Benthic Mapping from Fish and Habitat Transect Data Using GIS Technology

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ABSTRACT

The mapping of benthic habitats and corresponding fish fauna is essential for understanding the role of habitat in controlling the spatial distribution of fish abundance, diversity and production. Any approach to mapping must first standardize habitat definitions and classification, as well as a data collection methodology. Visual transects are a standard tool for quantifying fish abundance and habitat characteristics. Yet, for purposes of mapping and analysis these data must be scaled up to their relative areas. We report on a methodology using stratified sampling and Geographic Information System (GIS) technology to convert transect data into larger-scale habitat maps, illustrating the procedure with data from La Parguera, Puerto Rico. Sampling strata are determined using two criteria. The first is Lindeman's cross-shelf habitat (CSH) classification system adapted to the local insular shelf; the main determinants are position in the cross-shelf direction and depth. The second criterion is based on a visual inspection of the array of different habitat mosaics (100's m^2) present within any CSH stratum (e.g., grassbed, sand/algae plain, gorgonian/coral field). Representative transects, replicated where possible, are placed in the different habitat-mosaics, and associated fishes and habitats are quantified. Areas within each habitat-mosaic stratum can be determined using a variety of approaches such as field mapping with Global Positioning System (GPS) coordinates, or remote sensing using aerial photography or side-scan sonar. Use of GIS technology allows transect data to be overlain on the habitat-mosaic and CSH strata and facilitates further analyses such as calculation of total abundances and estimation of both fish and habitat diversity.

KEY WORDS: Habitat, Fish Abundance, GIS

INTRODUCTION

Fisheries managers are now recognizing the importance of habitat in understanding and managing marine resources. Habitat plays a crucial role in the spatial distribution of fishes (Green 1996, Appeldoorn et al. 1997, Friedlander and Parrish 1998). The types, abundance and arrangement of habitats are also important for determining the fisheries productivity of a system. Specific locations act differentially as nursery and feeding grounds for juvenile and adult marine organisms, and as sites for spawning aggregations. Maintaining the integrity of these areas is necessary for the persistence of these functions. The flow of energy between habitats and to higher trophic levels is in large part controlled by the movement of fishes, and this, in turn, is influenced by the distribution of habitat (Appeldoorn et al. 1997, Kramer and Chapman 1999). Whether fishes move through and across habitats in feeding migrations, ontogenetic migrations, or predatory movements, they are bringing about a net transfer of energy. This provides the energetic link between one habitat and another. Understanding the role of habitat in controlling these important processes allows for their protection. Furthermore, with this understanding, easily collected habitat data may serve as a surrogate for more detailed life-history data, thus facilitating management. For example, distributions of habitat may be useful for determining those areas that are truly critical for the system ("Essential Fish Habitat") or for siting marine reserves (e.g., Recksiek and Appeldoorn, 1998; Recksiek et al., 2000).

Habitat classification systems provide a logical framework for organizing the collection and interpretation of data on both habitat and fish distributions (Lindeman et al. 1998, Recksiek and Appeldoorn 1998, Mumbry and Harborne 1999). In Lindeman's Cross-Shelf Habitat (CSH) matrix (Lindeman et al. 1998), each cell describes a unique combination of specifically defined habitat types (at 1 m^2 resolution) and geomorphic position. The main determinants of the latter are position in the cross-shelf direction and depth. Diver-based habitat characterization and visual census are commonly applied field methodologies, but they are spatially limited in both the area covered and the area over which their results can be extrapolated. Application of results to a CSH matrix allows one to determine where species exist in matrix space and if habitat use is broad or narrow, and hence potentially limiting. However, matrix space is not geographic space, and application of the CSH matrix alone cannot determine how much area is occupied by each cell, how this area is divided (number of patches, size distribution of patches) and how this area is arranged in the larger landscape. Thus, there needs to be a mechanism to allow detailed studies to be scaled up to shelf-wide dimensions. This is true not only for habitat data but for fish sampling as well. Since species distributions will be related to habitat distributions, one must sample the array of habitats and expand these to larger scales to estimate overall abundances and diversities.

Here we report on a methodology for expanding small-scale estimates of habitat and species abundances and distributions. For purposes of illustration, this methodology is applied to the forereef of an outer emergent reef off the southwest coast of Puerto Rico.

METHODS

Basic input data for our approach are maps of habitat and fish distributions. These were obtained by divers visually mapping distributions across 24 x 4 m transects, using the methodology of Recksiek et al. (2000). Habitats are described on a 1-m^2 basis from a pre-defined list of 18 potential habitat types based on predominant benthic cover and its relief (sand, algae, coral, rubble, etc.), while the position of individuals or schools of fish from 45 species are recorded onto the habitat map. Also recorded are the number of fish at each location and their size range (see Recksiek et al., 2000 for details and examples). In order to relate individual transects to the distribution of fishes and habitats across a larger spatial scale, transect positions must be determined within some kind of sampling framework. We use a two-stage, stratified sampling protocol. Strata are determined using two criteria. The first is a cross-shelf habitat (CSH) classification system (Lindeman et al. 1998) adapted to the local insular shelf (Figure 1). The second criterion is based on a visual inspection of the array of different habitat mosaics (100's m^2) present within any CSH stratum (e.g., grassbed, sand/algae plain, gorgonian/coral field). Use of this second stratification procedure ensures that the complete variety of habitats within an area will be sampled and, thus, that the vertical components of the CSH matrix will be identified for each area. This procedure allows us to relate habitat abundances on a spatial scale, thus allowing for estimation of scale specific indices of habitat diversity and the description of the arrangement of habitats on a scale larger than that of the original transects.

In practice, a given geomorphic area is chosen as the first stage for sampling, based in general terms on the CSH strata. For example, on Laurel, a large emergent offshore reef off La Parguera, Puerto Rico (Figure 2), we sampled three general areas: the forereef, the backreef and the eastern end of the reef. These each constitute a first stage of our multistage approach. Within each area fall several CSH strata. Each general area is then surveyed to assess the kinds of different habitat mosaics present. Assessments are qualitative, but are made on the basis of visually distinct boundaries. For example, on the forereef of Laurel, four such zones were identified (from shallow to deep): a fire coral zone with high relief, a low relief barren hard bottom zone, a gorgonian zone and a mixed coral gorgonian zone. Representative transects, replicated where possible, are then placed in the different mosaics. If a habitat mosaic crosses a CSH stratum boundary, then transects would normally be located in both areas. The locations of transects are determined with differentially corrected Global Positioning System (GPS).

We use a Geographic Information System (GIS) to organize, integrate, manage and analyze all data. The GIS software used was Intergraph's GeoMedia Pro v3.0x, chosen for its shallow learning curve, its full compatibility with multiple GIS platforms (e.g., ArcInfo, ArcView, etc.) and full integration with Microsoft's popular Operating Systems. To insure spatial accuracy, the 24 x 4-m transect grid was recreated using Computer Aided Design (CAD) software. The grid was georeferenced following the State Plane Coordinate System (zone number 5200: Puerto Rico and US Virgin Islands) as the projection parameter standard and used as a basic template to recreate the transects in the GIS. Habitat and fish location maps were scanned and digitized. Data on fish species, number and size of individuals were entered into the GIS database.

For each transect, the digitized maps were vectorized and other data (habitat, fish) were linked to their respective polygonal areas. A color-coded scheme was used to depict each of the 18 habitats types, while fishes were placed as either points, depicting individuals, or as polygons, depicting aggregations (see Recksiek et al., 2000 for examples). The GIS calculated habitat areas, perimeters and relationships among fishes and the habitats they occupied.

For the expansion of transect data to a larger scale, it is necessary to determine the spatial extent of the strata sampled. We used a bathymetric map to determine the location of the CSH strata (Figure 2). This was scanned and digitized, then geo-referenced and vectorized within the GIS. Within the general area of the transects (selected area), the locations of the 9 and 18-m depth contours (boundaries of the deeper CSH strata) were determined using a fathometer and GPS. These were entered into the GIS to aid in geo-referencing the CSH map. It was also necessary to determine the spatial extent of the habitat mosaic strata. Again, within the selected area encompassing all transects, boundaries of the habitat mosaics were marked at intervals with surface buoys, and their positions were determined with GPS. These points were entered into the GIS database and used to describe polygons for each habitat mosaic. For comparative purposes, we also examined the possibility of using aerial photographs to determine the extent of habitat mosaics. An aerial photograph (LARSIP NASA Depository, 1994) of Laurel was digitized, geo-referenced and vectorized in the GIS. Easily distinguished features were converted into polygons. Their biotic characteristics were determined in the field by divers. The GIS was used to calculate the areas of the cross-shelf and habitat-mosaic strata and their intersections.

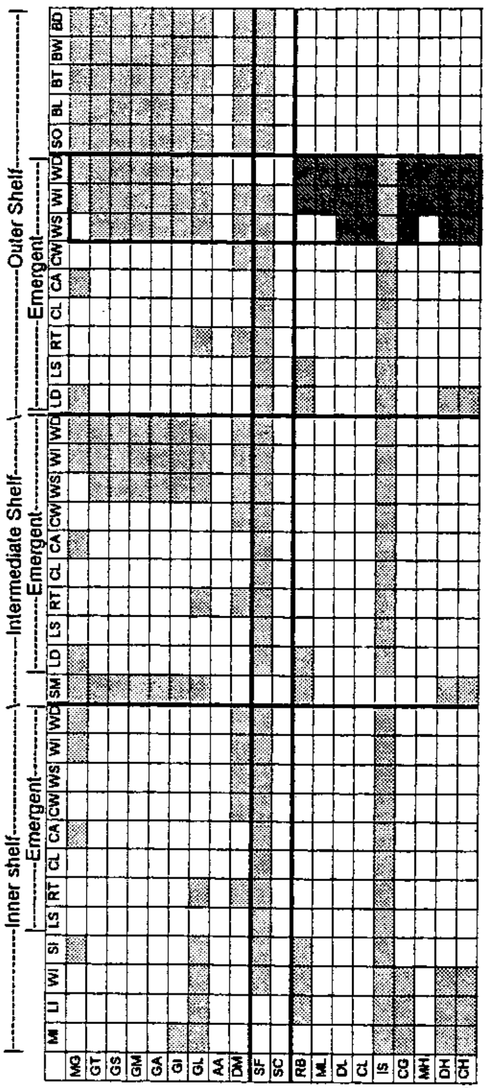

Figure 1. Cross-shelf habitat matrix for La Parguera, Puerto Rico. Vertical axis is habitat type; horizontal axis is cross-shelf stratum. Light gray boxes indicate habitat-cross shelf combinations thought not to occur. The box in bold shows the area sampled: forereef of Laurel. WS: Windward Shallow, WI: Windward Intermediate, WD: Windward Deep. Dark gray boxes indicate habitat-cross shelf combinations found in the habitat transects. See Figure 4 for habitat codes.

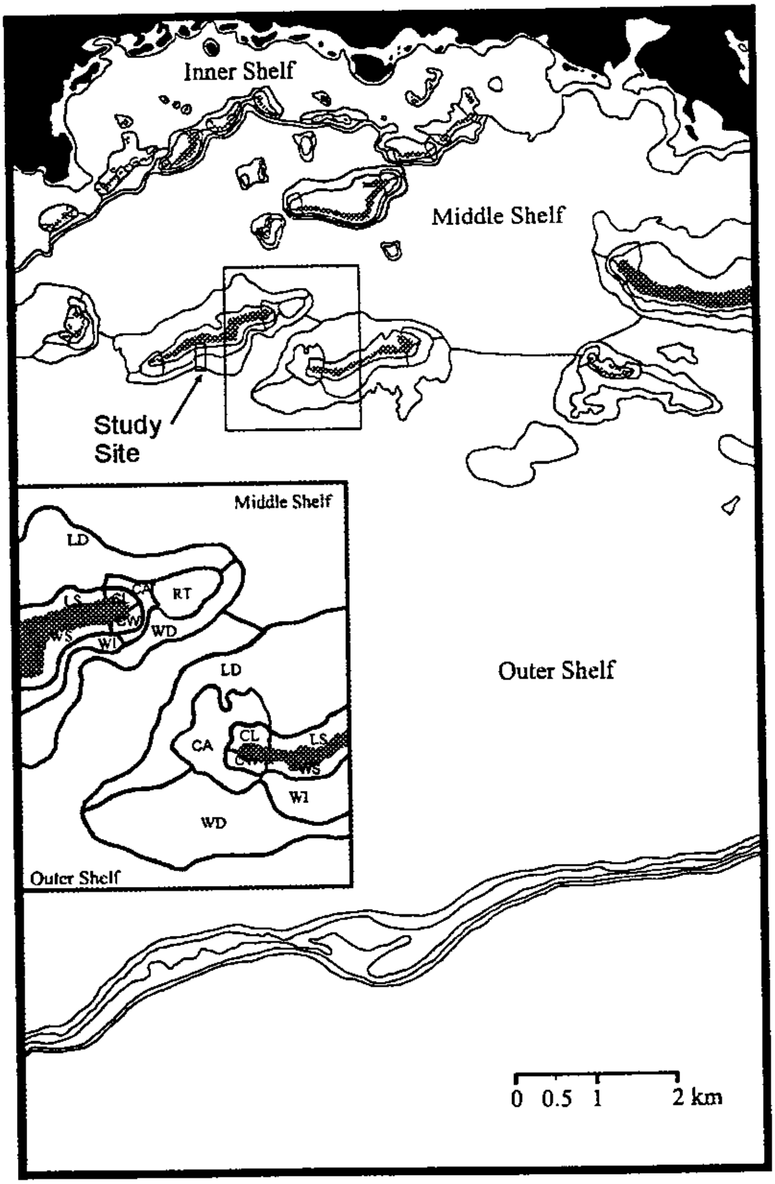

Figure 2. Cross-shelf strata for La Parguera, Puerto Rico based on bathymetry. Study site on Laurel is the small box indicated by the arrow.

A first estimation of habitat diversity was calculated by applying Shannon's index (Shannon and Weaver 1949)

$$H' = -\sum p_i \text{Log}\, p_i$$

where p_i is the probability of encountering a patch of habitat type i. Probabilities were calculated as the number of patches of habitat type i in a stratum divided by the total number of habitat patches in that stratum. Thus, this formulation does not directly account for differences in the size of individual patches, nor the proportion of area occupied by a particular habitat type.

Calculations of fish abundances and diversity follow directly from the expanded strata areas using similar calculations. For brevity we report only the results for habitat.

RESULTS

On the forereef of Laurel, habitat and fish distribution data were collected from 8 transects, representing two replicates in each of the four types of habitat mosaics. These are shown in Figure 3. The area studied covered three cross-shelf strata: Windward Shallow (WS), Windward Intermediate (WI) and Windward Deep (WD) from an outer emergent reef; their position on the CSH matrix is outlined in Figure 1, while their geographic position is given in Figure 2. For logistical reasons, no transects were located in WD; but since the transects in WI were located near the WI-WD boundary (Figure 3), and because they shared the same habitat mosaic, we extrapolated the results of the deepest two transects into the WD stratum. Table 1 gives the areas of the cross-shelf and habitat-mosaic strata and the their intersections, as calculated within the GIS.

The basic unit for the expansion of the habitat areas to larger scales was the sum of each pair of replicate transects (192 m^2); this consisted of the number of different habitat types, the number of patches of each habitat and their respective percent areas. To expand transect results, the following procedure was used. If a cross-shelf stratum consisted of a single habitat mosaic, the percent area of each habitat type from the transects was multiplied by the area of the stratum to get the total area of each habitat type. The total stratum area divided by the area of the transects (192 m^2) was used to multiply the number of patches within the transects to get the total number of patches of each habitat within the stratum. When the cross-shelf stratum consisted of more than one habitat mosaic, the *selected area* of each mosaic within the stratum was divided by the area of the transects. This number was then used to multiply the transect results (number of patches and their proportional areas) for each mosaic. The results from the two habitat mosaics were then added to obtain the results for the stratum as a whole within the selected area. This was then used to expand the results for the entire stratum.

For example, two habitat mosaics (fire coral, bare hard bottom) were found in the WS stratum (Figure 3). Within the selected area around the transects, the WS stratum occupied 6,934 m^2, of which 1,365 m^2 was of the fire coral habitat mosaic and 809 m^2 was of the bare hard bottom mosaic (Table 1). Within the fire coral habitat mosaic four habitat types were found (Table 2). The area of this habitat mosaic within the selected area of the WS stratum (1,365 m^2) divided by the area of the transects (192 m^2) is 7.1. Thus, the number of patches and areas of each habitat within the fire coral mosaic were multiplied by 7.1 to get the total number for each habitat within the selected areas of the WS stratum.

Table 1. Areas (m^2) of cross-shelf and habitat-mosaic strata and their intersections. WS: Windward Shallow, WI: Windward Intermediate, WD: Windward Deep

	Total	WS	WI	WD
Selected Area	16,815	2,174	6,934	7,708
Total Area	446,641	54,242	146,264	246,130
Fire Coral	1,365	1,365		
Bare Hard Bottom	1,050	809	241	
Gorgonian	1,766		1,704	
Coral-Gorgonian	12,695		4,988	7,708

Table 2. Spatial coverage of habitats within transects located within the fire coral habitat mosaic. Area is in m^2. N is number of patches of each habitat observed in the transects.

Habitat Type	Area	% Area	N
Coral-High Relief	41	20.8	19
Coral-Low Relief	1	0.6	1
Dead Coral-High Relief	27	14.3	18
Dead Coral-Low Relief	123	64.3	4

A similar set of calculations was made for the bare hard bottom habitat mosaic, and the sum of these were added to the results obtained for the fire coral mosaic. The proportion of each habitat thus obtained within the selected area of the WS stratum would be multiplied by the total area of the stratum to get the final estimates of the total area of each habitat within the WS stratum.

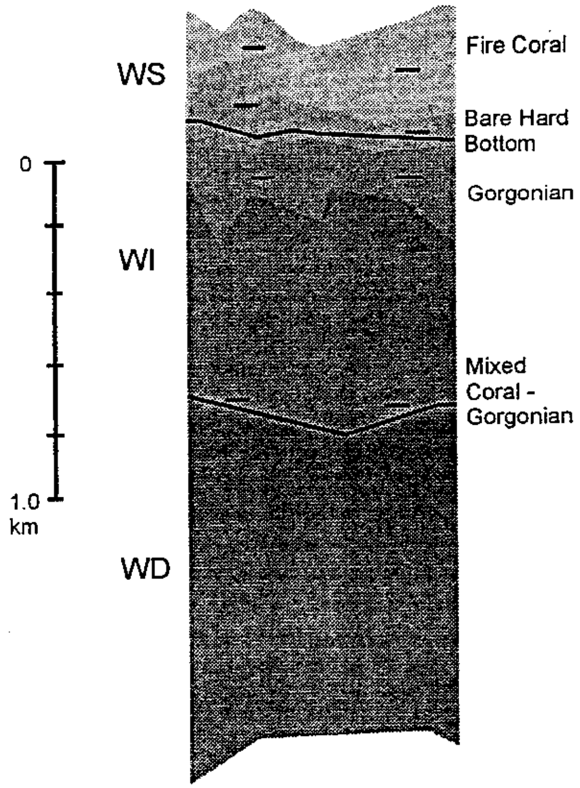

Figure 3. Selected area of the forereef of Laurel. Short black lines show position of transects (drawn larger than scale); long black lines show the boundaries of the cross-shelf strata: WS - Windward Shallow, WI - Windward Intermediate, WD - Windward Deep. Different colored areas represent the four habitat mosaics.

The results of the above procedure applied to all strata are given in Figure 4, which shows the percent area for each combination of habitat and cross-shelf stratum over the entire forereef. The cell areas in Figure 4, then, represent the relative areas of the cells in the CSH matrix (Figure 1). Thus, we have converted matrix space into true geographic space. The figure shows how the percent areal coverage of the different habitat types changes among the cross-shelf strata. For example, dead coral-low relief is the habitat most abundant in the WS stratum, but its importance is low in the remaining cross-shelf strata and for the forereef as a whole.

Habitat diversities (H') calculated for each cross-shelf stratum were as follows: WS = 0.559, WI = 0.806, WD = 0.747. These results compare well with the habitat distributions shown in Figure 4. The shallow stratum has fewer habitat types and a more uneven distribution, both contributors of lower diversity. Interestingly, Figure 4 is based on total area coverage, while the Shannon index is based on number of patches of habitat.

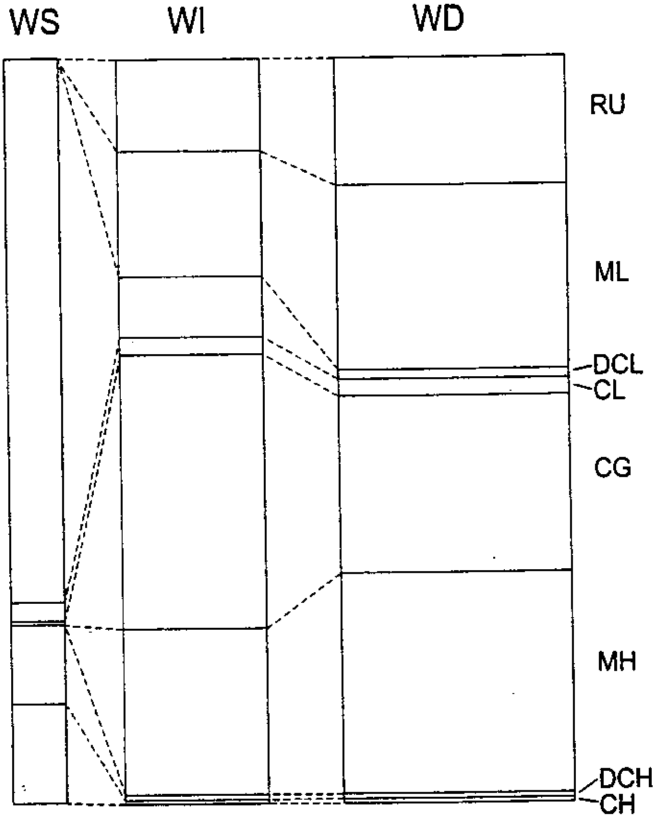

Figure 4. Bottom habitat cover within the three windward cross-shelf strata of Laurel (WS - Windward Shallow, WI - Windward Intermediate, WD - Windward Deep). Within each cross-shelf stratum, the area of each habitat type represents it proportional to bottom cover. RB: rubble, ML: mixed invertebrate-low relief, DL: dead coral-low relief, CL: coral-low relief, CG: gorgonian, MH: mixed invertebrate-high relief, DH: dead coral-high relief, CH: coral-high relief.

DISCUSSION

There are several advantages to the approach outlined here. One of the principal ones is that it allows use of transect data. Such data are often available, either from past studies or because it is easily collected and does not require expensive or complicated technologies. Such data are easily placed within the logical framework of the CSH matrix.

Using our double stratification method (cross-shelf strata and habitat mosaics) increases the probability of sampling the range of existing habitats and species, while still allowing expansion of results to larger scales based on easily obtainable bathymetric data. Because species distributions are related to habitat distributions, this approach can be used to reduce the variance on estimates of population abundance. Species-habitat locations in the CSH matrix can identify critical habitats, and the methods used here can show the availability and distribution of such critical habitat.

The method is flexible and can use different approaches to define habitat mosaics. Remote sensing (e.g., aerial photography, side scan sonar) is often used to map habitat mosaics. This usually has a coarser resolution but broader areal coverage. In our case, a georeferenced aerial photograph of Laurel, when overlain on the diver-generated map of the habitat mosaics, clearly showed the boundary between the bare hard bottom and gorgonian habitat mosaics. However, it failed to differentiate between the fire coral and bare hard bottom mosaics or between the gorgonian and mixed coral-gorgonian mosaics. The best method will, of course, depend on the goals of the study and the resources available.

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