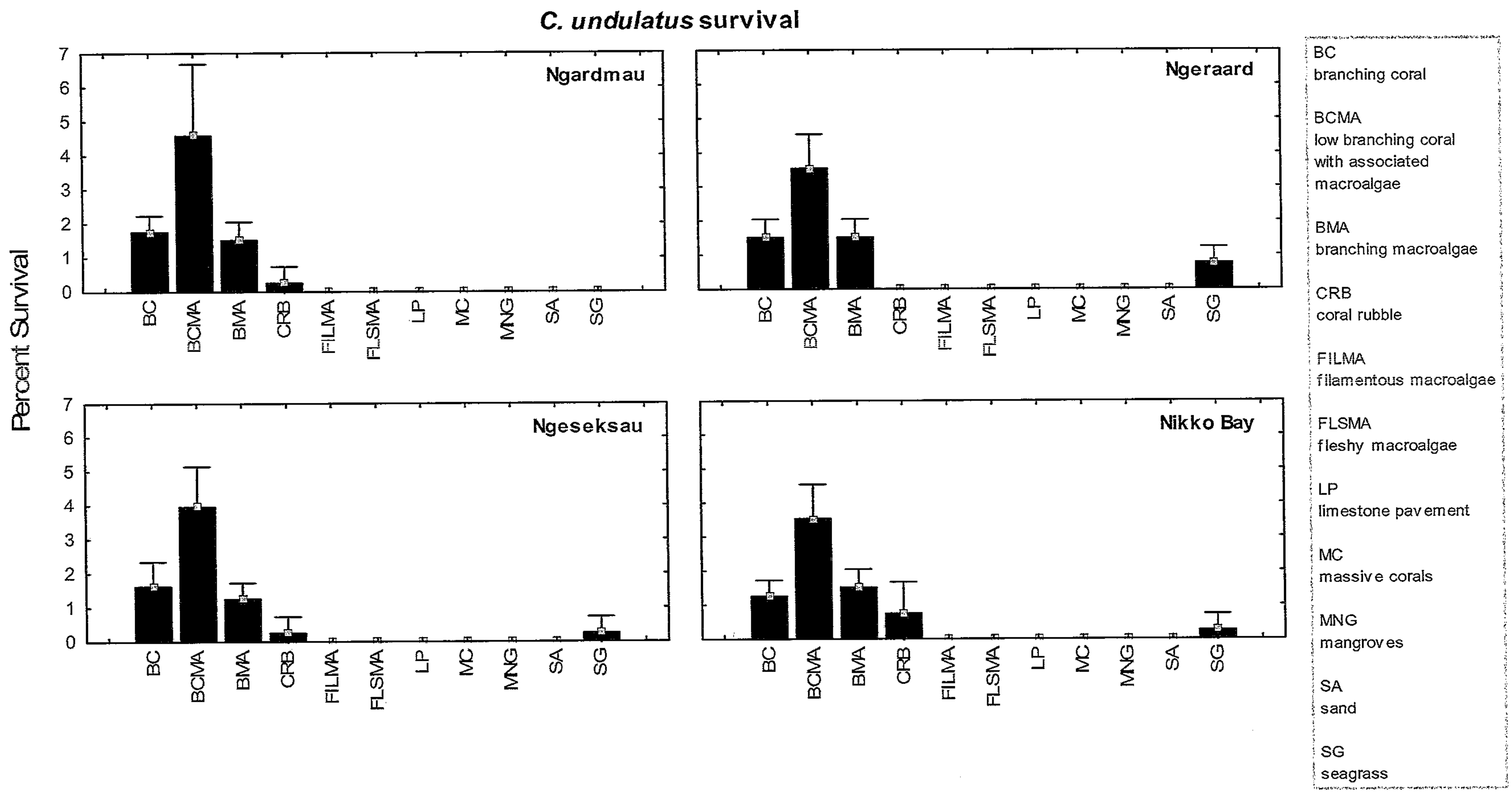


Figure 5. Among-habitat variation in growth of humphead wrasse, *Cheilinus undulatus*, at 4 sites in Palau.

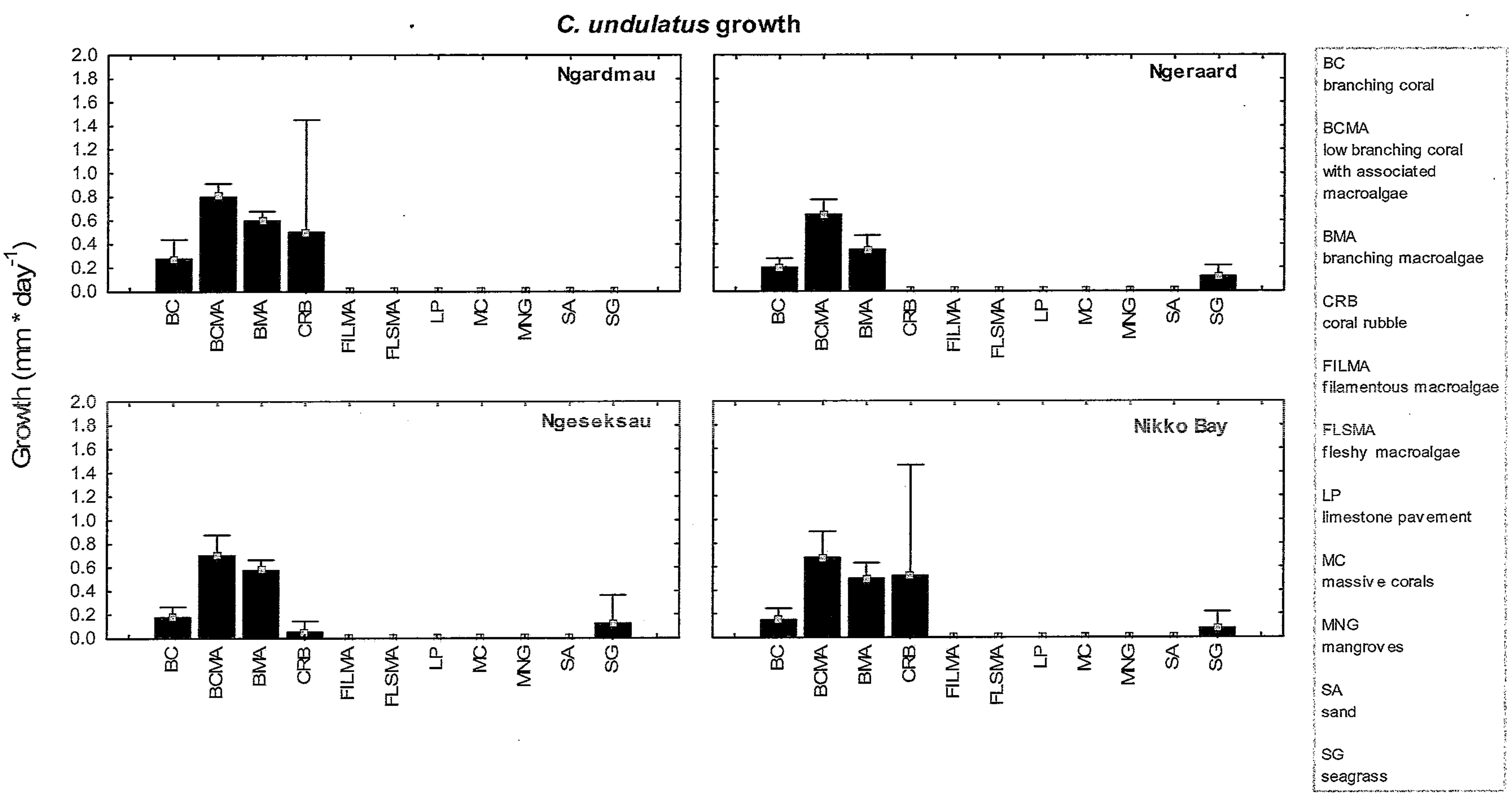


Figure 6. Length frequency of humphead wrasse in shallow bank habitats at Babeldoab, Palau.

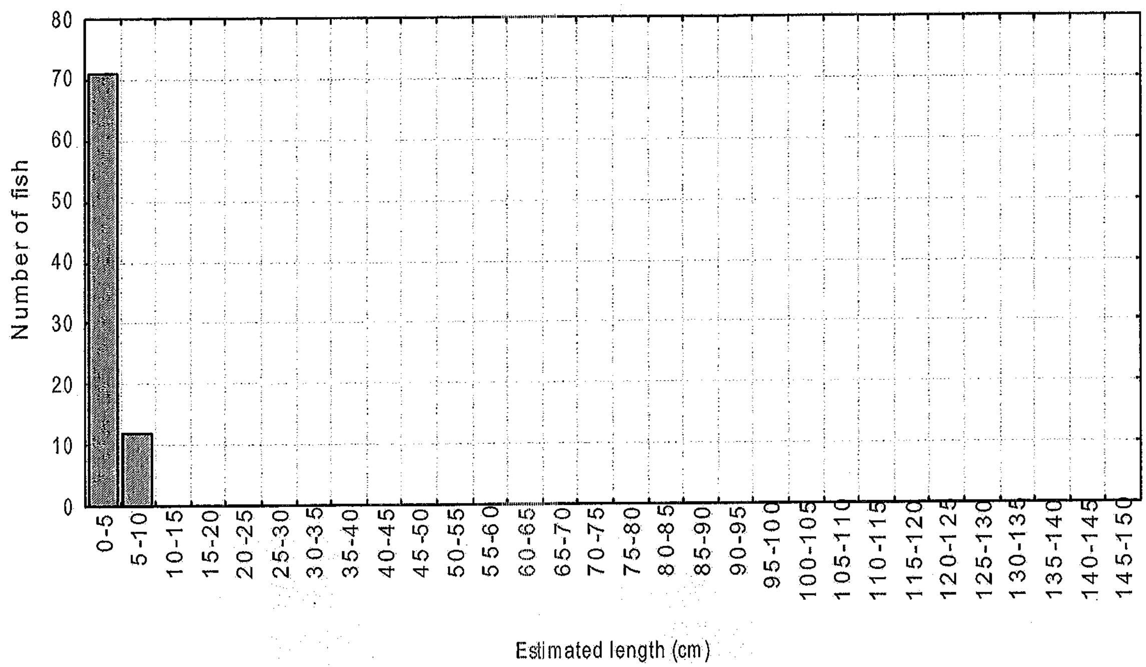


Figure 7. Length frequency of humphead wrasse in shallow patch reefs at Babeldoab, Palau.

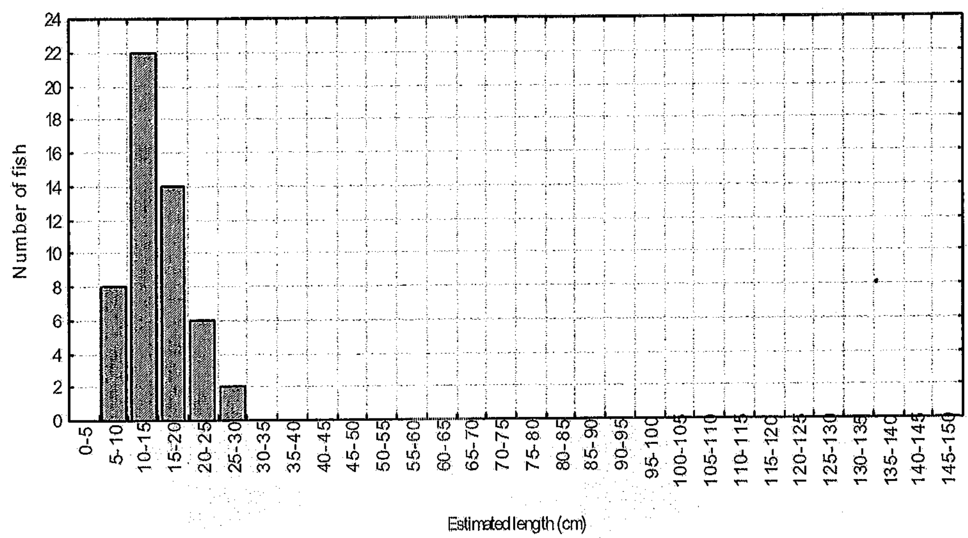


Figure 8. Length frequency of humphead wrasse on deep lagoon reefs at Babeldoab, Palau.

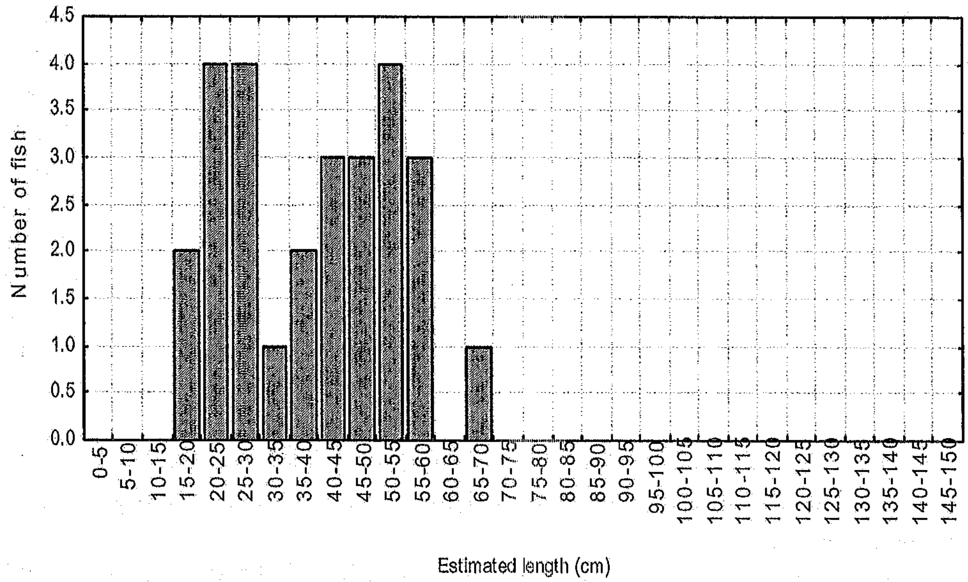
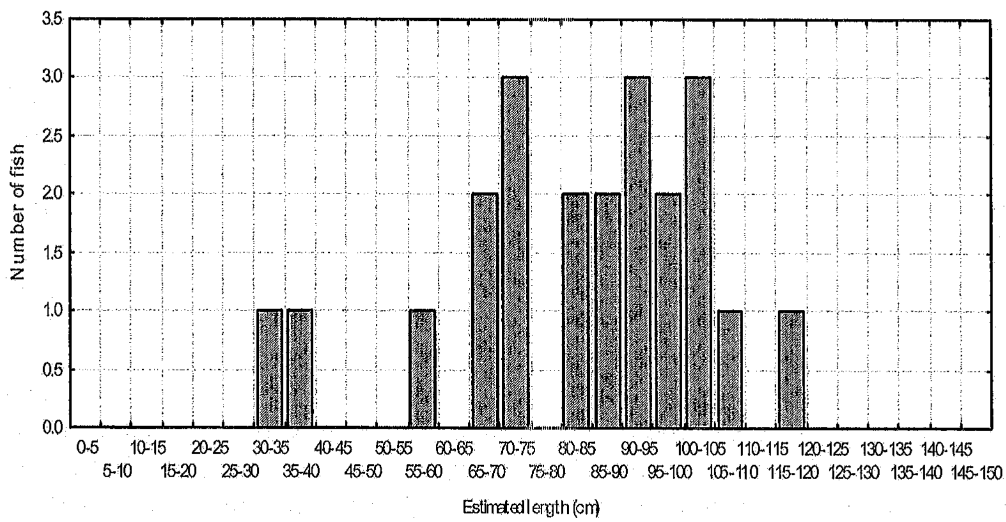


Figure 9. Length frequency of humphead wrasse on the outer barrier reef at Babeldoab, Palau.



An important question that remains unanswered is how this pattern of ontogenetic habitat shifts will vary between islands with different geomorphologies and therefore different habitat availabilities. For example, while Cocos Lagoon in southern Guam has lagoon and barrier reef habitats similar to Palau, other areas of Guam have narrow reef flats that drop off immediately to deep fringing reefs. It seems likely that humphead wrasse in these areas may remain longer (and thus grow larger) in reef flat habitats. Alternatively, they may move into deeper habitats at smaller sizes, which could lead to higher predation mortality.

These results represent the first targeted study of habitat utilization by humphead wrasse, an important species commercially and ecologically in the Indo-Pacific. This study will provide critical information for ecosystem-based management of this species.

Habitat utilization by early juvenile grouper

The use of fish anesthetic in a wide variety of habitats allowed us to capture and mark newly settled juvenile groupers. A total of 40 newly settled squaretail coral grouper (*Plectropomus areolatus*) and 54 newly settled camouflage grouper (*Epinephelus polyphekadion*) were tagged at Fantasy Island, Neseksau, Ngeraard, Ngardmau, and Nikko Bay. Squaretail coral grouper were found almost exclusively in coral rubble along the sides of tidal channels, at a depth of 5-6 meters. Only 2 squaretail coral groupers were found on patch reefs, and none were found in any of the other 10 habitat types (Figure 9). Apparently, these grouper species are much more habitat-specific at the early juvenile stage than humphead wrasse. Camouflage groupers were occasionally found in rubble, but were more common on patch reefs, particularly in deeper, more turbid areas (Figure 10). Survival of *P. areolatus* was quite high in rubble areas, with juveniles persisting in rubble habitats for about 1 month before leaving for deeper lagoon waters (Figure 11). Survival/persistence of juveniles in all other habitats was zero. Camouflage groupers persisted for 2-3 weeks on deeper patch reefs (> 10 m), especially in turbid areas such as channel bottoms (Figure 12). In all other habitats, camouflage grouper observed in a given census were never seen in subsequent censuses.

Growth of both grouper species was highest in coral rubble habitats. This occurred by default for *P. areolatus*, since it survived only in that habitat (Figure 13). For *E. polyphekadion*, the difference in growth between coral rubble and other habitats (Figure 14).

Movement of spawning camouflage groupers and squaretail coral groupers

As of August 2005, we relocated 51 of 80 tagged grouper. One obvious trend that appeared was that camouflage grouper tended to stay resident at the spawning site for a few days on either side of the new moon in Palau and then quickly disperse. However, tagged fish did not disperse far, and most remained within 1-2 km of the spawning site throughout the year. No fish were detected in the southern portion of the array, including hydrophones at Blue Corner, German Channel, and Ngedbus Island. To date, no fish have been detected in the northern lagoon area, and no fish that were tagged at the Ngerumekaol aggregation showed up at the Ebiil aggregation site. Initial data for squaretail coral grouper in Pohnpei indicate similar site fidelity.

Both species arrive at the aggregation site several days prior to the new moon and then leave within 1 or 2 nights after the new moon (Figure 16). *P. areolatus* first arrived in April and May and return monthly until August or September. *E. polyphekadion* arrived in June and July and also return monthly until August or September, although some individuals appear to remain at the aggregation site throughout the spawning period. In 2005, 17 of the 26 camouflage groupers tagged in 2004 returned to the aggregation, indicating that these groupers probably use the same site each year, in addition to each month within the spawning period.

The hydrophones also provide us with information on grouper behavior at the aggregation site. Both species are active during the day and rest within the coral at night (Figure 17). In addition, groupers tend to be more active during periods of slack tide, and rest within the reef during mid-tide, when the current in Ulong Channel is very strong. At the end of each spawning month, usually a day or two after the new moon, most groupers leave the aggregation site via the back of Ulong Channel, apparently dispersing into the western lagoon (Figure 18). Some may leave via the entrance and disperse along the barrier reef, however only 5 grouper were relocated along the barrier reef outside Ulong Channel.

Figure 10. Among-habitat variation in settlement of squaretail coralgrouper *Plectropomus areolatus* at 5 sites in Palau.

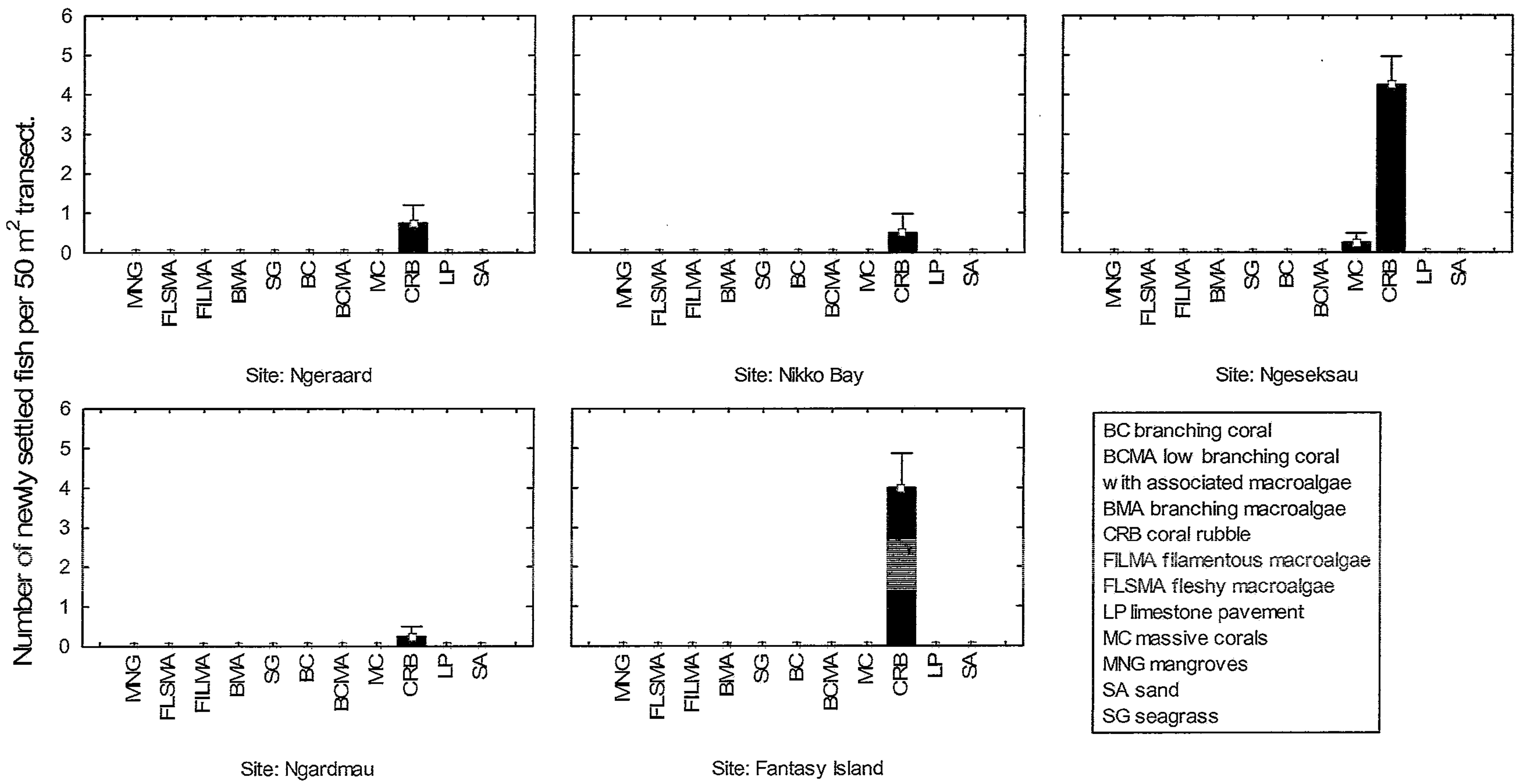


Figure 11. Among-habitat variation in settlement of camouflage grouper *Epinephelus polyphekadion* at 5 sites in Palau.

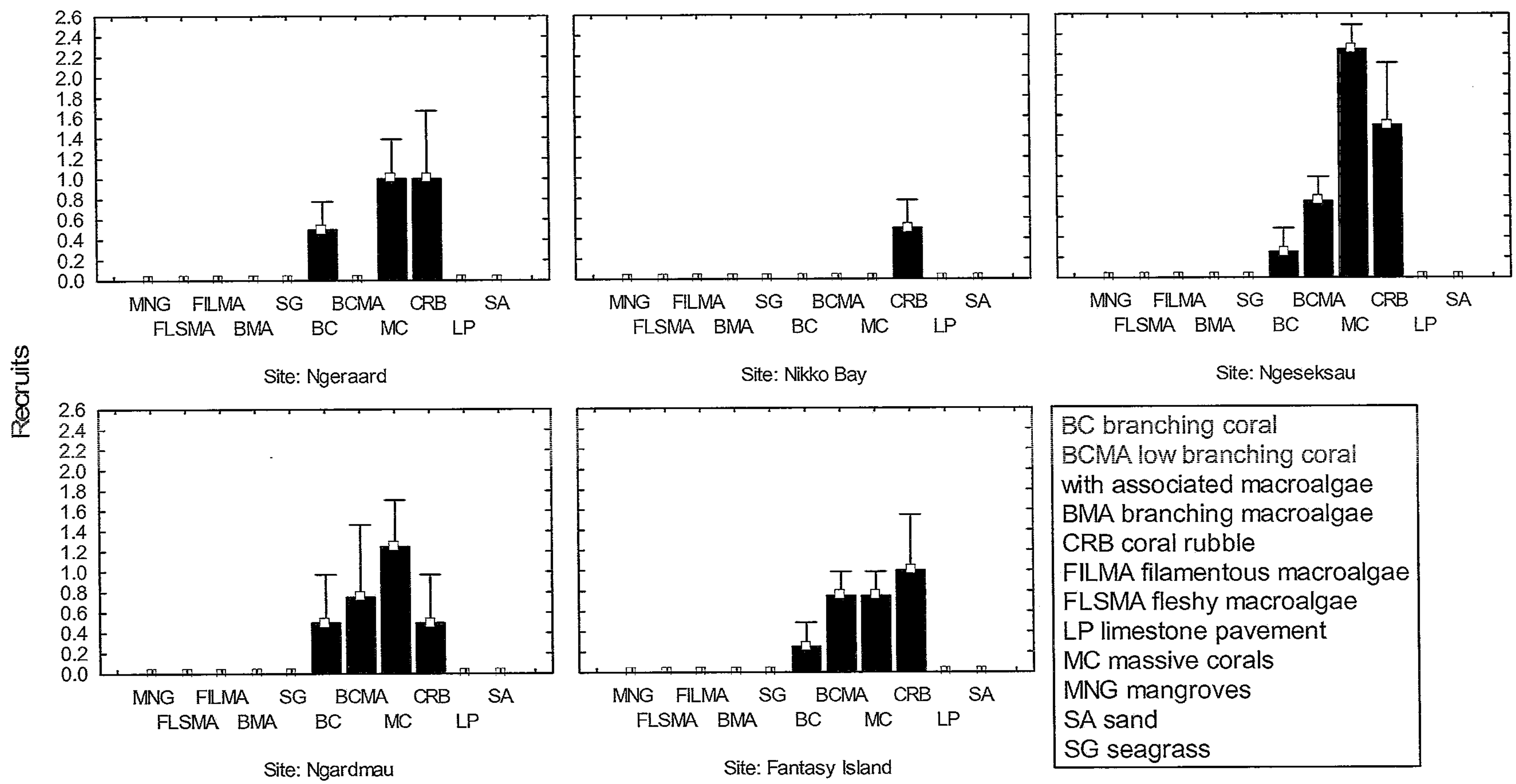


Figure 12. Among-habitat variation in survival of squaretail coralgrouper *Plectropomus areolatus* at 5 sites in Palau.

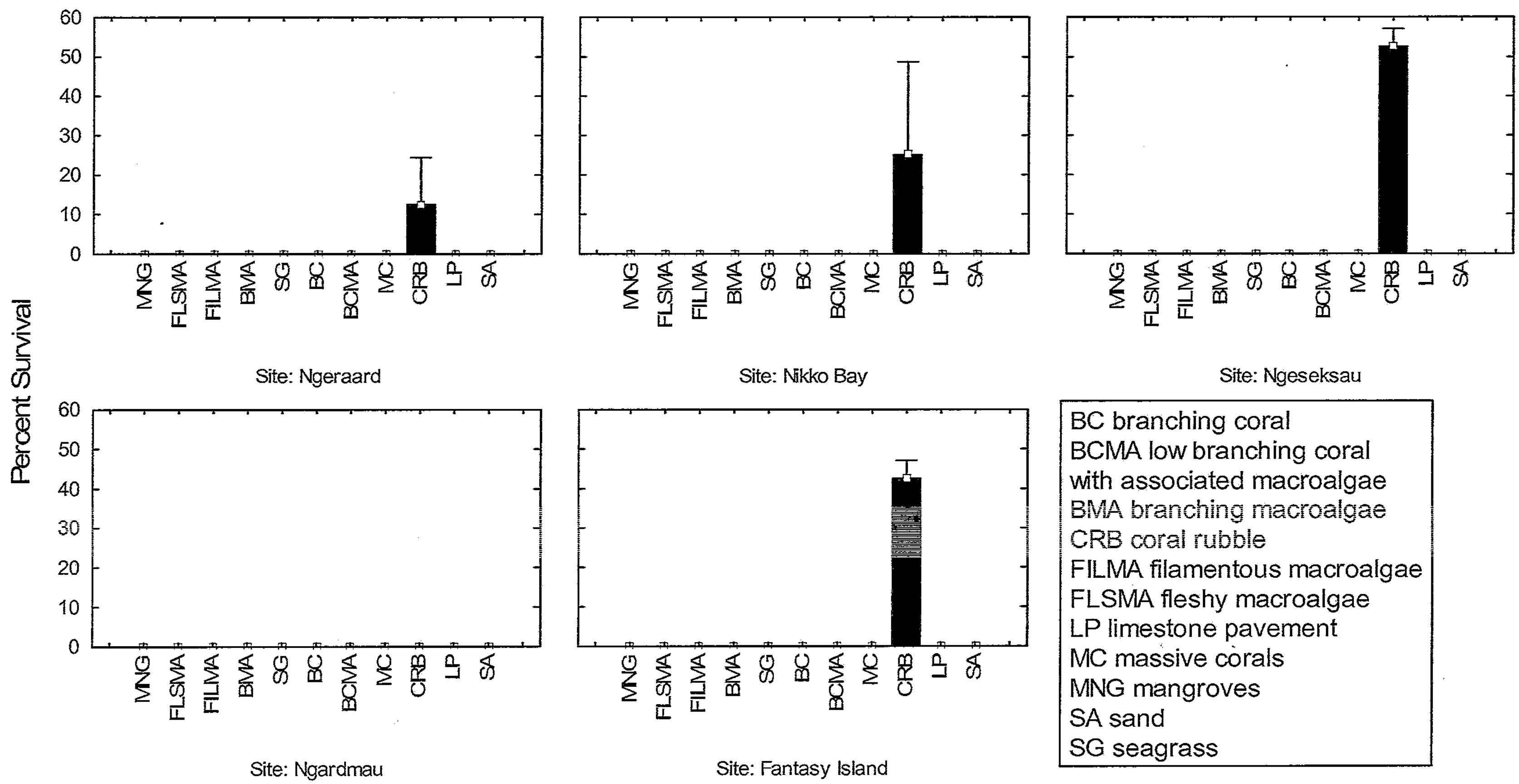


Figure 13. Among-habitat variation in survival of camouflage grouper *Epinephelus polyphekadion* at 5 sites in Palau.

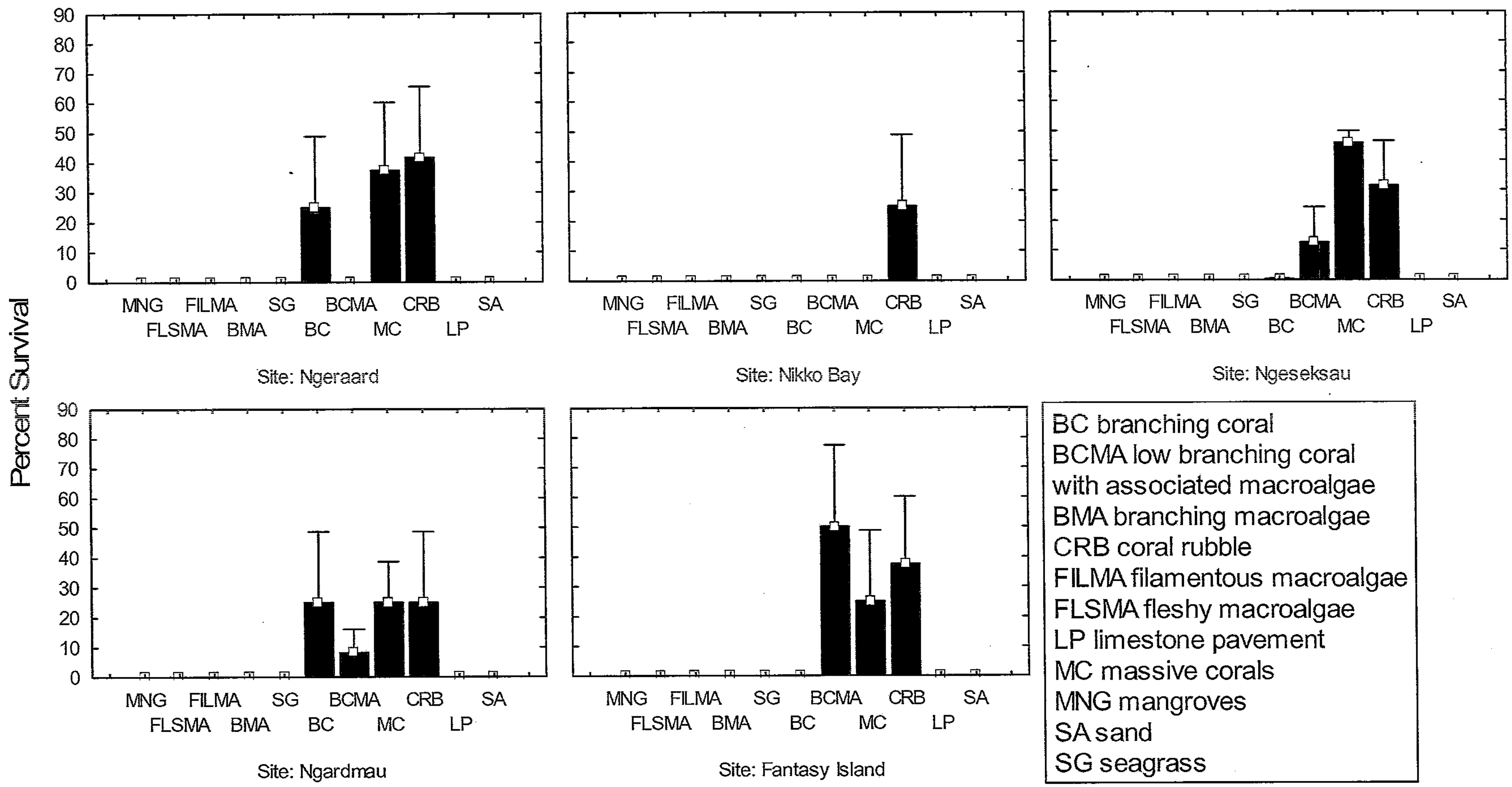


Figure 14. Among-habitat variation in growth of squaretail coralgrouper *Plectropomus areolatus* at 5 sites in Palau.

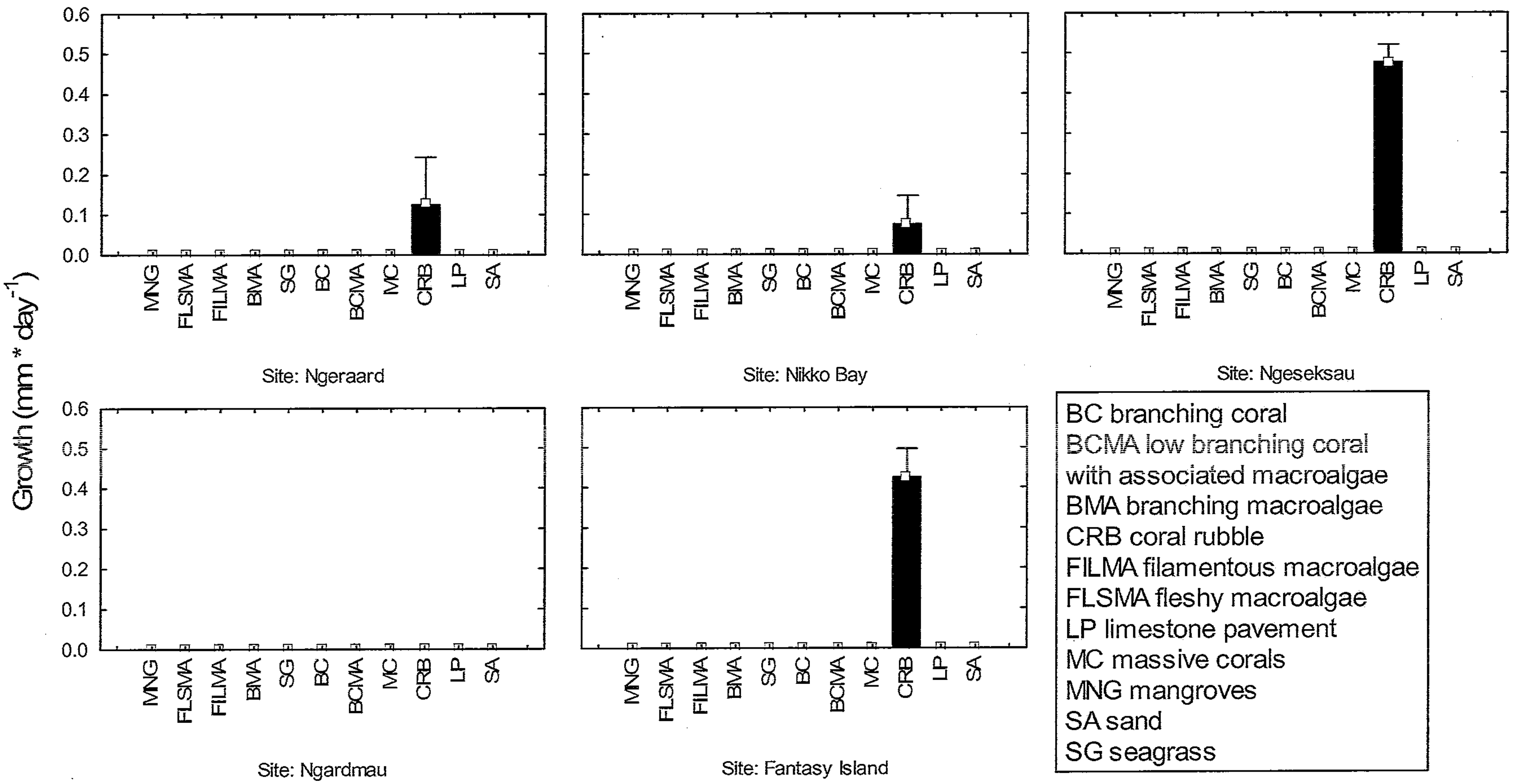


Figure 15. Among-habitat variation in growth of camouflage grouper *Epinephelus polyphekadion* at 5 sites in Palau.

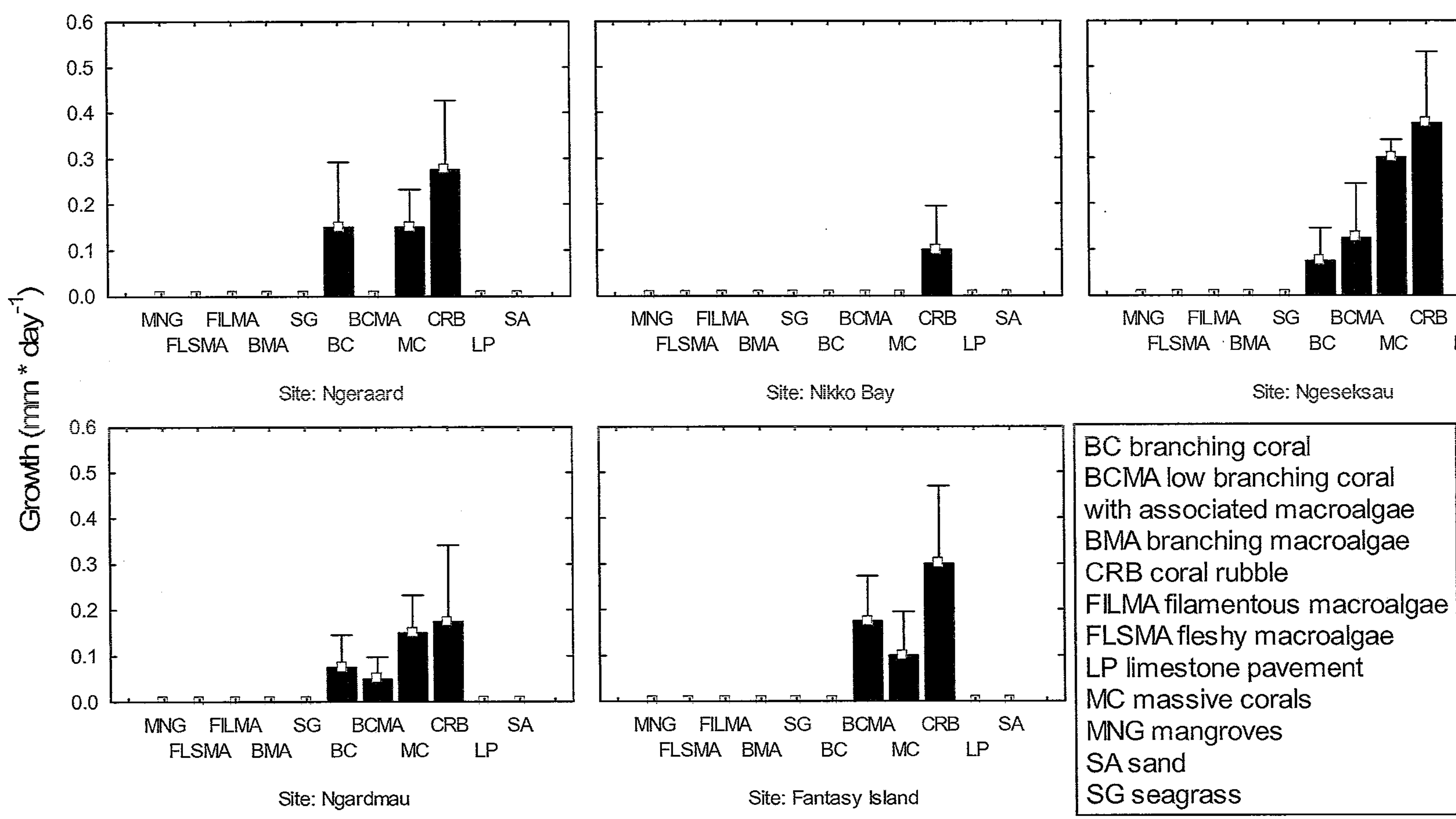


Figure 16. Occurrence of tagged groupers at the 2005 Ngerumekaol spawning aggregation. The colored dots at the top of the graph are squaretail coralgroupers tagged in April 2005. The red dots at the bottom of the graph are camouflage groupers tagged in July 2004, that returned in 2005.

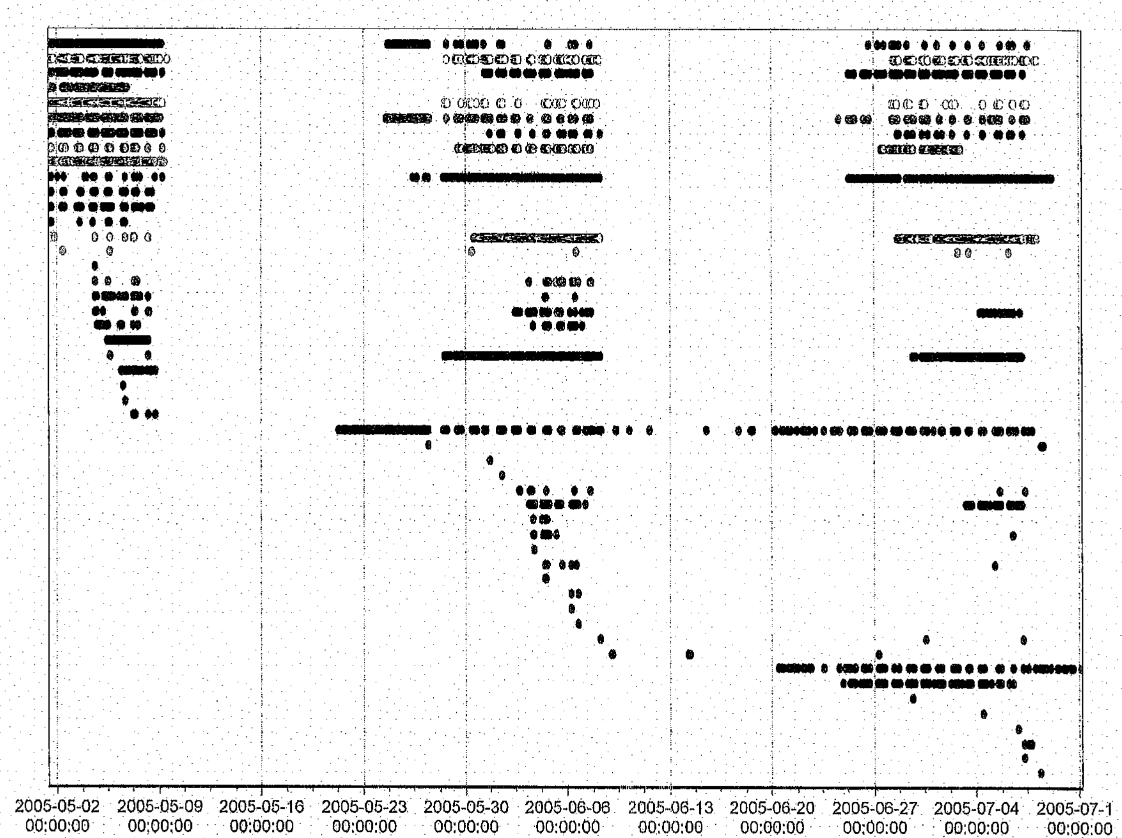


Figure 17. Close-up of grouper activity at Ngerumekaol aggregation site. Spaces between dots indicate times when groupers are probably resting within the coral, thereby interrupting the signal from the ultrasonic transmitter

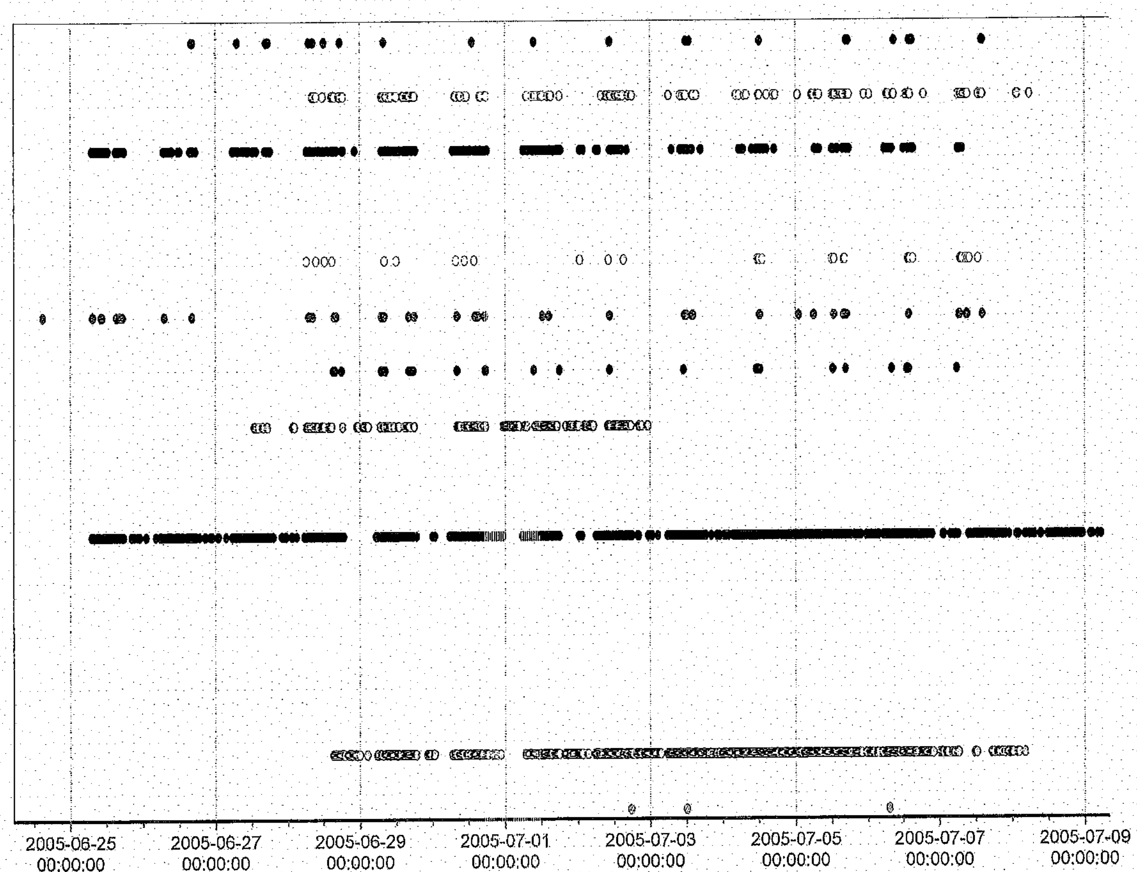
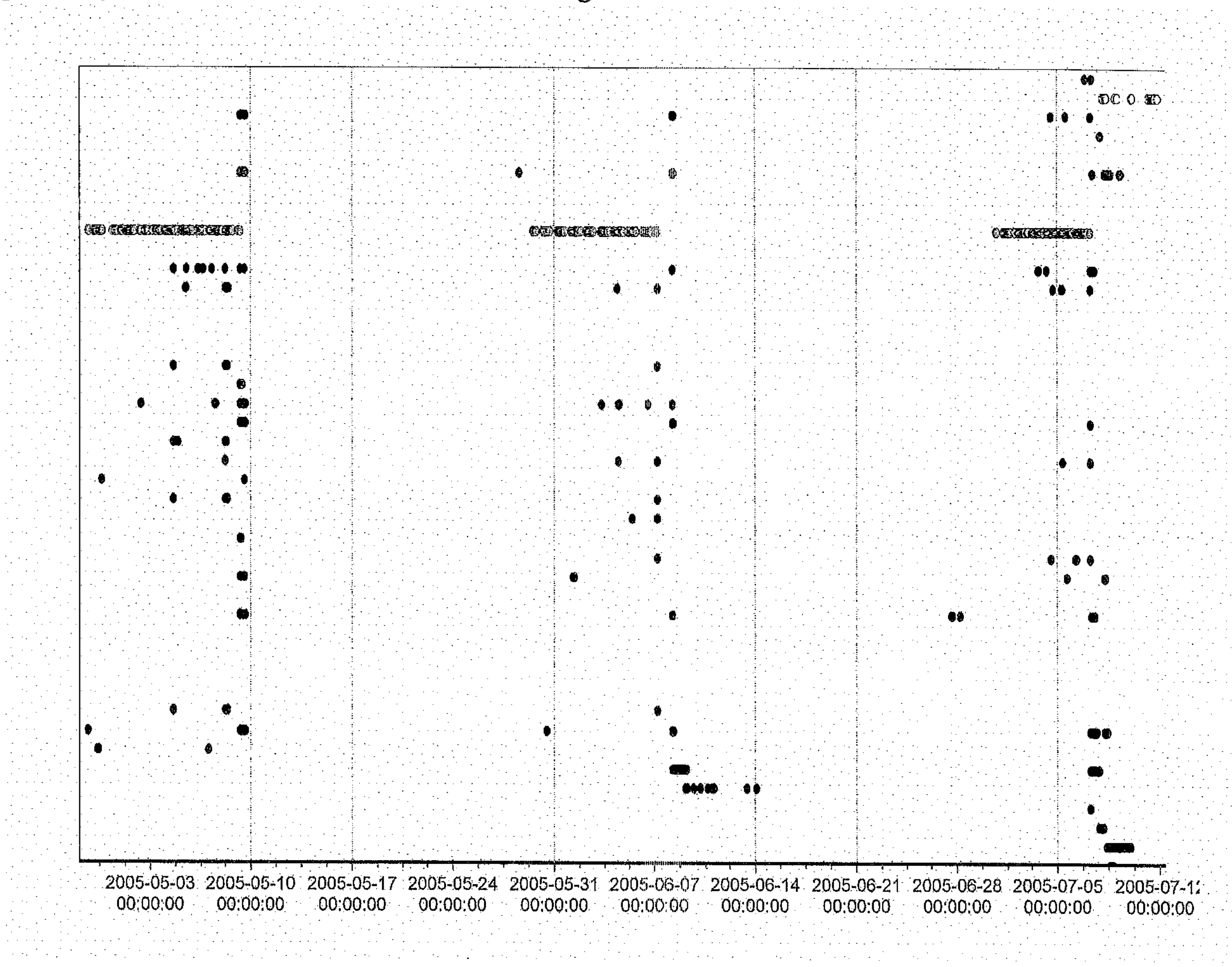


Figure 18. Occurrence of groupers at the back of Ulong Channel. Most of these individuals passed the hydrophone at the end of each monthly spawning season for a short time only, probably on their route back to the western lagoon.



Agent-based Model

The basic environment for the agent-based model was created using IKONOS imagery of western Babeldaob in Palau. To date, we have constructed the model only for humphead wrasse, but we will expand the model to include groupers in the future. Because of the very immediate threat of erosion and sedimentation from road construction on humphead wrasse nursery areas, we designed the first phase of this model to predict the impacts of sedimentation on recruitment and habitat utilization patterns of juvenile humphead wrasse. A detailed description of the model is given in Appendix I. Because the programming process is very time-consuming, and the mapping of all humphead wrasse essential habitat is incomplete, it will take roughly another 6-12 months to have a working model that can be presented to managers as a useful decision support tool.

Research Products

At this point the principal investigators have several manuscripts in advanced stages of preparation, including the following which should be submitted within the next month:

Tupper, M. (in prep.). Defining and mapping essential nursery habitats for commercially valuable groupers and humphead wrasse in Palau. For submission to Marine Ecology Progress Series.

Tupper, M. (in prep.) Export of juvenile groupers from a marine protected area to exploited adult habitat in Palau. For submission to Marine Ecology Progress Series.

Dixon, P. and M. Tupper (in prep.) Dynamics of grouper spawning aggregations in Palau. For submission to Marine Biology.

An oral presentation titled "Defining and mapping essential fish habitat for western Pacific coral reef fishes" was presented at the 10^{th} International Coral Reef Symposium on June 29^{th}, 2004. The presentation covered some of the results found in this report and is available on CD-ROM.

A Master's thesis by University of Guam graduate student Peter Dixon should be completed within the next 4-6 months. The tentative title is "Dynamics of a grouper spawning aggregation at Ngerumekaol Conservation Area, Palau".

Literature Cited

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Tupper M and RG Boutilier (1995). Effects of habitat on settlement, growth and post-settlement survival of Atlantic cod (*Gadus morhua*). Canadian Journal of Fisheries and Aquatic Sciences. 52: 1834-1841

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Tupper M and F Juanes (1999). Effects of a marine reserve on production dynamics of grunts (Pisces: Haemulidae) in Barbados. Environmental Biology of Fishes 55:53-63

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Appendix 1. Agent-based Model Description

InREEF (Individual-based model for Researching Environmental Effects on Fishes)

Model Purpose

The primary purpose of this first model construction is to predict the effects of habitat loss---especially through sedimentation---on immature life stages of humphead wrasse. Specifically, the model represents how sedimentation events affect settlement of larval wrasse and, therefore, the number and timing of production of juvenile wrasse. As more data are gathered on adult fish movements, catch and effort in different habitats, etc., the model will gain more general predictive capability.

Conventions

1. Habitat spatial units: m
2. Fish length: mm
3. Time rates: weekly
4. Dates: MM/DD/YYYY format.

Fundamental Assumptions

Biological resolution

Only one species is represented: humphead wrasse. Two life stages are represented explicitly.

- Young of year: start with settling of larvae. Life stage ends when a length of 75 mm is reached. YoYs feed on small invertebrates and require dense cover to avoid predation. YoYs are stationary: they have been observed to move less than 5 m over their life span.

- Juveniles, defined as having length between 75 mm and 200 mm. These fish are much less vulnerable to predators and have developed the ability to feed on (bivalves?), so they occupy deeper, more open habitat. Juveniles are retained in the model only so that it displays all the wrasse within the lagoon/reef system.

Spatial resolution

The model's spatial resolution ("grain size") is square grid cells 40 m (?-confirm) on each side. The fish are assumed relatively immobile, although the distance over which they forage for food increases with size. Movement or selection among patches of habitat is assumed negligible once the fish have settled into a patch. It is not necessary to model fish location within a cell because (a) habitat variability within a cell is not represented and (b) wrasse are not territorial, and density-dependent competition is assumed negligible.

Spatial extent

The model is designed to represent one lagoon/reef system. However, there are no built-in limits to how large or small the system is. The extent of the spatial model is determined only by the cell data file used as input.

Sediment input from land is a key process. The model is designed so sediment can enter the system at a variable number of locations.

Time step

None of the processes currently in the model are fast, so a weekly time step is used.

Temporal extent

The model can run for a user-selected time period. Settlement of larvae occurs over the full year but with major peaks in May-June and October-November. For its purpose of simulating sedimentation effects on larvae settlement and juvenile production, we anticipate that the model will normally be run (a) over a year of settlement and sediment events, followed by an additional 1-2 years of YoY growth and advancement to the juvenile life stage.

Classes, Variables, and Processes

Each of the following sections describes one class of entity in the model, its state variables, and the processes it simulates.

Habitat types

Habitat types are simply objects that represent the characteristics of the different habitat categories. Each habitat cell is assumed to obtain most of its characteristics from its habitat type. The types are defined in the following table.

Habitat type name	Defining characteristics
Sand	At least 50% open sand bottom
Seagrass	At least 30% cover by seagrasses
Mangrove	Fringing mangrove forests lining the coast of Palau
Limestone	Hard bottom, or dead coral reef, either lightly or not colonized
BranchedCoral	Live or dead corals with prominent branching structure
MassiveCoral	Live or dead coral heads with no prominent branching structure
BushMacroalgae	Fleshy or foliose macroalgae, particularly red and brown algae
FilamentMacroalgae	Filamentous algal turf, particularly green algal turf
BranchedCoral_Macroalgae	Combination of small branching corals with bushy macroalgae
CoralRubble	At least 50% cover by dead coral rubble
Land	Used to categorize cells that are above water
DeepOcean	Water outside the reef system too deep for use by juvenile wrasse

Variables

1. isExcluded: Is the habitat a type (especially, land) where the modeled fish never go, even during dispersal?

2. isUsableByYoY (boolean): Is the habitat type usable by YoY wrasse. Set to "Yes" except for habitat type "Land" and types where YoY are never observed.

3. Maximum settlement rate (number of YoY per m^2 per week): Rate at which new YoY settle in the habitat type, during the peak settle times.

4. Survival probability for YoY (unitless): Probability of YoY survival per week. Currently, these values were calculated by raising Mark's field values of monthly survival rate to the power ¼---so the probability of survival for four consecutive weeks equals Mark's monthly survival rate.

5. Growth rate for YoY (units??): Rate at which YoY grow in length in the habitat type.

6. isUsableByJuv (boolean): Is the habitat type usable by juveniles? Set to "Yes" except for habitat type "Land" and types where juvenile wrasse are never observed.

Habitat Cells

Variables

1. UTM Northing, UTM Easting: UTM coordinates of the cell's midpoint.

2. Habitat type

3. Sediment thickness: The amount of sediment accumulated in the cell, as an average layer thickness (m). Initialized to zero; incremented by sediment events. Never decreases.

4. Sediment effect on settlement: A function for how larvae settlement rate is reduced by the cell's current sediment thickness. The function is a logistic function of sediment thickness, defined to be 0.1 at sediment thickness 0.005 m, and 0.9 at thickness of 0.002 m. (Use Model Swarm parameters sedSettlementEffect01, sedSettlementEffect09.)

Processes

Sedimentation: Assume deposition occurs during discrete events. The thickness of sediment deposited in a cell is a linear function of its distance from where the sediment originates. Read in, for each event-

1. Date of event

2. Sediment origin: UTM coordinate of river mouth

3. Thickness of new sediment deposition near its origin

4. Distance at which sediment deposition becomes zero

Calculate deposition (sediment added) for each event. Assume no loss of sediment over time.

Young-of-year Fish

Variables

1. Length (mm)
2. Cell
3. Age (weeks)

Processes

Growth

Modeled as constant rate of length increase (?). Parameter is obtained from the cell's habitat type.

Survival

Modeled as constant survival rate. Parameter is obtained from the cell's habitat type. Dead YoYs are moved to a list from which statistics can be obtained. Fish that do survive have their age incremented by one week.

Recruitment

When a length threshold is met by the YoY, it creates a new Juvenile object, removes itself from the model, and adds itself to a list of successful (and no longer existant) YoYs. The length threshold is defined by a Model Swarm parameter yoYToJuvLength, with a value of 75 mm.

Juvenile Fish

Juveniles are simulated only to display their presence within the lagoon/reef system.

Variables

1. Cell
2. Age (weeks)
3.

Processes

Dispersal

This action is undertaken only once, on the time step when a juvenile is created. The fish undertakes a random movement until it finds a new cell that has a habitat type suitable for juveniles.
This one-time random dispersal is modeled using these steps:
1. The fish selects a cell randomly from among the up to 8 neighboring cells and moves to it. However, a cell is excluded as a destination if (a) it is the fish's current cell, (b) it does not exist because no cell was provided adjacent to the fish's current cell, or (c) the cell's habitat type has a value of "Yes" for its attribute isExcluded (i.e., it is a habitat type that fish can never enter). If no destination cells exist, then stop and leave the fish where it is.

2. If the randomly chosen cell belongs to a habitat type with the attribute isUsableByJuv equal to "Yes", then stop. Otherwise, repeat steps 1-2.

3. If the cycle is repeated > 1000 times without finding a cell where isUsableByJuv is "Yes", then simply stop and leave the fish where it is.

Movement

This action is taken by juveniles every time step. It does not affect simulation results, but disperses juveniles throughout their habitat and makes the graphical display more interesting. A parameter juvenileMoveRange (provided in Model.Setup) defines the maximum distance (m) a juvenile can move each time step. The following steps are used.

1. Calculate the number of cells a juvenile can move (this could be done once when the juvenile is created): moveRadius = (int) (juvenileMoveRange/cellSize) + 1. (This assumes that the division truncates the remainder upon conversion to an integer.)

2. Get a random cell from within the moveRadius. This is a cell randomly chosen from within a square centered on the juvenile's current cell, extending in all four directions by the number of cells equal to moveRadius. Therefore, if moveRadius is 1, then the random cell is chosen from among the fish's current cell and its 8 surrounding cells; if moveRadius is 2, then the random cell is chosen from a 25-cell square centered on the fish's current cell.

3. Exclude the random cell as a destination if (a) it does not exist because it is beyond the habitat model's extent, (b) it has a habitat type with attribute isExcluded equal to Yes, or (c) it has a habitat type with attribute isUsableByJuv equal to No. If the cell is excluded, another cell is randomly drawn. If no acceptable cell is drawn after 100 attempts, then the fish remains in its current cell.

4. The fish moves to the randomly chosen cell.

Update age

The age is increment by one week

Initialization

Cells

Set habitat type, cell color
Set sediment thickness to zero

Timing and number of fish per cell

- Input file: date, relative settlement rate. These rates describe what fraction of peak settlement rate (which is a habitat type variable) applies at the specified date.Assume that the last relative settlement rate read in applies until date in the next input line.
- Number of initial fish per cell per time step = max settlement rate (#fish/m2/wk) x the current relative settlement rate x cell size (m2) x sediment effect (a cell variable)

Fish size

Length of each individual drawn from a uniform distribution. This distribution is defined by ModelSwarm parameters yoYMinInitialLength (12 mm) and yoYMaxInitialLength (15 mm).

Schedule

Cells

Read sedimentation file; execute sediment events, update sediment depth, update color

YoYs

1. Settlement: Read settlement file
2. Settlement: Create new fish (loop through cells)
3. Mortality
4. Growth
5. Advancement to juvenile

Juveniles

1. Dispersal (for new juveniles)

2. Movement

4. Increment age

Overhead

1. Clean up lists

2. Draw habitat cells

3. Draw fish (for now, just put a dot in their cell. Bigger dot, different color for juveniles. YOYs are white; Juveniles- Yellow-green)