Managing Habitat in Coral Reef Ecosystems for Fisheries: Just What is Essential?

KASSANDRA CERVENY[1,2], RICHARD S. APPELDOORN[1], and CONRAD W. RECKSIEK[3]
[1]*Department of Marine Sciences, University of Puerto Rico, Mayagüez, Puerto Rico 00680-9000*
[2]*Marine Conservation Biology Institute, 600 Pennsylvania Ave SE, Suite 210, Washington, DC 20003 USA.*
[3]*Department of Fisheries, Animal and Veterinary Sciences, University of Rhode Island, Kingston, Rhode Island 02881 USA.*

Essential Fish Habitat (EFH) is a concept easily understood for single species but difficult to define and incorporate into management across the complex of exploited coral reef fishes. We define EFH by examining distribution patterns across life stages for 28 species of surgeonfishes, groupers, snappers, grunts and parrotfishes in La Parguera, PR. Patterns were mapped on a Cross-Shelf Habitat (CSH) framework that incorporates and defines both habitat types and geomorphic zones of the insular shelf to create a matrix of individually unique CSHs. Visual counts of 21,877 fishes were mapped on habitats in 24x4-m transects. Patterns were summed across species for early juveniles, juveniles and adults to determine community-scale patterns. Fishes use a wide variety of CSHs during ontogeny, yet certain CSHs stand out in importance. For early juveniles these include vegetated areas (mangrove and *Thalassia*) inside the inner reef line, low relief dead coral areas on the Inner Shelf, and in the Outer Shelf in coral dominated areas associated with the emergent reef. The intermediate-depth forereef of the inner emergent reef is of importance for all life stages. Nevertheless, it would be difficult to target for protection specific CSHs occurring within a broad seascape, especially since some threats (turbidity, eutrophication) act at the seascape scale. Management should target larger scale priority areas where the full complement of essential CSHs occurs or where threats can be isolated. Management of threats in such priority areas could protect areas critical for fish production and be an important component in regional coastal and marine spatial planning efforts.

KEY WORDS: Essential fish habitat, coral reefs, fish-habitat distributions, reef fisheries management, marine spatial planning

Manejando el Hábitat de los Arrecifes de Coral para las Pesquerías: ¿Que Es Esencial?

PALABRAS CLAVE: Hábitat, arrecifes de coral, manejando pesquerías

En Maniant l'Habitat des Récifs de Corail pour les Pêcheries : Qui Est Essentiel ?

MOTS CLÉS: Habitat, récifs de corail, maniant les pêcheries

INTRODUCTION

Many fishes utilize a variety of habitats ontogenetically as they develop through various life stages, e.g., newly settled, early and late juveniles, sub-adults, adults (Appeldoorn et al. 1997, Lindeman 1997). Werner and Gilliam (1984) hypothesized that preferred fish habitat is selected by balancing the need for refuge while maximizing growth. While some Caribbean studies document fish habitat use over life cycles, there is a lack of characterization of differential habitat use during ontogenetic migrations in terms of the cross shelf continuum. Modern fishery management does not capture this or any spatial heterogeneity of fish populations and their habitat usage (Norse 2010, Halpern et al. 2008). In fact, traditional fisheries management is based on fisheries biology, which is based on population biology, which ultimately ignores that fish populations are an active factor within their ecosystem (Pauly 2009). As Norse (2010) and Wilen (2004) note, failing to integrate spatial patterns and processes into management of marine fisheries and ecosystems weakens the process. When queried as to why the trend towards destruction and ruin is so difficult to stop (much less reverse), National Center for Ecological Analysis and Synthesis meeting members concluded that proximate threats such as overfishing and habitat loss are merely the symptom of the underlying disease of sectoral governance (Crowder et al. 2006).

While the structure of management may prevent needed management action, the lack of appropriate approaches and tools for incorporating habitat concepts into fisheries management is an equal impediment. The first approach into ecosystem-based management (EBM) was the requirement for identification and protection of Essential Fish Habitat (EFH), which was defined in the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act of 2006 as "those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity" (16 U.S.C. 1802 (10)). However, this definition views EFH within the context of single species management, and its extension into a multispecies or EBM approach remains problematic. Are there truly essential areas based on the whole community of commercially exploited fishes and invertebrates, or do the summed habitat requirements across all species identify practically all areas of a seascape? If the latter, what would be the basis for prioritizing areas for conservation or management?

The primary objective of this study is to address these questions using the distribution of reef fishes off of La Parguera, Puerto Rico. The species selected for evaluation were chosen based on their economic and ecological importance, and consist of five Caribbean reef fishes: Acanthuridae, Haemulidae, Lutjanidae, Serranidae, Scaridae. Patterns of habitat use for each species across ontogeny were developed using a Cross-Shelf Habitat (CSH) framework (Lindeman et al. 1998), which classifies habitat on the basis of habitat type and location across the shelf. Information for all species was combined to see if certain cross-shelf habitats had greater importance for the protection of habitat and biodiversity. By estimating the abundance of each species categorized by life stage for each cell, the framework reveals preferential habitat usage. This effectively produces a "map" of the marine environment for each species that identifies key cells within the matrix. These patterns can then be compared across species to identify the cells (cross-shelf habitats) or cell complexes that are key for conservation efforts in support of fisheries production.

METHODS

This study sampled sites across the local seascape on the southwest coast of Puerto Rico, within the La Parguera shelf (17˚58.3' N, 67˚02.8' W) (Figure 1). The shelf edge is approximately 12 km from shore, and there are a series of three emergent reef lines between it and the shoreline that act as breakwaters. The nearshore environment of La Parguera is composed of *Thalassia testudinum* beds and mangrove coastline dominated by *Rhizophora mangle*. The three reef lines stratify the insular shelf into inner, middle, and outer shelf reef sites, and define the cross-shelf classification (Recksiek et al. 2001, Appeldoorn et al. 2001, Kimmel 1985).

In this study *habitat type* is based on benthic substratum on small spatial scales (1 m^2) according to its structure. In contrast, *geomorphic zones* are based on the cross-shelf geomorphology (depth, distance from shore, current/wave exposure, wind exposure, etc.) at large scales. The combination of the two define *cross-shelf habitat*. The axes of habitat type and geomorphic zone form a framework of spatially arranged cells, with each unique cell signifying an individual cross-shelf habitat. Thus, a habitat can occur multiple times over the cross shelf continuum, but each CSH framework cell represents a unique combination of habitat type and location across the shelf.

The CSH framework originally developed for La Parguera (see Recksiek et al. 2001, Murphy 2001, Foley and Appeldoorn 2007) had a potential 720 cross-shelf habitats (36 geomorphic zones x 20 structural habitat types) of which 521 were judged by Appeldoorn et al. (2001) to occur in the La Parguera area. For this study, this framework was modified as follows. The deep shelf edge geomorphic zones were not sampled due to the depth limits on SCUBA diving. Instead, an additional zone, "Near

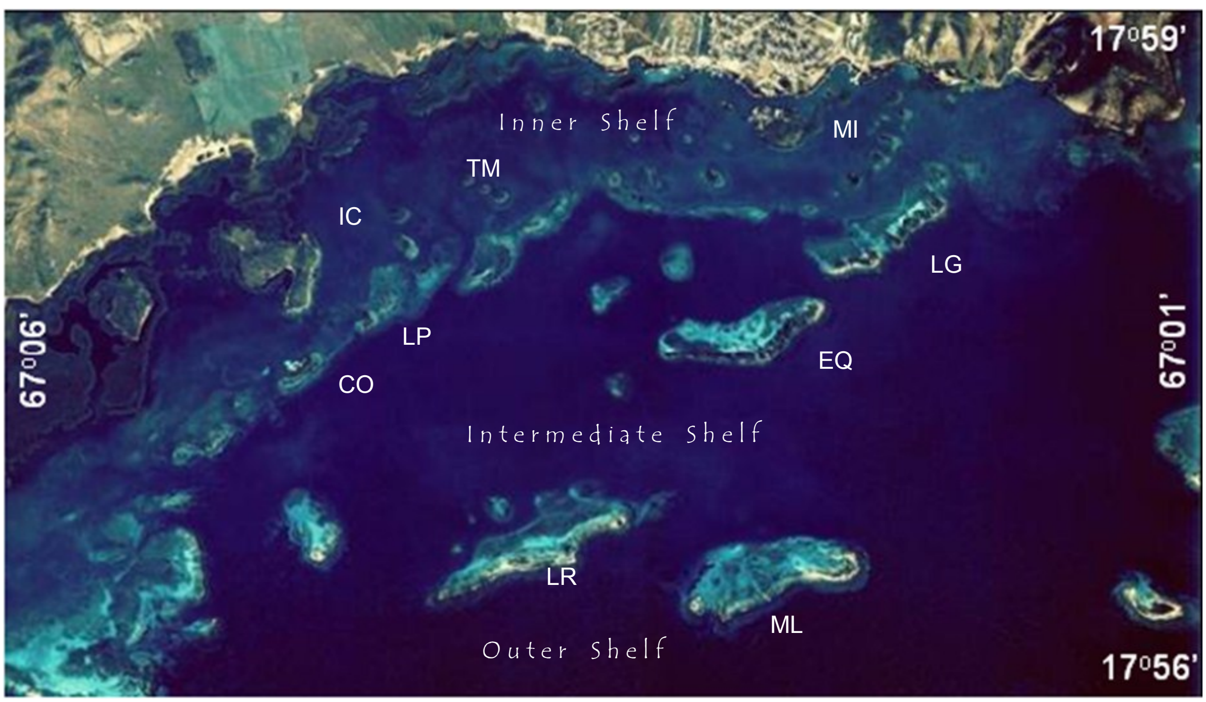

Figure 1. Inshore area of La Parguera, Puerto Rico, showing the three shelf regions and the location of major emergent reefs. Inner emergent reefs: CO = Collado, LG = La Gata, LP = Las Pelotas. Intermediate emergent reef: EQ = Enrique. Outer emergent reefs: ML = Media Luna, LR = Laurel. Other sites: IC = Isla Cueva, MI = Magueyes Island field station, TM = Tres Marías.

Shelf Edge," was added in an attempt to record changes in species distributions expected at the edge of the insular shelf. Emphasis in this study was given to the patterns around emergent reefs. The reef top geomorphic zone, which applies to non-emergent reefs, was not sampled. Additionally, the central channel axis zone on the single intermediate reef was difficult to adequately delineate in the field, so just the leeward and windward zones were used. Furthermore, as large barrel sponge dominated bottom habitat did not to occur in La Parguera and broad areas of encrusting sponge were discovered, the "invertebrate-sponge" label was redefined to classify this habitat type (Appendix A).

Full details of the methodology for sampling and processing fish density and habitat data are given in Cerveny (2006). Briefly, fishes were sampled using visual census on 4 x 24 m transects, where each species was identified, length estimated, and mapped on the habitat type over which it was observed. The result of this process was the density, by size class, of fish within each combination of habitat type and geomorphic zone, i.e., cross-shelf habitat. The length-frequency distributions were used to calculate density by life stage within each cross-shelf habitat. Three stages were considered: early juveniles, juveniles and adults. To depict habitat use for each species by life stage, density data were grouped into quartiles. The quartile group of each cell in the CSH framework was then coded (by shading), which gives a graphical view of the cross-shelf habitats used and their relative importance.

By viewing EFH on a larger scale and finding common key cross-shelf habitats among species, efforts for conservation can target groups of species, life stages, families, etc. Two combined frameworks are developed here. One framework targets areas of priority usage, by life stage, based on addition across species as the simplest first approach to the problem. To construct this framework, each cross-shelf habitat was scored according to the highest quartile density observed in any species. Thus, for example, a cell given highest priority had at least one species for which that cross-shelf habitat showed the highest density quartile.

A second framework was constructed on the basis of the frequency of importance a particular cross-shelf habitat had across all species. This approach removes the disproportional effect that abundant and ubiquitous species give to the first approach. For this framework, key cross shelf habitats were sorted into three groups of primary, secondary and tertiary importance. Primary key cross-shelf habitats are defined as those cells including 90% or more of the sampled species. Secondary key cross-shelf habitats were defined as occurring in 50% - 90% of the sampled species, and tertiary as 25 - 50%. This was done by life stage for all species.

RESULTS

Life Stage Distribution Patterns

Early juveniles (nursery habitats) — Fifty-two percent of observed quartile densities in the vegetated habitats were for early juveniles, while 88% were for early juveniles and juveniles combined (Table 1). Fifty-seven percent of those observed quartile densities for early juveniles and juveniles in the vegetated habitats occur in the inner shelf geomorphic zone, 20% in the intermediate shelf and 10% in the outer shelf. Across all habitat types, 45% of all observed quartile densities occurred in the inner shelf, 16% in the intermediate shelf, and 39% in the outer shelf.

Juveniles — Thirty-six percent of the observed quartile densities within the vegetated habitat grouping were of juveniles, while 41% of the observed quartile densities in the hardbottom and invertebrate habitat group were of this lifestage. In the geomorphic zones, juveniles were prominent both in the inner (37%) and outer (46%) shelf.

Adults — Adults showed similar percentages of quartile densities in the sediment (23%) and hardbottom/ invertebrate (26%) habitats, while the vegetated habitats had low observed quartile densities 12%. In terms of

Table 1. Percentages of observations per shelf location per lifestage per habitat in La Parguera, Puerto Rico. Column percentages for habitats sum to 100. The last column (% per Lifestage) is the sum across rows.

Lifestage and Shelf Location	% in Vegetation	% in Sediments	% in Hardbottom/ Invertebrates	% in all Habitats	% per Lifestage
Early Juvenile Inner	33.9	9.6	10.6	16.9	44.8
Early Juvenile Intermediate	11.1	13.3	3.5	6.1	16.1
Early Juvenile Outer	7.1	13.3	18.1	14.8	39.1
Juvenile Inner	23.8	7.2	11.3	14.5	36.5
Juvenile Intermediate	8.7	10.8	5.7	6.8	17.1
Juvenile Outer	3.3	22.9	24.3	18.4	46.3
Adult Inner	8.7	4.8	6.9	7.3	32.6
Adult Intermediate	1.4	2.4	1.6	1.6	7.0
Adult Outer	2.1	15.7	18.0	13.5	60.5

geomorphic zones, the adults showed highest observed quartile densities in the outer shelf (60%) followed by the inner shelf (33%) and intermediate shelf (7%).

Key Cross-Shelf Habitats

The summed frameworks by priority usage, by life stage, are shown in (Appendix B.1-3). These illustrate essential fish habitats based on importance to any species within the study. Although the range of cross-shelf habitats is broad (the sum of all species), those cells of highest priority are more restricted. In addition, Appendix B.1 clearly shows the role of coral habitats as nursery areas specifically those located in the windward areas of an inner emergent reef and across the reef structure on the intermediate and outer reefs.

As important as knowing habitat usage and priority, knowledge of which areas are not key is equally illuminating. This is revealed by identifying all cross-shelf habitats that were not essential fish habitat to any species at any life stage, i.e., the blank cells of Appendix C. The result allows for an initial survey of habitats nominated for conservation or fishery production zoning to be more narrowly targeted to habitats actually utilized by reef fishes at a specific life stage and turning the regulatory knob on non-fishery activities in those areas not used by fish to meet the objectives of fishery management and planning efforts.

Results from the second framework, based off the frequency of importance a particular cross-shelf habitat had across all species, are shown in (Appendices D). Early juveniles across all species sampled shared many key cross-shelf habitats. Two of these were of secondary importance (50 - 90% of all species sampled occurred in the cell), while 34 were of tertiary (25 - 50%) importance (Appendix D.1). The interesting aspects of this analysis are the groupings. Vegetated areas of the inner shelf shoreward of the channel axis constitute about a third of the sites, with mangrove and *Thallasia* areas being particularly important. Low relief dead coral areas on the inner shelf were also important. Another cluster can be seen in the Outer Shelf, in coral dominated areas associated with the emergent reef.

Key cross-shelf habitats in the juvenile stage (Appendix D.2) are more scattered than those for early juveniles. Leeward shallow mangrove and *Thallasia* habitats (both Inner and Intermediate Shelf) remain important, as does use of dead coral habitats on the inner and outer shelf, but now more toward the windward of the emergent reef lines. The only key area identified on the outer plain was the mixed coral low relief habitat.

Three secondary and nine tertiary key habitats were identified for adults (Appendix D.3). By this stage most fish have moved out of the vegetated areas and into the coral dominated habitats of the inner and outer shelves. The Inner Shelf – windward intermediate zone is particularly important. Dead low relief coral associated with the outer emergent reef was also important, and importance of the mixed coral low relief habitat of the outer plain increased.

DISCUSSION

Overall, the patterns observed across all species identify inshore mangrove and seagrass areas as important areas for early juveniles. This functional nursery for fishes inhabiting coral reefs as adults is well documented from studies in Panama (Weinstein and Heck 1979), Belize (Sedberry and Carter 1993), Curacao (Nagelkerken et al. 2000), Bonaire (Nagelkerken et al. 2000), and Puerto Rico (Appeldoorn et al. 1997, Hill 2001, Murphy 2001, Aguilar Perera 2004, Foley 2004, Foley and Appeldoorn 2007). These habitats are within close proximity to coral reefs and are non-estuarine. Shallow, well-vegetated habitats provide shelter for smaller fishes that can then shift to a more open habitat type like coral dominated areas as they gain a larger size. However, the present study also identified the role of coral habitats as nursery areas for some species, and this seems to be underappreciated in the literature. Lindeman and Snyder (1999), Lindeman et al. (2009) and Schärer-Umpierre (2009) have illustrated the importance of nearshore hardbottom habitats as nursery areas for those ecosystems that are lacking in appropriate mangrove and seagrass habitats. Given that such nearshore hardbottom habitats are extremely limited in La Parguera, the importance of these habitats as nursery areas along the shallow forereef of the inner emergent reef many reflect an homologous behavior.

The protection of key cross-shelf habitats under the mandate of EFH will be essential for both biodiversity conservation and the protection of the productive capacity of the ecosystem. Still remaining is the question of how to make this operational for management. This work was done on a small scale – smaller than management can normally operate. Yet the study suggests several considerations that can be dealt with. For example, this study brings into sharp relief the importance of the Inner Shelf – windward intermediate zone for all lifestages of reef fishes studied, and the clustering of younger life stages in both vegetation dominated areas and shallow low, dead coral dominated areas. The inshore nature of these sites makes them vulnerable to external, non-fishing threats. Examples would include land-based pollution, mangrove removal, reduction of seagrass bed suitability due to increased turbidity or sedimentation, and burial of nearshore hardbottom via beach "renourishment". Management should thus take strong action against activities or processes degrading nearshore habitats. Equally on this scale, cross-shelf habitats shown to be of lesser importance can be targeted for small scale activities (e.g., recreational anchoring) that otherwise threaten important reef associated habitats.

The scalability of the CSH framework makes it an ideal tool for coastal and marine spatial planning as well as fisheries management. By managing marine systems at a larger scale comprised of multiple cross-shelf habitats collapsed together, the appropriate scale can be achieved from this data, and management decisions can be a more science-grounded, ecosystem-based management endeavor. At the largest scale, it is obvious that the vast majority of cross-shelf habitats are important for at least one species. This suggests that management should focus on identifying and protecting key portions of the shelf, from shoreline to shelfedge, that serve as potential production centers and target management and conservation efforts to protect these. Targeting larger scale priority areas that encompass a variety of key cross-shelf habitats critical to fulfill the desired conservation or fishery objectives then allows place-based management to isolate these areas from external threats. In this manner, the CSH framework can be used to inform delineations of protected areas or usage zones.

When a sectoral approach to ocean governance is the dominant paradigm, fragmented decision making occurs (Norse 1993), leading to many federal and local agencies with authority over ocean activities and none with ultimate responsibility. With agencies looking after their own specific mandate, and disempowered to act beyond their authorities, tradeoffs within a sector may be considered, but trade-offs between sectors rarely occur if they are even considered at all (Rosenberg and Sandifer 2009). Trade-offs can include threats upon marine systems and fish populations. These tradeoffs between sectors, like amongst fishing interests and water quality, must occur as we utilize comprehensive, ecosystem-based marine spatial planning that encompasses fishery management to meet the objective of healthy marine ecosystems.

In response, the United States is committed to coastal and marine spatial planning as a tool to implement the National Ocean Policy, which strives to integrate and alter federal activities within the coastal and marine environment in a manner which will protect, maintain and restore ocean ecosystems (Executive Order No. 13547, 2010 and The White House Council on Environmental Quality, 2010). Fishery management should be an activity considered in the development of regional plans, and having a better understanding of the spatial heterogeneity of fish populations in those regions is critical. The CSH framework is a viable tool that can be employed across regions to gather and combine the necessary data to successfully illustrate fish distributions and habitat usage to incorporate fishery management into regional planning efforts. Our results, which suggest that management identify and target large scale priority areas, both fully support a spatial approach and provide a mechanism to assess area suitability.

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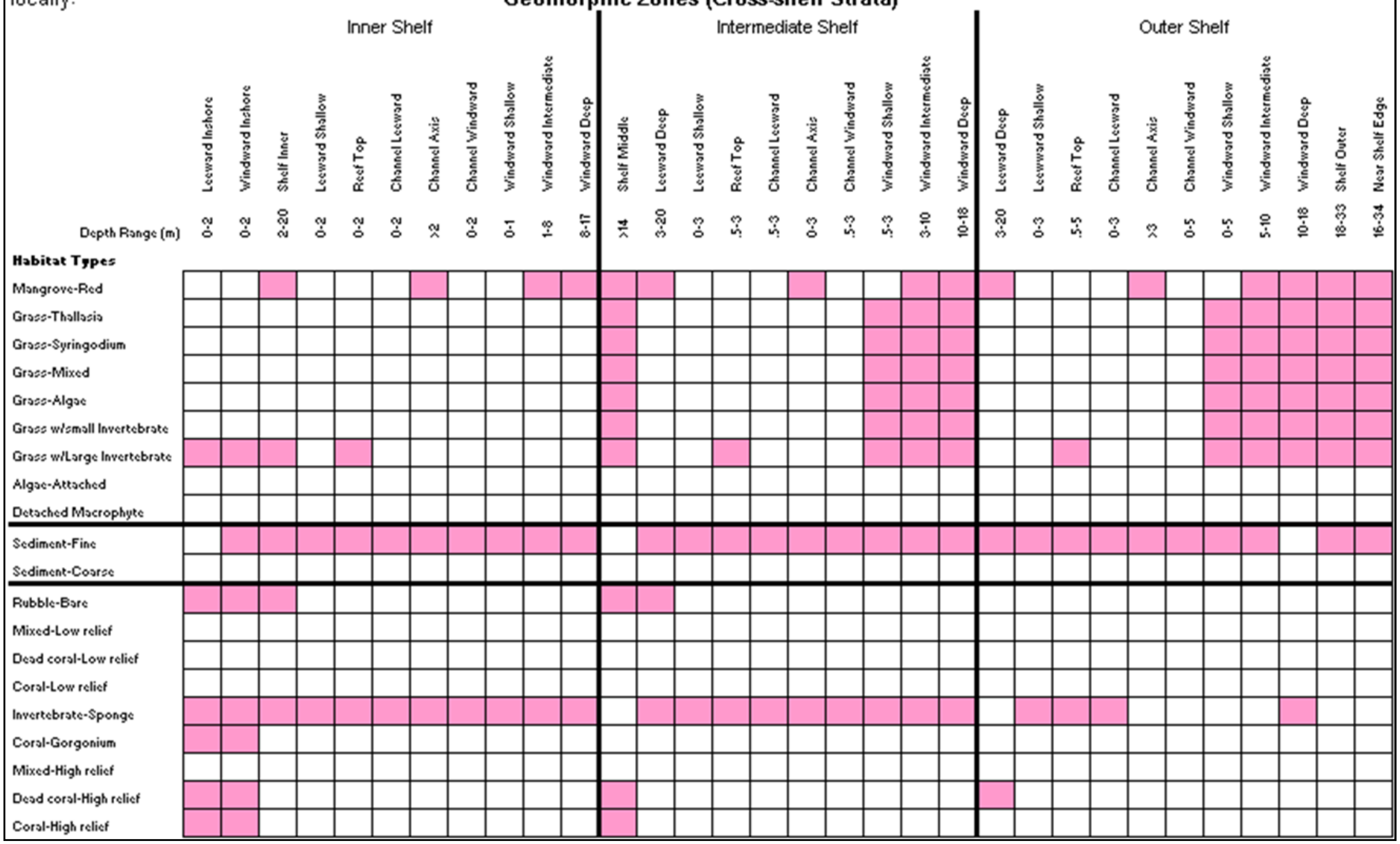
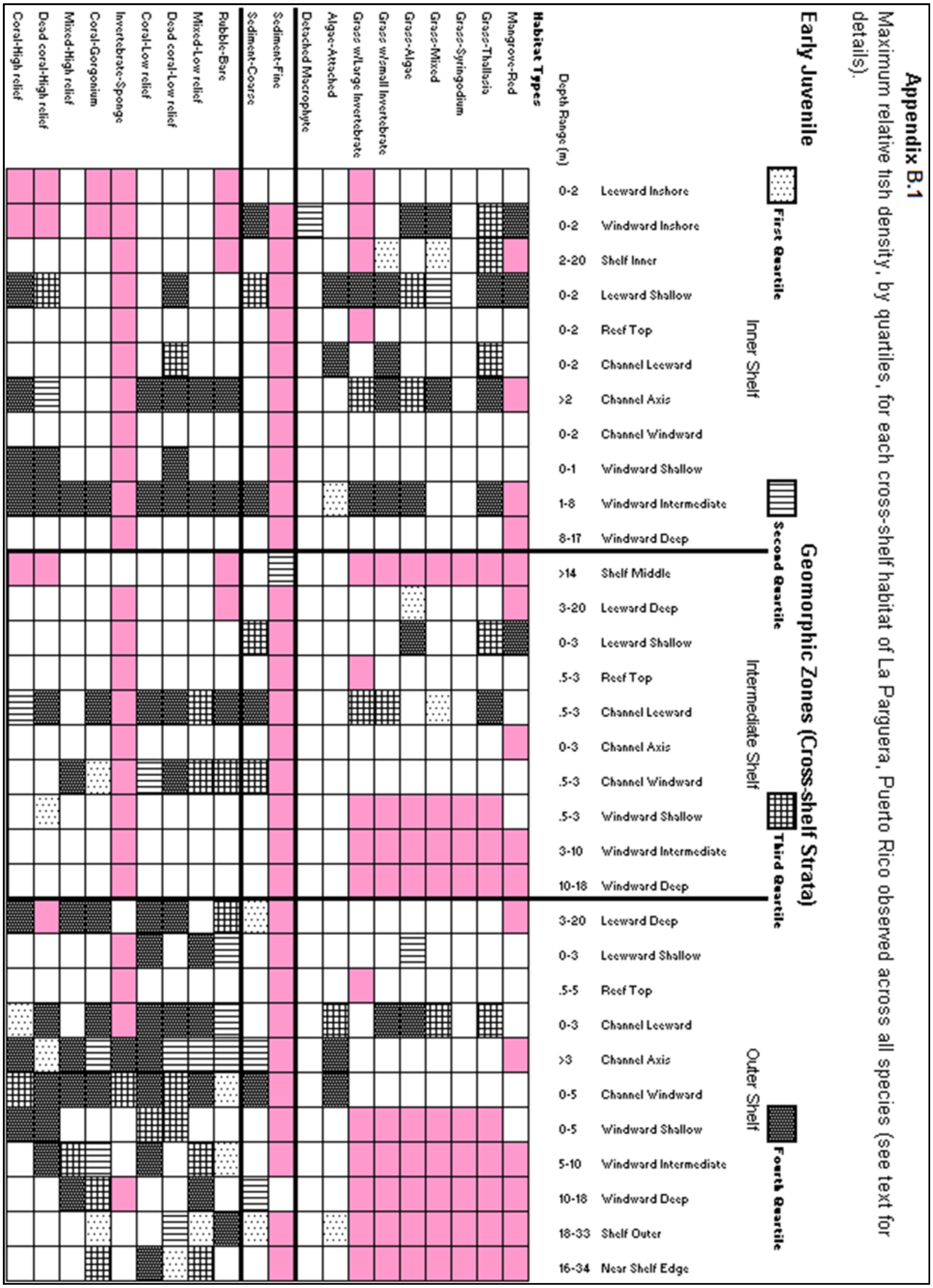
Appendix A

Cross-shelf habitat framework integrating structural habitat types and geomorphic zones of La Parguera, Puerto Rico shelf area, as presented in Appeldoorn et al. (2001). The cross-shelf habitat matrix is composed of 660 cells, of which 529 occur in La Parguera. Shaded cells do not occur locally.



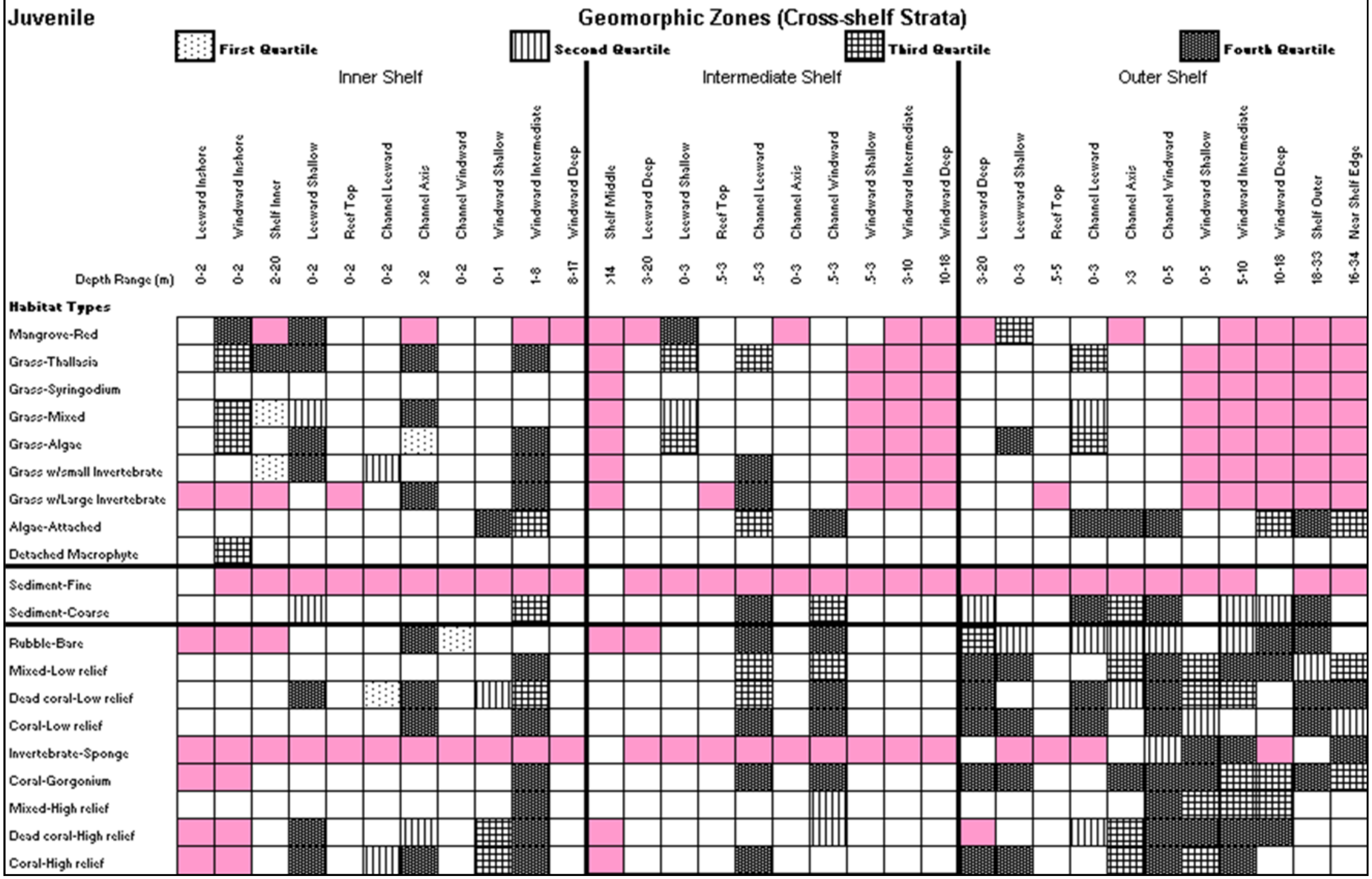
Appendix B.1

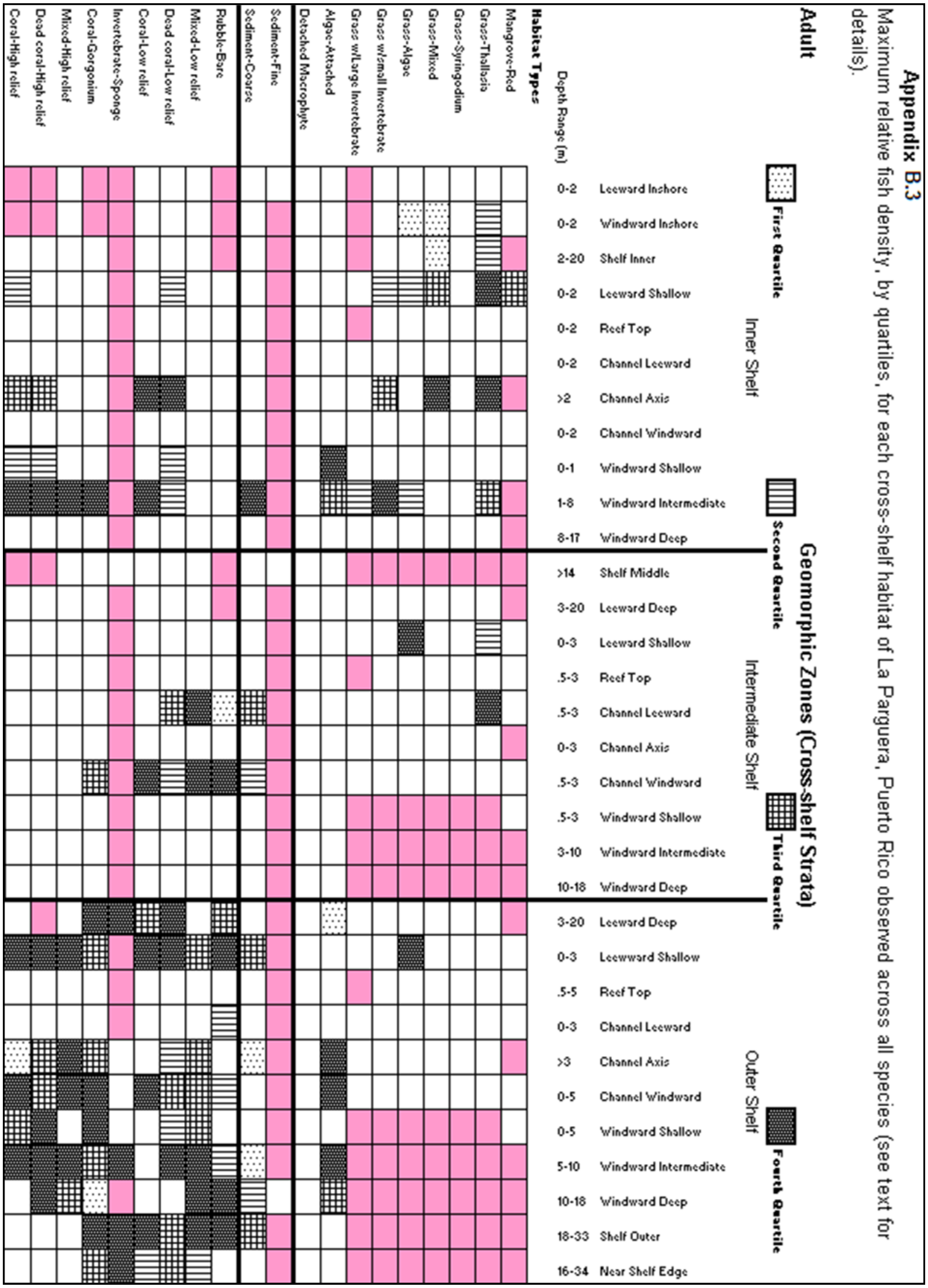
Maximum relative fish density, by quartiles, for each cross-shelf habitat of La Parguera, Puerto Rico observed across all species (see text for details).



Appendix B.2

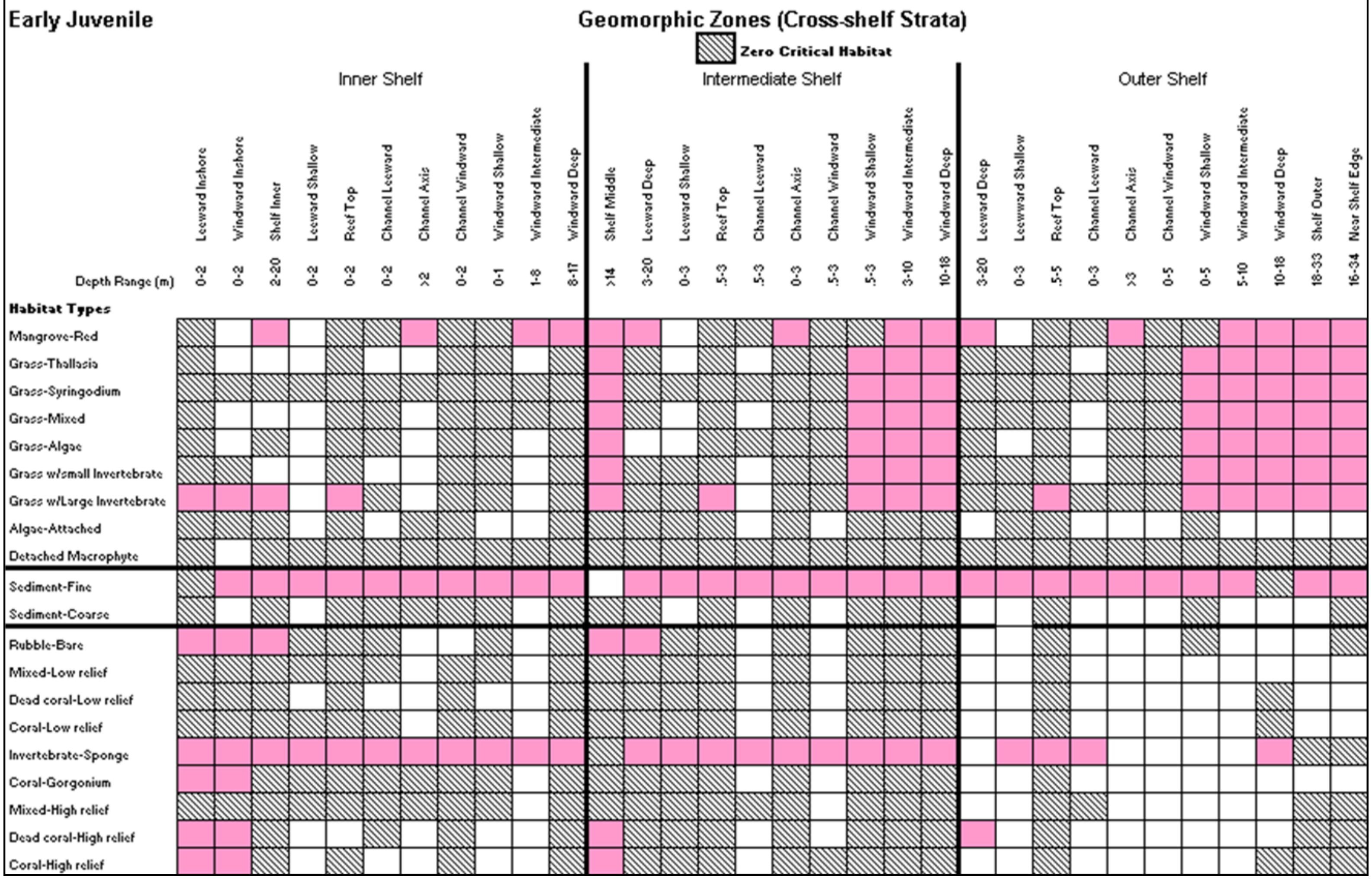
Maximum relative fish density, by quartiles, for each cross-shelf habitat of La Parguera, Puerto Rico observed across all species (see text for details).

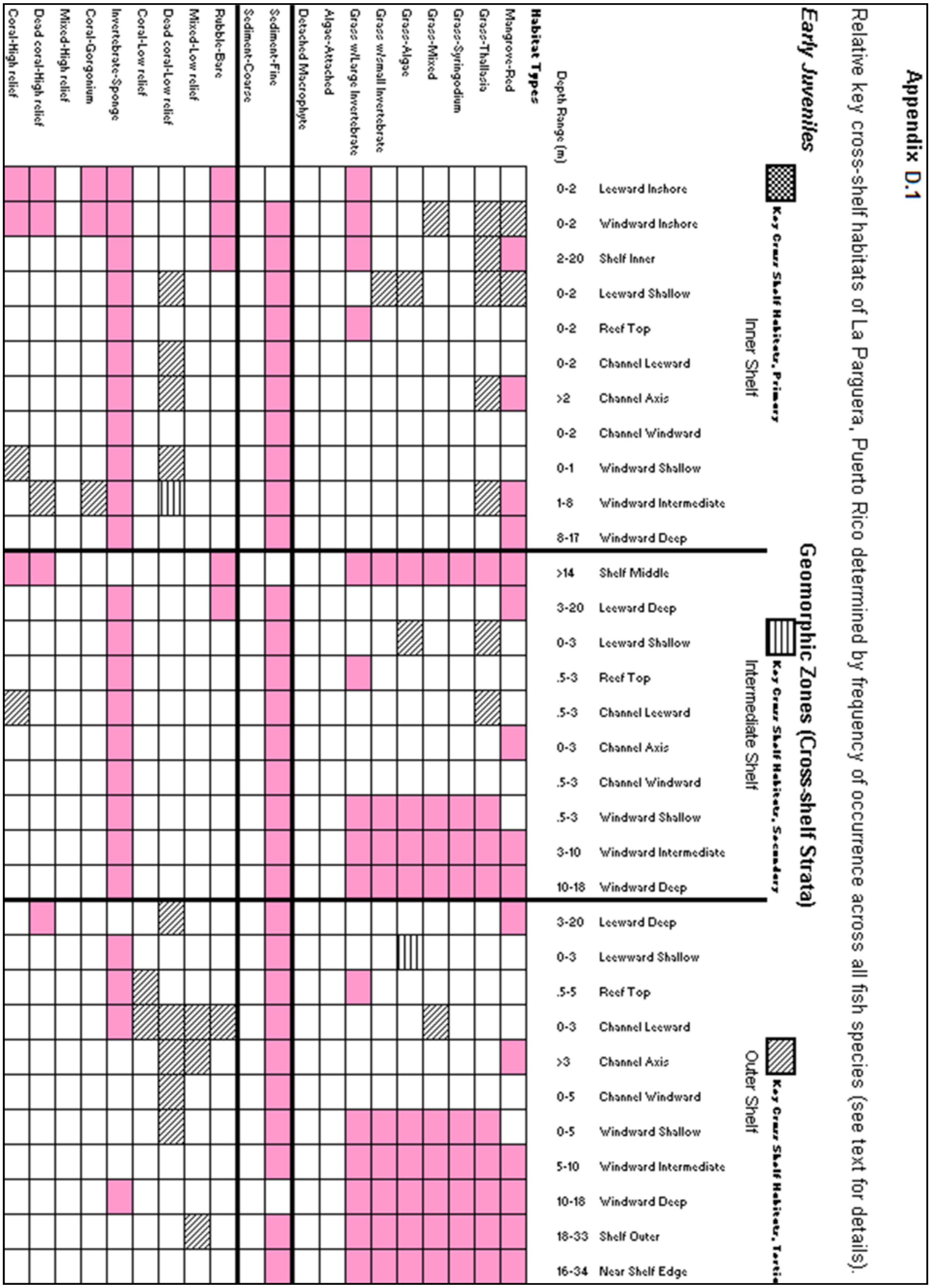


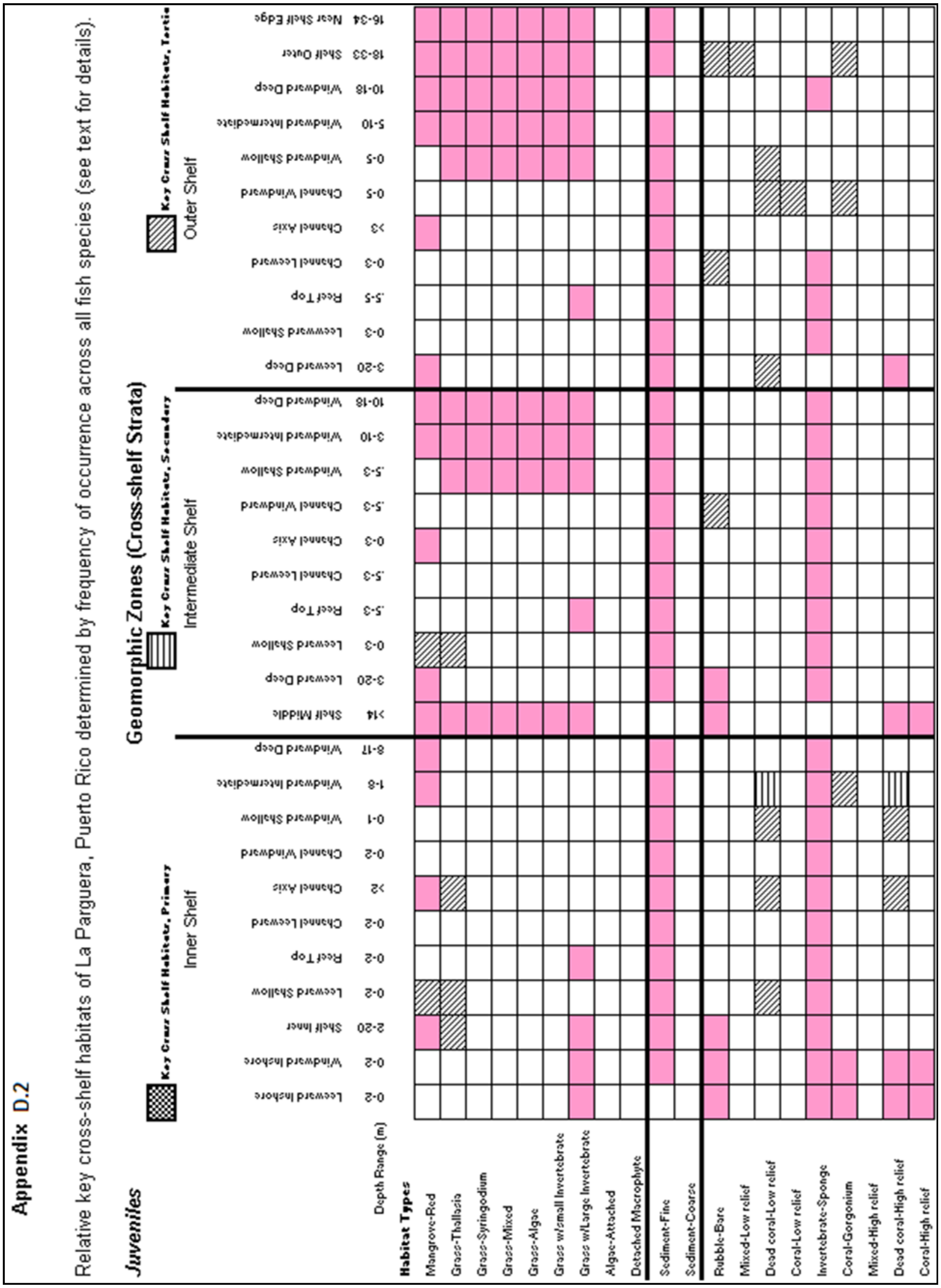

Appendix B.3
Maximum relative fish density, by quartiles, for each cross-shelf habitat of La Parguera, Puerto Rico observed across all species (see text for details).
Adult
First Quartile
Second Quartile
Third Quartile
Fourth Quartile
Geomorphic Zones (Cross-shelf Strata)
Inner Shelf
Intermediate Shelf
Outer Shelf
Depth Range (m)
Habitat Types
Mangrove-Red
Grass-Thallasia
Grass-Syringodium
Grass-Mixed
Grass-Algae
Grass w/small Invertebrate
Grass w/Large Invertebrate
Algae-Attached
Detached Macrophyte
Sediment-Fine
Sediment-Coarse
Rubble-Bare
Mixed-Low relief
Dead coral-Low relief
Coral-Low relief
Invertebrate-Sponge
Coral-Gorgonium
Mixed-High relief
Dead coral-High relief
Coral-High relief
0-2 Leeward Inshore
0-2 Windward Inshore
2-20 Shelf Inner
0-2 Leeward Shallow
0-2 Reef Top
0-2 Channel Leeward
>2 Channel Axis
0-2 Channel Windward
0-1 Windward Shallow
1-8 Windward Intermediate
8-17 Windward Deep
>14 Shelf Middle
3-20 Leeward Deep
0-3 Leeward Shallow
.5-3 Reef Top
.5-3 Channel Leeward
0-3 Channel Axis
.5-3 Channel Windward
.5-3 Windward Shallow
3-10 Windward Intermediate
10-18 Windward Deep
3-20 Leeward Deep
0-3 Leeward Shallow
.5-5 Reef Top
0-3 Channel Leeward
>3 Channel Axis
0-5 Channel Windward
0-5 Windward Shallow
5-10 Windward Intermediate
10-18 Windward Deep
18-33 Shelf Outer
16-34 Near Shelf Edge

Appendix C

Cross-shelf habitat framework integrating structural habitat types and geomorphic zones of La Parguera, Puerto Rico shelf area. Shaded cells do not occur locally, cross-hatched cells had zero encounters in all species in all lifestages of this study.




Appendix D.1
Relative key cross-shelf habitats of La Parguera, Puerto Rico determined by frequency of occurrence across all fish species (see text for details).
Early Juveniles
Key Cross Shelf Habitats, Primary
Key Cross Shelf Habitats, Secondary
Key Cross Shelf Habitats, Tertiary
Geomorphic Zones (Cross-shelf Strata)
Inner Shelf
Intermediate Shelf
Outer Shelf
Depth Range (m)
Habitat Types
Leeward Inshore
Windward Inshore
Shelf Inner
Leeward Shallow
Reef Top
Channel Leeward
Channel Axis
Channel Windward
Windward Shallow
Windward Intermediate
Windward Deep
Shelf Middle
Leeward Deep
Leewward Shallow
Shelf Outer
Near Shelf Edge
Mangrove-Red
Grass-Thallasia
Grass-Syringodium
Grass-Mixed
Grass-Algae
Grass w/small Invertebrate
Grass w/Large Invertebrate
Algae-Attached
Detached Macrophyte
Sediment-Fine
Sediment-Coarse
Rubble-Bare
Mixed-Low relief
Dead coral-Low relief
Coral-Low relief
Invertebrate-Sponge
Coral-Gorgonium
Mixed-High relief
Dead coral-High relief
Coral-High relief


Appendix D.2
Relative key cross-shelf habitats of La Parguera, Puerto Rico determined by frequency of occurrence across all fish species (see text for details).
Juveniles
Geomorphic Zones (Cross-shelf Strata)
Key Cross Shelf Habitats, Primary
Key Cross Shelf Habitats, Secondary
Key Cross Shelf Habitats, Tertiary
Inner Shelf
Intermediate Shelf
Outer Shelf
Depth Range (m)
0-2 Leeward Inshore
0-2 Windward Inshore
2-20 Shelf Inner
0-2 Leeward Shallow
0-2 Reef Top
0-2 Channel Leeward
>2 Channel Axis
0-2 Channel Windward
0-1 Windward Shallow
1-8 Windward Intermediate
8-17 Windward Deep
>14 Shelf Middle
3-20 Leeward Deep
0-3 Leeward Shallow
.5-3 Reef Top
.5-3 Channel Leeward
0-3 Channel Axis
.5-3 Channel Windward
.5-3 Windward Shallow
3-10 Windward Intermediate
10-18 Windward Deep
3-20 Leeward Deep
0-3 Leeward Shallow
.5-5 Reef Top
0-3 Channel Leeward
>3 Channel Axis
0-5 Channel Windward
0-5 Windward Shallow
5-10 Windward Intermediate
10-18 Windward Deep
18-33 Shelf Outer
16-34 Near Shelf Edge
Habitat Types
Mangrove-Red
Grass-Thallasia
Grass-Syringodium
Grass-Mixed
Grass-Algae
Grass w/small Invertebrate
Grass w/Large Invertebrate
Algae-Attached
Detached Macrophyte
Sediment-Fine
Sediment-Coarse
Rubble-Bare
Mixed-Low relief
Dead coral-Low relief
Coral-Low relief
Invertebrate-Sponge
Coral-Gorgonium
Mixed-High relief
Dead coral-High relief
Coral-High relief

Appendix D.3

Relative key cross-shelf habitats of La Parguera, Puerto Rico determined by frequency of occurrence across all fish species (see text for details).