Linking Fine-Scale Groundfish Distributions with Large-Scale Seafloor Maps: Issues and Challenges of Combining Biological and Geological Data

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Abstract. Groundfishes are an important fishery resource on the West Coast of the United States, but their population sizes have undergone dramatic declines in recent years. A number of area-based management and assessment strategies have been suggested to help rebuild and monitor these populations. Most groundfish species have strong affinities with specific substratum types, resulting in spatially patchy distributions. Hence, incorporating information on the types and amounts of seafloor substrata present (i.e., habitat availability) into sample design and biomass assessment of groundfish populations could increase the precision and accuracy of fish density and, consequently, population abundance estimates. The success of using habitat availability as a proxy for fish abundance, however, is contingent on the ability to identify those measurable habitat characteristics (e.g., substratum type, depth, relief, etc.) that fish respond to, precisely estimating fish densities within those habitats, and accurately characterizing and delineating these same characteristics across large areas (i.e., seafloor substratum maps). Characterizing seafloor substratum over a large area is not an exact process, but rather, it commonly uses remotely collected information (e.g., acoustic data, sediment samples, and local geology) to infer the seafloor characteristics. As a consequence, combining estimates of fine-scale fish density per unit area of habitat and the amount of each habitat type to generate a population abundance estimate will reflect the combination of the uncertainty and error in both estimates. If sampling uncertainty or error is large for either estimate (error and uncertainty around the largest mean will be the most critical), then the final population abundance estimate might be of little use to managers. We examine a case study in which an in situ groundfish survey, conducted in an area where a detailed seafloor substratum map was available, suggested that maps—even with suboptimal resolution—could be used to increase precision in estimates of fish density. In considering the issues and challenges encountered in linking geological and biological data, it is vital to determine the level of resolution required in the seafloor substratum map, which will depend on the degree of habitat specificity to which the organism responds. Further considerations include whether the mapping technology and methodology can achieve this level of resolution and, finally, whether this sampling approach is cost effective.

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Introduction

Groundfishes, in particular rockfishes *Sebastes* spp., on the West Coast of the United States have supported a commercial fishery since the early 1900s and a substantial recreational fishery since the 1950s (Love et al. 2002). However, fishing pressure along with adverse environmental conditions over the last 3 decades have reduced stocks of many rockfish species (e.g., bocaccio *Sebastes paucispinis*, cowcod *S. levis*, Pacific ocean perch *S. alutus*, widow rockfish *S. entomelas*, canary rockfish *S. pinniger*, darkblotched rockfish *S. crameri*, and yelloweye rockfish *S. ruberrimus*) to below acceptable fishery levels (Pacific Fishery Management Council 2002a). Stock assessment is the cornerstone of all fisheries management approaches, where recruitment and adult numbers are estimated using a range of fishery-dependent and fishery-independent methods and used to model the population dynamics of targeted species. Recent assessments of populations of bocaccio, darkblotched rockfish, canary rockfish, and yelloweye rockfish indicated that these stocks were at less than 25% of their unexploited size and, as a consequence, were declared overfished. The bycatch of these species in other fisheries alone would account for the allowable take in 2002 and 2003 (Pacific Fishery Management Council 2002a). These findings recently led to the closure of all targeted groundfish fisheries on the shelf by the Pacific Fishery Management Council for California, Oregon, and Washington (Pacific Fishery Management Council 2002b).

Groundfish species are not randomly distributed over the seafloor but rather are associated with specific substratum types such as soft sediments, cobbles, boulders, and bedrock (Stein et al. 1992; Yoklavich et al. 2000, 2002; Love et al. 2002). These abiotic substratum types, in part, define groundfish “habitat” (i.e., “the locality in which a plant or animal naturally grows or lives,” Oxford English Dictionary 1989). We recognize that biotic components of habitat (e.g., plants and invertebrates that provide structural refuge for fishes) and a range of environmental factors (“environment”) is “the conditions under which a thing lives,” Oxford English Dictionary 1989), such as geographic range, water depth, and food availability, also are important in defining where an organism lives, but in this paper, we focus our discussions on substratum type (sediment facies) as an important component of, and covariate with, groundfish habitat. Terminologies, such as habitat, substratum, and environment, are used commonly in biology, geology, oceanography, and chemistry, to name a few disciplines, but are frequently used with different intent within context and discipline. In writing this paper for a multidisciplinary audience, we have become more aware of the subtle differences in terminology among disciplines, which in itself highlights an additional challenge to linking interdisciplinary research.

Area-based management, in which abiotic habitats (e.g., substratum types) that can support large numbers of groundfishes are considered as a proxy for the populations themselves, is now receiving more attention. The National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Service (NMFS), and fishery management councils are mandated to identify, describe, and protect essential fish habitats under the Magnuson-Stevens Fishery Conservation and Management Act. At the state level, California’s Marine Life Management Act and Marine Life Protection Act explicitly recognize that habitats, not just species populations, must be managed (Weber and Heneman 2000). Where the relationship between a species and its habitat can be reliably determined (e.g., mean and SE) and the distribution of those habitats can be measured (e.g., by seafloor mapping ± SE), then management decisions can be made about the magnitude of threats to a species and what management actions can be taken. Recent and proposed designations of marine protected areas (MPAs) are being used to protect critical habitats as a means either to complement catch-based fisheries management (Rowley 1994; Hastings and Botsford 1999; Murray et al. 1999; Mangel 2000a, 2000b; Weber and Heneman 2000) or to conserve marine biodiversity and marine resources that are used by a wide range of stakeholders (Bohnsack 1998; Weber and Heneman 2000). This move toward managing areas rather than single species implies that seafloor mapping and inventory of characteristics such as substratum type must be explicitly linked to the distribution of exploited species.

Mobile organisms such as groundfishes can be specific in their choice of habitats. Their local distribution can be modified by the type, structure, and patchiness of the habitat. In addition, organism–habitat relationships may occur at a number of different spatial scales ranging from m, through tens to hundreds of m, to the scale of hundreds of km (Wiens 1989). Understanding and predicting fish distribution and abundance in space, therefore, requires an implicit understanding of associations with habitat over these scales. Including information on fish–habitat associations in area-based population assessments also is likely to be fundamental to making more accurate and precise density estimates. Similarly, for other spatially explicit management approaches, such as implementation of MPAs, fish–habitat information is important to determine what proportion of the population is receiving protection and to monitor the effectiveness of the MPA (Yoklavich et
The successful inclusion of habitat information into area-based fishery management approaches and other spatially explicit approaches such as MPAs will be dependent on obtaining sound estimates of fish densities at the scale of sampling and on the ability to scale up those densities to the spatial extent of the biological population or management area. This presents a considerable challenge.

The simplest approach to estimating population abundance is to define the area occupied by the species and sample fish densities in an unbiased way over that area. Fish densities could then be multiplied by the total area occupied to yield an estimate of population abundance. Here, the sample universe (i.e., the total study area that is to be extrapolated to) should be defined (e.g., fish living in a specified area or in a specified depth range) and then subdivided into a set of possible samples from which an unbiased subset is selected (see Underwood 1998). There are many ways of achieving unbiased sampling, such as systematic, random stratified in space, or complete random sampling, and each of these aims to distribute samples over the area of inference so that all areas within the sample universe have an equal probability of being sampled (see Legendre and Legendre 1998).

Bias is anathema to this sampling model, but it is important to realize that bias may not occur only in the sample allocation procedure but also in the methodological application itself. Many methods have been used to sample groundfish densities or catchability. Visual surveys have been used to estimate fish densities in a range of habitats and provide measures of finescale relationships between a species and habitat type. The success of visual surveys is contingent on their ability to sample fish in proportion to their availability and across the range of habitats that they occupy. Visual surveys undertaken by scuba, for example, are limited to nearshore, shallow habitats (<30 m) and might not be able to sample the deeper portion of the population. Deepwater visual fish–habitat surveys require more technically elaborate sampling equipment, such as manned subsurfaces (Peary et al. 1989; Krieger 1993; Yoklavich et al. 2000, 2002) and remotely operated vehicles (ROVs; O’Connell and Carlile 1994; Adams et al. 1995), and might incur biases due to the presence of illuminated vehicles and differences in fish detectability with different equipment.

Trawl surveys (both fishery dependent and independent) also are widely used to estimate fish densities. However, trawl effectiveness is strongly dependent on substratum type. Trawl gear can get tangled, damaged, and lost in complex, rocky habitats and, consequently, a potentially important subset of groundfish habitat cannot be adequately sampled with this type of gear (Jagielo et al. 2003). Fishery hook-and-line surveys, on the other hand, provide an alternate means of sampling abundance in high-relief habitats. However, hook-and-line surveys do not sample densities directly; they actually sample catchability. Converting catchability to density is itself subject to error as fish are “enticed” from an unknown distance, and catchability may vary with time and local fish density (see Ralston et al. 1986).

Clearly, as with any type of survey tool, there are many methodological biases that need to be considered in addition to potential biases in sample allocation.

If unbiased sampling can be achieved by careful design and methodological consideration, then calculating the population mean (within a given area) and its associated error is straightforward. For example, if the total study area is 1,000 m², with an estimated mean density of 5 fish per 10 m² and SE of 2 fish per 10 m², then the predicted extrapolated mean abundance is simply a constant multiplied by the density (5), where the constant is the multiplicative extrapolation factor k (1,000/10 = 100). The standard error of this estimate (SEest) is k × SE, or 100 × 2. In other words, the predicted extrapolated abundance of fish in a 1,000 m² area is 500 ± 200 individuals.

\[
SE_{est} = \text{total area/sample area} \times SE
\]

\[
= 1,000/10 \times 2
\]

\[
= 200.
\]

Two advantages of this sampling approach are that no information is required about habitat and that the fish density estimates will be unbiased. The primary disadvantage of this approach is that where fish distributions are patchy among habitat types, many samples will be required to improve precision of the density estimate and, hence, the accuracy of the total abundance estimate (Creese and Kingsford 1998).

A more efficient and precise way of estimating fish densities might be to explicitly incorporate information about the habitat (e.g., substrata used by fishes) into a stratified random sample procedure (Cochran 1977). Stratification by habitat allows for sampling effort to be differentially allocated based on variability in fish densities with habitats and does not require that all habitats be sampled in proportion to their availability. However, in order to extrapolate fish densities to the sample universe, the relative amounts of each habitat must be known. In a stratified sampling design, the habitat-area estimates are themselves estimated with uncertainty and error and, consequently, the SEs must be calculated differently. Here, for example, estimates of both fish density and habitat-area are known for three habitat types (a, b, and c). Habitat a covers 280 m² ± 60 m² and contains 6 ± 2 fish per 10 m². Habitat
The standard error can be estimated by first calculating the three multiplicative $k$ factors and by rescaling the SEs by the sample unit size.

\[
k = \text{estimated area/sample unit area}; \quad \text{SE} = \text{SE/sample unit size};
\]

\[
k_a = 280/10 = 28; \quad \text{SE}_{a} = 60/10 = 6; \quad k_b = 400/10 = 40; \quad \text{SE}_{b} = 40/10 = 4; \quad k_c = 320/10 = 32; \quad \text{SE}_{c} = 20/10 = 2.
\]

The combined error is then calculated using the formula for error of a compound quantity:

\[
\text{SE} = \sqrt{\text{mean}_1^2 \times \text{SE}_1^2 + \text{mean}_2^2 \times \text{SE}_2^2}.
\]

Thus, the error for the Habitat $a$ abundance estimate, $6 \times 28 = 168$, is:

\[
\text{SE} = \sqrt{28^2 \times 6^2 + 2^2} = 168.
\]

Similarly, the abundance estimates for the other habitats are $80 \pm 160$ fish in Habitat $b$ and $288 \pm 73$ fish in Habitat $c$. These abundance estimates can be combined to yield a total abundance of $168 + 80 + 288 = 536$ individuals, with an SE of 243:

\[
\text{SE}_{\text{total}} = \sqrt{\text{SE}_{a}^2 + \text{SE}_{b}^2 + \text{SE}_{c}^2} = \sqrt{168^2 + 160^2 + 73^2} = 243.
\]

Three points are apparent from these calculations. First, any multiplication of variables measured with error will itself have a large error. Second, it is more important to reduce error on the variable with the largest mean. Third, to successfully combine fish density estimates with habitat availability, the fusion of scientific methods from biology and geology will be required at scales both relevant to the organism and appropriate to the management measures. If the aim is to extrapolate fish densities to the larger sample universe, the amount of each substrata present within this sample universe must be estimated as precisely as possible. Defining the sample universe, however, will depend on the spatiotemporal range of the organism. Where a larger “regional” sample universe is critical, determining the relationship between groundfishes and habitat over fishery management scales, such as Washington–Oregon–California–Mexico, would require habitats to be sampled over the species latitude and depth ranges and should be measured in conjunction with changes in broader range chemical and physical oceanography. Regardless of the spatial scale, the initial estimate of fish density will be greatly improved by incorporating a habitat-stratified sampling design. However, the accuracy of the final estimate extrapolated to the sample universe will now depend largely on the level of error and uncertainty in the habitat-area estimate. How much uncertainty and error is present in the habitat-area estimates and how are these estimates derived? To understand this, one first needs to know how seafloor substratum maps are produced.

Multibeam and side-scan sonar methods are the primary tools used to map and infer the surficial geology of large areas (one to hundreds of km) of the seafloor. Multibeam and side-scan sonar operate in different ways to characterize the seafloor (Miller et al. 1997). Multibeam sonar is generally mounted on the vessel and measures seafloor depths over a wide swath in addition to acoustic backscatter (reflectivity) if suitably equipped. Navigation is precise because a differential geographic positioning system is used in combination with corrections for vessel movement including heave, pitch, and roll. In contrast, side-scan sonar systems are usually towed at a depth behind a vessel and record acoustic backscatter (reflectivity) of the bottom. Side-scan sonar systems have relatively large navigational uncertainties in their spatial position due to “layback” error and cross-track ocean currents. Side-scan sonar does not collect bathymetric data.

An advantage of multibeam systems is that they provide good spatially referenced depth measurements, but the spatial resolution of the measurements is dependent on the beam resolution and the water depth. Each beam will average the depth signal over a greater area at increased depth, and at increased angles from nadir. Although side-scan sonar systems are hampered by poor absolute positioning of each data point, represented by a pixel, higher image resolution (more pixels per m$^2$) can be achieved by flying the system close to the bottom.

Both methods can provide clues to the geological composition of the seafloor. Acoustic backscatter, or the amount of acoustic energy that is reflected back to the receiver, can be used to infer shapes and textures of the seafloor (Urck 1983; Blondel and Murton 1997). For example, hard materials, such as rock, reflect more sound than do soft materials, such as mud; and rough surfaces, which reflect energy at an angle away from the incident wave (Blondel and Murton 1997), generate more backscatter than do smooth surfaces. Relief can also be measured directly using multibeam bathym-
Translating acoustic data into seafloor maps is not a trivial procedure. The physics of sound wave propagation in water, in combination with reflective and absorptive properties of the surficial and buried substratum, are complex and present an initial technical challenge. Subjective visual interpretations of black-and-white acoustic images have been commonly employed to identify seafloor features (e.g., Eittreim et al. 2002; Yoklavich et al. 2002). The subjectivity of this approach has led to increased efforts, using models and expert systems, to objectively define seafloor characteristics by interpreting the acoustic signal using a set of rules and conditions (e.g., Mitchell and Hughes Clarke 1994; Dartnell 2000).

Given the potential uncertainties in acoustic interpretation, groundtruthing using direct visual observations, seafloor samples, seismic profiles, or photography (Burrough 1986; Gardner et al. 1991; Tlusty et al. 2000; Bax and Williams 2001) is an important component of seafloor mapping. Groundtruthing can be, and is commonly, used to “train” the interpretation of the backscatter signatures. It can also be, but less commonly, used to “verify” the interpretation of the existing seafloor map. It is preferable that samples that are to be used to train interpretations should always be collected in conjunction with acoustic surveys. In contrast, samples used to verify the existing interpreted maps can be collected at any time, as they provide an independent estimate of map accuracy. However, seafloor groundtruthing samples are costly to collect and, hence, many groundtruthing efforts are opportunistic and might not be optimal at measuring map accuracy.

The next level of complexity lies in interpreting the acoustic and geological information as groundfish habitat. Fishes respond to their habitat at a range of spatial scales, usually in species-specific, idiosyncratic ways. For example, a fish species might perceive boulders and bedrock as contrasting habitats and use them in different ways (O’Connell and Carlile 1993). Successfully linking this species to one or the other habitat will be contingent on the ability of the seafloor substratum map to reliably resolve these two habitats. A disjunction in scales of resolution between the seafloor substratum maps and the habitats perceived and used by the fishes could be considerable. For example, assume species a was associated with boulder habitats at a density of 5 ± 2 fish per 10 m² but was not found over bedrock. If a study area contained 500 m² of bedrock and, hence, it was surmised that there were no fish present or, conversely, that the area was entirely composed of boulders and, hence, the abundance would be estimated at 250 ± 100 fish. Incorporating this magnitude of uncertainty and error into population abundance estimates is unlikely to be valuable to resource management.

There is a clear need, therefore, to reconcile the resolution of seafloor substratum maps with the resolution at which fishes perceive and respond to their habitat if we are to reduce this uncertainty. We demonstrate some of the issues and challenges related to linking fine-scale biological information of important fishery species with a seafloor substratum map using a real example in southern Monterey Bay, California.

Case Study

This study is not meant to represent either a blueprint or an example of combining “optimal” technologies from both the fish sampling and geological mapping perspectives. Instead, it represents a real situation where in situ fish–habitat data (Delta submersible survey) have been sampled over an area of seafloor that also was geologically mapped (multibeam survey) in independent studies. We use this opportunity to illustrate several issues and challenges related to linking biological and geological data. Our study area covers a 12-km × 10-km area in the vicinity of Italian and Portuguese ledges in southern Monterey Bay off Point Pinos in central California (Figures 1, 2). This general region has been subject to an important groundfish fishery that operated commercially since the mid- to late 1800s, which initially targeted a generic “red rockfish” species later identified as including a variety of rockfish species such as bocaccio, widow rockfish, yellowtail rockfish S. flavidus, vermilion rockfish S. miniatus, and canary rockfish (Phillips 1939). A sizeable recreational fishery also has existed since the 1970s.

A fine-scale in situ groundfish–habitat survey was conducted using the Delta submersible in October of 1993. Thirty-three georeferenced, visually censused strip transects (2 m wide × 15 min duration) were allocated to different substrata based on available bathymetry, seafloor sediments (Gallither 1932), and side-scan surveys (H. G. Greene, Moss Landing Marine Laboratories, and Yoklavich, unpublished data). The initial groundfish–habitat survey was intended to determine the relationship between demersal rockfishes and fine-
scale substrata (i.e., potential habitats). Transects were conducted from the starboard side of the Delta. Fish within each transect were identified and counted in situ by the observer and were also recorded with an external video camera mounted on the starboard side of the submersible. Postprocessing of audio (observer’s counts and identification) and videotape were used to categorize and demarcate fine-scale habitat types within each transect based on the primary (>50% cover) and secondary (>20% cover) habitat protocol of Yoklavich et al. (2000) and Stein et al. (1992). Groundfish–habitat relationships were evaluated at both a broad scale (transects within strata) and a fine scale (patches within transects). From this we ascertained the habitat components that each species responded to and at which scales these responses were important and measurable.

A year later, in 1995, the 12-km x 10-km study area was acoustically surveyed as part of a larger geological survey of the Monterey Bay National Marine Sanctuary aimed at characterizing the seafloor geology and substrata (Eittreim et al. 2002). Multibeam echo sounding was conducted using a hull-mounted Kongsberg Simrad EM1000 multibeam bathymetric system that recorded bathymetry (5-m resolution) and multibeam acoustic backscatter (2.5-m resolution). Geological seafloor characterizations were interpreted based on the acoustic backscatter signature and auxiliary seafloor samples such as seismic reflection profiles, sediment samples, and drop-camera photography (Anima et al. 2002; Eittreim et al. 2002). Six seafloor geological types, such as the Purisima and Monterey formations, were characterized and delineated (Eittreim et al. 2002).

The provision of this seafloor map presented the opportunity to use the in situ visual strip transects collected from the Delta submersible to determine how accurately the seafloor map depicted groundfish habitats. Three substratum categories (hard, hard mixed...
with soft, and soft substratum) could be reliably depicted from the seafloor map (Figure 2): 69.6% of the study site (120 km² seafloor) was comprised of contiguous soft substratum and was described as such by visual observations; 19.9% was comprised of hard substratum mixed with soft substratum observed as low-relief patches of cobbles within a matrix of mud; and 10.5% was comprised of hard substratum observed as complex rock outcrops, boulder, and sand patches (Figures 2, 3).

Groundtruthing data, collected from the biological and multibeam mapping surveys, verified the three interpreted substratum categories (including several strata interfaces) and their geographic locations. However, these data did not coincide with all of the backscatter interpretations and verified only a small number of the substrata boundaries seen in the backscatter image. This is important because verifying the position of habitat edges is a critical step to obtaining an accurate estimate of the area comprising each substratum. As we have little independent data to verify the exact location of edges, we have little means to determine the potential error around the estimates of the three substratum categories. Therefore, we use mean estimates of the area occupied by the three substratum categories, but we cannot provide an independent estimate of error.
around these means. Consequently, the accuracy (cf. precision) of the calculated estimates is unknown.

While fish survey transects were sampled from the three preidentified substratum categories (i.e., hard, mixed, soft), video analysis within transects revealed finer scales of seafloor heterogeneity than those identified from the seafloor maps (Figure 3). Importantly, many fish species responded in different ways to this finer-scale complexity. For the purpose of this case study, we will present three examples of groundfish–habitat associations to illustrate both the range in fish-habitat associations and the corresponding level of resolution in the seafloor map required to gain useful population estimates. Sanddabs *Citharichthys* spp. were highest in transects placed in soft and mixed substrata. At finer scales (within-transects), sanddabs were found in soft-sediment patches, both within contiguous soft-substratum transects and, to a lesser degree, in the soft-sediment matrix of mixed substratum transects (Figure 4a). Halfbanded rockfish *S. semicinctus* were found primarily in transects placed in the mixed substratum. However, at finer scales, unlike sanddabs, halfbanded rockfish were aggregated over discrete habitat patches containing cobbles and boulders surrounded by soft-sediments (Figure 4b). The three broad-scale substrata (hard, mixed, and soft) adequately described the distribution and abundance of both sanddabs and halfbanded rockfish. These three substrata could also be reliably distinguished and quantified from the multibeam seafloor substratum map. Consequently, incorporating these three substrata into the biological sampling design and estimation procedure should yield more precise estimates of both sanddab and halfbanded rockfish population sizes than sampling or estimation without regard to these substrata.

In contrast, densities of squarespot rockfish *S. hopkinsi* were highest in transects placed in hard substratum. At finer scales, squarespot rockfish were strongly aggregated in rock-boulder patches (i.e., patches containing >50% bedrock and >20% boulders) and boulder-sand patches (>50% boulders, >20% sand; Figure 4c). Unlike cobbles and boulders in the previous examples, different types of hard substratum within a single outcrop could not be resolved from the seafloor substratum map. Consequently, where differences in habitat heterogeneity within a rock outcrop are large, we would expect this to be reflected in high between-transect variation in fish densities. An optimal solution would be to introduce another level of stratification, in which rock-boulder and boulder-sand could be distinguished from other habitats within rock outcrops. However, the lack of acoustic contrast between different types of hard substratum means that this would not be achieved with the existing seafloor map. Although stratification using the three broad-scale habitat substrata would still generate a more precise density estimate than a simple random sample design, the benefits for squarespot rockfish would be less than for those species whose habitat associations corresponded to acoustically distinct seafloor characteristics.

Given that species-specific habitat preferences are the norm, what are the consequences of ignoring within-transect habitat heterogeneity? The answer will depend, in part, on the spatial complexity of the seafloor and how homogeneous the transects themselves are. If transects within a broad habitat differ in their within-transect habitat structure, this will be manifested in a highly variable (imprecise) estimate of species density. Importantly, the size of this effect also will be strongly dependent on the behavior of each individual species. Sanddabs, although associated with contiguous soft sediments and soft sediments within mixed habitats, are usually solitary or found in small groups. Differences in abundance between transects, due to differences in sediment availability, are, therefore, unlikely to be large. In contrast, many rockfishes such as the halfbanded rockfish and squarespot rockfish can form
large aggregations around very specific habitat features (e.g., small patches of cobbles). Consequently, small errors in estimating the areal coverage of these features will be magnified by this group behavior and, therefore, translated into large errors in the overall abundance of these species.

**Issues and Challenges**

Even though the biological and geological approaches used in this case study were not designed explicitly to link fine-scale fish distributions with seafloor substratum maps to estimate total population abundance, the data were of sufficient resolution to potentially be useful. Abundance estimates of species that were associated with the three substrata, readily distinguished in the seafloor map, are likely to be greatly improved by incorporation of these 3 substrata into the sampling design and, ultimately, the statistical estimation of the mean density. In contrast, improvement of abundance estimates was less for those species that occupied specific types of hard-rock habitat. This is due largely to the inability of the equipment used in the mapping sur-

**Figure 4.** Fish densities for patch (within-transect habitat types) and transect habitats (coarse-resolution strata) for three groundfish species (sanddabs, a; halfbanded rockfish, b; and squarespot rockfish, c). The left series of graphs depict densities of fishes in patch habitats defined by a primary and secondary habitat type, where R = rock, B = boulders, C = cobbles, S = sand, and M = mud habitats. For example, patches with a primary habitat of rock (>50% of the patch) and a secondary habitat (>20% of the patch) of boulders would represent a rock–boulder patch and would be depicted as RB. The right series of graphs depicts densities of fishes within the three broad-scale substratum.
vey to detect finer-scale habitat boundaries within the broader category of hard substratum even though some groundfish species were associated with habitats at finer scales of resolution. It must be recognized, of course, that the acoustic data used in developing the geological classification of Monterey Bay was not designed to resolve the fine scales important to groundfish species, which emphasizes that detailed substratum maps may not provide the necessary information or resolution to achieve all objectives.

As some fishes responded to habitat features at spatial scales less than those resolved by commonly used acoustic systems, we were challenged to find solutions. A first approach would be to generate higher-resolution maps. The development of remote mapping technologies to characterize finer-resolution seafloor maps is an area of active research (e.g., high-resolution multibeam, improved laser line scan, LIDAR), but today’s solutions are expensive and cover limited areas. An alternative approach is to use the existing suboptimal seafloor substratum maps and conduct formal groundtruthing surveys to differentiate and delineate the finer-scale seafloor characteristics. A grid of nonoverlapping transects using visual observations either over the extent (i.e., the length and width) of the area or at selected areas of interest, could enable internal boundaries and interfaces of finer-scale habitats to be delineated without incurring the cost of remapping the entire region. This method, however, relies on precise navigation of the groundtruth survey system, such as submersible, towed video camera, or ROV.

These options must each be considered in the context of the question to be answered. The original intent of our case study was to assess whether information from seafloor substratum maps could be used to obtain more precise estimates of groundfish abundance within a particular area. To resolve this question, it was necessary to distinguish between the types of soft sediment, hard mixed with soft sediment, rocky outcrops, and boulders within bedrock habitats. This level of resolution was dictated by the fishes’ associations, identified from in situ fish–habitat observations. With the exception of the boulder–bedrock distinction, the existing map fulfilled these requirements. From the biological standpoint, while it was then necessary to estimate the mean groundfish density and its associated SE within each of these three broad-scale substratum types (i.e., hard, mixed, soft), it is important to note that the biological sampling (e.g., of each organism) does not require precise georeferencing; as long as the sampling unit (in this case, the transect) was conducted within the broad-scale substratum category, then the true position of the sample is irrelevant for generating a classical estimator of the mean. Precise sample positioning is only required if using a geostatistical estimation process such as kriging (Burrough 1986).

A profitable approach, from a practical standpoint, may be to identify the minimum geological and biological data requirements required to answer the question. In this particular example, it was sufficient to know the relative proportions of the three broad-scale substratum types. Even the initial side-scan sonar information, despite its limited positioning ability, could provide this information. The densities of fishes that occupied soft-sediment and mixed substrata were generally less variable than those in hard substratum. Consequently, less biological sample effort would be required in soft and mixed habitats to achieve a given level of precision. The inability of the existing map to distinguish between bedrock and boulder could be countered in two ways: (1) higher-resolution mapping or grid-coverage groundtruthing in selected areas of interest (e.g., complex rock outcrops) could enable more sample strata to be defined; or (2) more biological samples (i.e., submersible transects) could be allocated within the hard sample stratum to reduce the SE of the mean estimate. The cost effectiveness of submersible time versus mapping operations should then be evaluated.

Summary

Area-based population assessment holds considerable promise if fish respond to coarse-resolution habitats such as hard, mixed, and soft substrata. Empirical models of groundfish-habitat associations, in conjunction with seafloor substratum maps, could improve area-based management of these resources. Successful application of such models and maps may be more difficult when the arrangement of substrata is complex. For example, cobble habitat may lie within and, hence, be indistinguishable from bedrock habitat. If groundfish respond to the complex structure of the rock matrix itself, then this is of less importance because the broad-scale “hard” classification will be an adequate sample stratum. However, if fish respond to specific habitats such as rocks, boulders, or cobbles within this stratum, then delineating these internal boundaries would be a useful enterprise but might present a major challenge. Alternatively, it might be more cost efficient to allocate more samples to complex strata to reduce the variability of the fish-density estimate. The success with which fine-scale biology can be linked with large-scale seafloor maps will, to some degree, be contingent on the complexity of the fish-habitat association and on our ability to discern this fine-scale complexity across large-scale management areas. However, even in a less-than-perfect world, routine incorpor-
tion of geological and biological information is likely to provide more precise answers to fisheries management questions than either approach in isolation.

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