

Abstract—The objective of this study was to investigate the spatial patterns in green sea urchin (*Strongylocentrotus droebachiensis*) density off the coast of Maine, using data from a fishery-independent survey program, to estimate the exploitable biomass of this species. The dependence of sea urchin variables on the environment, the lack of stationarity, and the presence of discontinuities in the study area made intrinsic geostatistics inappropriate for the study; therefore, we used triangulated irregular networks (TINs) to characterize the large-scale patterns in sea urchin density. The resulting density surfaces were modified to include only areas of the appropriate substrate type and depth zone, and were used to calculate total biomass. Exploitable biomass was estimated by using two different sea urchin density threshold values, which made different assumptions about the fishing industry. We observed considerable spatial variability on both small and large scales, including large-scale patterns in sea urchin density related to depth and fishing pressure. We conclude that the TIN method provides a reasonable spatial approach for generating biomass estimates for a fishery unsuited to geostatistics, but we suggest further studies into uncertainty estimation and the selection of threshold density values.

Estimating exploitable stock biomass for the Maine green sea urchin (*Strongylocentrotus droebachiensis*) fishery using a spatial statistics approach

Robert C. Grabowski

School of Marine Sciences
5741 Libby Hall
University of Maine
Orono, Maine 04469
Present address: Flat 6, Falmer House
16-17 Marylebone High St.
London, W1U 4NY, England
E-mail address: grabowskirc6@yahoo.com

Thomas Windholz

The GIS Training and Research Center
Idaho State University
Pocatello, Idaho 83209-8130

Yong Chen

School of Marine Sciences
5741 Libby Hall
University of Maine
Orono, Maine 04469

The green sea urchin (*Strongylocentrotus droebachiensis*) is an important resource of the fishing industry in the State of Maine, where it currently ranks fourth by value. The commercial fishing industry began in the late 1980s as a result of expanding foreign markets. Landings reached a peak of more than 22,000 metric tons (t) in 1993. However, declining stock abundances have caused landings to diminish over the last decade, and in 2001, less than 5,000 t were landed (Chen and Hunter, 2003). Considering the economic importance of the fishery and its persistent decline in yield, it is essential that we establish an accurate quantitative assessment of the stock in order to develop an effective management plan.

The Maine Department of Marine Resources (DMR) has collected fishery-dependent information since the beginning of the state's commercial fishery. This information, including catch and size-composition data, has formed the basis of most management decisions in the fishery. The fishery is

currently managed through limited entry, a restricted number of opportunity days, and sea urchin size limits, in which legal-size sea urchins have a test diameter between 52 mm and 76 mm. The fishing grounds are divided into two management areas based on spatial and temporal variations in spawning (Fig. 1), in which management differs only by fishing seasons (Vadas et al., 2002).

Chen and Hunter (2003) conducted the first formal stock assessment for the Maine green sea urchin in 2001. Fishery-dependent data and sea urchin life history parameters were used to assess the population dynamics of the Maine urchin stock. A length-based stock assessment model was used with a Bayesian approach to determine probabilistic estimates of current stock biomass and exploitation rate. The study estimated that the current stock biomass was extremely low, about 10% of the virgin biomass. Only fishery-dependent data were available at the time the stock assessment was conducted, but in

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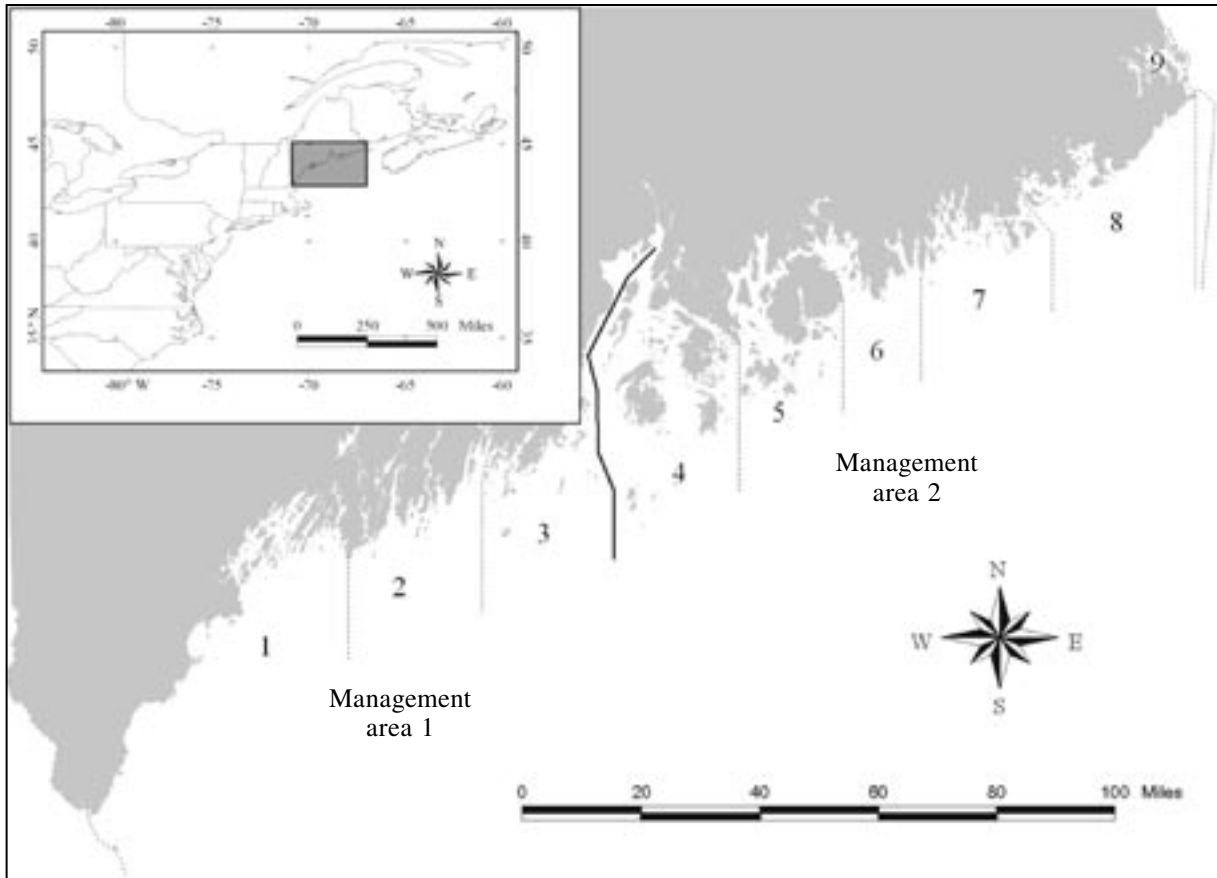


Figure 1

Map of the Maine coastline, showing the two management areas and the nine study strata from the fishery-independent survey program for green sea urchins (*Strongylocentrotus droebachiensis*).

2001 the DMR began an extensive fishery-independent survey program. This program generates large, spatially referenced, scientific data sets each year, which can be incorporated into stock assessments by using either fisheries population dynamics models or spatial analysis techniques.

Spatial statistics, also known as spatial statistics or geostatistics, encompasses a diverse group of techniques that can be used to model the spatial variability of a process, such as sea urchin density, to estimate the value at unobserved locations (Bailey and Gatrell, 1995; Petitgas, 2001). Spatial variability is routinely divided into two categories: first- and second-order effects, or similarly, large- and small-scale variability. Large-scale variability is the variation in the mean value of the process over the study area, whereas small-scale variability is the spatial dependence of the process, in other words the similarity between neighboring sites (Bailey and Gatrell, 1995).

Intrinsic second-order methods, along with kriging, have become the most popular geostatistical tools and are now commonly used to estimate exploited fish stock biomass (e.g., Simard et al., 1992; Petitgas, 1993; Pelle-

tier and Parma, 1994; Maravelias et al., 1996; Lembo et al., 1998; Maynou et al., 1998; Rivoirard et al., 2000; Petitgas, 2001). Two assumptions must be met to use intrinsic geostatistical methods: 1) independence between the variable and the region's geometry and 2) stationarity (Petitgas, 1993; Warren, 1998; Rivoirard et al., 2000). If these assumptions are violated, we can attempt to modify the data to make them more applicable or we must use other spatial analysis techniques to estimate the spatial patterns.

Tessellation is a spatial analysis technique that investigates first-order, or large-scale, spatial variability of a process (Ripley, 1981; Bailey and Gatrell, 1995). Triangulated irregular networks (TINs), or Delaunay triangulation, are the simplest and most common tessellation technique, in which a three-dimensional surface of contiguous, non-overlapping triangles is created by linear interpolation of the variable. TINs are most commonly used for visualization purposes but can be used to estimate the biomass of a process (Simard et al., 1992; Guan et al., 1999). They have received limited use in fisheries stock assessment, however, because if a stock exhibits stationarity, second-order methods tend

to provide more precise biomass estimates, as well as a quantification of their variances (Simard et al., 1992; Bailey and Gatrell, 1995; Guan et al., 1999).

The objective of our study is to investigate the spatial trends in green sea urchin density using spatial analysis techniques to estimate stock biomass. In doing so, we address the suitability of second-order methods to analyze a fishery with a target species that is highly spatially variable over a large, complex study area. We compare biomass estimates from several techniques to address the suitability of TINs for biomass estimation in the green sea urchin fishery.

Materials and methods

Data collection and processing

Sea urchin density and size-frequency information were obtained from the 2001 pilot study for the State's annual fishery-independent survey. The Department of Marine Resources conducted the survey in June and early July, after the fishing season had ended. The survey was restricted to rock and gravel habitats along the Maine coast and we used two modes of data collection, divers and video. In the first part of the study, divers sampled 144 sites according to a stratified random sampling design. The design consisted of 16 sites in each of 9 survey strata, where the width of a survey stratum was inversely proportional to the commercial landings in the region. At each site, SCUBA divers randomly sampled 30 quadrats (1 m² each) along three parallel linear transects set perpendicular to shore, for a total of 90 quadrats per site. The sampling intensity was divided equally among three depth zones: 0–5 m, 5–10 m, and 10–15 m. At each site, size-frequency data were obtained by randomly subsampling one quadrat in each depth zone, in which test diameters were measured for all individuals in the quadrat. An additional 148 sites were sampled, in a 15–40 m depth zone, with a video camera that recorded 10 quadrats (0.5 m² each) at each site. Because of the low sea urchin densities at these sites, test diameters were measured for all recorded specimens. Mean sea urchin density values were calculated for each site ($n=292$) and for each depth zone within a site ($n=580$). An analysis of variance (ANOVA) was used to test if there were significant differences in mean sea urchin density and test diameter among survey strata.

Five test diameter categories were created to more accurately represent the wide range of individual sea urchin weights. The categories were based on the state's minimum and maximum size restrictions, allowing us to separately estimate the biomass of sea urchins that have not yet recruited to the fishery, sea urchins within the fishery, and sea urchins that have escaped the fishery. The minimum (50 mm) and maximum (80 mm) size limits for our study were set slightly wider than the those of the state, because, according to the fishery regulations, up to 10% of the catch can be illegal-size sea urchins. Size-frequency data from sub-

sampled quadrats were applied to the mean sea urchin density for the specific depth zone and site, to generate density values for each size category. Weight per sea urchin was calculated from the mean length of the category by using a length-weight relationship (Scheibling et al., 1999).

Spatial interpolation

A sample semivariogram, often abridged to variogram, was generated from mean sea urchin densities by site, to examine the second-order spatial variation in the data set. The sample variogram was calculated with the following equation (Bailey and Gatrell, 1995):

$$\gamma(h) = \frac{1}{2n(h)} \sum_{S_i - S_j = h} (z_i - z_j)^2, \quad (1)$$

where S_i and S_j = sampling point pairs with (x,y) coordinates;

n = the number of sample point pairs;

h = the distance between pairs; and

z = mean urchin density for the sample.

Trends in the variogram provide insights into the viability of second-order methods for the sea urchin data.

Representations of the large-scale trends in sea urchin density were created by using Delaunay triangulated irregular networks (TINs) (ArcView 3.2a, 3D and Spatial Analyst Extensions, Redlands, CA). First, the sample points were plotted by using sea urchin density (/m²) as the z value. Second, each point was connected to the three nearest sites by linear interpolation, forming a continuous surface of nonoverlapping triangles (Fig. 2) (Bailey and Gatrell, 1995; Guan et al., 1999). Thus, the z value of any location within a triangular surface is based solely on the three nearest sites. TIN surfaces were generated for 40 different scenarios, according to the size category, depth zone, and management area, which minimizes variability and allows us to produce more realistic biomass estimates. Finally, using a customized C++ program,¹ we modified each surface to include only areas of appropriate sea urchin habitat. The green sea urchin is most commonly found on rocky substrate in the shallow subtidal (Scheibling and Hatcher, 2001), and, accordingly, the original survey program was limited to areas with predominately rock or gravel substrata in areas less than 40 meters deep. Therefore, we used a map of surficial geology to identify areas of the correct substrate type (1:100,000 scale) (Kelley et al., 1997) and digital gridded bathymetry data to create a plot of 5-m isoline contours. The bathymetry data source consisted of digital bathymetry data sets from sources such as NOAA and the Naval Oceanographic Office (15 arc second resolution) (Roworth and Signell, 2002).

¹ The C++ code used in this study is available upon request from the principal author (RCG).

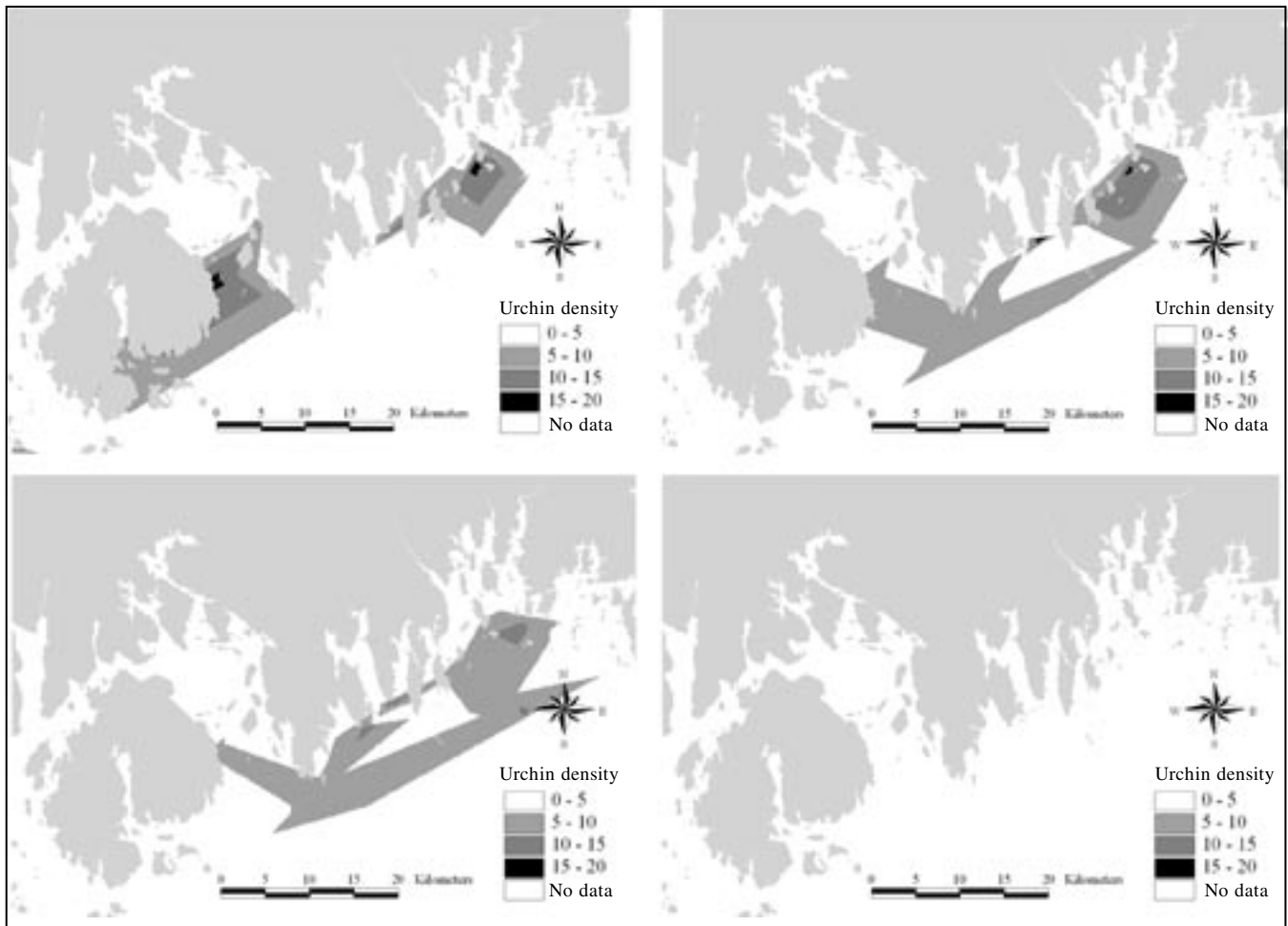


Figure 2

Representations of the triangulated irregular networks (TINs), used to characterize the large-scale patterns in green sea urchin (*Strongylocentrotus droebachiensis*) density (number of sea urchins/m²), for the 50–64 mm sea urchin size category in the central portion of management area 2. Top left, 0–5 m depth zone; top right, 5–10 m depth zone; bottom left, 10–15 m depth zone; bottom right, 15–40 m depth zone.

To determine total sea urchin biomass (b) for each scenario, the volume beneath the modified TIN surface was calculated, from Riemann sums, and multiplied by the mean weight (w) according to the following equation:

$$b = w \sum_{i=1}^n f(s_i) g, \quad (2)$$

where s_i = the spatial location (x, y) on an ASCII grid;
 n = the number of grids squares;
 $f(s_i)$ = the TIN surface and corresponds to a z value for each grid cell; and
 g = the grid cell size, which was 1.72 hectares for area 1 and 1.82 hectares for area 2.

Fishable biomass is defined as the biomass of all legal-size sea urchins and is simply the subset of the total biomass corresponding to legal-size sea urchins. Exploitable biomass corresponds to the legal-size sea

urchins that are available to the fishery. Some areas included in this study may not be subject to fishing pressure because of geographic isolation or low sea urchin densities. Because information on historical fishing grounds is insufficient, exploitable biomass was estimated by using a threshold density value. Only areas with densities greater than the threshold were included in the exploitable biomass estimates.

Two different types of threshold values were tested: 1) a threshold based on total sea urchin density and 2) a threshold based on the density of legal-size sea urchins. The threshold values make different assumptions about the fishery: method 1 assumes that fishermen target areas based on total sea urchin density, whereas method 2 assumes that fishermen target areas based on the density of legal-size sea urchins. Interviews were conducted with state sea urchin biologists and fishermen to determine an appropriate threshold value. The reported threshold values, the minimum total sea

urchin density that could attract fishermen, ranged from 20–50 sea urchin/m². For the first scenario, the mean density from the range of recommended values, 35 sea urchin/m², was selected. Therefore, the biomass of legal-size sea urchins was calculated only in areas where total sea urchin density was equal to or greater than 35/m². For the second scenario, we estimated that commercial divers target areas that have greater than 10 legal-size sea urchins/m².

Estimation of uncertainty and stock assessment

Because information on uncertainty cannot be directly obtained from the TIN method, cross validation was employed to approximate uncertainty in the estimation process. Cross validation involves randomly removing a site from a data set and predicting its value based on the other data points using the TIN process (Bailey and Gatrell, 1995). Residuals, or prediction errors, are calculated between the predicted and true values at the site. The process is repeated n times, resulting in an observed set of n prediction errors, or residuals. The frequency distribution and spatial distribution of residuals provide insights into the accuracy of the model; an ideal model would have a mean residual value of 0 and positive and negative residuals would be distributed randomly over the study area.

Sea urchin biomass values were also calculated with the arithmetic mean to provide comparisons with the spatially derived estimates. For total biomass, mean sea urchin densities by survey strata were multiplied by a spatially derived area estimate of suitable sea urchin habitat (<40 meters in depth) in the strata and the mean sea urchin mass per strata. Fishable biomass was calculated the same way but sea urchin density values were scaled by the proportion of legal-size sea urchins in the stratum. Finally, exploitation rates, or the ratio of commercial landings to the exploitable biomass estimates, were calculated to facilitate comparison with the results generated from the population dynamics stock assessment and a recent study on biological reference points (Chen and Hunter, 2003; Grabowski and Chen, 2004).

Results

Sea urchin density and size frequency, which were used to calculate biomass, varied considerably along the coast of Maine. Density (number of sea urchins/m²) differed significantly among survey strata ($P < 0.05$; ANOVA), showing a general large-scale trend of increasing density from stratum 1 to 9 (Table 1). Density also varied by depth; the sea urchin density in the 15–40 m depth zone was 0.32 sea urchins/m², significantly lower than those of the three shallow (<15 m) depth zones ($P < 0.05$, t -test), which each had approximately 9.50 sea urchins/m². Sea urchin test diameter varied from 3 mm to 114 mm (mean at 35.90 mm). Test diameter differed significantly among survey strata ($P < 0.05$; ANOVA), in which strata 4, 5, and 9 had the smallest size sea urchins, and strata

Table 1

Quadrat density counts (/m²) for the green sea urchin (*Strongylocentrotus droebachiensis*) by management area and survey strata. Sample size, n , is the number of quadrats observed.

Area	Stratum	Density			SD	n
		Min.	Max.	Mean		
1	1	0	36	0.17	1.62	1706
	2	0	130	2.57	10.63	1600
	3	0	141	3.20	11.29	1580
2	4	0	180	4.20	14.13	1490
	5	0	127	4.24	12.52	1580
	6	0	147	10.06	17.59	1530
	7	0	113	7.90	13.85	1498
	8	0	113	13.50	20.38	1570
	9	0	280	34.45	44.03	1540

Table 2

Sea urchin test diameter (mm) for green sea urchins (*Strongylocentrotus droebachiensis*) subsampled in the fishery-independent survey program.

Area	Stratum	Density			SD	n
		Min.	Max.	Mean		
1	1	7	80	38,69	21,07	29
	2	3	81	39,01	22,19	627
	3	4	89	45,25	18,90	855
2	4	3	89	32,99	19,82	1148
	5	3	77	29,25	17,56	1034
	6	4	110	39,87	16,23	1734
	7	5	92	47,23	16,07	1283
	8	3	114	42,11	16,86	2567
	9	3	114	28,84	12,90	5263

3 and 5 had the largest (Table 2). No meaningful trend was evident in the sample variogram, which showed a pure nugget effect (Fig. 3). This result indicates that the sea urchin density data were too spatially variable to be analyzed by intrinsic small-scale methods.

Total sea urchin biomass was estimated at approximately 250,000 metric tons (t), and legal-size sea urchins accounted for 165,000 t (Fig. 4). Most of the biomass was found in management area 2, which accounted for over 75% and 80% of the total and fishable biomass, respectively (Table 3). For both estimates, biomass varied by depth, being highest in the 0–5 m depth zone and lowest in the 15–40 m depth zone (Fig. 5).

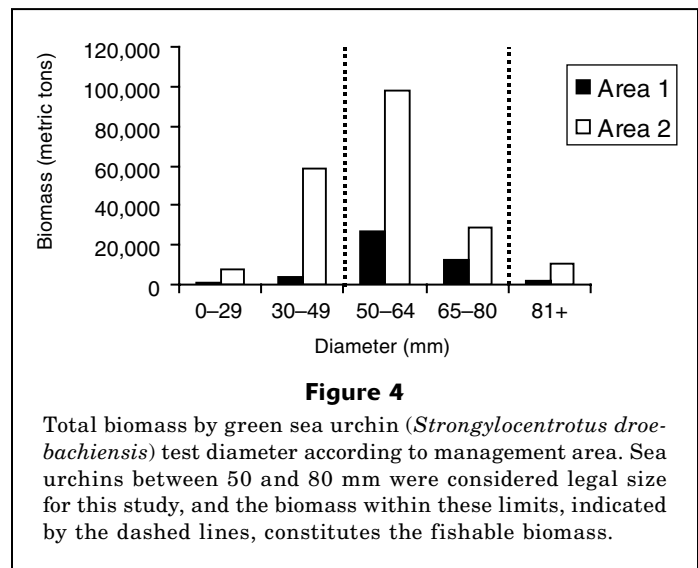
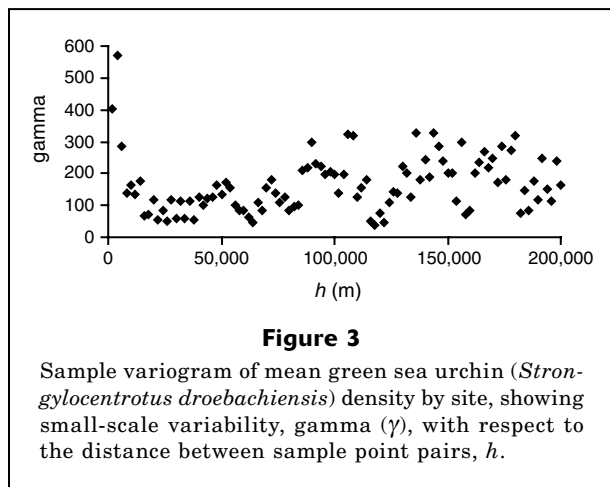
The two methods used to estimate exploitable biomass produced different biomass estimates with unique

Table 3

A summary of 2001 biomass estimates and 2000-2001 landings, in metric tons, for the Maine green sea urchin fishery. Biomass estimates for the TIN method and arithmetic mean were generated in this study, whereas the population dynamics estimates are from Chen and Hunter (2003). Area 1 consists of strata 1-3 and area 2 consists of strata 4-9. When possible, 95% confidence intervals are included, in italics.

	Area 1	Area 2	Total
TIN method			
Total biomass	45,868	204,304	250,172
Fishable biomass	39,060	126,725	165,786
Exploitable biomass			
Method 1	3645	5793	9438
Method 2	10,886	12,069	22,955
Arithmetic mean			
Total biomass	47,933	290,954	338,887
	<i>(42,399-54,331)</i>	<i>(274,632-307,977)</i>	<i>(317,031-362,308)</i>
Fishable biomass	24,241	90,185	114,426
	<i>(21,575-27,287)</i>	<i>(85,144-95,144)</i>	<i>(106,719-122,723)</i>
Population dynamics	6550	8452 ¹	15,002
	<i>(4041-9450)</i>	<i>(5866-11,701)</i>	<i>(10,307-21,151)</i>
2000-2001 landings	2148	3213	5361

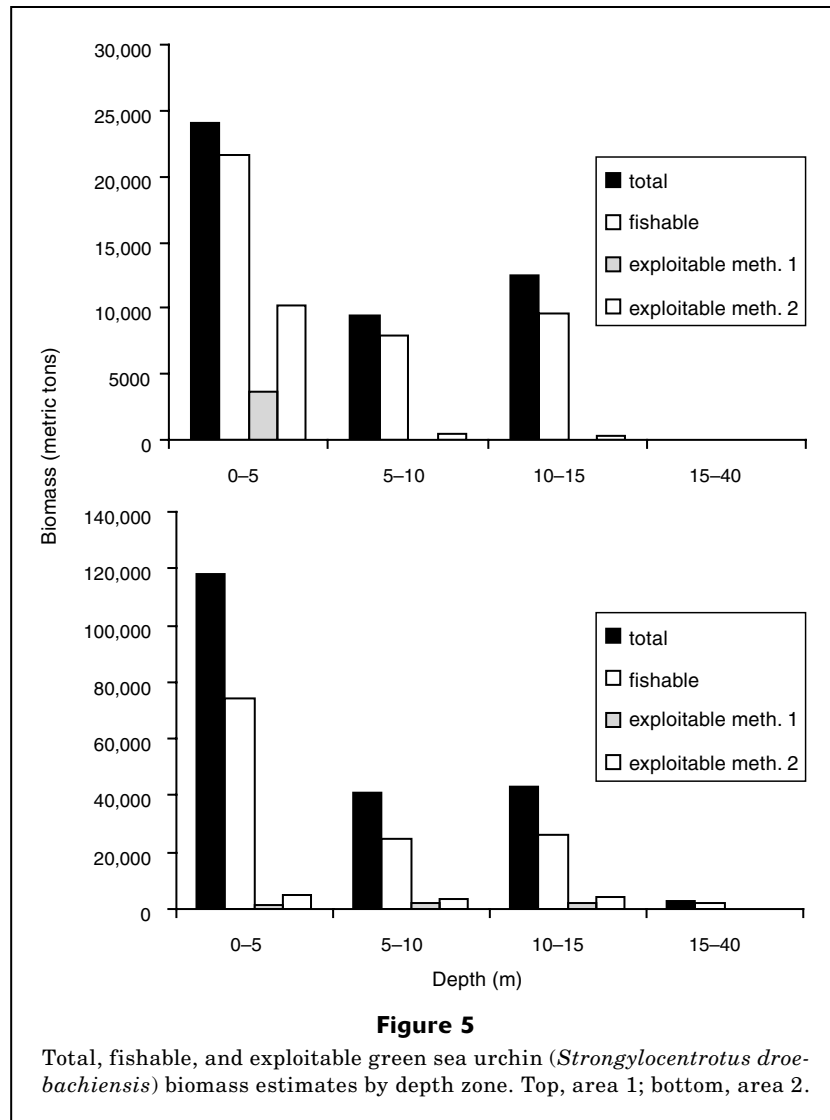
¹ 2000 value.



spatial distributions. Exploitable biomass estimates for method 2 were more than 2 times greater than those for method 1 (Table 3). With method 1, legal-size sea urchins were concentrated in the northeastern corner of management area 2, but with method 2, they were concentrated in the northeastern portion of area 1 and the central portion of area 2 (Fig. 6). Exploitable sea urchin biomass showed different patterns by management area and depth than did total biomass and fishable biomass (Fig. 5). For example, management area 1 had a larger share of the total exploitable biomass, 39% or 47%, for methods 1 and 2, respectively, and

this biomass was almost exclusively found in the 0-5 m depth zone, accounting for 98% or 93%, respectively, of the area's biomass.

TIN biomass estimates were similar to ones produced with the arithmetic mean but were higher for total biomass and lower for fishable biomass. Exploitation rates for method 1 were estimated at 0.59 and 0.55 for management areas 1 and 2, respectively, and 0.20 and 0.27 for method 2, respectively. Exploitation rates



from the population dynamics modeling approach were 0.38 and 0.57 (2000) for management areas 1 and 2, respectively.

Cross validation of sea urchin density surfaces yielded a mean residual of 0.50 (median=0, standard deviation=1.86, skewness=2.80, $n=60$) (Fig. 7). Residuals were greatest in regions with the highest spatial variability, such as sites within depth zones 1 and 2 and in the eastern survey strata.

Discussion

Spatial variability and distribution

The objective of this study was to investigate the spatial variability in green sea urchin density to estimate the biomass of the Maine stock. However, several factors limited the choice of spatial statistical approaches that

could be used to assess the fishery. In particular, the physical structure of the study area, the dependence of sea urchin variables upon the environment and a high degree of small-scale spatial uncertainty make small-scale approaches inappropriate.

First, the study area was neither uniform nor continuous. Because the aim of the fishery-independent survey program was to assess the whole population of sea urchins in Maine, the study area had to span the entire coastline. Consequently, the study area encompassed many features that create discontinuities in a spatial model at varying, yet relatively small, spatial scales. These features included the highly indented coastline, the presence of several hundred islands and the exclusion of regions because of environmental constraints. Second, green sea urchin variables were not independent of the study area; rather, they were dependent on several environmental, ecological, and anthropogenic factors. In particular, depth, substrate type,

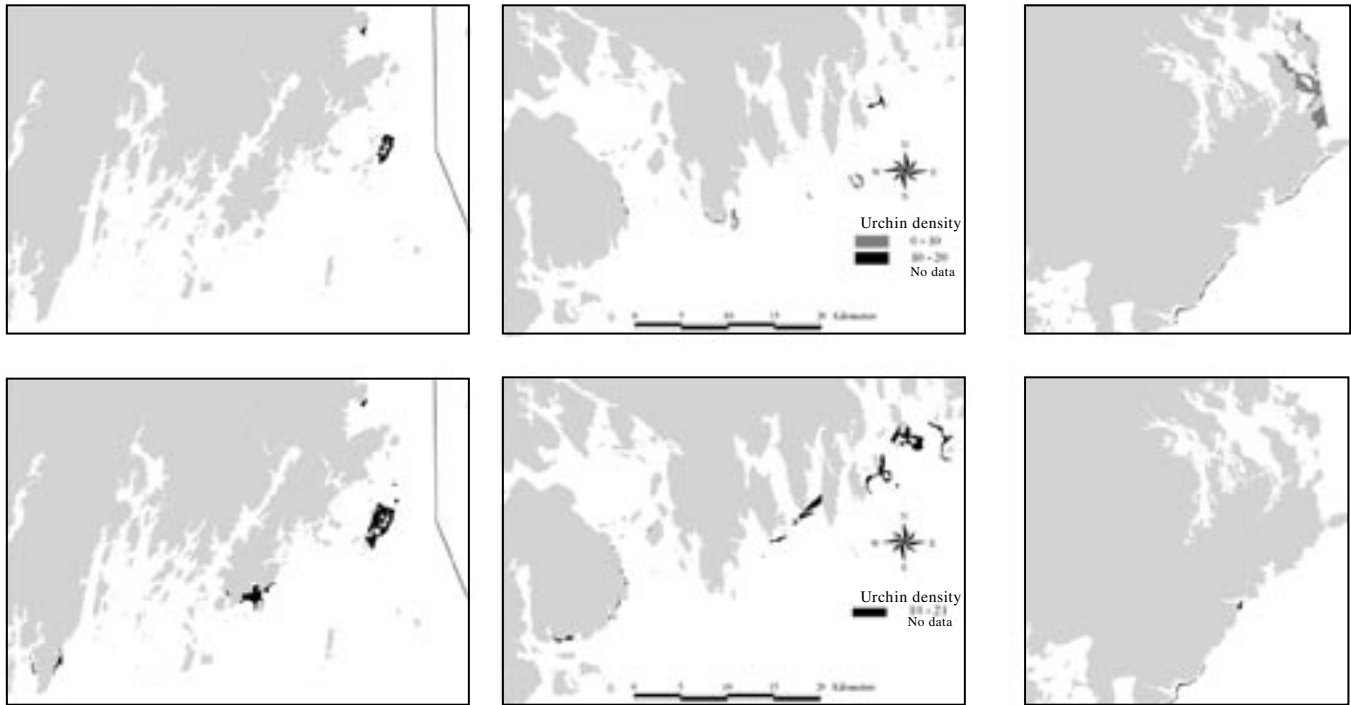


Figure 6

Final spatial representations of the density of exploitable green sea urchins (*Strongylocentrotus droebachiensis*). Top row, method 1: threshold was based on total sea urchin density. Bottom row, method 2: threshold was based on legal-size sea urchin density. Left column, eastern portion of management area 1; middle column, central portion of management area 2; right column, northeastern corner of management area 2.

benthic algal presence, and the presence and level of fishing or predatory activity all greatly affect urchin density, growth rates, and size frequency (Vadas et al., 1986; Scheibling and Hatcher, 2001). Mean sea urchin density and size frequency were not constant over the study area (Tables 1 and 2). Density exhibited large-scale spatial trends along the coast, which are related, at least, to depth and fishing activity. The eastward increase in total sea urchin density along the coast corresponded well with the historical patterns of commercial sea urchin fishing in the State of Maine (Table 1). The fishery began in the southwest, but as sea urchin densities dropped in those regions, the fishery steadily progressed northeastward along the coast. Spatial patterns in density by depth (0–15 m vs. 15–40 m) may have been caused, in part, by the difference in sampling techniques, yet the magnitude of the differences and support from ecological studies indicate that there is a pattern. Finally, sea urchin densities varied dramatically on small spatial scales—variations on the order of one magnitude within the same habitat, and sometimes only meters apart, are not uncommon (Scheibling and Hatcher, 2001). This variability was evident in the variogram analysis, which showed no meaningful small-scale spatial structure and thus no stationarity (Fig. 3).

We were interested in identifying a spatial statistical approach that would generate reasonable estimates

of stock biomass. The numerous discontinuities in the study area, the dependence of variables on ecological factors, and the high spatial variability indicated that an intrinsic spatial statistical approach was not appropriate for the investigation. Therefore, we needed an approach that was geared towards the detection and modeling of large-scale variability and that also exhibited some robustness to discontinuities caused by the indented coastline, islands, and habitat constraints. We believe the TIN approach used in this study satisfies these requirements, and, additionally, allows for varying levels of resolutions, with finer resolution in high density sampling areas.

Biomass estimates

We calculated exploitable biomass in two different ways because of the different assumptions they make about the fishery. Method 1 assumes that fishermen target areas based on total sea urchin density, whereas method 2 assumes that fishermen target areas based on the density of legal-size sea urchins. The spatial distributions of legal-size sea urchin density, which were used to calculate exploitable biomass, were distinctive and showed little overlap between methods (Fig. 6). The spatial distributions appear to reflect different aspects of the sea urchin fishery. When the threshold was based on total density (method 1), exploitable biomass was

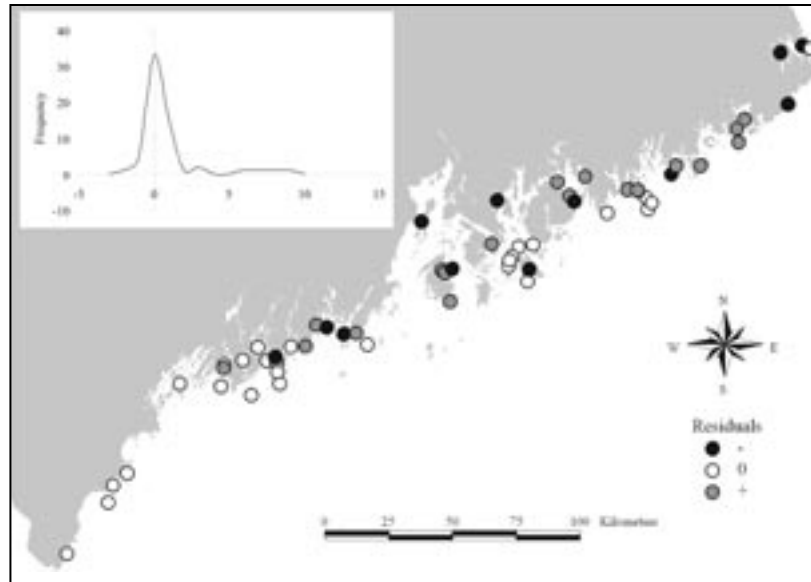


Figure 7

Spatial distribution of residuals and frequency distribution, insert (median=0, standard deviation=1.86, skewness=2.80, $n=60$), from the cross-validation study that addressed uncertainty in the TIN estimation process for estimating biomass for the green sea urchin (*Strongylocentrotus droebachiensis*) fishery.

concentrated in the eastern corner of management area 2, which is the most northeastern location on the coast of Maine. This area has high total sea urchin densities, but relatively low densities of legal-size adults, and is an important location for the trawling industry. When the threshold was based on the density of legal-size sea urchins (method 2), however, exploitable biomass was concentrated in the eastern portion of management area 1 and the central portion of area 2. These regions have lower average sea urchin densities, but higher percentages of legal-size adults, and are key fishing grounds for the state's dive-based fishery.

Because the two methods reflected different aspects of the fishery, it is not surprising that they produced different estimates of exploitable biomass (Table 3). Nevertheless, these estimates did not differ considerably from those of the population dynamics model. The spatial analysis estimates bordered the ones derived from the population dynamics model; method-1 estimates were smaller than those derived from the population dynamics model whereas method-2 estimates were larger. The biomass estimates were similar despite the fact that they were derived from different models (spatial analysis and population dynamics model) using entirely different data sources (fishery-independent and fishery-dependent).

The status of a fishery is often determined by comparing the current fishing mortality or stock biomass with biological reference points (BRPs) (Hilborn and Walters, 1992). The previous stock assessment study estimated that the sea urchin stock biomass in Maine is only about 10% of the virgin biomass, implying that the

fishery has been severely overfished. A preliminary investigation into BRPs recently estimated a BRP $F_{0.1}$ for the urchin fishery, based on a yield per recruit analysis, and concluded that estimates of the current exploitation rate are much higher than the BRP, which means that the fishery is being overfished (Grabowski and Chen, 2004). However, when we compare the TIN exploitation rates with the preliminary mean BRP $F_{0.1}$, which ranged from 0.37 to 0.43 depending upon uncertainty levels, we get an unclear assessment of the stock status. The fishery is being drastically overfished according to method 1, but is healthy according to method 2. We believe that the assessment generated by method 2 was unrealistically optimistic, considering the results from the stock assessment and the decade-long declining trend in landings.

Uncertainty and further studies

The TIN method was an appropriate spatial statistical approach for estimating biomass for the sea urchin fishery; however, a disadvantage of this technique is that there is no straightforward method to estimate the uncertainty in the biomass estimates. Because the technique does not incorporate a variance structure into the estimation process, we could not directly estimate uncertainty. Therefore, we used cross-validation to approximate the uncertainty associated with the TIN method (Fig. 7). We found that the mean residual did not equal zero, indicating that there is a global bias in the TIN surfaces and that biomass estimates were likely overestimated (Simard et al., 1992). This bias was most likely caused

by a combination of the underlying patterns in spatial variability, the linear interpolation method employed in TIN formation, and the effects of sample selection in the cross-validation study. There are several possible ways to reduce the bias in the estimation process, such as incorporating a smoothing function or weighting based on neighbors into the TIN model. This procedure would not completely address uncertainty, however, because it would only acknowledge uncertainty in the TIN estimation process. To obtain confidence intervals for biomass estimates, we needed to incorporate uncertainty in mean density and in TIN estimation. We are currently investigating methods to estimate confidence intervals, such as using a Monte Carlo simulation approach. A thorough examination and quantification of uncertainty is beyond the scope of this article.

In this study, we identified a basic approach for investigating spatial patterns, and estimating stock biomass in situations where second-order methods are inappropriate. The TIN technique generated realistic biomass estimates that are similar to those derived with other approaches, but before we can recommend this technique for the green sea urchin fishery, several points must be addressed. First, the two methods used to estimate exploitable biomass must be integrated because they reflect different aspects of the fishery and result in different stock assessments. Second, a process must be established to estimate threshold levels because they have a large control over exploitable biomass estimates. Finally, a technique must be developed to estimate uncertainty in biomass. We would also recommend further investigations into tracking fishing pressure and identifying its effects on the benthic ecosystem and the spatial distribution of sea urchins.

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Literature cited

- Bailey, T., and A. Gatrell.
1995. Interactive spatial data analysis, 413 p. Pearson Education, Essex, England.
- Chen, Y., and M. Hunter.
2003. Assessing the green sea urchin (*Strongylocentrotus droebachiensis*) stock in Maine, USA. *Fish. Res.* 60:527–537.
- Guan, W., R. H. Chamberlain, B. M. Sabol, and P. H. Doering.
1999. Mapping submerged aquatic vegetation with GIS in the Caloosahatchee Estuary: evaluation of different interpolation methods. *Mar. Geod.* 22:69–92.
- Grabowski, R., and Y. Chen.
2004. Incorporating uncertainty into the estimation of the biological reference points $F_{0.1}$ and F_{max} for the Maine green sea urchin (*Strongylocentrotus droebachiensis*) fishery. *Fish. Res.* 68:367–371.
- Hilborn, R., and C. J. Walters.
1992. Quantitative fisheries stock assessment: choice, dynamics and uncertainty, 570 p. Chapman and Hall, New York, NY.
- Kelley, J. T., W. A. Barnhardt, D. F. Belknap, S. M. Dickson, and A. R. Kelley.
1997. The seafloor revealed: the geology of the northwestern Gulf of Maine inner continental shelf, 55 p. Open file source 96-6. Maine Geological Survey, Natural Resources Information and Mapping Center, Augusta, ME.
- Lembo, G., T. Silecchia, P. Carbonara, A. Acrivulis, and M. T. Spedicato.
1998. A geostatistical approach to the assessment of the spatial distribution of *Parapenaeus longirostris* (Lucas, 1846) in the central-southern Tyrrhenian Sea. *Crustaceana* 72:1093–1095.
- Maravelias, C. D., D. G. Reid, E. J. Simmonds, and J. Haralabous.
1996. Spatial analysis and mapping of acoustic survey data in the presence of high local variability: geostatistical application to North Sea herring (*Clupea harengus*). *Can. J. Fish. Aquat. Sci.* 53:1497–1505.
- Maynou, F. X., F. Sarda, and G. Y. Conan.
1998. Assessment of the spatial structure and biomass evaluation of *Nephrops norvegicus* (L.) populations in the northwestern Mediterranean by geostatistics. *ICES J. Mar. Sci.* 55:102–120.
- Pelletier, D., and A. M. Parma.
1994. Spatial distribution of Pacific halibut (*Hippoglossus stenolepis*): an application of geostatistics to longline survey data. *Can. J. Fish. Aquat. Sci.* 51:1506–1518.
- Petitgas, P.
1993. Geostatistics for fish stock assessments: a review and an acoustic application. *ICES J. Mar. Sci.* 50: 285–298.
2001. Geostatistics in fisheries survey design and stock assessment: models, variances and applications. *Fish and Fisheries* 2:231–249.
- Ripley, B. R.
1981. Spatial statistics, 252 p. John Wiley & Sons, New York, NY.
- Rivoirard, J., J. Simmonds, K. G. Foote, P. Fernandes, and N. Bez.
2000. Geostatistics for estimating fish abundance, 206 p. Blackwell Science, Oxford, UK.
- Roworth, E., and R. Signell.
2002. Construction of a digital bathymetry for the Gulf of Maine. <http://woodshole.er.usgs.gov/project-pages/oracles/gomaine/bathy/data.htm>. [Accessed 22 October 2002.]
- Scheibling, R. E., A. W. Hennigar, and T. Balch.
1999. Destructive grazing, epiphytism, and disease: the dynamics of sea urchin-kelp interactions in Nova Scotia. *Can. J. Fish. Aquat. Sci.* 56:2300–2314.

- Scheibling, R. E., and B. G. Hatcher.
2001. The ecology of *Strongylocentrotus droebachiensis*.
In *Edible sea urchin biology and ecology* (J. M. Lawrence,
ed.), p. 271–304. Elsevier, New York, NY.
- Simard, Y., P. Legendre, G. Lavoie, and D. Marcotte.
1992. Mapping, estimating biomass, and optimizing sam-
pling programs for spatially autocorrelated data: case
study of the northern shrimp (*Pandalus borealis*). *Can.*
J. Fish. Aquat. Sci. 49:32–45.
- Vadas, R. L., R. W. Elner, P. E. Garwood, and I. G. Babb.
1986. Experimental aggregation behavior in the sea urchin
Strongylocentrotus droebachiensis. *Mar. Biol.* 90:
433–448.
- Vadas, R. L., Sr., B. D. Smith, B. Beal, and T. Dowling.
2002. Sympatric growth morphs and size bimodal-
ity in the green sea urchin (*Strongylocentrotus*
droebachiensis). *Ecol. Monogr.* 72:113–132.
- Warren, W. G.
1998. Spatial analysis for marine populations: factors
to be considered. In *Proceedings of the North Pacific*
symposium on invertebrate stock assessment and man-
agement (G. S. Jamieson and A. Campbell, eds.), p.
21–28. *Can. Spec. Publ. Fish. Aquat. Sci.* 125.