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MPA design using sliding windows: Case study designating a research area

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ABSTRACT

Coastal managers presently rely on a limited set of decision support tools for designing marine protected areas (MPAs) or subzones. A new approach, defining potential sizes and shapes of MPA boundaries early in the design process, is presented in a case study. A sliding window of the same dimensions as potential boundary configurations was regularly shifted throughout the study area and used to quantify variables representing preferred biophysical and socioeconomic characteristics. The technique offers advantages in spatially restricted areas, areas where habitat connectivity is critical, and situations wherein providing stakeholders with an up-front understanding of potential boundaries is required.

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1. Introduction

The diverse and often highly localized challenges of marine protected area (MPA) design and subzoning are driving the need for a greater variety of tools to aid MPA planners and coastal managers. Despite a recent surge in the number of publications and software tools to aid coastal managers in MPA boundary design [40,39,34,2,27,35,38,15,33,19,31,6,24,30,28], only a handful of unique decision support systems and approaches have been devised.

Most MPA design tools are variations on a cell based approach and consider the efficiency of various irregularly shaped clusters of cells to serve as the MPA or network of reserves [40,39,2,35,15,19]. While the present suite of decision support tools is especially effective at identifying networks of MPAs, existing tools do not provide a good fit for solving every MPA design or subzoning problem. Among these problems are defining MPAs with simple boundaries to ease compliance and enforcement, encompassing areas with adjacent bottom types necessary for organisms to complete ontogenetic or daily habitat shifts, restricting options to those with a large core area to reduce edge effects, selecting single areas in need of subzoning rather than for network design, and comparing a discrete range of option sizes and shapes that fit into a limited space as is often the case in MPA subzoning. These issues challenge reserve planners to not only improve interpretation of existing procedures but also to develop additional techniques that simplify the science behind MPA design and provide coastal managers with a greater variety of decision support tools to meet their diverse MPA design and subzoning situations.

A novel approach in MPA design, defining potential sizes and shapes of reserve boundaries as a first step in the design process, can be appropriate before any aspects of physical location are considered. For example, home range size of target organisms is increasingly known from tagging, telemetry, and marine landscape ecology studies thereby enabling informed selection of reserve size and necessary core area (e.g. [14]). The same data may indicate that a combination of habitats must be included adjacent to each other to accommodate daily or ontogenetic migrations. In such cases, analysis should focus only on reserves with size, shape, and orientation suitable for capturing a contiguous series or cross-section of these habitats; merely including some of all bottom types in a discontinuous reserve network is insufficient. In other situations, the potential space for the reserve may be small, as occurs in MPA subzoning, thereby limiting the range of shapes and sizes that represent viable boundary options. Early constraints on size and shape in such tight situations can be used to restrict options to only those that best fit the space and are feasible relative to enforcement and compliance. Discontinuous scatterings of cells that merely accomplish habitat area goals or other conservation targets, as can result from many present design approaches, are not optimal in these situations.

Early definition of shape and size options warrants consideration for additional reasons. Stakeholders participating in the MPA design process can be provided with an up-front understanding of what the boundaries of a potential reserve may look like. Ultimately, such boundary shapes and sizes are the ones to be dealt

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with, not some smoothing of edges or additional process of connecting separate clusters of cells as must be done with most cell based techniques. This informs the expectations of stakeholders very early in participatory design processes, something deemed critical to the success and acceptance of MPAs [10,38,5]. In addition, most existing MPA design tools are cell or parcel based partly because their lineage has roots in terrestrial reserve design where individual parcels of land comprising an eventual reserve have to be individually acquired. This is not the case for MPAs wherein a large window of simple configuration may often "simply" be rezoned in the marine realm where state or federal governments have ownership of the seafloor.

Another useful, but often unfeasible, feature of good MPA design tools is the ability to conduct real-time analysis of alternative boundary scenarios at stakeholder or public meetings [32]. Quickly answering questions through real-time evaluation of the overlap among often conflicting socioeconomic and conservation concerns is informative to stakeholders involved in participatory design processes. The ability to rapidly examine the results of alternative design scenarios can more quickly advance a group toward consensus relative to days or months between suggestions at meetings and subsequent analysis, discussion, and acceptance of results.

To meet these diverse concerns, we developed a new technique in MPA design and subzoning that can be added to the existing suite of tools available to coastal managers. The approach developed in the following case study compared fixed reserve shapes comprehensively floated throughout a region of interest using a sliding window to optimally place a reserve. Acceptable candidate sites were identified through a step-wise process wherein reserve options were sequentially reduced to those having both the proper biophysical characteristics and the least user displacement.

1.1. Case study

A research area (RA) is under consideration as a subzone within Gray's Reef National Marine Sanctuary (GRNMS), an MPA located centrally in the South Atlantic Bight, USA. Located 32 km off the coast of Georgia at a relatively uniform depth of $\sim$20 m, the rectangular sanctuary is 6.5 km $\times$ 9 km and is composed of 8% flat sand, 67% rippled sand, 25% sparsely colonized live bottom, and <1.0% densely colonized live bottom (hereafter referred to as 'ledge') [12]. Bottom types, prior research sites, and fishing activities all have an irregular distribution in the sanctuary (Fig. 1). The sanctuary is a popular recreational fishing destination.

An RA is a specialized type of MPA designed and created specifically to support scientific research [23,9,24] but that has received little consideration in coastal management and MPA design literature. RAs provide space in which to conduct controlled manipulative or observational studies and observe natural ecosystems and their variability in the absence of confounding factors [7,27]. This enables discrimination between natural and human induced change and to quantify how natural systems respond to stressors (e.g. anchoring, trap fishing, hook and line, or spear fishing). As a result, RAs typically prohibit extractive or destructive activities that may interfere with those studies [22]. Only fishing conducted under scientific permit for research purposes, such as quantifying catch-per-unit-effort or impacts to fish communities, would be allowed. As with other MPAs that limit use, RA placement must be sensitive to displacing current user groups. In addition, because long term monitoring and research are primary objectives, sites with a large preexisting body of research are particularly desirable.

There are several reasons for GRNMS to subzone an RA. Designation documents for the sanctuary require research on live bottom ecosystems [25]. Public comments during the 1999/2000 management plan review for GRNMS requested that an RA be considered. At present there are no continental shelf habitats designated specifically for research anywhere in the South Atlantic Bight [26]. Major gaps exist in the understanding of human influences, such as fishing, on natural resources in this region [21]. Because GRNMS encompasses bottom types and fish community's representative of the South Atlantic Bight [13] and is already subject to specialized management, it represents an ideal setting and opportunity for an RA subzone.

A consensus-driven, constituent-based working group, similar to those created in other recent MPA zoning processes [10,38,5], was created to explore the potential for implementing an RA. The working group consisted of representatives from science, conservation, recreational and commercial fishing, management, law enforcement, education, and recreational diving. After first recognizing the need for an RA at GRNMS, the working group identified the general criteria that should guide its placement. Due to the relatively small size of the sanctuary, the working group recommended considering placement of a single RA large enough to accommodate many sites that would serve as experimental and monitoring replicates. Given that primary research questions focused on the influence of bottom fishing on benthic resources, it was determined that, above all else, the RA should include a large number and diversity of ledge habitats. These ledge habitat areas are also the favored target of bottom fishermen and the bottom type associated with the highest abundance of bottom fish and invertebrates [13]. The working group secondarily indicated the need to include other bottom types to achieve full representation of seafloor types in the region and to encompass ecological linkages between ledges and their surrounding habitats [36,8]. The working group was also interested in including a large amount of prior research within the RA because a diversity of research has been conducted within GRNMS for many years and would serve as a valuable reference for future investigations. Lastly, because bottom fishing would be restricted such that only scientific investigations would be permitted within the RA, the working group wanted to place it in a location that would minimize the displacement of recreational fishermen.

Following the identification of the general site-selection criteria, the working group next selected a range of potential options for the size and shape of the RA *a priori* based on ease of enforcement, statistical considerations (e.g. number of ledges to include as experimental replicates), known ecology and home range size of study organisms, and scientific usefulness. Although a small RA would ease enforcement and acceptance, larger options would best meet statistical and scientific considerations. A larger RA would likely include more replicate ledges for study and be more likely to include the daily home range of a greater diversity of bottom fish of interest to researchers [37,29,16,1,14,18,3,13]. However, a sufficient group of control or comparison ledges outside the RA, but still within GRNMS, may not be available if the RA is too large. Furthermore, restricting fishing throughout much of the sanctuary as a result of a large RA would also not be acceptable to the public.

Apart from these broad guidelines, quantitative criteria for defining characteristics of an acceptable RA, such as some minimum number or area of ledges to include, were not provided. As is the situation confronting most coastal managers, this was due to a lack of understanding about the spatial distribution of bottom features, prior research, and preferred fishing locations and how these variables might overlay with the various RA size and shape options under consideration. A procedure to inform these issues was needed that would enable the overlap of these data with respect to potential RA boundaries to be explored by the working group in real time.

Ultimately the working group sought to identify placement options for the RA that could be put forward for official

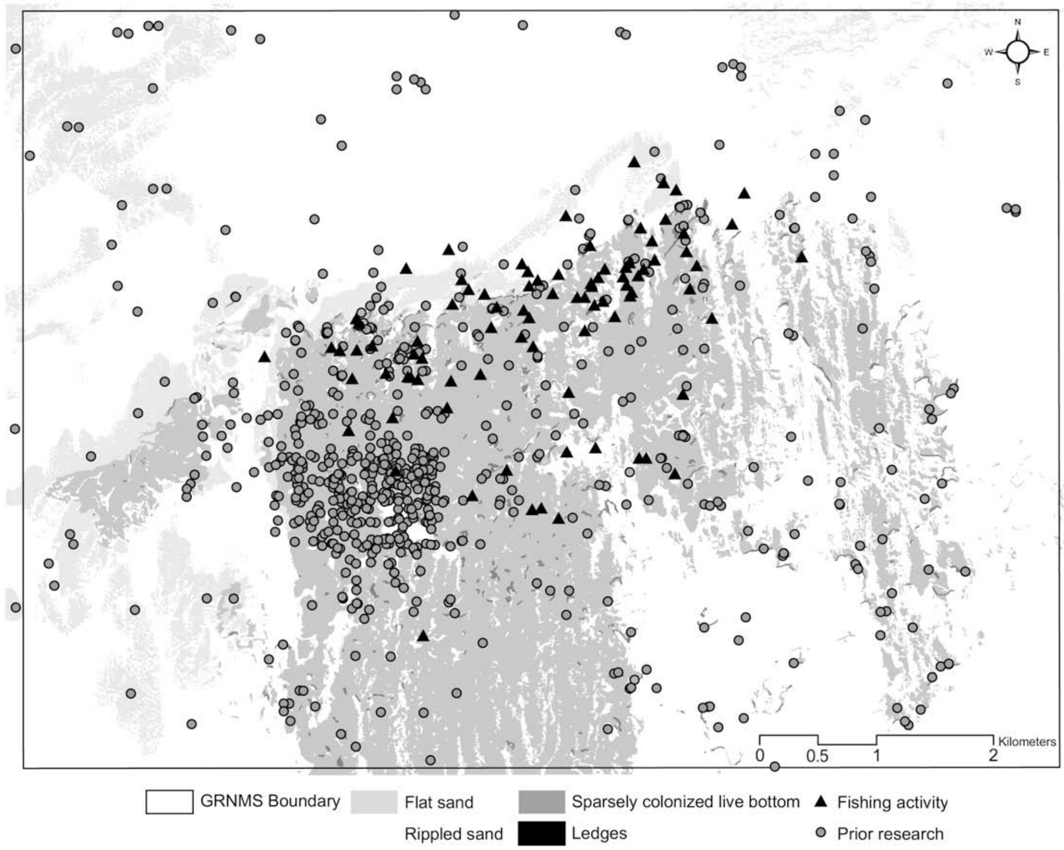

Fig. 1. GRNMS and the spatial distribution of variables within it that were used in the analysis.

consideration through the National Environmental Policy Act [20]. Specifically, three scenarios were of interest. First, a preferred scientific option was to be identified. This scenario would be driven solely by scientific needs such as inclusion of representative habitats. Second, an option that minimized displacement of fishermen but still met some reduced set of scientific needs was to be identified. Last, the group sought to identify a third option that was a compromise between the first two.

The goals of this analysis were to: (1) systematically analyze a range of potential RA sizes and shapes throughout GRNMS, quantify the bottom types included, prior research, and fishing pressure within and outside of each option, (2) enable an informed and iterative approach by which the working group could select acceptable quantitative criteria for an RA, (3) enable interactive evaluation of alternative RA's in real time for use in working group or public meetings, (4) use the criteria defined by the working group to identify acceptable sites for a potential RA, (5) quantify and compare the characteristics among the three scenario's described above, and (6) document the approach to reserve selection or subzoning and further diversify the range of decision support tools available to coastal managers.

2. Methods

A Geographic Information System (GIS) was developed to systematically analyze the space within the entire sanctuary and determine suitable placement options of an RA according to the general characteristics and boundary configurations requested by the working group. All relevant bottom data, locations of prior research, and information that could be used to identify preferred fishing locations were incorporated. A novel "sliding window" approach was developed in which each potential boundary configuration (e.g. 4×4 km square) was systematically floated throughout the sanctuary. The boundary or window was regularly paused so that its intersection with variables of interest for siting the RA could be quantified (conceptualized in Fig. 2). An elimination process based on criteria identified by the working group was then used to identify an acceptable set of candidate sites.

2.1. Input data

A group of 25 variables from 11 data sets was identified that represented the general criteria provided by the working group (Table 1). These included four broad categories of variables that spatially depicted (1) the amount and diversity of ledge habitat, (2) all other bottom types, (3) prior research sites, and (4) bottom fishing activities.

Ledge features in recent benthic maps of the sanctuary [12] were labeled in equally sized groups as short, medium, and tall in height as well as small, medium, and large in area to reflect the diversity of ledge types. Mapped features representing the three other bottom types present in the sanctuary (sparsely colonized live bottom, flat sand, and rippled sand) were also included. The locations of prior research were compiled as a point file and plotted. Two types of information were used to represent spatial distribution of users: boat count data [11] and a survey of marine debris items that were directly associated with fishing [4]. Locations with larger amounts of boats and fishing gear were assumed to receive higher fishing pressure and be preferred fishing sites.

2.2. Boundary shapes and orientations

The variety of size, shape, and orientation options for the RA boundary was developed by the working group and limited to 18

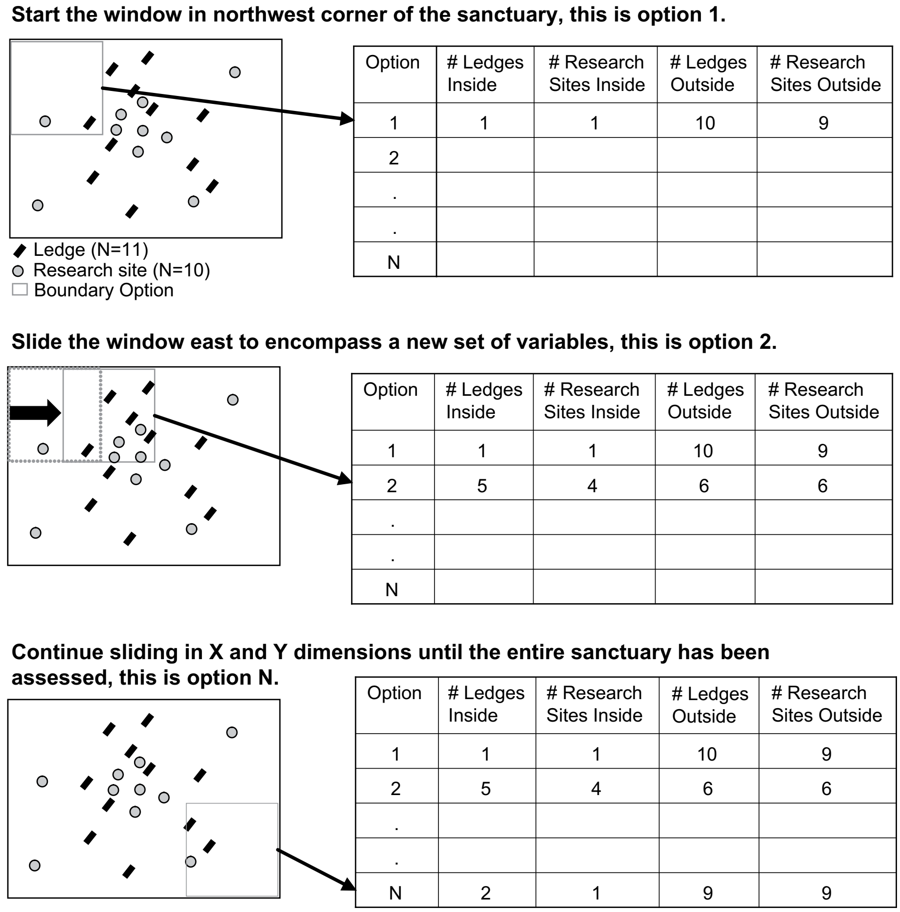

Fig. 2. Conceptual diagram of the sliding window approach.

configurations (Table 2). Sizes included 4 km^2, 6 km^2, 9 km^2, and 16 km^2. Larger and smaller size options were considered but rejected as either too large and therefore unacceptable to fishing interests or too small to encompass the daily home range of many fish species to be studied, respectively [37,29,16,1,14,18,3,13]. Shapes included squares, rectangles, and hexagons. Squares and rectangles were considered good shapes because they are simple to mark with 4 corner buoys and may be easiest for both enforcement and compliance. Hexagons were considered because they nearly approximate a circle, which maximizes core area and minimizes edge effects, but can be marked with only 6 buoys. Other shape options were considered but dismissed by the working group as lacking adequate core area or as too problematic for marking, enforcement, and/or compliance. Orientations for square and rectangular options included those with edges parallel to latitude/longitude, rotated 45°, and rotated 30° counter clockwise. The rotated shapes were considered since those axes align with local ledge geomorphology and therefore may have more efficiently encompassed the target bottom features. These 18 boundary configurations served as the “windows” in the sliding window approach.

2.3. Extracting data from each RA option

A “sliding window” method was used to systematically analyze the entire space within the sanctuary. In this approach, a given boundary configuration or window was first positioned entirely within the northwest corner of the sanctuary (Fig. 2). The 25 variables of interest (Table 1) that were encompassed within the window were summarized and retained as the first row of an RA options table. This entry represented the first potential location for the RA. The analysis window was then “slid” a short distance to the east and each of the variables within the new position was recorded as the second row in the options table. The window was slid the same short distance repeatedly and throughout the entire sanctuary in the *X* and *Y* dimensions. The values of selection variables were recorded as new RA location options each time the window paused at a new position. Each boundary shape and size went through the same sliding window process and had values added to the RA options table.

An appropriate distance to slide the analysis window between consecutive boundary options was determined based on the spatial properties of ledges, the most important variable according to the working group. To define an appropriate distance, the assumption was used that successive options should each include an entire new ledge rather than merely a small fraction of one. This is appropriate given that whole, individual ledges would likely serve as experimental units in the RA. Ledge sizes and the separation between them indicated that sliding the analysis window ~100 m between consecutive window stops would be sufficient to capture whole new ledges rather than fragments, but would not skip past multiple ledges. Sliding each of the 18 boundary shapes 100 m at a time throughout the entire sanctuary resulted in a comprehensive set of potential RA placement options.

Maintaining adequate areas outside the RA was also a consideration. Therefore, for each of the 25 variables of interest, the number or area of features falling outside each successive boundary option was also stored in the options table (Fig. 2). This resulted in a total of 50 variables described for each option, 25 that described the ledge, other bottom types, prior research, and fishing effort

Table 1
List of variables, categories, and sources for each data set.

Category	Variable	Source
Ledges (12 variables)	Number of short ledges	Modified [12]
	Total area of short ledges	Modified [12]
	Number of medium height ledges	Modified [12]
	Total area of medium height ledges	Modified [12]
	Number of tall ledges	Modified [12]
	Total area of tall ledges	Modified [12]
	Number of small ledges	Modified [12]
	Total area of small ledges	Modified [12]
	Number of medium size ledges	Modified [12]
	Total area of medium size ledges	Modified [12]
	Number of large ledges	Modified [12]
	Total area of large ledges	Modified [12]
Other bottom types (3 variables)	Total area sparse live bottom	[12]
	Total area of flat sand	[12]
	Total area of rippled sand	[12]
Research (8 variables)	Total bottom time of roving surveys	REEF[a]
	Number of point surveys	REEF[a]
	Number of tagging sites	MARMAP[b]
	Number of trap sites	MARMAP[b]
	Number of sediment/ contaminant sites	NOAA/CCEHBR[c]
	Number of Long Term Research sites	NOAA/GRNMS[d]
	Number of transect surveys	NOAA/Biogeography Team[e]
	Number of benthic/debris surveys	NOAA/Biogeography Team[e]
Fishing (2 variables)	Number of stationary boats	Various sources
	Total gear pieces ÷ number of surveys	NOAA/Biogeography Team[e]

[a] Reef Environmental Education Foundation: www.reef.org.
[b] Marine Resources Monitoring, Assessment, and Prediction: www.dnr.sc.gov.
[c] National Oceanic and Atmospheric Administration, Center for Coastal Environmental Health and Biomolecular Research: www.chbr.noaa.gov.
[d] National Oceanic and Atmospheric Administration, Gray's Reef National Marine Sanctuary: www.graysreef.nos.noaa.gov.
[e] ccma.nos.noaa.gov/about/biogeography.

inside each option, and 25 variables that described the same components only in the space *outside* each option. This table provided the quantitative basis for comparing all of the potential placement options.

2.4. Comparing options

Ideally, identification of suitable RAs from all of the possibilities in the options table could have proceeded at this point with the use of simple cut-off values for each of the variables. For example, all options with fewer than x ledges or that displaced more than y fishermen may be unacceptable and could be eliminated. The result would be a set of suitable boundary alternatives from which to choose. This would have been the preferred method by which to proceed and may be possible in other MPA/sub-zoning design situations; however, the working group at GRNMS could not identify specific acceptable cut-off values for the variables in the analysis. How the various boundary configurations overlaid with the variables of interest and the RA characteristics that they represented were totally unknown at the outset. Instead, a more informative approach for quantifying and comparing RA options was needed to first inform the group about the range of possible characteristics associated with the various boundary shapes and sizes under consideration.

Traditional statistical techniques to identify or compare different groups of options could not be used because they typically rely on independence of samples (i.e. boundary options). Sliding the analysis window a small fraction of the total window size in this approach (e.g. 100 m for a 3×3 km boundary) allowed a thorough dissection of placement options within the sanctuary but caused successive options to be autocorrelated. This resulted in a gradient of options rather than individual choices with clearly separated characteristics. A simpler scoring procedure was therefore devised to categorize options, convert the diversity of variables to a common scale to enable relative comparisons, and inform the working group on how variables were distributed relative to the various boundary configurations.

2.5. Scoring data from each RA option

First, the minimum and maximum values of each of the 50 variables in the options table were identified. Within this range of values, five categories were created along equal intervals (a different number of divisions could have been used) and each RA option was assigned a score from 1 to 5 for each variable. For example, an option that encompassed few tall ledges relative to the others would receive a score of 1 indicating a poor option whereas an option with many tall ledges would receive a score of 5. This process standardized the huge diversity of raw values for each variable into a common scale and enabled easy comparisons among variables. The fishing effort category was the only variable category considered a bit differently. Having a large number of fishing occurrences outside, rather than inside, a given boundary option was better according to the siting criteria. Therefore, a score of 1 inside the boundary indicated the best sites due to fewer boats and less occurrence of fishing related debris, whereas a score of 5 indicated the worst options as potentially favored fishing areas.

To condense the 25 input variables, the 0–5 values within each of the 4 variable categories (Table 1) representing the siting criteria were averaged into a single number. Hereafter, this was called a "category score" since this single number represented one of the variable categories that matched a particular siting criterion specified by the working group.

2.6. Process for identifying viable placement options

In October 2007, the working group reconvened to use the GIS tool and the options table to identify a set of boundary alternatives

Table 2
Potential boundary shapes and the corresponding number of placement options within the sanctuary.

Shape	Size (km)	Number of RA options
Square – sides parallel to lat/long	2×2	3060
	3×3	2030
	4×4	1200
Square – rotated 30° (counter clockwise)	2×2	2257
	3×3	1149
	4×4	340
Square – rotated 45°	2×2	2160
	3×3	1012
	4×4	256
Rectangle – sides parallel to lat/long	2×3	2380
	3×2	2610
Rectangle – rotated 30°	2×3	1624
	3×2	1666
Rectangle – rotated 45°	2×3	1537
	3×2	1537
Hexagon	4 km^2	2680
	6 km^2	2108
	9 km^2	1529

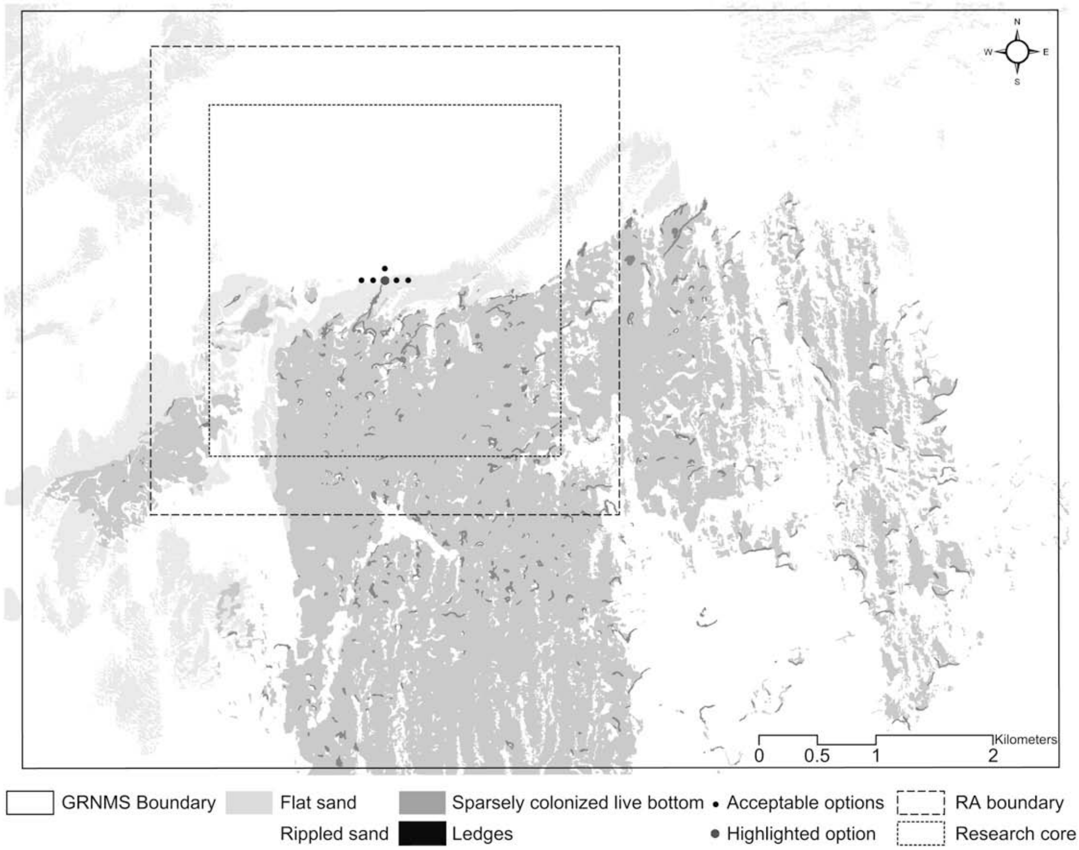

Fig. 3. Centroids of the six RA placement options under scenario 1. The boundary and core of one of the options are shown.

according to the three selection scenarios. The category scores and the individual variable values in the options table were the basis of the elimination process to reduce the options table to a set of suitable RA options in each scenario. An iterative process examined the diverse tradeoffs among siting criteria based on boundary shape, size, and rotation. A wide diversity of category score combinations was evaluated to gain an understanding of the resources and user activities that intersected with the various boundary configurations. This was done by iteratively adjusting the category scores and determining the number of options remaining given various levels of selectivity. Then the actual values behind the category scores (e.g. number of short, medium, or tall ledges) were examined to see what each option actually represented on the ground. Depending on the level of selectivity in choosing acceptable category scores or raw values for each variable, it was possible to have many options left – or none at all – once all variables had been considered to represent a given combination of selections. Criteria can be applied in any order without affecting the results.

Through this approach an understanding of the tradeoffs among variables, boundary configurations, and locations was achieved. Following this preliminary exploration of the data, the working group decided upon a combination of category scores and specific variable values to come up with the three planning scenarios. The working group picked minimum threshold values for some raw variables such as ledges. For others such as fishing use, reliance on the category scores during site selection was preferred.

It was determined by the working group that a minimum of 20% or $n = 30$ of each ledge type (short, medium, and tall) would be needed to accomplish RA experimental and monitoring goals. Ledge height is the primary influence on sessile benthos and fish community structure [13]. This would leave 80% of the ledges of each type available for fishing and scientific controls outside the RA.

In addition, only un-rotated squares were considered further. Boundary rotation improved alignment with ledges in some areas but the effect was not considered large enough to outweigh the complications in marking, enforcement, and ease of compliance relative to boundaries aligned with latitude and longitude. Shapes besides squares were also eliminated. Hexagonal boundaries were dismissed as too complicated for marking or enforcement and rectangular boundaries were dismissed as having too high of an edge effect.

The working group also determined that a buffer would be needed around the research area to insulate it from the effects of fishing along its edges. The necessary minimum width of the buffer was determined to be 0.5 km based on present knowledge of the home range size of many of the benthic fish species to be studied [37,29,16,1,14,18,3,13]. For example, a 4×4 km research area would be composed of a 3×3 km core area in which the research would be focused, plus a surrounding buffer of 0.5 km (Fig. 3). Fishing displacement would apply throughout the entire area but habitat requirements would apply only to the core area to be used for research. This aspect of the analysis was facilitated by the fact that 4×4 km squares in the sliding window analysis shared a common centroid with 3×3 km squares nested within them. Different criteria could be applied to the core area (e.g. some minimum number of ledges) versus the entire RA (e.g. some maximum number of fishermen displaced).

Last, it was determined that prior research was not to be a guiding factor since the data exploration process indicated that a diversity of prior research sites would be included practically no matter where the RA was placed. In addition, no specification for some minimum number of ledges or area of other bottom types outside the RA was made since preliminary analysis revealed that the 20% ledge goal ensured that a large majority percentage of the ledges would lie outside the RA.

Table 3
Summary of key RA characteristics from each of the three planning scenarios. Values are the mean (range) of all acceptable options under each of the scenarios.

Variable	Scenario 1, $n=6$	Scenario 2, $n=19$	Scenario 3, $n=22$
Ledge short inside	36 (34–38)	38 (30–51)	73 (66–74)
Ledge med inside	31 (30–33)	39 (33–44)	39 (32–46)
Ledge tall inside	36 (34–37)	33 (30–37)	34 (31–38)
Ledge small inside	33 (31–34)	41 (34–52)	69 (63–73)
Ledge med inside	37 (35–38)	39 (34–42)	45 (38–50)
Ledge large inside	33 (32–35)	31 (28–34)	32 (29–35)
Flat live bottom inside	31% (29–33%)	85% (78–88%)	45% (39–52%)
Flat sand inside	10% (9–10%)	0.04% (0–0.1%)	16% (13–17%)
Rippled sand inside	58% (57–60%)	13% (11–20%)	39% (33–46%)
Boat sightings inside	68% (62–78%)	16% (13–20%)	36% (33–39%)
Flat live bottom outside	23% (22–23%)	15% (15–16%)	19% (16–21%)
Flat sand outside	7% (7–7%)	9% (9–9%)	5% (5–6%)
Rippled sand outside	70% (69–70%)	75% (74–76%)	75% (73–78%)
Boat sightings outside	32% (22–38%)	84% (80–87%)	64% (61–67%)

2.7. Selection scenarios

The resulting RA positions and key characteristics were provided for each the three scenarios: preferred scientific, minimal fishing displacement, and compromise.

2.7.1. Scenario 1: preferred scientific

Selection criteria for this planning scenario were based solely on research needs. For this scenario, the full size of the RA was selected to be 4×4 km (16 km^2) including the 0.5 km buffer and 3×3 km core area (9 km^2) to be used for research. First, all options were eliminated except for 3×3 km, non-rotated squares (research core of the 4×4 km RA). Next, remaining options were reduced to only those with bottom types represented in proportions similar to those of the entire sanctuary. To determine this, the areas of each bottom type needed to meet this goal within a 3×3 km (9 km^2) area were calculated. For example, since 25% of the entire sanctuary is sparse live bottom, 25% of the 9 km^2 RA (2.25 km^2) would need to be this bottom type. Being so specific in target area values resulted in very few options. Therefore, to allow some flexibility, but still achieve a high level of proportional representation, the target area values for each bottom type were multiplied by 85% (0.85). These resulting area values were used as acceptable minima to identify viable RA options. Remaining options were then further reduced to only those with the minimum of 30 of each ledge type: short, medium, and tall. Last, the 0.5 km buffer surrounding the acceptable options according to these criteria was added in by identifying the 4×4 km options that shared centroids with the remaining 3×3 km options.

2.7.2. Scenario 2: minimal fishing displacement

Selection criteria for this scenario were based on identifying areas that would have the least impact or displacement of fishermen while meeting the absolute minimal scientific requirements in ledge inclusion. For this scenario, the full size of the RA was selected to be 3×3 km (9 km^2) including the buffer and 2×2 km core area (4 km^2) to be used for research. First, all options were eliminated except for 3×3 km, non-rotated squares. Next, remaining options were reduced to only those with category scores ≤ 1 for fishing inside the RA. This step identified the 20% of the options with the fewest boats and lowest density of fishing related marine debris. Remaining options were further reduced to only those that had a minimum of 30 of each ledge type (short, medium, and tall) within their 2×2 km core area. No restrictions on habitat proportion were specified in this scenario.

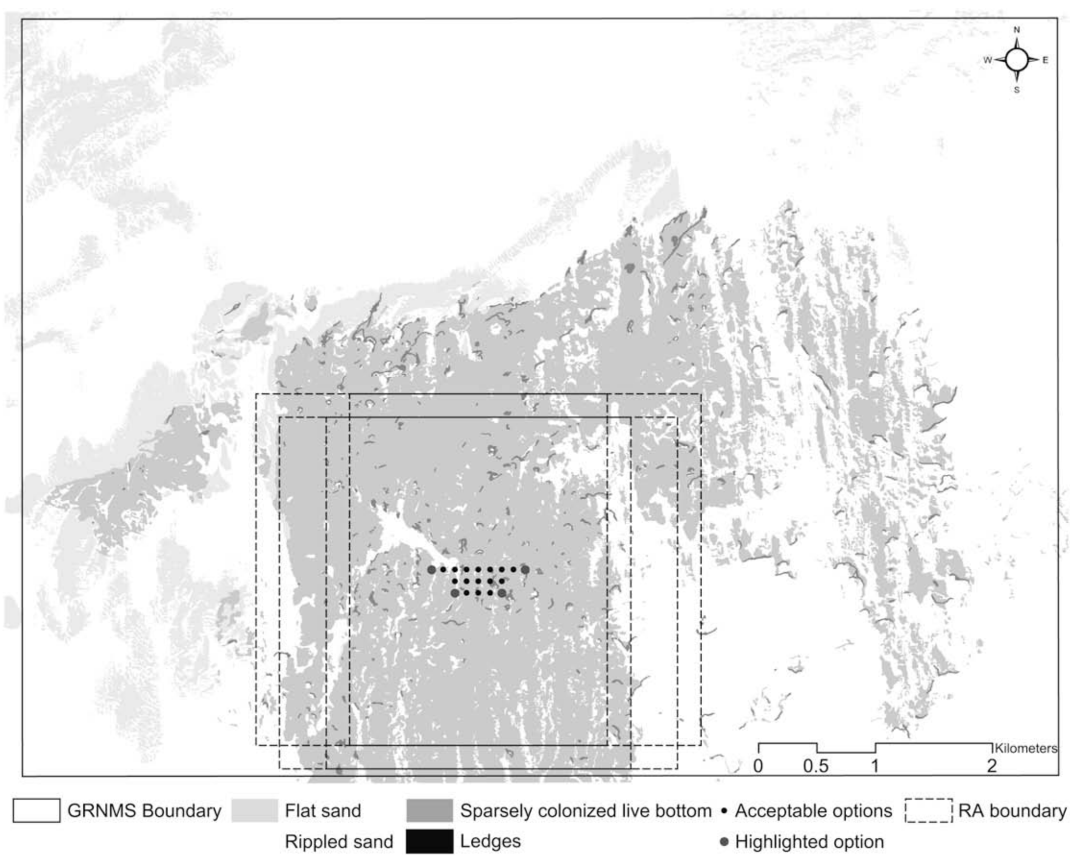

Fig. 4. Centroids and a subset of boundaries for the 19 placement options for the RA under scenario 2.

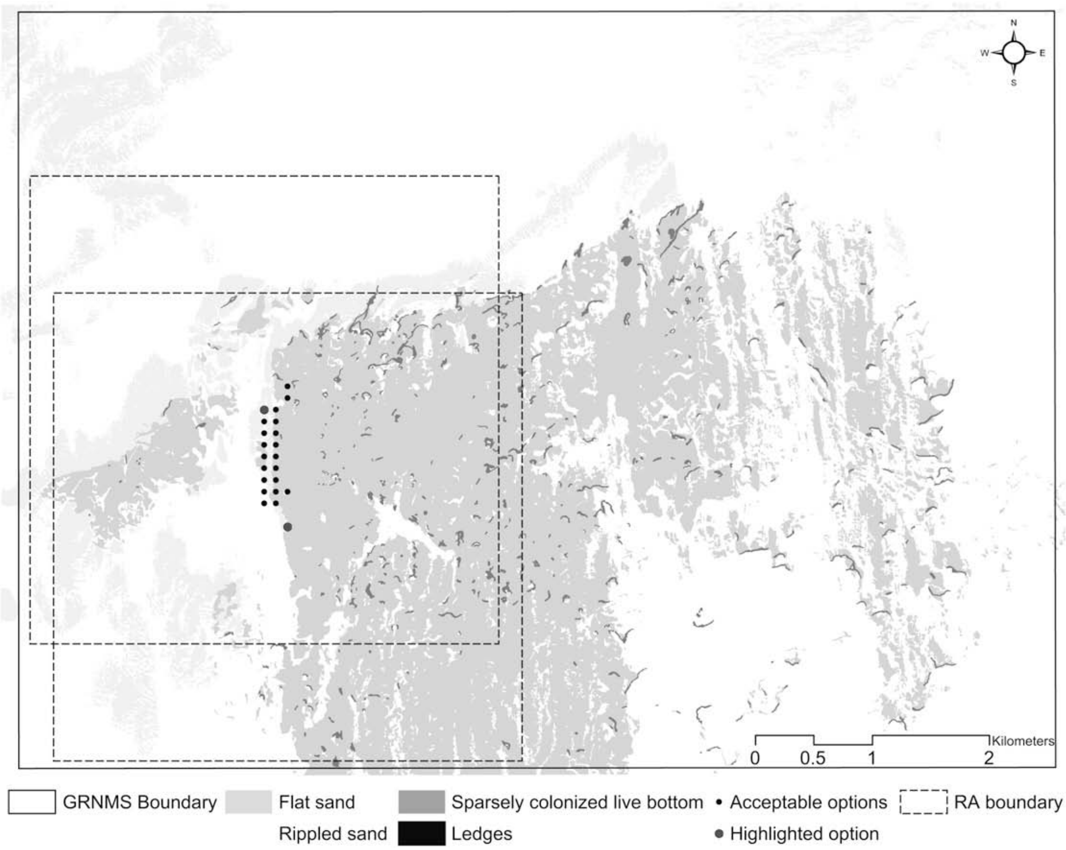

Fig. 5. Centroids and a subset of boundaries for the 22 placement options for the RA under scenario 3.

2.7.3. Scenario 3: compromise

Selection criteria for this scenario were based on moderate values for both fishing displacement and scientific needs. The full size of the RA was selected to be 4×4 km including the buffer and 3×3 km core area (9 km^2). First, all options were eliminated except for 3×3 km, non-rotated squares. Next, remaining options were reduced to only those with a minimum of 30 of each ledge type. Remaining options were then reduced to only those with bottom types represented in proportions similar to those of the entire sanctuary. This was determined using the same process as in scenario 1 only the minimum area values for each bottom type were multiplied by a much less restrictive value of 50% (0.5) (scenario 1 required values to be within 85% of sanctuary-wide proportions). The 0.5 km buffer was then added around each of the remaining options so that their total area was 4×4 km as in scenario 1. Fishing displacement within these 4×4 km options was then minimized by selecting only those with category scores ≤ 2 for fishing inside the RA. This step identified the 40% of the options with the fewest boats and lowest density of fishing related marine debris (scenario 2 allowed only the lowest 20%).

The boundaries resulting from each of these three scenarios with respect to specific features important to fishermen were plotted and shown at a public meeting for comment in January 2008. This included the coordinates of 4 popular fishing ledges provided by a local fishing club and those of the NOAA Data Buoy (Station 41008), a popular site to catch baitfish.

3. Results

A total of 30,307 discrete RA placement options resulted from the sliding window analysis and were provided in the options table, each had the potential to become the boundaries of the RA. The three scenarios resulted in very different positions within the sanctuary for the RA. Many closely spaced and related options were found within each of the planning scenarios, respectively. A subset reflecting the widest diversity among the acceptable options from each scenario was highlighted and discussed. Key aspects of each scenario were summarized in tables that included the number of potential options available, the range of key variables such as ledge number and boat displacement for the acceptable options, and the actual variable values for the highlighted options. The values for all 50 variables in each option were made available to the working group, however, only a subset of key variables is given here for brevity (Table 3).

3.1. Scenario 1: preferred scientific

Six suitable options out of the 30,307 possible choices were found based on the criteria in this scenario. These were centered in the northeast quadrant of the sanctuary (Fig. 3). At least 79 of all ledge types were located outside of these 6 options and would be available for both fishing and comparative research. Similarly, large areas of all bottom types were located outside of these options. The 6 options encompassed large portions of preferred fishing area and were observed to overlap with 62–78% of the boat sightings in the sanctuary (Table 3).

Scenario 1 was preferred from a research and monitoring standpoint in that all bottom types and ledge varieties were adequately represented. However, because 2/3 of the primary fishing area, 2 of the 4 popular fishing ledges as well as the Data Buoy were encompassed within Scenario 1 boundaries, the scenario represented a considerable sacrifice for fishermen and was least acceptable to them.

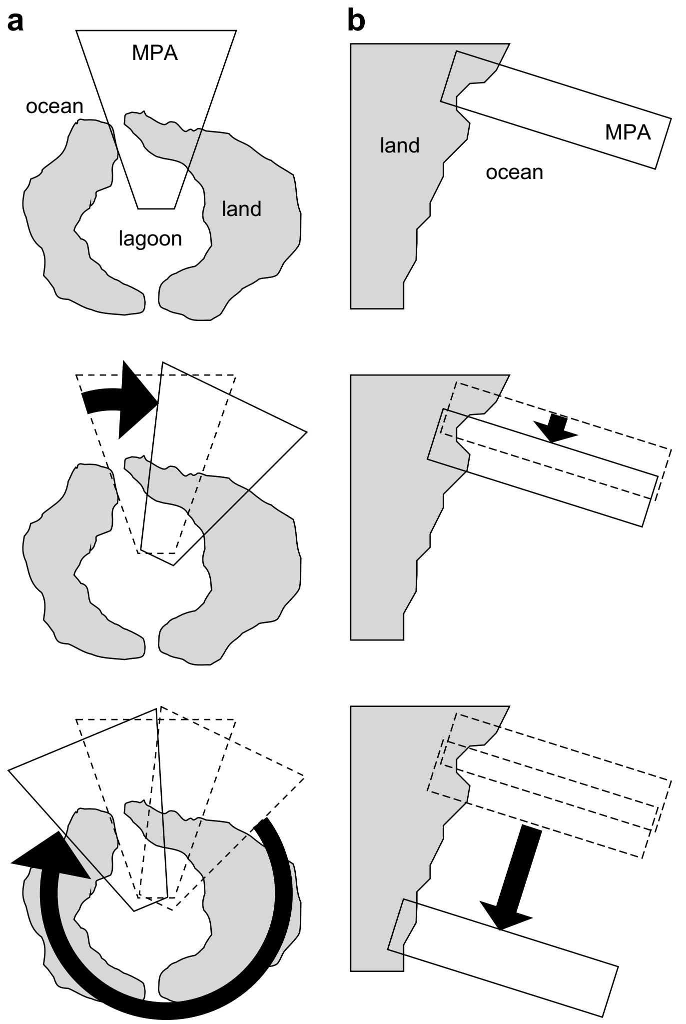

Fig. 6. Alternate orientations to apply the sliding window approach in an (a) island/atoll, or (b) coastal setting.

3.2. Scenario 2: minimal fishing displacement

A group of 19 acceptable options were obtained based on the criteria in this scenario. These were centered in the south-central region of the sanctuary (Fig. 4). At least 58 of all ledge types were located outside of these 19 options. Little or no flat sand (0–0.1% of the potential RA) or rippled sand (11–20%) was present in any options. Only 13–20% of the boats observed in the sanctuary occurred in within the boundaries of these 19 options (Table 3).

Scenario 2 options included adequate representation of ledges, although all options did not include every bottom type. In addition, scenario 2 options were smaller and therefore would not include the home range of as many fish species and would also be more susceptible to edge effects making them less useful scientifically. However, these options did not encompass large proportions of primary fishing area. Neither the Data Buoy nor any of the coordinates for specific fishing sites were encompassed by any of these options and therefore were more acceptable to fishermen.

3.3. Scenario 3: compromise

A group of 22 acceptable options were obtained based on the criteria in scenario 3. These were located along the western edge and southwest corner of the sanctuary (Fig. 5). At least 52 of all ledge types were located outside of these options. Ample areas of all bottom types were inside and outside of the boundaries as well. The boundaries encompassed 33–39% of boat sightings in the sanctuary (Table 3).

Scenario 3 was a compromise between the first two scenarios in that two of the criteria, minimizing fishing and approximating sanctuary-wide habitat proportions, were relaxed. Options that met criteria of scenario 3 had some of all bottom types, included sufficient numbers of ledges of all types, and avoided ~1/2 of the primary fishing area. Two of the 4 sets of fishing coordinates and the Data Buoy were shown to be outside of the options in this scenario.

4. Conclusions

The present study provides a new approach in the growing suite of options available to investigate not only RA placement and subzoning as was demonstrated here, but the approach can also be used for general MPA design. A diverse set of tools will aid coastal planners and managers confronted with similar problems but with local peculiarities that prohibit a "one size fits all" analytical solution [17]. While the present approach is not applicable in all situations, existing tools do not meet the diversity of needs of MPA designers and coastal managers. This novel approach to MPA design using a sliding window analysis enabled the exploration of the tradeoffs among boundary size, shape, and orientation and how these choices affected inclusion of target bottom types and favored fishing locations. At first glance, ledges and fishing effort appeared highly correlated spatially and finding a location with a large amount of ledges, but with lower use by fishermen, seemed improbable. This analysis enabled a process for coastal managers and stakeholders to identify the locations and degree to which acceptable compromises could be made in RA placement.

The sliding window approach provides an effective way to comprehensively evaluate alternative boundary scenarios within a region of interest. The process includes the following steps: (1) define the desired MPA or subzoning characteristics being as quantitative as possible including minimum acceptable cut-off values, (2) identify data or quantitative variables to represent the characteristics in step 1, (3) select possible boundary shapes and sizes that fit local geographical, logistical, and biological constraints, (4) define the sliding window direction(s), (5) determine the optimal distance to slide the analysis window between options, (6) tally the variables representing the selection criteria at each pause of the sliding window, (7) eliminate unacceptable boundary options that fall below the minimum acceptable values for each variable, and (8) present the resulting list of suitable options from which to select an MPA or subzone to stakeholders.

Once the sliding window analysis has been run, a comprehensive suite of boundary alternatives throughout an entire region of interest was easily queried for "real-time" presentation and discussion during MPA design workshops or during public comment meetings, an ability which has proven useful in previous MPA design processes [32,5]. This is in contrast to long pauses of hours or days between multiple meetings for new analyses to be run, results to be summarized, and a group reconvened to assess the findings.

The sliding window approach and early definition of possible boundary shapes and sizes are new, but the participatory process in which they were implemented is not. These scenarios will go forward into the National Environmental Policy Act [20] process where they will be subject to additional public comment and ultimately be considered through an Environmental Impact Statement, a process expected to last 12–24 months. Additional suggestions for RA boundaries could be provided and formally considered through this process. For example, in response to specific inquiries by stakeholders, bottom characteristics of the SE and SW quadrants of the sanctuary were examined but did not meet scientific requirements and were therefore dismissed.

A search of the Marine Managed Area Inventory Database [26] revealed 185 sites in the United States that at least partly identify research as a purpose of their site. Apart from the National Estuarine Research Reserve System (NERRS) and Tortugas Ecological Reserve (TER), little information on methods for site placement for RAs is available. While these two examples provide structured selection processes, they lack the objectivity, quantitative rigor, and comprehensive spatial analysis of borders enabled by the present study. The TER process analyzed five specific alternative boundaries for a research area within the Dry Tortugas National Park [23]. It was similar to the present study in that selection criteria included habitat, prior research, user displacement, and enforcement elements, however, the process was less systematic and quantitative in its investigation of variations in boundary configuration and tradeoffs among variables. The NERRS process also has similar selection criteria to those considered here, although their focus is on acquiring representative sites in a coastal network [24]. A relative value is assigned to sites based on both quantitative and subjective considerations. Yet, systematic analysis of alternative boundary configurations, as was demonstrated in the present case study, is absent in the NERRs process.

Most approaches to MPA design concentrate on networks of several reserves to meet conservation or management goals. While a single zone was the focus in the present study, the approach can be modified to include multiple areas to spread risk, achieve wider biogeographic representation, and achieve other goals associated with multiple and replicated protected areas [27]. In addition, to position the RA at GRNMS the potential boundary shapes were slid equally in the *X* and *Y* dimensions, but the general sliding window approach could be modified to examine reserve placement in an island or atoll setting or along a cross-section of coast/shelf habitats. For example, a pie shaped wedge could be systematically rotated around an island (Fig. 6a) or a cross-section of shelf could be systematically slid down a coastal region (Fig. 6b).

Selecting acceptable boundary configurations at the start of the MPA design process may in some cases be a better alternative than the grid or parcel agglomerating approaches that currently dominate the theoretical and applied literature. This may include situations where some minimum acceptable contiguous area such as home range size of a target organism is known, where certain combinations of habitat types must occur adjacent to each other such as those required for ontogenetic shifts, or where the space for placing the reserve is limited and constrains the shape and size of potential boundaries. The sliding window technique described here provides comprehensive analysis of all possible placement options within an area of interest, lacks complex equations, is easy to understand by stakeholders, and allows an up-front understanding of how large and what the boundaries of a potential reserve may ultimately look like.

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