

The role of acoustics in ecosystem-based fishery management

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For more than half a century, acoustics has been a leading tool in fishery stock assessment. Today, the need for ecosystem-based management poses new challenges for fishery scientists: the need to assess the ecological relationships of exploited species with predators and prey and to predict the potential effects of climate variability and climate change on recruitment. No research tool is likely to prove as effective as acoustics in meeting these needs, if it is properly integrated into interdisciplinary research programmes involving ecology and oceanography, as well as fisheries. Integration of data from acoustics and ocean-observation, as well as from satellites and other high-resolution oceanographic mapping tools, is likely to lead to major advances in fishery oceanography. New developments in acoustic technology, such as three-dimensional, multibeam acoustics, and shelf-scale acoustic mapping, may also lead to significant advances. Notwithstanding these developments, critical biases and shortcomings of acoustic methods that were noted 50 years ago remain with us. For example, the identification of insonified biota and single-target discrimination remains relatively primitive. Progress is urgently needed in these basic underpinnings of the acoustic method.

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Introduction

The potential that acoustics might play in fishery operations and research was recognized before World War II (Sund, 1935; Balls, 1948), and acoustic technology has continued to co-evolve since then with fishery research needs. Calibrated acoustic instruments are now standard quantitative tools for fishery research and stock assessment.

Although the role of the environment in regulating fish population dynamics has been recognized for a century (Hjort, 1914), conventional fisheries management has until recently focused on the exploited stocks, with the primary objective of estimating the maximum sustainable yield or some variant: e.g. optimum sustainable yield or $F_{0.1}$. However, recent years have witnessed a significant paradigm shift, with a growing consensus that single-species stock assessment alone is not sufficient to manage fisheries sustainably (Pikitch *et al.*, 2004).

Ecosystem-based fishery management (EBFM) is predicated upon the need to assess broader fishery effects on the ecosystem, i.e. on the predators, competitors, and prey of the exploited species, as well as on bycatch species and the essential habitat. Therefore, the role of exploited species must be assessed within the ecosystem where they live. The effects of changing environmental conditions on recruitment to exploited populations must also be understood and, if possible, predicted, so that the exploitation levels can be adjusted to achieve sustainability. Marine ecosystems change across a range of time-scales, e.g. interannual, ENSO (the *El Niño*–Southern Oscillation), decadal, etc., and the equilibrium generally assumed in management models has long been recognized to be a convenient and artificial construct (Isaacs, 1976). However, the quest for predictive models of fishery recruitment, based on an understanding of the underlying oceanographic

mechanisms, has generally proved disappointing, although Hjort (1914) set out the main hypotheses that regulate recruitment variability almost a century ago. The broader ecosystem effects of environmental variability, i.e. the effects of natural and anthropogenic stressors on predators, prey, bycatch, and other affected species, must also be evaluated.

Therefore, the expectation that fishery management will now be based on ecosystem considerations, as well as on traditional, single-species assessments, poses a considerable challenge to oceanographers and fishery scientists. Ocean models are best developed for the physics of ocean circulation. As one adds chemistry and biology—the phytoplankton initially, then the zooplankton—they become progressively less developed with poorer predictive power. The so-called “end-to-end” models that extend from the physics to the fish are particularly challenging and generally poorly developed to date.

The thrust of this paper is to assess the contribution that acoustics can make in meeting the challenge of implementing EBFM and, in particular, to review progress, to examine why only modest progress has been achieved to date, and to suggest how greater progress may be achieved in future. It is the general view of this author that acoustics is the most promising tool for implementing EBFM. It is only a tool, however, and must be properly integrated into a multidisciplinary programme of oceanographic, ecological, and fisheries research for its potential to be realized.

Ecological and fishery models

Most ecological models that cover mid-to-higher trophic levels—thus including most exploited species, their predators and prey—are mass-balance models, such as Ecopath and its variants (Pauly *et al.*, 2000). Such models require biomass estimates of predators

and prey, as well as the exploited species, along with estimates of their productivity and predator–prey interactions. The limited data requirements of these models are among their chief advantages; they provide an easily achieved, first-order assessment of fishery effects on predators, prey, and competitors. However, the models assume a steady-state or equilibrium condition; they lack spatial and temporal dimensions, are non-dynamic, and are generally not very useful for assessing the effects of climate variability or climate change on recruitment.

Dynamic models of ecosystem interactions must be based on the analysis of the spatial and temporal distributions of key species in relation to predators, prey, and topographic and oceanographic features. These more sophisticated models, such as NEMURO (Werner *et al.*, 2007; related papers in this volume), may couple hydrodynamic, biogeochemical, and fish models. They may be spatially explicit and are more realistic, as well as having the potential to address issues related to climate variability and change. On the downside, their greater complexity entails the need to assess many more parameters and, therefore, to understanding the behaviour of the model is more difficult. Dynamic models incorporating fish are still primitive, in part because of our limited understanding of how fish interact with their environment.

The strengths and limitations of acoustic data

Acoustic methods are among the most promising to meet these scientific challenges, if used in conjunction with other oceanographic tools and appropriate models. The frequencies best suited for detection of organisms in the size range from euphausiids (and even layers or aggregations of large copepods) to micronekton and nekton – approximately 12–200 kHz – are also able to sample effectively from 100 to >500 m through the water. No other sampling tool can “see” through so much of the water column. The currently available downward-looking acoustic systems can provide continuous, calibrated, high-resolution backscatter data while underway on a vessel. The appropriate analysis of such backscatter, in combination with data to identify the size and species composition of the insonified targets, their target strength (*TS*) as a function of physical size and, if possible, their orientation in the acoustic beam, can provide continuous survey data on the abundance and biomass of the biological community by species or species group. There are standard texts (Simmonds and MacLennan, 2005) and software, e.g. Echoview (Myriax, 2008), to assist in this exercise.

Acoustic data are, in many ways, eminently suited to fisheries-ecosystem modelling. Avoidance reactions are minimized, except in the near-surface layer where organisms may avoid the vessel or be too near the surface to be adequately sampled by downward-looking echosounders (Gerlotto and Freon, 1992; Gerlotto *et al.*, 1999; Hjelvik *et al.*, 2008). In general, however, the high spatial resolution of acoustic data facilitates the analysis of spatially explicit behavioural and ecological interactions, if they are examined in relation to high-resolution physical and biological oceanographic data. These may come from satellites, gliders, and water-column profilers, such as “tow-yoed” video-plankton recorders, SeaSoar, the Moving Vessel Profiler, and similar instruments (Benfield *et al.* 1998). The challenge of analysing such complex datasets is being met by the development of powerful new tools for multivariate, geospatial visualization and analysis of data (Calzone *et al.*, 2008). However, although acoustic sampling avoids many of the biases

in net sampling, it is subject to a suite of other potential biases and shortfalls. Target identification and *TS* have proved to be the most enduring issues.

Target identification

Various methods are used to identify insonified targets, including optical sampling by video or camera (Graves, 1977; Long and Aoyama, 1985), as well as net sampling (McClatchie *et al.*, 2000). However, the well-recognized net-sampling biases in estimates of size and species composition can translate directly into biased acoustic-abundance estimates. The bias in net sampling of micronekton is generally considerable, often an order of magnitude, whether relatively small- or commercial-sized midwater trawls are used (Koslow *et al.*, 1997); smaller organisms can escape through the meshes of large trawls, and larger organisms can avoid small trawls. Certain taxa, such as large squids and large, fragile, midwater scyphozoans, are notable for their complete absence from net samples. If unrepresented in the “ground-truth” samples, such taxa risk being unrepresented in the acoustic estimates of community composition as well; the backscatter from such groups may be attributed to better-sampled taxa. Certain taxa may evade optical samplers as surely as they evade nets (Koslow *et al.*, 1995). Because of these sources of potential bias, several approaches to assessing community composition have now been proposed, based on the analysis of the acoustic returns themselves.

Multifrequency acoustic systems are now routinely used to separate organisms with markedly different size and swimbladder characteristics, based on their different reflectance at low and high frequencies. Examples of the types of organism successfully discriminated in this way include fish with swimbladders (e.g. hake or pollock) distinguished from euphausiids (Cochrane *et al.*, 1991; Kang *et al.*, 2002); layers of large copepods, euphausiids, and small fish distinguished on a whale feeding ground (Macaulay *et al.*, 1995); and three classes of fish: small vs. large fish with swimbladders (e.g. myctophids vs. macrourids and morids) and large fish without swimbladders (orange roughy) (Kloser *et al.*, 2002).

In ecosystems where the differences among key species are less well-defined, investigators have also explored the use of various forms of discriminant analysis of the echo returns themselves, with varying degrees of success (Rose and Leggett, 1988; Scalabrin *et al.*, 1996). Habitat associations have also been used to improve classification (Richards *et al.*, 1991). The *in situ* *TS* distribution, obtained from split-beam and dual-beam echosounders, can also provide insight into species and size composition (Barange *et al.*, 1994). However, *TS* measurements are subject to their own biases, such that larger targets may be detected preferentially, or overlapping echoes from two or more fish may be counted as one larger target (Soule *et al.*, 1995). In general, however, the ability to discriminate acoustically among taxa remains coarse and works best in relatively low-diversity systems with a few well-defined and acoustically distinct groups (Horne, 2000). Fortunately, highly productive ecosystems in upwelling regions or at temperate and high latitudes tend to meet these criteria.

Target strength

There are several unresolved issues related to acoustic *TS*. First, the *TS* of particular organisms is generally highly sensitive to their tilt angle (McClatchie *et al.*, 1996) and may also vary with depth, because of the expansion or contraction of gas-filled bladders

(Gorska and Ona, 2003). Fish may react to vessels or towed bodies, by diving for example, at distances of more than 100 m (Kloser *et al.*, 1997); this is a significant potential source of bias for *in situ* TS measurements.

The TS is also highly sensitive to the presence or absence of air-filled swimbladders or structures with hard parts (e.g. bones containing CaCO₃), because its magnitude depends on the density difference between seawater and structures within the organism. Backscattering, therefore, is generally not proportional to biomass, except within taxa; those without such structures (e.g. squid and gelatinous plankton) are underrepresented, and organisms such as pteropods, with calcareous shells or scyphozoans with gas-filled pneumatophores, may be overrepresented. The swimbladder composition of some taxa, such as various myctophids, may change ontogenetically, e.g. from gas-filled to fat-invested or becoming smaller (Butler and Percy, 1972), further complicating relationships between the TS and body size.

Acoustics applications for ecosystem-based management

Over the past two decades, acoustics, in combination with complementary technologies, has been the primary tool used to address a range of key issues related to ecosystem-based management of fisheries.

Benthic habitats

This review focuses mainly on the role of acoustics in pelagic fisheries oceanography. However, acoustics also plays a key role in characterizing and mapping benthic habitats, a key step in selecting sites for marine protected areas (MPAs) and other forms of spatial management. Acoustic methods employed to map benthic habitats range from the use of classification software to analyse the bottom-reflectance characteristics of echosounder signals (e.g. RoxAnn, Sonavision Ltd.; QTC-View, Quester Tangent Corporation), to side-scan and multibeam, swath-mapping sonars; these methods sample progressively larger areas of seabed per unit time. In general, although acoustic methods provide information on topography and substratum type, they must be combined with optical (e.g. video or photographic) data and, if possible, biological sampling to relate the substrata to actual biological habitats (Bax *et al.*, 1999); the need to complement acoustic with other sampling tools for ground-truthing is a common theme in the use of acoustics for marine-ecological research, whether in the benthic or pelagic realms.

However, the great strength of acoustic methods for benthic-habitat mapping is their capacity to do this rapidly and inexpensively. Because benthic communities are closely linked to the seabed depth, topography, and substratum, acoustic surveys provide powerful tools for benthic-habitat mapping. As the International Union for the Conservation of Nature (IUCN) has recommended, MPAs are most effective as a tool for marine conservation when established as a system that protects a representative network of key habitat types (Kelleher and Kenchington, 1992). Major programmes to map benthic habitats as the basis for marine conservation, as well as in support of fishery operations and geological assessments (Hill *et al.*, 1997), have been instituted in many parts of the world (Bax *et al.*, 1999; Diaz *et al.*, 2004). Acoustic methods of seabed classification were recently comprehensively reviewed by Anderson *et al.* (2008).

Benthic-habitat structure may also influence the distribution of fish even in the overlying water column, but as Mackinson *et al.* (2004) pointed out, few acoustic studies combine benthic and pelagic surveys with an integrated analysis of benthic-habitat and pelagic-community structures. In a particularly clear example of such interactions, Freeman *et al.* (2004) demonstrated that sandeels, *Ammodytes* sp., are not only associated with particular sediment types, but also influence the sediment's acoustic signature when they burrow into it, thereby providing information critical to acoustic assessments of sandeel stocks. Greater integration of benthic and pelagic acoustic surveys may thus considerably enhance our understanding of the several dimensions over which marine creatures integrate the use of their environment, as well as the efficiency and cost-effectiveness of ship surveys.

Pelagic habitats: ecosystem structure

Studies in many regions have combined acoustic, net, and other oceanographic sampling, to examine how topography and oceanographic features influence pelagic ecosystems from the physics to the fish. The literature in this field is growing rapidly, but the field of fishery acoustics remains in its infancy. As Massé and Gerlotto (2003) pointed out, although acoustic stock-assessment surveys have been carried out for decades in some regions, such as off Peru, the data have been greatly underutilized as regards understanding the interactions among species and between species and their environment. Such an understanding is critical as the basis for EBFM. Several studies noted below will illustrate the range of methods and their application to fishery oceanography.

Barange *et al.* (1998) studied how the subtropical convergence (STC) influences the distribution of phytoplankton, zooplankton, and micronekton in two sectors of the South Atlantic, just south of South Africa and in the open ocean. That study was notable for its integration of dual-frequency acoustics (38 and 120 kHz), which provided high-resolution data on the biomass of macrozooplankton and micronekton across the frontal region, with detailed physical and biological sampling, revealing the distribution and biomass of the relevant phytoplankton, zooplankton, and micronekton communities. Open-ocean and continental processes have been demonstrated to influence how the STC structures pelagic communities and production processes from "physics to fish" in the South Atlantic.

Acoustics played a key role in a similarly comprehensive study of foodweb processes supporting orange roughy on seamounts off southern Tasmania. A preliminary trophodynamic model (Koslow, 1997) indicated that only some 10% of the energy requirements of the aggregation could be met by *in situ* productivity over the seamounts. Seasonal cruises were carried out with day/night acoustic and vertically stratified pelagic-trawl sampling to determine how diel and seasonal vertical migrations of the micronekton, as well as their horizontal advection across the seamounts, sustained the population (Koslow *et al.*, 1997; Williams and Koslow, 1997).

An Ecopath model (Butler *et al.*, 2002) synthesized the results, based on studies of diet (Bulman and Koslow, 1992; Williams *et al.*, 2001; Bulman *et al.*, 2002), energetics (Koslow, 1996), and biomass estimates from acoustic and egg surveys of the orange-roughy population (Koslow *et al.*, 1995; Kloser *et al.*, 1996), which generally confirmed the role of advection across seamounts in supporting it. This work confirmed the importance of using acoustics to model pelagic communities; the acoustic estimates

of nekton and micronekton biomass were approximately sevenfold higher than the swept-area estimates from catches with a moderate-sized, 105 m² mouth-opening trawl. The seamount programme also provided insight into the complex interactions between near-surface and deep-water communities, and between the topographically fixed seamount aggregations and the deep-scattering communities over a much larger ocean area.

Results of the seamount programme were used to resolve a conflict between fishing-industry and environmental stakeholders in the creation of one of the world's first deep-water marine reserves south of Tasmania. The objective of the reserve was to protect the benthos and orange roughy over a cluster of the region's seamounts, but objections from drift-longline tuna fishers operating in the overlying waters threatened to block government approval. Based on the limited interaction between the near-surface and deep-water marine communities, it was deemed that the fishery could continue, while maintaining the integrity of the deep-water communities below 500 m depth (Koslow *et al.*, 1998).

Ecosystem dynamics: predator–prey interactions

Tuna are particularly wide ranging, and their micronekton prey is well suited to acoustic detection and survey. Several studies have therefore used acoustics to examine the abundance and distribution of tuna species in relation to open-ocean current systems and the distribution of their prey. Because net sampling of micronekton cannot cover the vast areas of the open ocean adequately, initial models assumed that tuna distributions could be predicted based on zooplankton abundance (Lehodey *et al.*, 1998). Although such relationships may be found on very large scales, Bertrand *et al.* (1999) demonstrated that the acoustically assessed distribution of the tuna's micronekton forage was affected by localized oceanographic conditions, such as oxygen availability, as well as the primary productivity in the central South Pacific.

Lebourges-Dhaussy *et al.* (2000) conducted acoustic studies of the tuna-forage species *Vinciguerria nimbaria* in the eastern tropical Atlantic and found that forage availability leading to tuna aggregations was again not simply related to productivity. The areas of highest, near-surface concentrations of *Vinciguerria* were in somewhat less productive waters, where the zooplankton aggregated in the chlorophyll-maximum layer. Exceptionally good tuna fishing off southeast Australia was also found related to the combination of oceanographic conditions, especially the influence of warm-core upwelling eddies, and the distribution of micronekton (Young *et al.*, 2001). French studies, such as ECOTAP, based on acoustic, net, and oceanographic sampling continue to build an ecosystem understanding that integrates tuna distributions, behaviour, and feeding in relation to oceanography and micronekton distributions in the region around French Polynesia (Bertrand *et al.*, 2003).

Multifrequency acoustic methods have been successfully applied to studying the dynamics of marine-mammal feeding grounds, particularly how local topography and oceanographic conditions result in the high forage concentrations that determine where marine mammals aggregate. Using three frequencies (38, 120, and 200 kHz) to discriminate between layers of fish, euphausiids, and copepods, the predictable appearance of blue whales off the Channel Islands in California was proved to be related to their feeding on swarms of euphausiids (*Euphausia pacifica* and *Thysanoessa spinifera*) that formed downstream of upwelling centres in areas of steep topographic relief (Croll *et al.*, 1998; Fiedler *et al.*, 1998). In the Northwest Atlantic, a similar approach

characterized the aggregation of right whales in the Great South Channel off New England, where the copepod *Calanus finmarchicus* occurs in dense near-surface layers associated with frontal features (Macaulay *et al.*, 1995).

The high-resolution data available from acoustic surveys allow detailed analyses of the relationships between predator and prey distributions across a range of scales. Rose and Leggett (1990) carried out spectral analyses to examine such relationships between the distribution of cod and its primary prey, capelin. They found that at large scales, the distributions of predator and prey were positively correlated, except when the capelin occupied low-temperature thermal refugia; however, at scales smaller than the fish aggregations, the two were negatively correlated unless the cod were actively feeding.

Acoustic surveys provide an important tool for monitoring and assessing the efficacy of fishery closures and MPAs. Therefore, when the sandeel fishery off southeast Scotland was closed in 2000, continued acoustic and other surveys were used to monitor the recovery of the population (Greenstreet *et al.*, 2006). Ancillary studies could then be used to assess the influence of the closure on regional seabird populations (Daunt *et al.*, 2008).

Acoustic studies have also contributed to our understanding of predator–prey behavioural interactions. Examples include studies of the behaviour of killer whales and adult herring (Similä, 1997) and of puffins and newly metamorphosed juvenile herring (Axelsen *et al.*, 2001). A study that combined oceanographic observations with visual and acoustic surveys of seabirds and krill revealed how the foraging behaviour of the planktivorous Cassin's auklet varied dramatically from year to year depending on the availability of krill, which is highly sensitive to upwelling conditions off the coast of California (Jahncke *et al.*, 2006). Such studies are critical for the development of integrated models of predator–prey interactions in relation to oceanography and climate.

The international fishery for krill (*Euphausia superba*) in Antarctic waters was the first to be managed explicitly based on ecosystem-based principles that were designed to conserve the various marine mammals and seabirds that depend on this species, as well as the krill itself (Hewitt and Linen Low, 2000; Constable, 2004). The relative simplicity of the Antarctic ecosystem, which the krill, appearing in vast monospecific swarms, dominate at the herbivore level, greatly facilitates the use of acoustic surveys. Conversely, the vast area over which the krill occur, the patchiness of their distribution, and the sensitivity of their *TS* to the krill's tilt angle have complicated such surveys and their interpretation (Demer and Conti, 2005). Notwithstanding these difficulties, the extended acoustic surveys carried out since the early 1980s provided an invaluable time-series for portions of the Southern Ocean (Hewitt and Demer, 1994; Brierley *et al.*, 1999), which are now the basis of studies of krill recruitment and population dynamics in relation to physical variability (Hill *et al.*, 2006). Krill recruitment and biomass are highly variable: over 11 years, the density of krill around the South Shetland Islands varied by almost two orders of magnitude (from 1 to 60 g m⁻²; Hewitt *et al.*, 2003), a key issue in krill fishery management. The extent of sea ice, which exhibits quasi-cyclic variability, as well as a long-term climatic trend, appears critical to krill population dynamics (Loeb *et al.*, 1997; Hewitt *et al.*, 2003). Large-scale oceanographic programmes, such as the Joint Global Ocean Flux Study (JGOFS) and the Global Ocean Ecosystem Dynamics (GLOBEC) study, combined with fisheries-oceanography

programmes, are leading to an understanding of the processes underlying these apparent relationships, especially how changes in the productivity of the system may affect this key species (Constable *et al.*, 2003, Hill *et al.*, 2006).

Recruitment

One of the most promising uses of acoustic methods in fisheries oceanography is in the study of the recruitment process. Year-class strength may be regulated by multiple factors over the early life history, and these may vary under different environmental regimes. It is therefore not surprising that attempts to find relationships between recruitment and environmental factors have often been frustrated by the breakdown of simple correlations (Myers, 1998). Studies before the 1990s mostly focused on the larval stage (Cushing, 1975; Lasker, 1975; Rothschild *et al.*, 1989), which can be sampled adequately with plankton nets. However, it is now apparent that year-class strength is often determined later in the life history. Many species begin schooling in the juvenile phase and are then amenable to study using acoustics and pelagic-trawl sampling. Acoustic tools can sample over large spatial scales and can also resolve processes on reasonably fine scales. Recruitment may be regulated by advection, feeding conditions, and predation over a range of spatial and temporal scales. Elucidating the processes regulating recruitment for a given species therefore requires multidisciplinary study of the system's physical oceanography, phyto- and zooplankton production, and the distribution and behaviour of major predators, as well as the distribution, feeding, growth, and mortality of the species of interest. Only particularly valuable or critical species will justify this level of research.

A good example of such a research programme is the study of recruitment processes in the eastern Bering Sea pollock stock (*Theragra chalcogramma*). Research on the 0-group juvenile stage demonstrated how acoustics combined with other sampling methods could elucidate underlying physical and biological mechanisms. The distributions of 0-group walleye pollock and zooplankton have been examined on the pollock nursery ground near the Pribilof Islands using multifrequency (38, 120, and 200 kHz) acoustics; exploratory image analysis and non-parametric, generalized additive models (GAMs) have been used to explore the data for potential relationships (Swartzman *et al.*, 1999a, 1999b). At low plankton densities, the fish remained close to plankton patches; up to intermediate plankton densities, the fish and plankton densities were still correlated. Above some threshold level, however, the fish were apparently saturated and the relationships broke down. Based on six years of acoustic surveys, Swartzman *et al.* (2002) demonstrated that smaller and larger juveniles followed different feeding strategies, with the former remaining above the thermocline to feed on copepods, whereas the latter migrated vertically through the thermocline to follow the krill, their dominant prey. A recent comparison of the trophic ecology of juvenile pollock between two years of contrasting recruitment success indicated that year-class success may be set by August and is related to the availability of prey with the right size composition for the different size classes of juveniles (Winter *et al.*, 2005). Bio-energetic models indicated that 0-group pollock were at times sufficiently abundant to deplete their prey resources. Further studies examined predation on juvenile pollock by larger pollock and puffins whose densities were correlated on particular spatial scales with that of their prey (Swartzman and Hunt, 2000). Winter and Swartzman (2006)

synthesized data from acoustic surveys to develop predictive relationships for pollock recruitment based on the fish abundance and distribution around the Pribilof Islands, their nursery ground, and the co-occurrence of pollock with their preferred prey at different stages in their 0-group period; predator-abundance indices were also believed to be important.

The future

There are several particularly promising avenues for future advances in the use of acoustics to inform EBFM. One involves the greater integration of acoustics with satellite oceanography to inform sampling design and interpretation, as well as with other instruments for high-resolution physical and biological sampling, e.g. SeaSoar, the Moving Vessel Profiler combined with a Laser Optical Plankton Counter, the Video Plankton Recorder, and multibeam seabed mapping (Dickey and Bidigare, 2005; Kaltenberg *et al.*, 2006). These instruments all permit high-resolution two- and three-dimensional mapping of benthic and pelagic habitats, which can be related to biota in the mid-to-higher trophic levels mapped acoustically and sampled with nets. These technologies combined with enhanced computing power and developments in analytic and visualization software (Calzone *et al.*, 2008) must underlie advances in ecosystem-based management.

Other promising applications of acoustic technology include the use of instruments on moorings to obtain data with high temporal resolution; this is only just beginning to be explored along with acoustic deployments on gliders and autonomous underwater vehicles (Fernandes *et al.*, 2003; Scalabrin *et al.*, 2005; Brierley *et al.*, 2006).

This paper has focused primarily on developments in conventional acoustic technology and the scientific gains that can be achieved through their use in combination with complementary sampling tools. However, the history of oceanography is replete with examples of major advances based on the development of new technologies with a high-risk, but potentially high-gain, scientific strategy. Two such developments are the use of multibeam sonar to examine the three-dimensional structure of fish schools and other targets, and the development of shelf-scale acoustic mapping (Makris *et al.*, 2006).

Multibeam, side-scanning sonars have been developed to observe near-surface schooling fish that might otherwise avoid the vessel and acoustic detection. Viewing the schools in three dimensions, rather than two, enhances the study of school structure and behaviour (Gerlotto *et al.*, 1999; Axelsen *et al.*, 2001; Mayer *et al.*, 2002). However, the sampling volume and the related data are increased by an order of magnitude compared with those of conventional vertically profiling sounders. Quantitatively processing the data from a hundred to several hundred beams remains a challenge; these systems are generally deployed in conjunction with downward-looking echosounders.

Low-frequency acoustic methods, operating around several hundred Hz, hold exceptional promise for instantaneous imaging of shoaling fish populations over continental-shelf scales, using ocean-acoustic waveguide, remote-sensing techniques (Makris *et al.*, 2006). Thus far, this technology works best on continental shelves where the depth is reasonably constant and a waveguide is most readily formed between the seabed and sea surface. By instantaneously imaging fish aggregations on this scale, the technology provides unique insight into the distribution, behaviour, and ecology of these populations in relation to

oceanographic and topographic features. It should also provide more accurate and precise fish-stock assessments, if carried out in conjunction with direct fish sampling and conventional acoustic techniques.

Another technology that could result in major advances is the development of broadband acoustics, allowing acoustic instruments to probe the environment “like a dolphin” (Au and Benoit-Bird, 2006; Au *et al.*, 2006). Marine mammals appear able to “visualize” their environs acoustically, allowing them to discriminate among prey species. Conventional acoustic technology has advanced only incrementally from the early qualitative instruments used by Sund (1935) and Balls (1948). Fishery oceanographers are still awaiting the promise of acoustic technology to be fulfilled: to enable them to “see” through the opaque ocean medium and to discriminate, as well as to echo-locate marine mammals.

Developments in acoustic technology will surely enhance our understanding of ecosystem structure and the relationships between exploited and other key species with their predators, prey, competitors, and physical environment, but technological advances alone will not be sufficient. The complexity and variability of the marine environment across a range of spatial and temporal scales has frustrated earlier promises of rapid advances. Long-term observations are critical, along with the support of interdisciplinary teams that include acousticians, oceanographers, fishery scientists, and modellers, to developing a mechanistic understanding of the marine systems that must underlie ecosystem-based management. There will be no easy fixes; only a long-term commitment of researchers and resources commensurate with the complexity of the ocean environment and the issues confronting it today will suffice.

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