Vol. 373: 11–23, 2008
doi: 10.3354/meps07727

MARINE ECOLOGY PROGRESS SERIES
Mar Ecol Prog Ser

Published December 23

Applying marine protected area design models in large estuarine systems

Amanda E. Neely[1,2], Roman N. Zajac[1,*]

[1]Department of Biology and Environmental Science, University of New Haven, 300 Boston Post Road, West Haven, Connecticut 06516, USA

[2]*Present address:* ESRI, 880 Blue Gentian Road, Suite 200 St. Paul, Minnesota 55121, USA

ABSTRACT: Several types of design models are currently being used to develop marine protected areas (MPAs) for conservation of coastal and pelagic ecosystems. However, few studies have applied these models in large estuaries which have unique characteristics that need to be considered in MPA design, including strong physical, chemical and biological gradients and significant human impacts. We explored how one design model, MARXAN, can be applied to estuarine systems by developing MPA design scenarios for Long Island Sound, an estuary in the northeastern USA. Using sedimentary texture as a proxy for habitats, we modeled and tested several scenarios where conservation goals differed with respect to location and spatial scale but included 10 to 20% representation of target habitats and spatially contiguous MPAs. When the entire estuary was modeled, potentially critical locations were not included in the solutions. Dividing the estuary into regions to account for spatial gradients proved a better approach. Final MPA solutions were tested for effectiveness by comparing benthic species richness and community composition inside and outside solutions. Solutions in the eastern region of Long Island Sound generally contained higher species richness, likely due to the inclusion of highly heterogeneous portions of the sea floor within most solutions, but community composition varied. In contrast, solutions in the western/central region of the estuary usually had lower species richness but similar community composition. We also made preliminary assessments of how human activities, including dredge disposal, resource extraction and sediment pollution, might affect MPA design in estuaries. Our results illustrate potential conflicts that may arise due to the geographic location of best MPA candidate areas in estuarine regions with environmental impacts and human activities. Several tradeoffs will likely affect MPA design and selection in large estuarine systems, and MPA design models may prove useful in focusing these efforts.

KEY WORDS: Conservation planning · Estuary · Long Island Sound · Macrobenthos · Marine protected areas · MPA · MARXAN · Sea floor landscape

INTRODUCTION

Marine protected areas (MPAs) are an increasingly important conservation and resource management tool in marine systems. They provide an ecosystem-based approach for addressing multiple, often difficult and competing ecological and social issues (Nicholls 1998, Agardy et al. 2003, Lubchenco et al. 2003). We define MPAs to include areas of the marine environment that have been spatially delineated and afforded some level of protection by varied regulatory and/or non-regulatory approaches. The main objectives of MPA establishment may include protection of ecological functions, preservation of biodiversity and habitats, instituting specific resource conservation goals and/or developing sustainable practices for use of natural marine resources. Such objectives will vary by region and spatial scale being considered. However, for any specific MPA or MPA network, the ultimate achievement of goals is affected by a set of common issues.

*Corresponding author. Email: rzajac@newhaven.edu

These issues include the process and ecological underpinnings of site selection, the actual establishment of the MPA, and its eventual management. Each of these issues includes both scientific and social components that are difficult to fully resolve. We focus on the process of MPA site selection, specifically the application of site selection models to large estuarine systems, with emphasis on sea floor habitats and macrobenthic communities.

Many marine conservation efforts to date have focused on designing MPAs in open coastal and oceanic systems. Except for the many reserves and sanctuaries that have a terrestrial coastal component (e.g. extensive salt marsh systems, islands, etc.), most MPAs are offshore on the continental shelf (see www.mpa.gov). There has been less emphasis on developing MPAs in large estuarine systems (Nicholls 1998, Edgar et al. 2000). Large estuaries such as San Francisco Bay, Chesapeake Bay and Long Island Sound in the US, can be challenging areas for MPA design. This is due to strong physical, chemical and ecological gradients characteristic of estuarine systems, coupled with high levels of human activity and associated impacts such as contamination, eutrophication, channel dredging and intense resource use and extraction. These gradients/characteristics generally change over smaller spatial scales in estuaries than in coastal/oceanic environments (Day et al. 1989, Cognetti & Maltagliati 2000). Additionally, estuaries often comprise different mixes of system modules such as a central embayment and peripheral tidal rivers, which can define structure and function (Tenore at al. 2006), and add to the overall complexity of designing MPAs. Conservation in estuarine areas with high human activity and distinct spatial trends in both habitats and species communities may require a different management approach that effectively addresses the specific characteristics of the system.

Despite the degradation and intensive development of estuarine systems, conservation of these areas has lagged behind terrestrial and marine conservation. This lag may be related to the extensive human activities in estuaries and perhaps the lower aesthetic appeal of estuaries compared to terrestrial and marine habitats (Edgar et al. 2000). Although challenging, estuarine conservation is an important component of overall marine protection because estuaries are among the most productive environments on earth and they play a critical role as nurseries for both estuarine and offshore organisms (Beck et al. 2001).

This study explores how MPA design could be implemented in large estuarine systems. We utilized a MPA siting algorithm based on simulated annealing (Kirkpatrick at al. 1983), as implemented in MARXAN software (Ball & Possingham 2000, Possingham et al. 2000, McDonnell et al. 2002). Simulated annealing determines a set of possible MPA configurations, or solutions, in a defined region so that specific conservation goals are met. Conservation goals can be based on specific target species, habitats and/or other biodiversity components. It can also be constrained by specific locations, desired spatial extent and configurations of the MPA or MPA network. Simulated annealing has been applied in a number of marine systems including the Gulf of Mexico (Beck & Odaya 2001), the Gulf of California (Sala et al. 2002), the Channel Islands off California (Airamé et al. 2003), British Columbia (Ardron et al. 2002), the Florida Keys (Leslie et al. 2003), Stellwagen Bank in the Gulf of Maine (Cook & Auster 2003) and the northeast continental shelf of North America (Cook & Auster 2005).

We assessed how the characteristics of a large estuarine system might govern the design and implementation of MPA models. MPA solutions were tested for their potential effectiveness by comparing resulting benthic species richness and community composition, and also by assessing potential conflicts with human activities using geographic information system (GIS)-based analyses. These results, coupled with those from other studies (e.g. as cited above), may help determine if different approaches are needed when designing MPAs in open ocean waters versus in large estuaries.

MATERIALS AND METHODS

Study area. Long Island Sound (LIS) is a large estuary (3418.7 km^2) located along the Atlantic coast of the US (Fig. 1). Its average depth is ~20 m, and salinity ranges from 23 psu in the western end to 35 psu at the eastern end. The benthic landscape (or benthoscape) is highly complex (Fig. 2), with bottom types ranging from silty muds to gravel/rock/outcrop hard bottoms, reflecting the spatially heterogeneous hydrodynamic regimes and sedimentary processes shaping these environments (Knebel & Poppe 2000, Poppe et al. 2000). Macrobenthic communities in LIS are related to this benthoscape structure at different spatial scales, with significant variation in the types of communities found in each sedimentary environment (Zajac et al. 2000, Zajac 2001). The western portion of LIS is highly urbanized. Smaller urban centers occur along the Connecticut coast and most of the remaining coastline is well developed. Over 20 million people live within 80 km of its shores, resulting in extensive impacts including eutrophication and low oxygen during portions of the year (e.g. Welsh & Eller 1991), sediment contamination (e.g. Mecray & Buchholtz ten Brink 2000) and toxicological effects on biota (Perry et al. 1991). LIS is also an important commercial waterway, with significant commercial fisheries primarily for lobsters, oysters and hard clams, but also recreational fisheries that are economically valued at >300M USD yr^{-1}.

General approach. We used sea floor sediment texture as a proxy for habitat type in developing MPAs. Sediment texture is a composite variable that describes sea floor habitats based on sediment grain-size mixtures (Poppe et al. 2000). It is well known that the distribution of many benthic invertebrates (e.g. Zajac et al. 2000) and demersal fish is related to sea floor characteristics (Auster et al. 2001), and many ecosystem functions differ with sediment type (Levin et al. 2001). Conservation goals are often centered on habitat types (Ward et al. 1999, Leslie et al. 2003) rather than specific species, as the spatial distribution of target species or communities are often unknown and unavailable as input for models. Thus, sediment texture may be a good proxy for habitats and species assemblages in sedimentary environments. The purpose of using sediment texture as a proxy in the modeling process was not to gain additional insights into relationships among benthic assemblages and sea floor characteristics in LIS, but rather to explore how our current knowledge of these can be used in the MPA selection process.

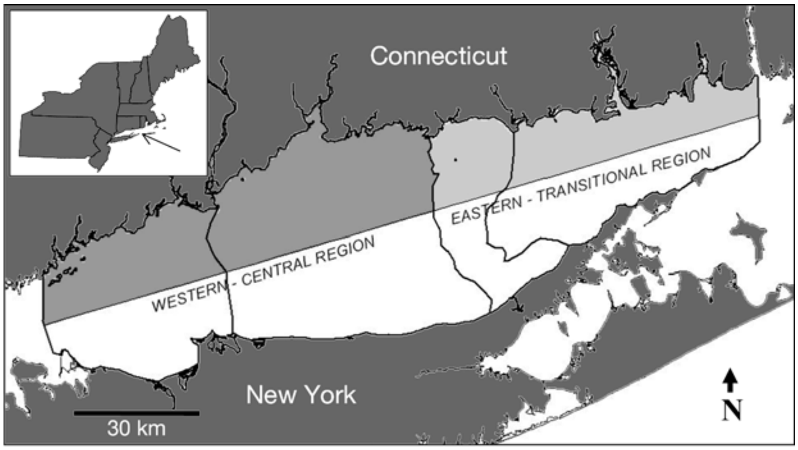


Fig. 1. Long Island Sound estuary showing subdivisions used in the MARXAN analyses. The estuary is located east of New York City and south of the state of Connecticut. Inset shows regional setting in the northeast United States with arrow pointing to Long Island Sound. The middle of the Sound is at ~72° 50′ W and 42° 10′ N. The shaded portions are Connecticut waters for which the MPA model runs and tests presented in this paper were conducted

We used MARXAN MPA modeling software (see: www.ecology.uq.edu.au/marxan.htm) and GIS to develop a series of MPA solutions with varying amounts of representation of different sediment texture types and varying numbers of sites. LIS was divided into 2 broad regions to account for large-scale spatial differences in sedimentary texture (Figs. 1 & 2). Our modeling considered both the different regions separately and the entire LIS. Different regional

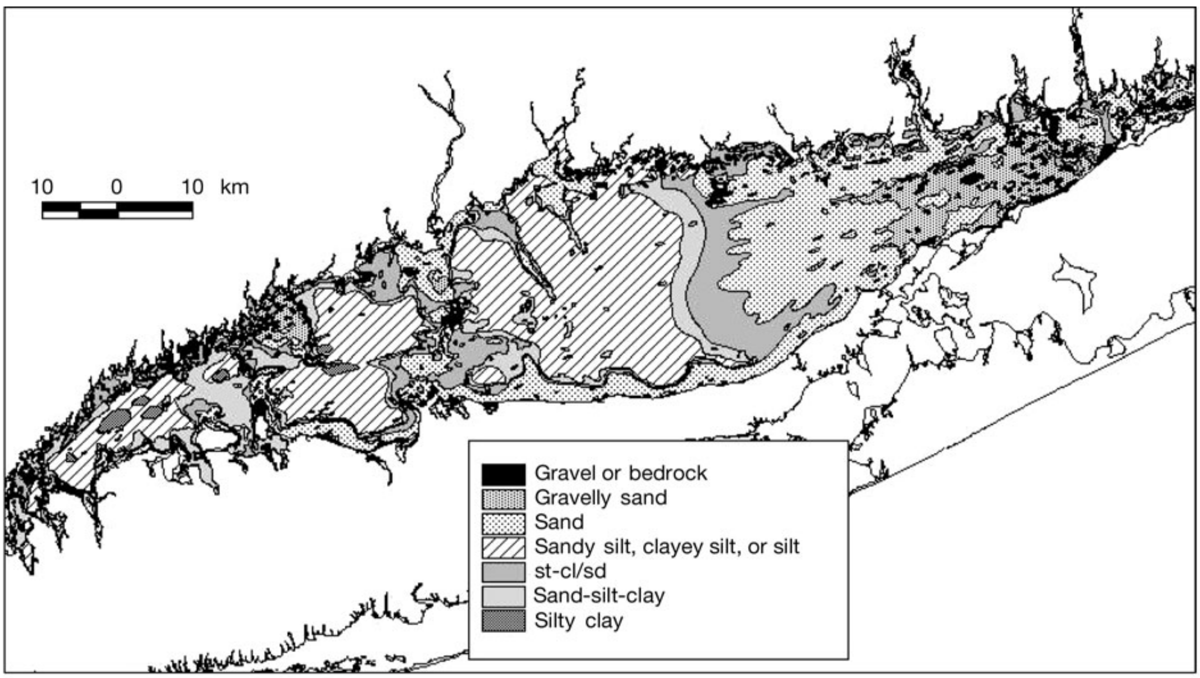


Fig. 2. Sea floor sediment types in Long Island Sound (see Poppe et al. 2000) used as habitat proxies for the MARXAN analyses; st-cl/sd: silt, clayey sand

models were tested because initial modeling showed that systemwide solutions were spatially disjunct, with different sites scattered over different portions of the estuary after each run of the model. In general, conservation planning within a region will try to identify MPAs that are restricted to 1 or 2 specific areas, except in the case of large-scale, extensive MPA networks, for various purposes (e.g. social and economic acceptability and easier enforcement of MPA regulations). Most of our modeling focused on generating MPA designs in the Connecticut portion of LIS because the macrobenthic data set that we used to test the efficacy of the model solutions came from a study conducted in Connecticut waters by Pellegrino & Hubbard (1983). This does not in any way bias the MPA solutions obtained, but simply defines the geographic extent over which the modeling is conducted, thus reflecting typical management scenarios where MPA selection is restricted to a particular region due to jurisdictional or other reasons. Such geographic constraining of MPA selection may not reflect the spatial characteristics of ecological structure and dynamics in a region, but is a typical management consideration.

MPA selection modeling. The MPA siting software MARXAN uses simulated annealing to determine an optimal MPA solution based on an iterative improvement process (Ball & Possingham 2000, McDonnell et al. 2002). The process of simulated annealing allows for many solutions to be examined while utilizing an iterative process which will accept or reject subsequent solutions based on their ability to minimize an objective function outlined by the user (Possingham et al. 2000). Using regional breakdowns, MPAs were designed for the eastern/transitional and western/central regions, for both the Connecticut portion and the entire LIS (Fig. 1).

Details on how files for MARXAN were created for this study are given at www.ecology.uq.edu.au/docs/marxan/MPA_design_tutorial.pdf. Briefly, a grid was overlain on the sedimentary texture data covering the entire LIS using GIS (Fig. 2). Seven types of sedimentary habitats were represented. Each grid square was 1 km^2 and represented a single planning unit. Using GIS, sedimentary data were extracted for each planning unit for all regional breakdowns, and were then manipulated in a spreadsheet to create the conservation feature files. Boundary length data was determined using the JNCC extension downloaded from the MARXAN website. Sedimentary data were summarized for each region using GIS, and brought into a spreadsheet where target representation files of 10, 20 and 30 % of each sediment type by area were created. Each target representation file contained information on the amount of each of the 7 sediment types to be included in the MPA design for each target level per scenario.

Numerous runs were performed for each region, using differing conservation parameters and boundary length modifiers (BLM) in order to determine which geographical areas were consistently selected by the annealing process and to generate solutions which primarily comprised 1 or 2 sites. The BLM determines the number of separate sites that are generated by a MARXAN run. Our goal was to develop 1- and 2-site solutions for all regional breakdowns for both Connecticut waters and the entire LIS because it is likely that in developing MPAs for large estuarine areas, initial criteria may focus on establishing one or a limited number of sites that meet the conservation goals. The number of scenarios run for each region depended on the number of attempts needed to arrive at 1- and 2-site MPA solutions. Once a 1- or 2-site solution was obtained, subsequent runs were performed to ensure that the derived solutions were replicable even after changing the BLM. If numerous 1- or 2-site solutions fell in different areas, this was taken into account during the selection phase for species and in community analyses. Target representation levels of 10 and 20 % were modeled for all regional breakdowns. MARXAN solutions resulted in full representation of the conservation features (i.e. the sediment type habitat proxy) while occupying the smallest area. Sometimes, changing the BLM did not change the layout of the MPA system, and specific solutions often continually fell in the same general area within a region. Thus, the best solutions were chosen based on the number of planning units that made up the MPA. If solutions yielded the same number of sites and similar numbers of planning units but different areas of a particular region, each was analyzed for effectiveness. In general, we considered the best solutions to be those with the lowest planning unit number and ≤2 separate sites.

Testing the solutions. Data used to test MPA solutions (Pellegrino & Hubbard 1983) included information on macrobenthic species richness and community composition at 413 sites in the Connecticut waters of LIS at a high degree of spatial resolution, as most sites were ≤1 km apart. The taxa inventoried included polychaetes, bivalves, gastropods and crustaceans. Zajac et al. (2000) analyzed these data and recognized 15 community types based on a level of similarity ≤50 to 55 %. Community types were identified using classification analysis of the 35 most abundant taxa found throughout LIS, via the unweighted pair-group method on a matrix of station similarities calculated with the Bray-Curtis index using untransformed data. MPA solutions were tested by comparing species richness (using the full data set of Pellegrino & Hubbard (1983) for 109 species) and community composition distributions inside versus outside each solution. All sampling sites outside the MPA solution in the region being analyzed were designated as outside sites. We considered an MPA solution to be effective if it exhibited equal or significantly higher species richness levels inside than outside the MPA. Species richness differences were tested using the Aspin-Welch unequal-variance *t*-test. For community composition data, we determined a solution to be effective if it captured the same frequency of community types inside as outside the solution. We feel this to be a very effective way of testing the solutions because the previously identified community types reflect specific assemblages that are distributed throughout LIS, thus testing MPA solutions at a higher level of ecological organization. Community composition distributions inside versus outside were analyzed using the Kolmogorov-Smirnov test for distributions. We also tested several solutions using multivariate analysis of similarities (ANOSIM) with PRIMER software (Clarke & Gorely 2001) as a secondary assessment of the solutions without reference to specific macrobenthic assemblages. Similarity among sites based on overall species composition and abundances using the full Pellegrino & Hubbard (1983) data set was calculated with the Bray-Curtis similarity function and then grouped as inside or outside the MPA solution for the ANOSIM test. The data for these tests were not transformed and 999 permutations were run.

The Pellegrino & Hubbard (1983) data set is the most comprehensive and spatially detailed data set for macrobenthos in LIS, but spans only the Connecticut portion of LIS (Fig. 1). Thus, we were restricted to testing only the MPA models developed for this portion of the Sound, but our approach could be extended to all portions of LIS as data become available.

Relationships to estuarine gradients and human activities. In order to illustrate the potential kinds of conflicts that may occur in MPA siting within a large estuary such as LIS, we conducted GIS overlay analyses using several solutions and data on variables representative of the human activities that would likely be considered in an MPA selection process. These included the location of dredge spoil disposal sites, coastal oyster beds that are leased by private growers and/or owned by local municipalities, and the concentration of mercury (Hg) in bottom sediments of LIS. The dredge spoil sites data were obtained from the US Army Corps of Engineers, the oyster lease areas from the state of Connecticut Department of Agriculture, and the mercury GIS data layers from the US Geological Survey.

RESULTS

Sets of MPA solutions were developed for several regions of LIS. In general, all solutions met conservation goals relative to the amounts of sediment types (habitats) that were included in each site, for each level of representation tested. Based on criteria noted above, specific configurations considered as the best solutions in each region were chosen to assess their effectiveness in equaling species richness levels and community type frequencies outside the solutions.

Eastern/transitional region

10% target representation

Fourteen scenarios were run for this region and target level. Most solutions were located in similar areas within this region, with ~70 to 80% overlap. Solutions chosen for analysis of effectiveness included one 2-site solution (BLM 0.05) and two 1-site solutions (BLM 1, BLM 2) (Fig. 3). The 2-site solution contained a few single planning units located along the western border of the region where there were less common sediment types. The 2 main areas included in this solution were located just southwest of the mouth of the Connecticut River and south of Niantic Bay. The 1-site solutions were very similar in spatial extent, with both being located south of the Connecticut River. These also had one planning unit that was on the border of the region. There were no differences in species richness

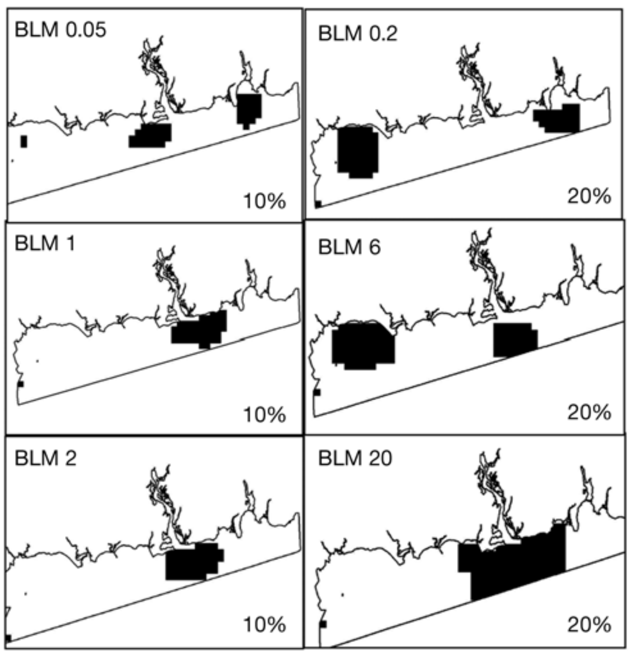


Fig. 3. Marine protected area (MPA) solutions generated for the eastern/transitional region of Long Island Sound. BLM = boundary length modifier, with percentages referring to the amount of each bottom type targeted in the scenario

inside versus outside the solutions for all 3 scenarios (Table 1). Moreover, no differences (p = 0.99) in community composition were noted inside versus outside for the 2-site solution (BLM 0.05) (Fig. 4). For the 1-site solutions, BLM 1 had marginally different community composition from the outside communities (p = 0.067), whereas community composition in the 1-site solution BLM 2 was significantly different from that outside the MPA (p = 0.03) (Fig. 4).

20% target representation

Many of the 12 scenarios run for this region and target level resulted in 2-site solutions falling in the same 2 areas, with one located in the eastern portion of LIS south of Niantic Bay and the other closer to the region's western boundary in an area of coarser sediments (Fig. 3). The 1-site solutions were generally located in the middle of the region, south of the Connecticut River. Solutions chosen for testing included two 2-site solutions (BLM 0.2 and BLM 6) and one 1-site solution (BLM 20) (Fig. 3). More 2-site solutions were chosen for testing because one of the locations making up these solutions fell in a somewhat different area. For the 2-site BLM 0.2 solution, there was no difference (p = 0.23) inside versus outside the solution for both community composition (Fig. 4) and species richness (Table 1). Community composition inside versus outside was significantly different for the BLM 6 and the BLM 20 solutions (p = 0.02 and 0.009, respectively) (Fig. 4). There was no difference in species richness inside versus outside the solutions for both BLM 6 and BLM 20 solutions (Table 1). We also tested community differences on a multivariate basis for the BLM 20 solution. An MDS ordination shows overlap in many of the inside versus outside sample stations, but an overall significant difference among them was noted (Global R = 0.077, p = 0.004), reflecting the different mixes of community types found inside and outside the solution area.

Central/western region

10% target representation

All MPA solutions for this region were located in a similar area in the western basin. Ten MPA solutions were run, and 3 were chosen for effectiveness testing (Fig. 5). The 1-site solution BLM 1 also included a single planning unit west of the main site in order to include the silty clay texture type (Fig. 5). There were no significant differences in benthic community frequencies inside versus outside for all 3 solutions (BLM 0.2, p = 0.721; BLM 0.5, p = 0.96; BLM 1, p = 0.98) (Fig. 6). However, species richness levels were significantly higher outside than inside for all 3 solutions (Table 1).

20% target representation

All MPA solutions for the 20% target representation captured a similar area in the western basin. A 3-site solution also captured a small area in the central basin. Eight scenarios were run for this region. The solutions chosen for effectiveness testing consisted of one 1-site solution (BLM 1) and one 3-site solution (BLM 0.3) (Fig. 5). The 2-site solutions for this region fell almost directly on top of the 1-site solution so only the 1-site solution was tested for effectiveness. Neither the mix of community types nor species richness showed significant differences inside versus outside the 3-site solution (BLM 0.3, p = 0.49) (Fig. 6, Table 1). A multivariate test of community composition for the 20% BLM 0.3 solution indicated no significant differences among stations inside versus outside the solution area (Global R = 0.085, p = 0.973).

Opposite results were obtained for the 1-site solution (BLM 1). There was significant difference in the mix of community types inside versus outside the

Table 1. Species richness per grab sample (mean ± SE, number of sample points inside or outside the solution areas in parentheses) for sample points lying inside and outside modeled marine protected area (MPA) solutions. Differences in species richness were tested using Aspin-Welch unequal-variance *t*-tests at 5% significance level. Target level refers to the specific MPA scenario modeled; see 'Materials and methods' for details. BLM = boundary length modifier

Target level	BLM	Inside	Outside	Aspin-Welch (p)
Eastern/transitional region				
10%	0.05	17.40 ± 3.29 (10)	20.26 ± 1.19 (98)	0.462
	1	19.75 ± 3.07 (12)	20.03 ± 1.21 (96)	0.933
	2	19.54 ± 3.07 (12)	20.06 ± 1.20 (95)	0.881
20%	0.2	23.32 ± 2.50 (25)	19.02 ± 1.21 (83)	0.140
	6	19.86 ± 2.10 (23)	20.04 ± 1.32 (85)	0.947
	20	19.11 ± 2.32 (28)	20.31 ± 1.29 (80)	0.650
Central/western region				
10%	0.2	9.86 ± 1.23 (22)	14.73 ± 0.52 (191)	0.001
	0.5	9.90 ± 1.22 (23)	14.73 ± 0.52 (190)	<0.001
	1	11.00 ± 1.10 (25)	14.66 ± 0.54 (188)	0.005
20%	0.3	14.25 ± 1.23 (40)	14.23 ± 0.54 (173)	0.985
	1	11.08 ± 0.89 (50)	15.20 ± 0.57 (163)	<0.001

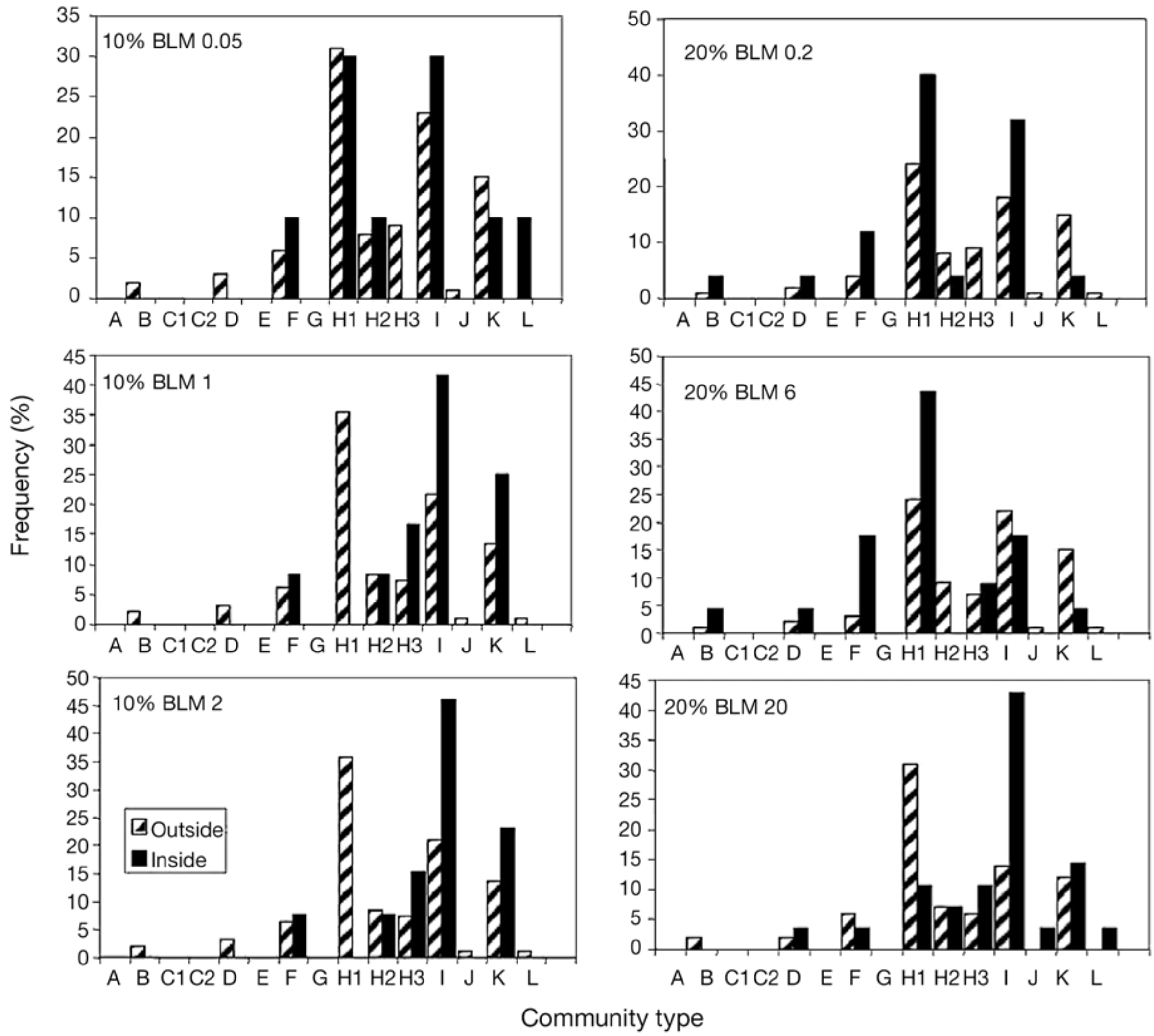


Fig. 4. Frequencies of community types inside and outside the MPA solution areas in the eastern/transitional region of Long Island Sound. Community types were determined by multivariate analyses of data given in Pellegrino & Hubbard (1983) by Zajac et al. (2000). Dominant species in each community type are given in Table 2

solution ($p = 0.007$) (Fig. 6), and species richness was significantly higher outside than inside the solution area (Table 1).

Estuary-wide solution

As an example of an estuarine-wide solution for LIS, we modeled a 20% habitat representation scenario for both the central/western and eastern/transitional regions constrained to 1 or 2 sites (Fig. 7). In the central/western region, the solution spanned much of the western basin and included only a small portion of the central basin. It included the area known as Stratford Shoals which is an area of heterogeneous sediments (Fig. 2) and bathymetry separating these 2 basins. In the eastern/transitional region, the solution showed 2 MPA sites: a larger one along the Connecticut coast, south and west of the mouth of the Connecticut River, and a smaller one in the middle of LIS, where there is a band of mixed sand-silt-clay and silty clayey-sand sediments.

Relationships to estuarine gradients and human activities

We conducted GIS overlay analyses using several of the solutions and data on human impacts and activities that would likely be considered in the MPA design and selection process (Fig. 8). Potential MPA sites generated in our modeling were generally not located in

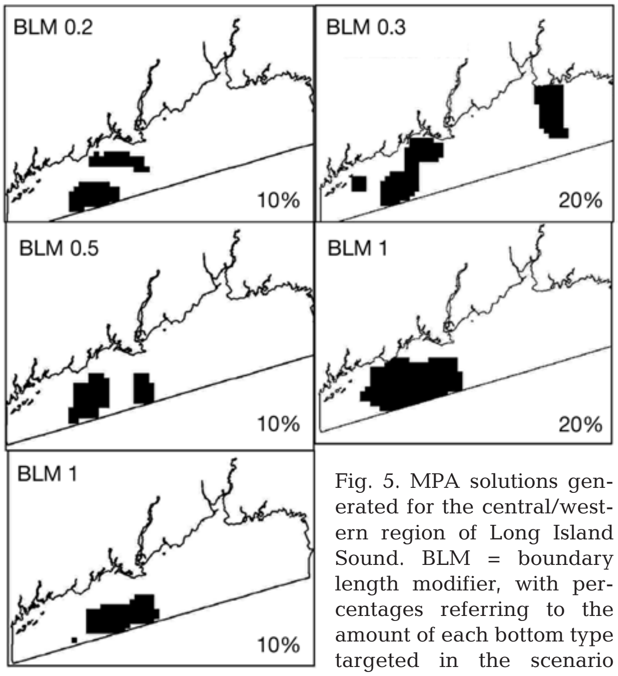
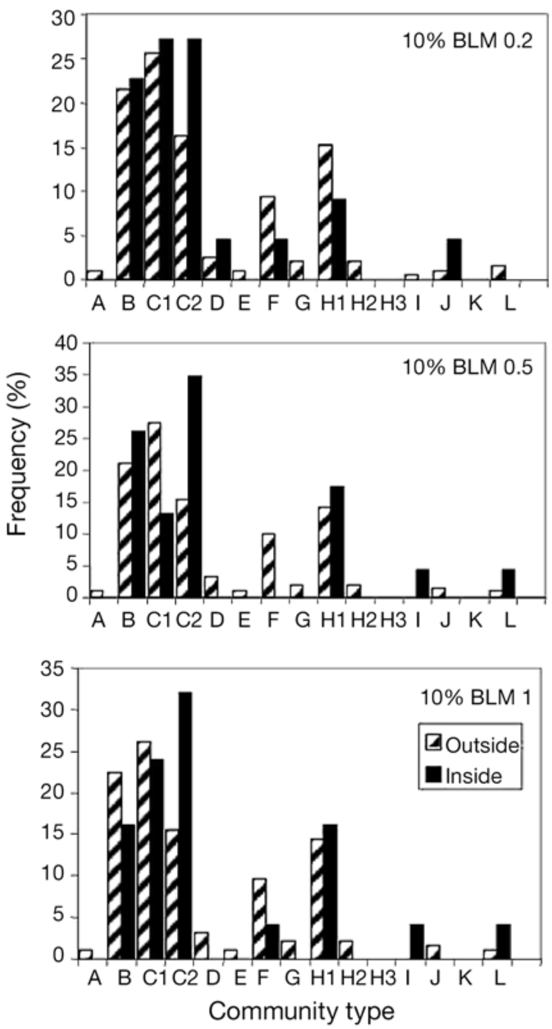


Fig. 5. MPA solutions generated for the central/western region of Long Island Sound. BLM = boundary length modifier, with percentages referring to the amount of each bottom type targeted in the scenario

areas of very high sediment Hg concentrations, although a significant portion of the MPA areas in the central/western MPA solutions are in locations with moderate sediment Hg concentrations. The central/western MPA areas overlap oyster growout locations along the Connecticut shore, with one of the solution sections being totally within a growout area. The eastern/transitional solution overlapped little with oyster growout areas. However, this solution showed considerable overlap with a dredge spoil disposal area south of the Connecticut River, and a small amount of overlap with a disposal site in the central basin of LIS (Fig. 8).

DISCUSSION

Numerous MARXAN runs were performed for both the entire LIS and Connecticut waters only. Entire LIS runs were initially done without dividing the estuary into regions, yielding solutions that included all 7 habitat (sediment) types at the targeted representation



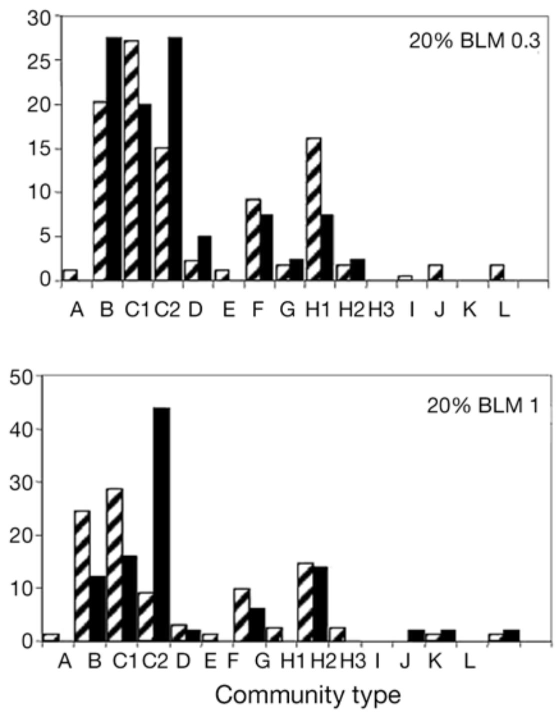


Fig. 6. Frequencies of community types inside and outside the MPA solution areas in the central/western region of Long Island Sound. Community types were determined by multivariate analyses of data given in Pellegrino & Hubbard (1983) by Zajac et al. (2000). Dominant species in each community type are given in Table 2

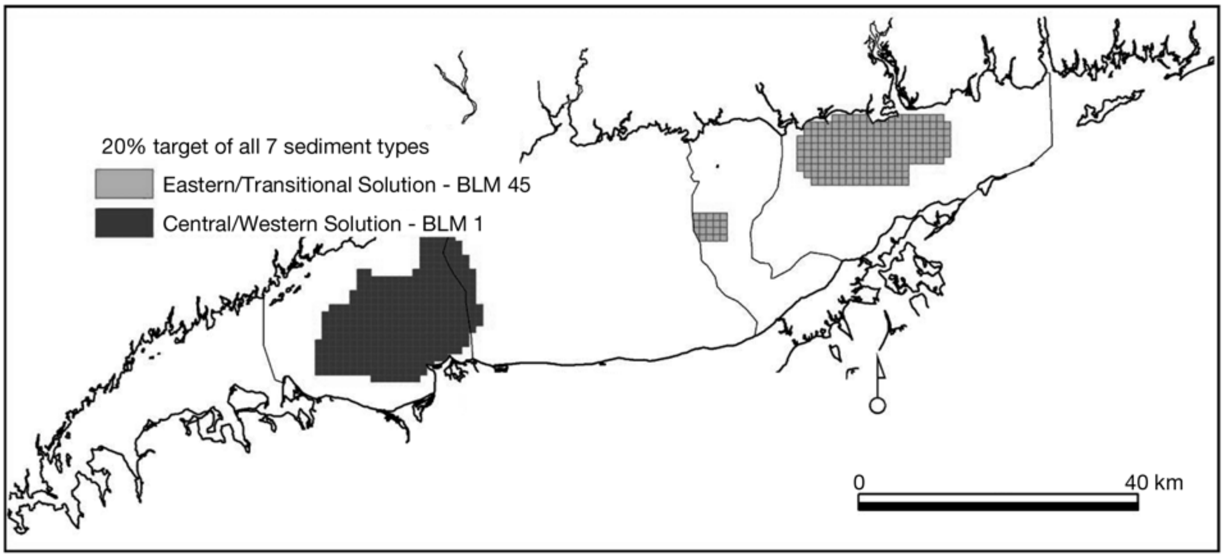


Fig. 7. Example of MARXAN solution for the whole Long Island Sound that includes potential MPAs in both the central/western and eastern/transitional regions. The conservation goal was 20% of the area of each habitat (sediment) type in each region

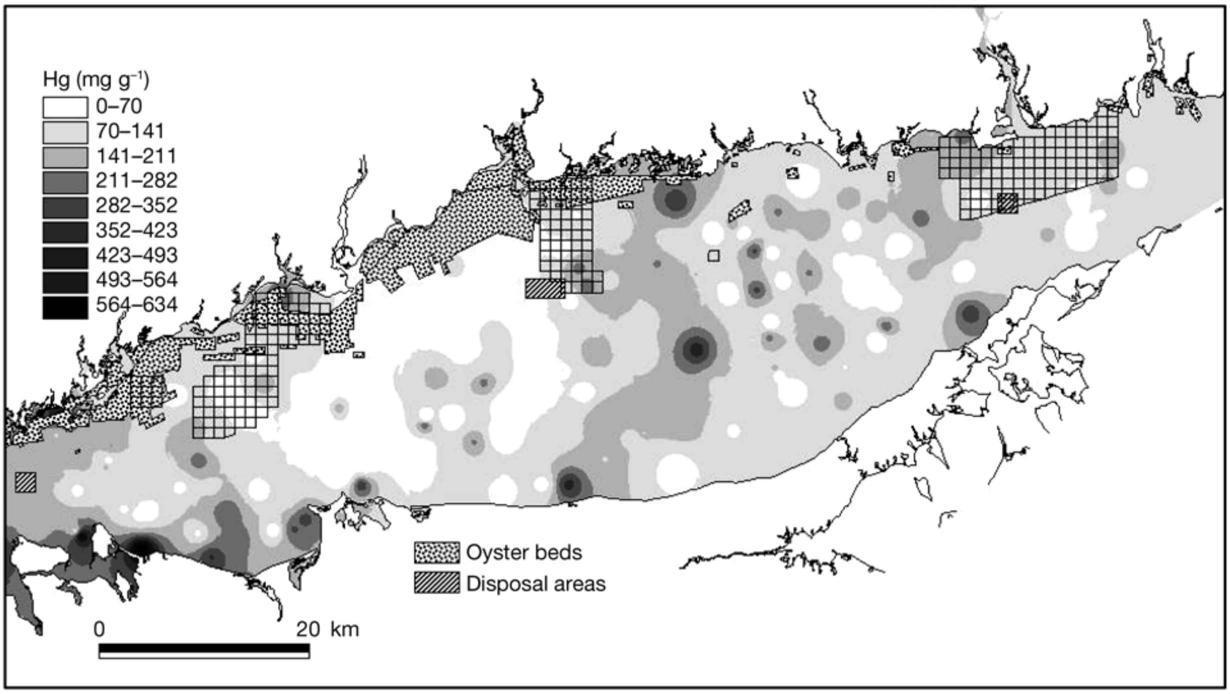


Fig. 8. GIS overlay map illustrating potential conflicts between MPA sites generated as solutions in the MARXAN analyses and various human activities and environmental conditions in Long Island Sound. MARXAN solutions which placed 20% of each habitat type into the MPA were used for these analyses. Mercury concentrations are in mg g^{-1} of sediment (see Mecray & Buchholtz ten Brink 2000)

levels. However, these solutions were either highly fragmented or, when consisting of 1 or 2 sites, omitted certain areas of LIS that contained different community types and suites of species. This is due to both the large-scale east to west gradients in sedimentary environments in LIS, and the smaller-scale sea floor heterogeneity (Fig. 2). Most large estuarine systems will have similar gradients; thus, one of the first steps in applying MPA site selection models is recognizing and establishing appropriate estuarine regions that encompass distinct sets of benthoscapes and their component patch/habitat types. It is also important to establish the extent to which water column physical (e.g. current patterns, density stratification) and chemical (e.g. dissolved oxygen, salinity) characteristics coincide in such regions, to inform the selection process on benthic and demersal fauna, particularly those that have dispersal and movement patterns that span the regions considered in the MPA selection process. For example, important estuarine species such as blue crabs *Callinectes sapidus* and many fishes exhibit estuary-wide movements either related to reproduction and/or seasonal migrations (Day et al. 1989).

We developed MPA solutions for several regions of LIS, but results for only 2 regional breakdown scenarios are reported here (solutions and analyses for the other regions and the entire LIS can be obtained from the corresponding author). The 2 regions chosen for analysis (Figs. 3 & 5) exhibit strong differences in sedimentary types, species richness and community structure, and therefore underscore the spatial variability that typifies large estuarine systems. In LIS, estuarine-wide sea floor heterogeneity led to differences among MARXAN solutions and their ability to capture the regional suite of benthic species and communities. In the eastern/transitional region of LIS, habitat changes are sharp (Fig. 2) and species richness is relatively high (Zajac et al. 2000). All MPA solutions for the eastern/transitional region showed no significant difference in species richness inside versus outside the MPA scenarios (Table 1), but differences in community structure were significant for most solutions. The mix of community types in all 1-site solutions were either different or marginally different, inside versus outside the MPA solution, as well as for the 20% BLM 6 solution. The community types that differed most were H1 and I (Fig. 4, Table 2). Community type H1 was dominated by several polychaetes (*Asabelides occulata* and *Spiophanes bombyx*), and the bivalve *Tellina agilis*. Community type I was dominated by the polychaetes *Cirratulis grandis*, *C. cirratus*, *Prionospio heterobranchia*, and *P. tenuis*; the amphipod *Aeginnia longicornis*; and the bivalve *Mytilus edulis*. The 10 and 20% 2-site solutions had similar mixtures of communities. Thus, while species richness did not differ inside versus outside all solutions for this region, the mixes of species differed as reflected in the significant differences in community types inside and outside of MPA solution areas. This may be due to a high degree of mesoscale variation in habitat structure in this portion of LIS, which leads to higher patchiness and more transitional areas among patches. These benthoscape features may support higher overall benthic species richness but also cause greater spatial heterogeneity in the mixes of macrofaunal assemblages (Zajac et al. 2003). These results suggest that 1-site MPAs in the eastern region of LIS would adequately capture high species richness levels, but using 2-site solutions may be more appropriate if the goal is to capture a representative suite of community types.

The western LIS contains lower species diversity compared to the eastern LIS, and habitat heterogeneity occurs at broader spatial scales (Poppe et al. 2000, Zajac et al. 2000). Trends in MPA solutions for this region showed more similarities in community composition inside than outside, but lower species richness inside than outside in all but one of the solutions tested. At the 10% target level, all solutions contained similar communities inside versus outside and higher species diversity outside the solution. Raising the representation to 20% enabled the 3-site solution to capture the regional species richness level (Table 1). When we attempted to derive a 1-site solution, species richness was much higher outside the solution area. Raising the representation level from 10 to 20% captured a higher species richness level but only in solutions that comprised >1 site. Thus, conditions in the western/central region of LIS appear to be opposite that of the eastern/transitional region. Most of the

Table 2. Dominant species in each of the community types shown in Figs. 4 & 6, based on analyses presented in Zajac et al. (2000)

Community type	Dominant species
A	*Mulinia lateralis*, *Nephtys incisa*, *Cistenoides gouldii*
B	*Mulinia lateralis*, *Nucula annulata*, *Nephtys incisa*
C1	*Nucula annulata*, *Mulinia lateralis*, *Nephtys incisa*
C2	*Mulinia lateralis*, *Nucula annulata*, *Nephtys incisa*
D	*Cistenoides gouldii*, *Corophium acheruscum*, *Mulinia lateralis*
E	*Nucula annulata*, *Nephtys incisa*, *Paraonis fulgens*, *Yoldia lamatula*
F	*Mulinia lateralis*, *Clymenella zonalis*, *Mediomastus ambiseta*
G	*Cistenoides gouldii*, *Clymenella zonalis*, *Pitar morrhuana*, *Asabellides oculata*
H1	*Asabellides oculata*, *Tellina agilis*, *Spiophanes bombyx*
H2	*Ampelisca vadorum*, *Corophium acheruscum*, *Spiophanes bombyx*
H3	*Unicola irrorata*, *Aricidea jeffersyii*, *Capitella capitata*
I	*Cirratulis grandis*, *Cirratulis cirratus*, *Aeginina longicornis*, *Prionospio tenuis*, *Prionospio heterobranchia*, *Mytilus edulis*
J	*Assabelides oculata*, *Polydora websteri*, *Spiophanes bombyx*, *Leptocherius pinquis*
K	*Protohaustorius wigleyi*, *Acanthohaustorius millsi*
L	No fauna

western/central region comprises large patches of muddy sediments (Fig. 2), with less habitat heterogeneity at large to meso-scales, although small-scale (m^2) differences are prominent (Zajac 1998). Differences in community structure across these benthoscape elements are more subtle than in the eastern region, and the spatial distribution of specific community types is broader (Zajac et al. 2000) (Table 2). Species are added to the overall species pool over broader spatial scales as well. Therefore, larger MPAs would be needed in the western/ central region to capture local species richness, and multiple site solutions could better capture the overall species pool, although community types may be adequately represented across a range of MPA sizes and configurations. In large estuaries, the unique conditions, the physical and chemical gradients of the system, as well as the geographic locations and characteristics of human activities, should be considered during the MPA design and implementation process. Our GIS overlay analyses indicate that some MPA design scenarios fell in areas with moderate levels of mercury contamination, and were close to or overlapped dredge disposal and shellfish harvesting sites (Fig. 8). Active dredge disposal sites have altered natural communities and habitat conditions in terms of both physical and chemical characteristics (Morton 1977). Implementing an MPA close to an active disposal site would likely run counter to the desired effects of MPAs due to possible habitat destruction and sediment contamination that could take place within the MPA. Even if MPAs are located away from areas of high human impact such as disposal sites or shipping terminals, it will also be important to consider bottom water currents which may disperse materials in the direction of the MPAs and could lead to habitat contamination and uptake by the organisms intended to be protected. If data are available, human activities such as fishing pressure (e.g. Sala et al. 2002) can be incorporated into the scenario modeling and accounted for directly.

Using sediment type as a habitat proxy in the site selection process yielded mixed results in terms of capturing macrobenthic species richness and community composition. This does not necessarily mean that this approach is inadequate for designing MPAs in large estuarine systems, but underscores the need to test the potential efficacy of using habitat proxies with available data on populations and communities. Using habitat proxies may be a good starting point if data on target species or communities are lacking or extend over limited areas of the system being considered. We assessed the efficacy of applying MARXAN to large estuaries based on differences in macrobenthic species richness and community structure inside and outside of potential MPA sites. Although this is a limited set of variables used to assess how well conservation goals may be attained, apart from specific representation and boundary length goals set in the modeling process, these variables provided an independent measure of the potential of each solution to capture ecological conditions within certain portions of the estuary by considering a range of potential solutions. Indeed, the process yielded solutions that met the criteria stated in terms of target representation levels of habitat type and macrobenthic species richness and community composition. Temporal changes in these variables were not addressed, but the general nature of benthic community structure and its spatial variation in LIS appear to be relatively constant over time (e.g. Sanders 1956, Pellegrino & Hubbard 1983, Zajac et al. 2000), although this should be tested as more data become available for broader portions of LIS. Since conservation of both recreational and commercial fish species are often the primary reason for establishing MPAs, other critical variables that should be included in tests of the potential efficacy of MPA solutions are fish community structure and specific resource species such as, particularly in the case of LIS, the American lobster *Homarus americanus*. Depending on the availability of these types of data, there may be more opportunities to make assessments of how well different solutions might capture the ecological goals set in the modeling scenarios in these systems. However, it is important not only to focus on inside versus outside comparisons (e.g. Parnell et al. 2005), but also to consider a variety of criteria and the scale of the data being used (e.g. Shriner et al. 2006) when assessing the potential effectiveness of an MPA.

In large estuarine systems, the spatial heterogeneity of habitats and processes across the entire extent of the system need to be considered when trying to develop an MPA or a network of MPAs. In other studies where MARXAN was used to develop potential MPA solutions, the environmental and biological gradients did not change as rapidly and regularly as they do in estuarine systems, although the systems contained a variety of habitat types and in some cases had a large spatial extent or crossed biogeographic provinces (e.g. Airame et al. 2003, Leslie at al. 2003). Large estuaries also typically comprise component systems or modules (Tenore et al. 2006) that include the main body of the estuary, freshwater inputs via rivers and streams, tidal rivers and embayments, salt marshes and other coastal features. All of these have smaller-scale, within-module gradients and environments that contribute to overall estuarine function. Given this complex mix of ecological conditions, the question is whether a different approach for the MPA site selection process in estuarine environments is needed. The goals of MPA site design generally center on identifying and protecting some mixture of representative and unique sites and species, and the habitats and overall species pool a region contains, in a geographic/spatial framework that meets societal needs and demands (Agardy 2000, Roff & Evans 2002). For large estuarine systems, it is crucial to recognize the need for a collection of sites that support the full range of estuarine functions, including smaller component systems that surround and interact with the main body of the estuary. MPA networks are receiving much attention as a way of better attaining the management and conservation goals associated with MPAs (Murray et al. 1999, Roberts et al. 2003). However, while it is feasible to establish such networks in coastal or oceanic systems, it would be difficult in large estuarine systems given the confined area and larger set of human uses and potential conflicts. Thus, we see effective MPA networks comprising a few areas in the main body of the estuary, such as modeled here for LIS, and some set of protected 'satellite' systems such as salt marsh complexes, tidal rivers, embayments and the lower reaches of freshwater rivers. This type of network would provide a higher probability for maintaining and protecting important estuarine functions relative to the life histories of organisms that inhabit these systems. Many species, particularly nekton, use a wide range of estuarine habitats as nursery and feeding grounds (Beck et al. 2001). The selection of the satellite systems may not necessarily have to be done using the simulated annealing approach taken here, but may be done using other selection methods (e.g. Edgar et al. 2000). Another aspect to the establishment of MPAs in estuaries is the idea of marine zoning (Norse 2002, Babcock et al. 2005, Norse et al. 2005), where certain human activities/structures, such as energy pipeline and cable crossings, would be confined to certain portions of the estuary, while zoning other areas for resource extraction (e.g. fisheries) or for conservation. Establishment of zones for different activities may reduce conflicts associated with establishing MPAs, and expedite overall environmental management of these systems.

Exploring alternative design scenarios and regional breakdowns for a particular conservation area is an important step in MPA designation. The process needs to be flexible as there are many possible ways of combining sites to attain specific conservation and management goals (Pressey et al. 1994), especially in large estuaries such as LIS. As shown here, a variety of results and effectiveness levels were achieved by changing the number of sites within a solution, as well as the desired representation level. MPAs that strive to conserve biodiversity and habitats can be important ways to protect the health of estuaries, but it is important to consider the social and economic constraints facing managers in these systems where human activity and resource extraction is high. Many potential tradeoffs will likely affect MPA design and selection in large estuarine systems. MPA design models may prove useful in focusing these efforts.

Acknowledgements. We thank R. Cook and H. Leslie for discussions regarding implementation of MARXAN and its application to MPA site selection, and for computer scripts that were used in file creation; I. Ball and H. Possingham for technical assistance; and 2 anonymous reviewers whose comments and suggestions improved the manuscript. This work was partly supported by a graduate assistantship to A.E.N. from the University of New Haven.

LITERATURE CITED

Agardy T (2000) Information needs for marine protected areas: scientific and societal. Bull Mar Sci 66:875–888

Agardy T, Bridgewater P, Crosby M, Day J and others (2003) Dangerous targets? Unresolved issues and ideological clashes around marine protected areas. Aquat Conserv: Mar Freshw Ecosyst 13:353–367

Airame SJ, Dugan E, Lafferty KD, Leslie H, McArdle DA, Warner RR (2003) Applying ecological criteria to marine reserve design: a case study from the California Channel Islands. Ecol Appl 13:170–184

Ardron JA, Lash J, Haggarty D (2002) Modelling a network of marine protected areas for the central coast of British Columbia, Version 3.1. Living Oceans Society, Sointula, BC

Auster PJ, Joy K, Valentine PC (2001) Fish species and community distributions as proxies for seafloor habitat distributions: the Stellwagen Bank National Marine Sanctuary example (Northwest Atlantic, Gulf of Maine). Environ Biol Fishes 60:331–346

Babcock EA, Pikitch EK, Murdoch K, Apostolaki MK, Santora P (2005) A perspective on the use of spatialized indicators for ecosystem-based fishery management through spatial zoning. ICES J Mar Sci 62:469–476

Ball IR, Possingham HP (2000) MARXAN (V1.8.2): marine reserve design using spatially explicit annealing, a manual prepared for the Great Barrier Reef Marine Park Authority. University of Queensland, Brisbane

Beck MW, Odaya M (2001) Ecoregional planning in marine environments: identifying priority sites for conservation in the northern Gulf of Mexico. Aquat Conserv: Mar Freshw Ecosyst 11:235–242

Beck MW, Heck KL Jr, Able KW, Childers DL and others (2001) The identification, conservation and management of estuarine and marine nurseries for fish and invertebrates. Bioscience 51:633–641

Clarke KR, Gorley RN (2001) PRIMER v5: user manual/tutorial. PRIMER-E, Plymouth

Cognetti G, Maltagliati F (2000) Biodiversity and adaptive mechanisms in brackish water fauna. Mar Pollut Bull 40:7–14

Cook RR, Auster PJ (2003) Alternatives for optimal representation of seafloor habitats in Stellwagen Bank National Marine Sanctuary. Final Report. Environmental Defense, Boston, MA

Cook RR, Auster PJ (2005) Use of simulated annealing for identifying essential fish habitat in a multispecies context. Conserv Biol 19:876–886

Day JW Jr, Hall CAS, Kemp WM, Yanez-Arancibia A (1989) Estuarine ecology. Wiley, New York

Edgar GJ, Barrett NS, Graddon DJ, Last PR (2000) The conservation significance of estuaries: a classification of Tasmanian estuaries using ecological, physical and demographic attributes as a case study. Biol Conserv 92: 383–397

Kirkpatrick S, Gelatt CD Jr, Vecchi MP (1983) Optimization by simulated annealing. Science 220:671–680

Knebel HJ, Poppe L (2000) Sea-floor environments within Long Island Sound: a regional overview. J Coast Res 16:533–550

Leslie H, Ruckelshaus M, Ball IR, Andelman S, Possingham HP (2003) Using siting algorithms in the design of marine reserve networks. Ecol Appl 13: 185–198

Levin LA, Boesch DF, Covich A, Dahm C and others (2001) The function of marine critical transition zones and the importance of sediment biodiversity. Ecosystems 4:430–451

Lubchenco J, Palumbi S, Gaines S, Andelman S (2003) Plugging a hole in the ocean: the emerging science of marine reserves. Ecol Appl 13: 3–7

McDonnell MD, Possingham HP, Ball IR, Cousins EA (2002) Mathematical methods for spatial cohesive reserve design. Environ Model Assess 7:107–114

Mecray EL, Buchholtz ten Brink MR (2000) Contaminant distribution and accumulation in the surface sediments of Long Island Sound. J Coast Res 16:575–590

Morton JW (1977) Ecological effects of dredging and dredge spoil disposal: a literature review. Technical Papers, U.S. Fish and Wildlife Series 94, Washington, DC

Murray SN, Ambrose RF, Bohnsack JA, Botsford LW and others (1999) No-take reserve networks: sustaining fishery populations and marine ecosystems. Fisheries 24:11–25

Nicholls HB (1998) Canadian east coast marine protected areas: a review. Ocean Coast Manag 39:87–96

Norse EA (2002) A zoning approach to managing marine ecosystems. In: Cicin-Sain B, Ehler C (eds) Proc Workshop on Improving Regional Ocean Governance in the United States. December 9, 2002. US National Oceanic and Atmospheric Administration, Center for the Study of Marine Policy/University of Dealware, US Environmental Protection Agency, and Coastal States Organization, Washington, DC, p 53–58

Norse EA, Crowder LB, Gjerde K, Hyrenbach D, Roberts C, Safina C, Soulé ME (2005) Place-based ecosystem management in the open ocean. In: Norse EA, Crowder LB (eds) Marine conservation biology: the science of maintaining the sea's biodiversity. Island Press, Washington, DC, p 302–337

Parnell PE, Lennert-Cody CE, Geelen L, Stanley LD, Dayton PK (2005) Effectiveness of a small marine reserve in southern California. Mar Ecol Prog Ser 296:39–52

Pellegrino P, Hubbard W (1983) Baseline shellfish data for the assessment of potential environmental impacts associated with energy activities in Connecticut's coastal zone, Vols I & II. Report to the State of Connecticut, Department of Agriculture, Aquaculture Division, Hartford, CT

Perry D, Hughes J, Hebert A (1991) Sublethal abnormalities in embryos of winter flounder, *Pseudopleuronectes americanus*, from Long Island Sound. Estuaries 14:306–317

Poppe JL, Knebel HJ, Mlodzinska ZJ, Hastings ME, Seekins BA (2000) Distributions of surficial sediment in Long Island Sound and adjacent waters: texture and total organic carbon. J Coast Res 16:567–574

Possingham HP, Ball IR, Andelman S (2000) Mathematical methods for identifying representative reserve networks. In: Ferson S, Burgman M (eds) Quantitative methods for conservation biology. Springer-Verlag, New York, p 291–305

Pressey RL, Johnson IR, Wilson PD (1994) Shades of irreplaceability: towards a measure of the contribution of sites to a reservation goal. Biodivers Conserv 3:242–262

Roberts CM, Branch G, Bustamante RH, Castilla JC and others (2003) Application of ecological criteria in selecting marine reserves and developing reserve networks. Ecol Appl 13:215–228

Roff JC, Evans SMJ (2002) Frameworks for marine conservation — non-hierarchical approaches and distinctive habitats. Aquat Conserv: Mar Freshw Ecosyst 12:635–648

Sala E, Aburto-Oropeza O, Paredes G, Parra I, Barrera JC, Dayton PK (2002) A general model for designing networks of marine reserves. Science 298:1991–1993

Sanders HL (1956) Oceanography of Long island Sound X. The biology of marine bottom communities. Bull Bingham Oceanogr Coll 15:245–258

Shriner SA, Wilson KR, Flather CH (2006) Reserve networks based on richness hotspots and representation vary with scale. Ecol Appl 16:1660–1673

Tenore K, Zajac RN, Terwin J, Andrade F and others (2006) Characterizing the role benthos plays in large coastal seas and estuaries: a modular approach. J Exp Mar Biol Ecol 330:392–402

Ward TJ, Vanderklift MA, Nicholls AO, Kenchington RA (1999) Selecting marine reserves using habitats and species assemblages as surrogates for biological diversity. Ecol Appl 9:691–698

Welsh B, Eller F (1991) Mechanisms controlling summertime oxygen depletion in western Long Island Sound. Estuaries 14:265–278

Zajac RN (1998) Spatial and temporal characteristics of selected benthic communities in Long Island Sound and management implications. Final Report, Long Island Sound Research Fund Grant CWF-317-R, Connecticut Department of Environmental Protection, Office of Long Island Sound Programs, Hartford, CT

Zajac RN (2001) Organism–sediment relations at multiple spatial scales: implications for community structure and responses to disturbance. In: Aller J, Woodin SA, Aller RC (eds) Sediment–organism interactions. University of South Carolina Press, Columbia, SC, p 119–139

Zajac RN, Lewis RS, Poppe LJ, Twichell DC, Vozarik J, DiGiacomo-Cohen ML (2000) Relationships among sea-floor structure and benthic communities in Long Island Sound at regional and benthoscape cales. J Coast Res 16: 627–640

Zajac RN, Lewis RS, Poppe LJ, Twichell DC, Vozarik J, DiGiacomo-Cohen ML (2003) Responses of infaunal populations to benthoscape patch structure and the potential importance of transition zones. Limnol Oceanogr 48:829–842

Editorial responsibility: Kenneth Heck, Dauphin Island, Alabama, USA

Submitted: June 14, 2007; Accepted: September 4, 2008
Proofs received from author(s): December 12, 2008