INTRODUCTION AND BACKGROUND

Populations of the eastern oyster (Crassostrea virginica) have been in long-term decline in many areas, including the proposed study area in New Hampshire (Kennedy 1989; MacKenzie 1996; Hargis and Haven 1999; Langan 2000; Smith 2002; Trowbridge 2002, 2005; Odell et al. 2006; EOBRT 2007). Most Atlantic coastal states have oyster management programs based on periodic monitoring of size, density, and other characteristics of the reef structures oysters typically form. However, there is no generally accepted protocol for accurately and economically obtaining such data. In part, this is because oysters occur in both intertidal and subtidal areas (Bahr and Lanier 1981; Burrell 1986). Although much remains to be learned, aerial photography is becoming a standard technique for mapping and characterizing intertidal oysters (Grizzle 1990; Finkbeiner et al. 2001; Grizzle et al. 2002; Martin et al. 2003; Vincent et al. 2003). Mapping and characterizing oyster reefs in deeper and/or turbid waters, however, remains problematic.

A variety of "traditional" monitoring methods exists for subtidal reefs and most rely on extractive sampling methods. For example, in New Hampshire oyster distributions and abundances have been estimated using a combination of methods, including quadrat excavation by divers, tonging, and dredging (Nelson 1982; Banner and Hayes 1996; Langan 1997, 2000). Similar methods are used in other coastal areas (Jordan et al. 2002; Powell et al. 2002; Mann et al. 2004). At best, these techniques yield estimates that are useful with respect to general location and abundances in selected areas. They are not, however, capable of providing accurate information on reef size and in practice rarely provide spatially extensive data because of the expense involved in taking and processing large numbers of samples. There is a need to develop better, cost-effective methods to remotely sense oyster reefs that provide spatially detailed information on distributions, abundances, and other reef characteristics.

It has been demonstrated that various acoustic techniques such as sidescan sonar and single beam sounders as well as underwater videography, can identify oyster reef bottom (Simons et al. 1992; Powell et al. 1995; Mayer et al. 1999; Paynter and Knoles 1999; Roberts et al. 1999; Wilson et al. 2000; Smith et al. 2001, 2003, 2005), but the extent to which reef characteristics such as shell densities can be remotely sensed using these techniques has not been thoroughly assessed.

OBJECTIVES, METHODS, AND BRIEF RESULTS

This project had the overall goal of development of new and innovative remote sensing techniques for characterizing subtidal oyster reefs, culminating in a recommended general protocol for further testing. We assessed the effectiveness of newly developing acoustic (sonar), visualization, videography, and GIS-based mapping methods. The following six major objectives with methods were addressed.
(1) Conduct acoustic surveys of three oyster reefs in New Hampshire using single beam, multibeam, and sidescan sonar

Acoustic surveys were conducted using a Knudsen 320 BP single (“narrow”) beam sounder (NBS) (at Adams Point and Nannie Island reefs; Fig. 1), a Kongsberg EM 3002 multibeam sonar (at Adams Point reef only), and a Klein 5000 sidescan sonar (at Adams Point and Nannie Island reefs). The Oyster River reef was not surveyed with sonar because shallow-water conditions restricted access by the survey vessels. The relatively shallow-water conditions in all three study areas (and other considerations discussed below) also resulted in a focus on NBS as the primary acoustic method tested. Sonar data were collected during the summers of 2001, 2003, 2004 and 2005.

The NBS data were collected at several frequencies and beam widths, but at all locations data were at least obtained at 50 kHz with a beam width of 24 degrees. Features used for classification were extracted from bottom return signals and included time domain as well as spectral domain features. The Kongsberg multibeam uses 254 dynamically focused beams which enables it to collect data from 1m to 200m below the transducer at three frequencies: 293, 300 and 307 kHz. Both bathymetry and backscatter intensity data were collected. The Klein 5000 sidescan sonar data were collected at 455 kHz using a 100 micro-second pulse at a 50-meter range setting. Differential GPS was used for positioning with accuracies of ~1 m, with the exception of 2005 in which RTK GPS was used in conjunction with Applanix POS-MV inertial navigation system with reported accuracies of ~4 cm.

Fig. 1. General location of study areas at three oyster reefs in the Great Bay Estuary system, New Hampshire.
(2) Determine the spatial extent of each study reef and characteristics (e.g., shell densities) potentially derivable from the acoustic data using sediment characterization and visualization software presently under development.

Several steps were involved in processing the NBS data (see Fig. 2 for example dataset). Returns were initially isolated by examination of ping intensity and time period, and a subset was selected for further processing following methods in Preston et al. (2006). Fast Fourier and wavelet transforms were then applied to derive 45 features representing the spectral characteristics of the data, followed by a low pass filter to extract rise time, total energy, peak amplitude and fall time. Bottom identification and verification were then achieved using sorting and forecasting methods described in (Dijkstra 2000).

![Fig. 2. TracEd (Dijkstra, 2000) visualization of NBS (ODOM CV 3) data. The upper image is a traditional echo sounder record with an overlay of bottom picks (green). Outliers appear as discontinuities in the green line, and may be edited using algorithms in TracEd. The lower images with blue background show ping time series centered around the location highlighted by the white line in the upper display. The left display is the entire time series while the right is zoomed to the bottom returns.](image)

After classification and verification, the data were segmented in two stages using unsupervised approaches in principle component analysis (Fig. 3). The resulting multivariate data were described by finite, parameterized Gaussian mixture models fit by likelihood maximization using an EM (Expectation-Maximization) method (Dempster et al., 1997) and Bayesian information criterion (BIC). MCLUST software (Fraley and Raftery, 2002) algorithms within the Lassoo visualization and segmentation software (Dijkstra and Mayer, 1996) were used for calculating ellipsoidal distributions of varying volume, shape and orientation.
Fig. 3. Example dataset showing bottom segmentation using EM clustering in MCLUST algorithms, and visualization of the segmentation in Lasoo (Dijkstra and Mayer, 1996). In this case the color specifies class and the axes represent the four feature dimensions extracted by principle component analysis.

Fig. 4. Two stages of bottom classification of NBS data from Adams Point reef. A) three bottom types were found, with the pink thought to be high densities of oyster shell. F) Feature data belonging to the potential “oyster” class were then resubmitted to the EM clustering algorithm to obtain the final distribution, with potential oyster reef shown in red.
After segmentation, each NBS dataset was classified into multiple “bottom types,” in this case potentially representing different levels of shell cover, densities or other characteristics associated with oyster reefs. A two-stage process involving repeated EM clustering methods (see above) were used to accomplish final classification for further assessment via groundtruthing methods (Objectives 3 and 4); this process is illustrated for the Adams Point reef in Figure 4.

(3) Videographically image each study reef at a spatial scale sufficient to determine the boundaries and other characteristics of each reef

All three study reefs were videographically imaged on multiple occasions using two different systems. One consisted of a black & white/infrared camera system (Aqua-Vu Model IR) mounted on a steel frame with the lens pointing directly toward the bottom, a Garmin differential GPS unit (Model GPS 76), laptop PC for navigation and GPS datalogging, and Sony digital video camera (Model DCR-TRV103) for recording (Fig. 5). The second system consisted of similar components to those shown in Figure 5, except the camera was mounted on a sled with the camera lens aimed at an oblique angle relative to the bottom.

Two of the three study reefs, Nannie Island and Adams Point, were partially (~80% coverage) imaged during summer 2004. During summer and fall 2005, imagery was collected from all three study areas using the same system and extending the coverage to ~100% of the areas thought to be “oyster bottom” based on earlier surveys. Based on analysis of this imagery, each study area was again imaged using the sled-deployed system during spring and summer 2006. Video imaging also was conducted in conjunction with water sampling for turbidity assessments on several occasions during 2004, 2005 and 2006 to determine the range of turbidity under which satisfactory image quality could
be obtained.

When imaging with the suspended system (Fig. 5), the frame with camera was suspended in the water column from a steel cable on a manually operated winch with a short arm extending over the boat's gunwale. After positioning the camera at a height suitable for obtaining adequate image quality and swath width (typically about 0.5 m), the unit was slowly towed (at speeds up to about 1.5 knots) so that it remained approximately directly below the winch. The video image was split onboard to a camcorder for recording and a monitor so the operator could see the imagery in real time. This allowed for quick adjustments of the camera height or other changes as needed. Ship tracks were monitored in real time on the PC with navigational software, and GPS data were logged. The video imagery and GPS data were synchronized by time, which was recorded in both datasets. The sled system was operated in similar fashion except the sled was deployed from a rope attached to the gunwale with the scope adjusted to maintain the sled directly under the stern. In both deployment modes, brief (3 – 5 sec) stops were made sporadically to insure high quality stills could be extracted from the video stream.

The continuous imagery was visually inspected and assigned a classification of "non-reef" (<10% bottom coverage by oyster shells), "low density reef" (10% to 50% coverage by oyster shells), or "high density reef" (>50% coverage by oyster shells). The entire video stream was inspected and breakpoints between classes were determined. Stills taken from each stationary imagery site were also individually classified in this way. Notes were also made on reef characteristics such as vertical relief, relative amounts of empty shells, and evidence of sediment accumulation. The classification types were then plotted on a base map and polygons were constructed manually, drawing each boundary line approximately midway between adjacent bottom type classes. Areas of polygons for "high density reef" and "low density reef" were determined using ArcGIS software for each of the reefs.

(4) Carryout groundtruthing of the information obtained from Objectives 2 and 3

Video imagery is typically considered groundtruthing for acoustics data, and this was the approach used in the present study. This suggests that video does not typically require groundtruthing. However, the present study also attempted to assess the limits of video imagery for obtaining various characteristics of the reefs such as shell density, live vs. dead shell, etc. Therefore, this objective consisted of two parts: groundtruthing the acoustics data with video, and comparing data derived from video imagery with data derived from diver-extracted quadrat samples.

For the acoustics data, video imagery was compared with maps produced from NBS and sidescan sonar. For NBS, results of the video transect classification (using “high density” and “low density” reef types, together considered to represent “oyster shell” bottom) were directly overlain onto the classified NBS data; this approach is illustrated for the Adams Point reef in Figure 6. For sidescan sonar and multibeam data, video imagery was compared using transect data as well as imagery from stills extracted from the video (Fig. 7 shows the latter approach for the Nannie Island reef).

For comparisons of quadrat data and video-derived data, 0.25 m² samples (quadrat size and size of area imaged) were taken on a total six different days during 2001-2005, and including all three study reefs. Samples were obtained by recording 5 to 10 seconds of video (which yielded a potential of 150 to 300 stills for analysis), then diver excavation of the imaged area and counting and measuring (shell height to nearest mm using calipers) of all live oysters in the sample. The video quadrats were analyzed independently by three individuals, each counting the number of “possibly live” (all individual oyster shells regardless of size except those obviously dead as indicated by disarticulation and typically showing the white interior of the shell) oysters in each image. The three individual counts were averaged and compared to the actual counts of live oysters from the same area imaged.
Fig. 6. Adams Point. Video transects (pink=non-reef; dark red=oyster shell) superimposed over the NBS classified data shown in Fig. 4.

Fig. 7. Nannie Island reef. Mosaic of sidescan sonar data with systematic grid overlay showing locations where video imagery was taken in drop camera mode. Selected stills extracted from video imagery from locations indicated by yellow dots.
The comparisons of video quadrat counts with diver extracted quadrat counts indicated that video can potentially provide useful data on oyster shell densities and sizes but there are limitations to its use in this respect. A total of thirty-five 0.25 m² quadrats were video imaged and extracted by divers for counts and measurements of live oysters. Data were obtained from all three study reefs and were made during 2001, 2004 and 2005. A scatterplot of the data and regression analysis showed no overall significant linear relationship between the two (Fig. 8). However, inspection of the scatterplot indicated that much of the variability between the two counts was at the upper ends of both datasets (circled areas in Fig. 8). The raw data showed that when there is abundant dead shell and when there is abundant spat, video counts do not reflect the quadrat counts. Otherwise, there is potential for using video to count and measure (though not done in the present study) live oysters. It is certainly possible to count and measure all shell (dead and live) present in an area.

![Fig. 8. Diver extracted quadrat counts of live oysters vs. quadrat counts of "possibly live" oysters from video still of the extracted area. See text for discussion of circled outliers.](image)

We also preliminarily quantified the relationship between video image quality and water clarity. These studies were conducted because the turbidity typical of estuarine waters is one of the most serious limitations on the widespread use of videography for oyster reef monitoring. On eight different occasions during 2005-2006 video imagery was recorded and water samples were taken for laboratory measurements of turbidity (nephelometric turbidity units; NTU) and/or total suspended solids (TSS; mg/L). An image quality scale was developed as the basis for this assessment (Table 1). Figure 9 below illustrates the range of potentially useful image quality (image quality values from 1 to 4; Table 1) with associated water clarity measurements.
Table 1. Criteria for assigning relative value to the quality of video images obtained under different water clarity conditions.

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<tr>
<th>Image Quality</th>
<th>Criteria</th>
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<tbody>
<tr>
<td>0</td>
<td>no seafloor features visible</td>
</tr>
<tr>
<td>1</td>
<td>some seafloor features faintly visible</td>
</tr>
<tr>
<td>2</td>
<td>some seafloor features faintly visible and identifiable, but accurate shell counts not possible</td>
</tr>
<tr>
<td>3</td>
<td>most seafloor features visible and identifiable, and accurate shell counts possible</td>
</tr>
<tr>
<td>4</td>
<td>all seafloor features visible and identifiable, with limitations only by camera resolution</td>
</tr>
</tbody>
</table>

Referring to Figure 9 below, at turbidity levels below ~5 NTU and TSS ~10 mg/L image quality was excellent, suitable for counting shells, determining potentially live oysters, making shell measurements, and determining other reef characteristics. As turbidity approached ~14 NTU and TSS ~20 mg/L image quality remained potentially useful for some purposes (e.g., determining relative shell densities) but was substantially degraded. At higher turbidity levels image quality was not useful, even with the camera height at only 20 above the seafloor.

These water clarity/image quality relationships represent the result of measurements on eight different occasions, across a wide range of water clarity conditions, and involving all three study reefs. They should, however, be considered preliminary for several reasons. Although a wide range of turbidity levels was included, most imagery was obtained when turbidity levels were low. There is a need to do more detailed studies focusing on moderate turbidity levels, a range of camera heights, and perhaps different types of cameras, to better characterize how image quality is affected. Although turbidity and TSS measurements were made during the study, TSS data were only measured on a few samples. Other measurements related to light penetration and reflectance by suspended particulates might also be made in future studies. Finally, studies need to be conducted in other estuaries.

The other two limitations on underwater videography, tow speed and swath width, are in part controlled by water clarity. Tow speed and swath width could be greatly increased over the 1-2 knots and 0.5 m, respectively, used in most cases during the present study if water clarity was sufficient. For example, Kvernevik et al. (2002) were able to obtain 5-m wide swaths with the camera 5 m above the seafloor when video mapping coral reefs. As already noted, most estuarine waters rarely if ever approach the clarity of tropical marine waters, but there are time intervals in many estuaries when the water is exceptionally clear and would allow increased tow speeds and greater camera height above the bottom.
Fig. 9. Example video stills with associated water clarity data (Nephelometric Turbidity Units [NTU] and TSS [mg/L]) to show the range of image quality (Table 1) under different water clarity levels.
A final aspect of videography not explicitly an objective of the present project but that emerged during the study, was an assessment of its use for obtaining data on reef characteristics not routinely collected as part of most monitoring programs but nonetheless potentially useful in assessing overall reef “health” (Grizzle et al. 2008). Video imagery provides a wealth of information on characteristics not provided by other monitoring methods. For example, nearly all oyster reefs in areas open to harvest in New Hampshire consist mainly of individual shells or at most small clusters. This is largely the result of harvesting by tongs and the overall effect is minimal vertical structure, which is readily characterized with video imagery (Figs. 7, 15 and 16). Organisms other than oysters that typically live on oyster reefs are also readily characterized with video. Reefs in New Hampshire that are in shallow water typically have abundant macroalgae attached to both live and dead shells (Fig. 10D), and in some cases eelgrass growing from soft sediments among the shells (not shown). Other suspension-feeding bivalves are also associated with the oysters on some reefs, including infaunal species such as razor clams in medium and low shell density areas (Fig. 10E). As measurement of the “ecosystem services” provided by oyster reefs becomes more a part of routine monitoring and restoration programs, videography can provide a powerful and non-destructive remote sensing tool (Paynter and Knoles 1999; Coen and Luckenbach 2000; Brumbaugh et al. 2006; Coen et al. 2007; Grizzle et al. 2008).

Fig. 10. Video stills from Adams Point reef showing low (A), medium (B), and high (C) shell densities (see overall reef map in Fig. 11 above), and Nannie Island reef showing low (D), medium (E), and high (F) shell densities (as mapped in Fig. 12). See text for other reef features discernable from these images.
(5) *Produce GIS-based maps of all study reefs*

A variety of GIS-based maps were produced for this project using sonar and video data alone and in combination; Figures 4, 6 and 7 above are examples. The figures below are examples of maps that provide additional comparisons of different kinds of datasets or represent typical management end-products such as shell density patterns. Figures 11 – 13 are examples of GIS-based approaches for visually comparing different kinds of sonar datasets; the focus of each map is given in the legend for the figure. Figures 14 – 16 are examples of video mapping aimed at determining spatial patterns in shell density. Such information could be used, for example, to design a stratified extractive sampling program for further study of each reef.

![GIS-based map example](image)

Fig. 11. Adams Point reef. The NBS classified data (Figs. 4 and 6) superimposed on multibeam bathymetry data collected with the Kongsberg EM 3002. This comparison indicates that the classification results are generally not driven by depth dependence; a common problem in bottom characterization. Similar comparisons of NBS classification with multibeam backscatter and sidescan data indicated better correlation by NBS to video groundtruthing data (Fig. 6) than multibeam or sidescan.
Fig. 12. Adams Point reef. Here, NBS data collected with Quester Tangent’s QTCView is superimposed on the data collected with the Knudsen 320 BP unit. Note that the Quester Tangent classification shows good correlation with the Knudsen data set. The dedicated nature of the approach described here allows the Lasso classification to focus more specifically on the presence of oysters. The locations where oysters were expected in some areas at Adams Point is gravel with diameters similar to those of the oysters present.
Figure 13. Nannie Island reef. Single beam survey and NBS classified data superimposed on sidescan mosaic (Fig. 7). In this case the NBS classification is clearly strongly correlated to the sidescan data.
Fig. 14. Adams Point reef. Shell density map based on video transects with polygons manually drawn delineating low density areas from medium and high density. This kind of map could be used to design a stratified sampling program for extractive sampling.
Fig. 15. Nannie Island reef. Shell density map based on video transects as described in Fig. 14.
(6) **Develop a recommended general protocol for mapping and characterizing subtidal oyster reefs emphasizing acoustics and videography while minimizing destructive sampling techniques**

This objective represented a synthesis of information obtained during the project. It consisted of a comparative assessment of the three techniques (acoustics, videography, quadrat sampling) in the context of potential end users, particularly practical management needs. The maps from Objective 5 were compared with respect to their relative effectiveness in two respects: delineating reef boundaries, and characterizing the reefs with respect to features such as shell densities, live vs. dead oysters, and vertical dimensions. The costs and ease of use of each technique were also considered. The intent was to determine the best use of each method as part of a proposed general protocol for routine monitoring of subtidal oyster reefs.
SIGNIFICANT FINDINGS

This project had the overall goal of assessment of new and innovative remote sensing techniques for characterizing subtidal oyster reefs, culminating in a recommended general protocol for further testing. The major techniques assessed were acoustic (sonars), underwater video, and extractive quadrat counts. The aim was to determine how far remote sensing methods (sonar and video) can be pressed to gather management-related data that have typically been gathered by techniques such as quadrat counts, dredges, or other extractive (and destructive) methods. We discuss the most significant findings by using our results to answer three questions. This is followed by a discussion of related topics.

What are the strengths and limitations of acoustics methods?

As noted, our project focused on single (narrow) beam sounders for several reasons. Multibeam and sidescan sonars are addressed here initially, followed by more extensive treatment focusing on our results for narrow beam units.

Multibeam and sidescan sonars are uniquely capable of providing high-resolution data over large areas because they ensonify wide swaths of seafloor, providing large and complex datasets on seafloor characteristics (NRC 2004). Their major strengths are the ability to relatively quickly gather bathymetric and backscatter data that can be processed to produce high-resolution maps of wide areas of seafloor topography and other features. Hence, multibeam and sidescan sonars are the focus of rapidly developing fields of research as well as widely applied approaches to seafloor mapping, including oyster reefs (Hughes-Clark et al. 1996; Auster et al. 1998; Mayer et al. 1999; Zajac et al. 2000; Kostylev et al. 2001; Smith et al. 2001, 2003; Noji et al. 2004; Allen et al. 2005). These previous studies and our research discussed above indicate that multibeam sonars readily characterize small-scale (centimeters) variations in topography typical of “rough” oyster bottom, and at sufficient shell densities the backscatter data can be used to differentiate between oyster shell and softer substrates.

Sidescan sonar also is capable of differentiating between bottoms dominated by shell and soft sediments and therefore providing high-resolution maps of reef shape, size, and spatial heterogeneity (Allen et al. 2005; but see Smith et al. 2001). These substantial strengths, however, come with limitations.

Probably the most important limitation is cost. High resolution multibeam and sidescan sonar units typically cost over a hundred thousand dollars and require much ancillary equipment that can drive the operating costs to very high levels. They also require highly trained personnel to acquire data useable for classification. Thus, their use for seafloor mapping typically occurs via subcontracts to consulting companies specializing in this service. Another consideration is the complexity of the datasets and the expertise needed for processing. A third limitation—something that is particularly relevant to oyster reef mapping—is that they are most effective in deeper waters because swath width is controlled by the distance between the sonar unit and the bottom. Water depth and survey swath are positively related, so the distance between ship tracks is also determined by water depth if full bottom coverage is the goal. Finally, some type of groundtruthing is required to verify the relationship between the sonar data and any inferences other than water depth for seafloor characteristics. Therefore, although multibeam and sidescan sonars can be used effectively on oyster reefs (Mayer et al. 1999; Smith et al. 2001, 2003, 2005; Allen et al. 2004) their use is not always practical. We turn now to a more in-depth consideration of single beam sonars.

Narrow beam sounders (NBS) were originally developed to aid in safety of navigation and to
increase the efficiency of mapping bathymetry, but not necessarily to map other bottom characteristics. Their most widespread use is in the form of inexpensive fathometers on small boats that typically only sense and process a portion of the overall acoustic signal. However, with the advent of low cost digitizers and mass storage it became possible to collect the envelope of the returned intensities, or even the full waveform. In our project, the major aim was to assess the usefulness of low-cost NBS systems to map and characterize oyster reefs using relatively simple to use software. And the focus was on using the envelope of the returned frequencies rather than the full waveforms because NBS units providing the capability of collecting full waveforms are relatively rare and more expensive. Also this type of data would require an in depth understanding of acoustics and signal processing from the end user. This was also because commercial systems for mapping the seafloor using NBS systems are commercially available and include QTCView and RoxAnn.

The major strengths of NBS units are the significantly lower cost and relative ease of operation, and minimal logistic demands. Although some amount of specific knowledge for successful data acquisition for oyster mapping is required, highly trained operators are not. The major limitations of these units are that they do not allow for analysis of the sonar signal returns as a function of angle of incidence, and the spatial coverage is not as comprehensive as that of multibeam and/or sidescan sonars.

What are the strengths and limitations of underwater videography?

The major strengths of underwater video for oyster reef mapping and monitoring include: (1) ability to provide high resolution imagery showing a variety of oyster reef characteristics; (2) straightforward deployment, image acquisition, and image interpretation; and (3) low cost. The discussion above under Objective 4 and the images in Figures 7, 9 and 10 illustrate the ability of video to provide imagery with higher spatial resolution than any other remote sensing method (also see Grizzle et al. 2008). The information can be obtained in a straightforward manner using small boats, and with minimal effort involved in image processing, interpretation, and final map production. System costs range from inexpensive off-the-shelf underwater cameras that can be used in custom configurations (as in the present study) to ready-to-use use sleds and drop camera units that are widely available (e.g., Seabed Imaging and Mapping System [SIMS]; Coastal and Ocean Resources, Inc.; www.islandnet.com/~cori/). The total cost of the systems used in the present study was ~$4,000 (2008 US$) each. These strengths make videography a potentially very attractive method for routine mapping and characterizing oyster reefs.

The major limitations of video include: (1) image quality strongly affected by water clarity; (2) relatively narrow swath of bottom area imaged; and (3) data acquisition rate limited to relatively slow ship speeds (less than ~2 knots). Of the three, the first is probably the most important from the context of the widespread use of video for oyster reef monitoring because oysters typically occur in estuarine waters characterized by high turbidity levels (Burrell 1986; Stanley and Sellers 1988). Our research has provided a preliminary assessment of this limitation, but more work needs to be done in other areas. The remaining limitations, swath width and ship speed, may be of less concern in most cases but they do place limitations on video and should be considered in determining its adequacy for a particular application.

What are the strengths and limitations of extractive methods?

Extractive methods include quadrat excavation by divers (as in our study), tongs, and dredges. All have the major advantage over remote sensing methods of providing a physical sample of the oyster
population for direct inspection and processing. Therefore, remote sensing methods generally should be viewed from the perspective of their potential to complement extractive sampling. From this perspective, there are three important limitations of extractive sampling for monitoring oyster reefs: (1) impractical for use in determining overall reef shape and size; (2) incapable of determining some reef characteristics relevant to assessment of ecosystem services; and (3) destructive.

Large-scale and long-term oyster monitoring programs in some areas have for decades relied upon periodic sampling with dredges, which typically can only achieve semi-quantitative data suitable for comparisons within a dataset but not across datasets from other areas and/or using other types of sampling gear (Powell et al. 2002; Mann et al. 2004). Diver-extracted quadrats and patent tongs probably are the most widely used quantitative gear types for monitoring oysters. However, to our knowledge neither method has been used to determine shape and size of oyster reefs due to the number of samples that would typically be needed. The second limitation of extractive methods is that they typically do not obtain a sample that can be used to characterize metrics such as vertical structure, associated organisms, and other features relevant to assessing some ecosystem services (Grizzle et al. 2005, 2008; Brumbaugh et al. 2006). The final limitation to extractive methods is that they are destructive. This is perhaps not an issue in most monitoring programs, particularly where the major aim is fishery management because the oysters are being harvested anyway. However, when the focus is on ecosystem services or reef restoration, minimizing destructive sampling may be important.

Can a general protocol be recommended for mapping and characterizing subtidal oyster reefs?

We recognize that no single study could yield a definitive monitoring protocol for the eastern oyster. This is in part because management agencies and others involved in oyster monitoring vary widely in their objectives. A variety of factors may be involved in the decision making process: general environmental conditions such as water depth and clarity, sampling traditions in each area, economic considerations, and others. Therefore, it seems unlikely any one protocol could be widely implemented. Our project, however, has resulted in new comparative knowledge that should be useful for managers seeking to rely more on remote sensing techniques while minimizing extractive sampling methods. Considering the above strengths-and-limitations assessment of acoustic and video techniques, we offer the following general suggestions discussed by major monitoring objectives. This is followed by a table that summarizes the relation between assessment objectives and recommended methods.

**Oyster density and size.** Quantitative extractive methods such as diver-excavated quadrats and patent tongs are the only methods for accurate measurement of oyster density and size, as well as other information (e.g., reproductive state, condition) obtainable only by removing oysters for further processing. Therefore, remote sensing methods in general should be viewed as complementary to extractive sampling if data on density and size are needed. Remote sensing methods, however, can be used to improve the design of extractive sampling programs. For example, acoustics and/or towed videography could be used to determine spatial dimensions and variations in features such as total shell density of a reef. Maps could then be produced to show areas of different shell density (as illustrated above in Figs. 14, 15 and 16), and a stratified (based on shell density) random sampling program designed to allocate extractive samples across the different strata.

**Reef shape and size.** Multibeam and sidescan sonars are capable of differentiating between oyster bottom and other substrate types, particularly soft sediments (Mayer et al. 1999; Wilson et al. 2000; Allen et al. 2005; Grizzle et al. 2005). If practical (considering costs, depth limitations, etc; see above),
multibeam and/or sidescan sonars would be the method of choice for obtaining data on the overall size and shape as well as some aspects of spatial heterogeneity of the reef. Because overall size and shape of a reef typically change on time scales of years or even decades in some cases (Grizzle et al. 2002), these surveys could perhaps be conducted less frequently than other monitoring efforts.

Single-beam sonars provide potentially low cost alternatives to multibeam, and reasonably priced commercial units are available that include hardware as well as software for processing and analyzing the data. Single-beam sonars used in seafloor mapping include relatively inexpensive echo-sounders (Kvernevik, et al., 2002), sub-bottom profiling devices (Smith et al. 2001, 2003), and units designed specifically for discriminating different bottom characteristics (Smith et al. 2003; Riegl, et al. 2005). A major difference between multibeam and single-beam sonars is the latter only insonify a narrow swath of the seafloor along each shiptrack. In a typical application, a relatively small portion of the overall survey area is actually sampled and interpolation techniques are used to infer bottom characteristics between shiptracks. The resulting dataset also requires substantial processing and interpretation as well as groundtruthing, as discussed above.

Underwater videography only recently has been explored as a mapping tool for oysters (Grizzle et al. 2005, 2008). It can be deployed in similar fashion to single-beam sonars, simultaneously logging video and position data along multiple shiptracks (transects) across the study area. And when water clarity is sufficient, video can be used with minimal effort involved in image processing and little or no groundtruthing to produce accurate maps of reef shape and size.

Miscellaneous reef characteristics. The recent emphasis on ecosystem services provided by oyster reefs has resulted in the need to characterize reef features not typically measured. The methods assessed in the present project are most relevant for measurement of the following features (all related to habitat value): shell density, vertical structure, and associated organisms. Shell density can be measured by extractive methods and most remote sensing methods. Vertical structure can be estimated to some extent by extractive methods, but information over large areas requires remote sensing. Most sonars and towed video are capable of detecting vertical variations of only a few centimeters. Identification and determination of abundances of organisms associated with oyster reefs can only be accomplished using underwater video.

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<th>Assessment Objective(s)</th>
<th>Recommended Method(s)</th>
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<td>oyster relative abundance, size, condition</td>
<td>any extractive methods</td>
</tr>
<tr>
<td>oyster density, size, condition</td>
<td>diver-excavated quadrats, patent tongs</td>
</tr>
<tr>
<td>reef shape and size</td>
<td>multibeam sonar, sidescan sonar, single-beam sonar, underwater videography</td>
</tr>
<tr>
<td>reef vertical structure</td>
<td>multibeam sonar, sidescan sonar, single-beam sonar, underwater videography</td>
</tr>
<tr>
<td>associated organisms</td>
<td>underwater videography</td>
</tr>
</tbody>
</table>

Table 2. Recommended remote sensing and extractive methods listed by assessment objective.
New research directions pursued

Plans have been made to supplement the present study with an assessment of Light Detection And Ranging (LIDAR), which uses laser pulses for topographic mapping (Tuell 2003; Tuell et al. 2004). Dijkstra has also developed classification algorithms for bathymetric LIDAR (Dijkstra 2004), and will evaluate these data for the detection of oysters.

Problems encountered

Significant delays were encountered during the first year (2004) of the project mainly due to an extended leave period (~3 months) by the lead investigator for medical reasons. The project was back on track during 2005, and all scheduled objectives were addressed by the end of 2006. Another problem was the unexpected restrictions on the use of multibeam and sidescan sonar over portions of the Adams Point reef and the Oyster River reef. This caused a shift in emphasis for the acoustics portion of the project to single (narrow)-beam sounders.

Outreach and industrial impacts

Our project involved end users in two major ways. First, the software being developed by Dijkstra, particularly TracEd, has considerable marketing potential. Interest in commercialization of this software has been expressed by a number of parties in the private sector, including a sonar manufacturer, a GIS developer, and a company selling seafloor characterization software. The commercial development of TracEd would guarantee the transferability as well as proper documentation of it. Furthermore, Sea Technology magazine (read by over 22,000 ocean professionals in over 105 countries) has approached Dijkstra concerning writing an article for publication, further expanding the exposure of this software tool to the community.

Secondly, the major end users for the general protocol primarily will be state-level managers. The New Hampshire Fish and Game Department was an active participant in the proposed study. The major potential change likely for their regular oyster reef monitoring is the addition of one or more remote sensing techniques to supplement the data obtained by divers. As a result of this project, Grizzle contracted with the New Hampshire Department of Environmental Services in 2003 to provide video mapping of two oyster reefs in the Great Bay Estuary for which areal coverage information was lacking (see Grizzle and Brodeur 2004).

Professional development

The following students and technicians were involved in the project.

Mark Capone, a graduate student in Grizzle's lab participated in the video mapping and was supported by hourly funds.

Mike Leo, a graduate student at the UNH/NOAA Center for Coastal and Ocean Mapping (C-COM), was involved in the sonar mapping and supported by hourly funds.

The 2006 “Hydrographic field camp” class of 14 of the C-COM collected the multibeam data as part of their practical course work.

Sarah Mikulak, Kaitlin Graiff, and Krystin Ward, undergraduate students in Grizzle's lab were involved in the video mapping and paid by hourly funds.

Krystin Ward completed an undergraduate Directed Independent Study on video mapping during
Holly Abeels, Jennifer Greene, and Melissa Brodeur, technicians in Grizzle's lab were involved in video mapping and/or quadrat sampling (with Brian Smith and other personnel from NH Fish and Game Department) components of the project.

Presentations


Grizzle, R.E. 2004. "Form and function in oyster reefs: mapping using towed video, and measurement and modeling of seston uptake" (invited seminar at the University of Florida on 8 October 2004 hosted by Dr. Shirley Baker of the Fisheries and Aquatic Sciences Department)


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