K. Tsukamoto, T. Kawamura, T. Takeuchi, T. D. Beard, Jr. and M. J. Kaiser, eds.
Fisheries for Global Welfare and Environment, 5th World Fisheries Congress 2008, pp. 335–349.

Coastal Artificial Habitats for Fishery and Environmental Management and Scientific Advancement

William Seaman

Department of Fisheries and Aquatic Sciences
University of Florida
Gainesville, Florida 32611, USA

E-mail: seaman@ufl.edu

Benthic reefs are the principal type of artificial habitat deployed in coastal waters worldwide to achieve fishery, ecosystem and other purposes. Ancient techniques to attract fishes to submerged natural objects for subsistence food harvest continue to be used, especially in tropical areas, while larger and more complex reefs commonly built of manmade materials and designed to meet an ecological life history requirement or limiting factor have been used in commercial fishing over the past 50 years, and more lately in marine ranching. Geographic centers of long-term artificial reef research and development include eastern Asia, the Mediterranean basin, India and North America. Trends in the use of this technology include a wider number of non-fishery applications, such as protection of habitat, conservation of biodiversity and socio-economic development, at a growing number of sites in over 50 countries. This paper presents significant findings and trends concerning the ecology of artificial reefs, their effects on fisheries and ecosystems, and appropriate applications of the technology. The maturation of long-term biological datasets has enabled quantification of ecological processes such as production of biomass at artificial reef sites, characterization of functional equivalence for artificial and natural reefs, and determination of sustainability of certain localized fishery harvests.

KEYWORDS artificial reefs; fisheries; environmental enhancement; habitat conservation; ecosystem restoration; eco-technology

1. Introduction

Artificial habitats are used in coastal waters worldwide for a variety of purposes concerning fishery and environmental management and sustainability. The most common application of this technology is in the form of artificial reefs, which include structures of natural or manmade origin intentionally deployed on the sea floor usually to modify ecological processes. Principal topics concerning artificial reefs addressed in this paper include their ecology and influences on fisheries and ecosystems, appropriate use of this technology, and progress toward their scientific understanding. The focus of this article is on common and somewhat larger benthic structures, so that small, less frequently used items such as plastic seagrass are not addressed. Also, suspended fish aggregating devices are not covered. Because they are prominent in certain situations, due to their role as *de facto* artificial reefs, very large objects including ships, petroleum production platforms, and rock breakwaters are included.

A growing body of evidence supports the argument that artificial reefs have merit as both natural resource management tools and research platforms in aquatic environments, giving them an appropriate place in mainstream Fishery Science. This gradual acceptance reflects a promise inspired by earlier practical successes and research advances reported only in the last decade, tempered by justified concerns for environmental and economic compatibilities still needing resolution.

2. Overview of Trends

In the past 20 years the use, modification and expansion of artificial reef practices have spread to all inhabited continents, and now include a more diverse set of practitioners than the earliest interests that, over millennia, have sought to increase subsistence fishing harvest. Modern applications of artificial reef technology include not only the earlier purposes of artisanal and commercial fishing to produce food, but also newer and broader objectives including recreational fishing and diving, eco-tourism, aquaculture and marine ranching, conservation and management of biodiversity, habitat restoration, education and research (e.g., Jensen 2002; Relini *et al*. 2007). (Some of these aims are beyond the scope of this paper.)

The historical approach of clustering rocks or weighted logs in shallow waters to attract fishes for easier harvest has been supplemented by use of opportunistic materials (e.g., derelict ships) as well as design, development and testing of larger modules and fabricated structures of concrete, fiberglass and steel that can approach the volume of small buildings as much as four or five stories tall (Fig. 1). Globally there is neither a formal compilation of physical locations and attributes of reefs, nor a directory or network of the interests that build and use reefs. The history of the field remains scattered in individual reports. It would not be possible to determine total fishery landings from all reefs worldwide. It can be estimated that the coastal waters of over 50 nations and territories contain artificial reefs, based on participation of 48 in at least one international conference since 1987 (Appendix 1); additional nations are recent entrants in the field. The spatial extent of reefs in coastal waters worldwide is not documented, although the largest relative coverage in any nation appears to be in Japan where, as of 1987, 9.3% of seafloor shallower than 200 m was dedicated to “fishing ground area” (Yamane 1989).

The emergence of a small number of private businesses that deal with the technology of artificial reefs is one anecdotal indicator of the growth of this field in recent years. Meanwhile, numerous university research centers and governmental ministries, agencies and laboratories at national, regional and

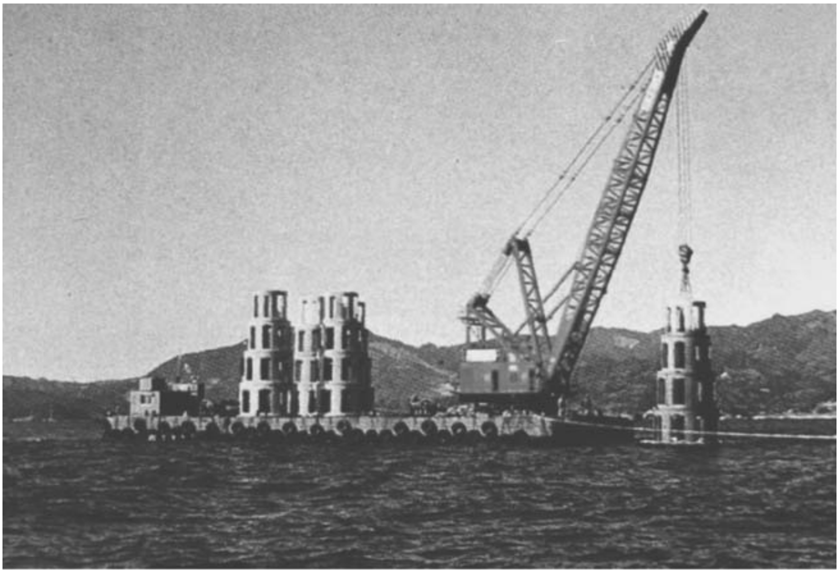

Fig. 1. Some of the largest artificial reefs, as used in commercial fishing in Japan (photograph courtesy of S. Otake).

local levels have engaged, for decades, in development, testing, inter-disciplinary research and deployment of artificial reefs. The earliest technological advances for reef development concerned physical attributes. Japanese interests pioneered this field in order to build and deploy large, manufactured structures in open-ocean, heavy-seas conditions. A series of engineering handbooks document this work (e.g., JNCFDA 1984), along with some of the earliest biological studies (e.g., Kakimoto and Okubo 1985).

More recently a notable trend has been the increasing use of science-based information in the biological aspects reef planning, design, construction, evaluation and management. Thus, it is worth investigation to determine if newer reefs, at least in some cases, have an overall ecological structure and function that more closely "mimics" natural reefs than older reefs. In other cases, newer reefs meet more closely the life history needs of at least some selected "target" species (Fig. 2). Manipulative ecological experiments have become more common in this field, as research has evolved beyond observational and monitoring studies. More long-term investigations are in progress.

Since the Fourth World Fisheries Congress (2004), which included a session on artificial reefs, artificial reef technology has been implemented in additional countries not identified in Appendix 1, such as Egypt, Malta and Tunisia; another in a series of global conferences on the subject has been held (2005); and the first formal, technical, international course on design and management of reefs for fisheries was conducted (2007).

Finally, significant resolution of perhaps the most contentious (and publicly visible and misunderstood) issue in this field—the so-called "attraction/production" debate—seems to have occurred, at least in much of the scientific community. The rigid either-or nature of the debate has been set aside in the sense that research results reported in peer reviewed journal articles and conference papers help quantify the spectrum of levels of biological production (versus aggregation) originally proposed by Bohnsack (1989). The

Fig. 2. Representative of efforts to incorporate biological design criteria into the physical structure of artificial reefs is the Box Reef, with open space in its upper level and confined space below (photograph courtesy of C. Kim).

longer term rigorous investigations urged by observers in the 1990s are now coming to fruition, yielding a rich database relevant to some of the trends introduced above, and others, as discussed in the following sections.

3. Key Sources of Information

In some aspects, artificial reef technology has been advanced considerably by the applied efforts of competent practitioners on-site in the field, while the theoretical and scientific sector initially lagged behind in its thinking. Much of the development of this field has been reported in conferences and journals. As many as 28 nations have been represented at such meetings at one time. As a proxy for a directory of reef-related research and development worldwide it is possible to use the literature provided by these meetings. Table 1 summarizes the record of contributions by authors from 48 countries and territories, who in any one conference presented as many as 180 oral reports and posters (1991) and published as many as 85 peer-reviewed journal articles (1994) and 101 non-reviewed proceedings articles (1995).

As a basis for analysis and synthesis of some recent trends and findings in research and management most recently reported at international conferences and in reviewed journals, the 55 papers published in *the ICES Journal of Marine Science* (2002, volume 59 [from 1999 conference]) and 20 papers in *the Bulletin of Marine Science* (2006, volume 78 [2005 conference]) were evaluated for content (Table 2). In addition to principal subjects covered, attributes of research including spatial and geographic locations, reef age and composition, and duration of study and overall database were noted, in part as an aid to forecasting future directions. It is informative to note that 34 of all the articles (75) reviewed for Table 2 address reef ecology primarily (45%), while 18 articles (24%) cover influences of reefs on fisheries, etc. and 23 (30%) cover planning and management-related issues. The analysis of literature is part of the basis for defining the

Table 1. Levels of effort for research and management related to artificial reefs indicated by number of presentations and published articles associated with international conferences (locations given in Appendix 1).

Conference Numbers				Publication Numbers			
Year	Countries of authors	Posters	Oral presentations	Year	Countries of authors	Abstracts	Papers
1983	7	14	43	1985*	7	26	29
1987	24	37	94	1989*	17	19	53
1991	25	(180 Combined)		1994*	25	127	85
1995	28	No Data	No Data	1995	27	0	101
1999	20	40	96	2002*	13	0	55
2005	20	25	68	2006*	9		20

*Articles peer reviewed

Table 2. Subjects addressed in peer-reviewed articles in journal compilations from two most recent international conferences on artificial reefs.

Overall theme discussed in paper and general subject area	Number of articles published: *ICES Journal of Marine Science*, 2002 (1999 conference)	*Bulletin of Marine Science*, 2006 (2005 conference)
Reef ecology:		
Species abundance, distribution, diversity	17	2
Behavior and movement	3	1
Diet and feeding	2	1
Productivity and production of biomass	6	2
Reef-environment interactions:		
Physical and chemical effects	4	1
Biological design criteria	3	2
Ecological and fishery effects	3	2
Ecological analysis and modeling	3	0
Reef use and management:		
Planning, policy, stakeholders	9	7
Reviews and methods	5	2
Total articles	55	20

following three sections. As much as possible, longer term studies are emphasized in this paper.

Time and space constraints did not permit extensive reviews of journals containing individual articles (i.e., included as "standalone" contributions), such as *Marine Ecology Progress Series* and *Hydrobiologia*. It is noteworthy that such journals are publishing more articles on artificial reefs in recent years, which may reflect growing emphasis on hypothesis-driven and manipulative investigations.

4. Artificial Reef Ecology

An ecological premise of responsibly deploying artificial reefs is that they target limiting factors, such as space for settlement, shelter or reproduction, and food. Bohnsack (1989) stated the rationale for reefs intended to increase biological production as providing "additional critical habitat that increases the environmental carrying capacity and eventually the abundance and biomass of reef fishes." Scientific documentation of the ecological structure and function of artificial reefs—often as objects worthy of study in their own right—began in earnest in the 1980s, subsequent to detailed engineering studies and ahead of socio-economic research. In a description of the progression of study in ecology, generally, from observational and descriptive to process-oriented and more experimental, Miller (2002) noted that "artificial reef research is an applied field and process-oriented study has often been given low priority" (p. S27). She also observed that artificial reef goals are "underpinned by ecological processes" including: recruitment, competition and trophic interactions (which bear on fisheries production); biogeochemical cycling and organism physiology (which bear on water quality enhancement); and life history/recruitment and species-habitat interactions (which bear on ecosystem restoration). Linkages between ecological processes and applied goals (such as the three indicated above) are part of the framework for this paper. Also, some of the methodologies used in research, and characteristics of reef sites are presented below.

There is not a universally used standard design of artificial reefs, for which commonly agreed measures of defined attributes might be made by the international research community. However, in numerous locations cubic modules of various designs are used in scientific studies and management trials and applications (Fig. 3).

Historically, early research worldwide has focused on species distribution and abundance, often at young sites just one or two years old. The purpose has been to characterize biodiversity using observational methods. Generally, the work has been in relatively shallow waters, performed by trained divers, whose techniques constitute a small body of literature derived from research on coral reefs and artificial reefs. The importance of long-term biological study has been recognized increasingly. For example, databases of 14 years from Portugal (Santos and Monteiro 2007) and 15 years from Italy (Relini *et al.* 2007) augment even longer term reports from the United States with a duration of as much as 25 years (Stephens and Pondella 2002). Fishes are the principal subjects of research, whereby of the 43 papers dealing with biological topics published in two journals after the two most recent international conferences, 29 dealt with fishes, 11 dealt with benthic invertebrates, three with plants.

Adding reef structure to the coastal benthic environment has been documented repeatedly to increase species abundance and diversity at the reef site. The rapid increase of adult fishes (via attraction) at newly constructed reefs is commonly observed. Also, patterns of colonization of increasing numbers of plant, invertebrate and fish species, to some plateau or equilibrium, have been documented; microbes remain unstudied. A 10-year database of 105 visual censuses at the Loano artificial reef (built of 8 m^3 concrete cubic modules) indicates that colonization and maturation of the site was a slow process (Relini *et al.* 2002), in which a nucleus of 15 fish species (present in over 25% of surveys) was joined at various times by 29 other species. The authors compared the Italian artificial reef site to a nearby natural rocky area in France, finding principal fish families in common (Sparidae, Labridae, Serranidae), and concluded that the artificial reefs "act in the same way as natural rocky seabed, increasing both species diversity and fish biomass" (p. S136).

In a nine-year study of a *de facto* reef created by disposal of 2,000,000 tonnes of waste steel slag in 40 m of water off southern

(A)

(B)

(C)

Fig. 3. Cubic modules with side dimensions of one to two meters are the closest structure used as a "standard" in artificial reef research and application. Convergence toward common design is illustrated by cubes used in (**A**) Taiwan, (**B**) Italy, and (**C**) United States (photographs courtesy of K. Tsao, G. Relini and W. Lindberg, respectively).

Taiwan from 1984 to 1989, Chou *et al.* (2002) determined by means of bottom trawling that number of fish species present at disposal area sampling sites (mean = 15.5, Shannon diversity index [H'] = 1.91) was significantly higher than at control sites (mean = 9.8, H' = 1.56). These authors report significantly different fish community structures as well, with the 12 km^2 slag disposal area favored by Bothidae and Scorpaenidae, for example. The nearby sandy control area favored Callionymidae and Mullidae. Overall number of individuals was not significantly different between the two areas. The conclusion of this study is that the material placed on the bottom increased habitat complexity.

Patterns of residence and site fidelity by red snapper, *Lutjanus campechanus*, on artificial reefs were determined by Schroepfer and Szedlmayer (2006). Using ultrasonic tags and arrays of remote receivers they determined that (1) for 99% of total time 87% of individuals stayed within 200 m of their original release site, and (2) median residence time was 373 days. They suggest "that artificial reefs provide suitable habitat for *L. campechanus*."

Artificial reefs can provide food for fish assemblages, and in turn contribute to production of biomass. A 25-year study of two embiotocid species, *Embiotoca jacksoni* (black surfperch) and *Rhacochilus vacca* (pile surfperch), is unique not only for its duration and rich database, but also for the viviparous life history of these species, whereby their entire ontogeny could be observed on the artificial reefs (Pondella *et al.* 2002). The site was 50 years old when the research began. The King Harbor artificial reef (a rock breakwater) supported significantly higher mean densities of both juveniles and adults of black surfperch (1.3 and 5.6, respectively, per 100 m^2) and also pile surfperch (0.39, 2.4) than did the nearest natural rocky-reef 9 km away (0.1 and 3.1, 0.08 and 0.13, respectively). The authors conclude that the artificial reef had a higher carrying capacity, and that its populations were self-maintaining and did not draw from natural reefs. Typically, trophic studies are much shorter. For example, in 1997–1999 Fabi *et al.* (2006) studied the established Senigallia artificial reef (built 1987, 11 m depth) and based on summer and autumn data determined that it "provided the main source of food" for the species of concern (i.e., *Sciaena umbra*, *Diplodus annularis*, *Lithognathus mormyrus*). Items in the diets included organisms from soft bottom (mollusks, polychaetes) and hard substrate (crustaceans).

The difficulties of evaluating (and comparing) production at artificial and natural reefs were identified by Pondella *et al.* (2002) as including lack of information about life history parameters (e.g., birth rates, mortality, immigration/emigration, growth), fluctuation of populations, and high variance over time. In a study of King Harbor breakwater (built in 1950–1958) and a control that lasted for 24 years, Stephens and Pondella (2002) not only documented long-term changes in environmental conditions, and corresponding change in fish assemblage composition, but also determined that the breakwater artificial reef contributed "generously" to the reef fish larval pool of the region, and at a magnitude comparable to natural reefs. The report of these findings (in 2002) addresses some of the information gaps identified in 1989 by Bohnsack.

Studies of epibiota on artificial reefs are relatively few. Of 17 articles concerning "species abundance" in the ICES 2002 document (Table 2), for example, only Collins *et al.* (2002a) address epifauna. Using an incubation chamber, over four summers (1995–1998) these authors determined respiration and oxygen production on a 12-m deep concrete block reef built in 1989 in Poole Bay, England. Research on macro-invertebrates and plants is somewhat more extensive and is addressed in a discussion of reef design criteria and ecosystem influences, below.

5. Artificial Reef Influences on Fisheries and Ecosystems

The effects of artificial reefs are broad, including physical, chemical and biological influences upon the natural environment, and they rightfully should be of concern. Leaching of deleterious chemicals, for example, must be evaluated in considering the use of so-called waste "materials of opportunity" such as tires, or ashes from combustion in electric power stations (e.g., Collins *et al*. 2002b). Also, entire reefs or their components may sink into substrate or else unexpectedly modify or be moved by hydrodynamic features such as prevailing currents and episodic storm surges (e.g., Sheng 2000). In this section the emphasis is on ecosystem and fishery influences of artificial reefs, consistent with the theme of the 2008 World Fisheries Congress. An important question to address is "What is the ecological response to the physical design of a reef?" More recent socio-economic issues are in the following section.

Japan's fishery reef-building enterprise and industry is the oldest and most extensive in the world, with large corporations having units that focus exclusively on design, fabrication and deployment of structures. Governmental, academic and private laboratories there and in several other nations have initiated research and development for artificial reef materials and construction. Kim *et al*. (in press) compare Japanese and Korean efforts. Reports from the two most recent international reef conferences include only one engineering paper, however, in which Duzbastilar *et al*. (2006) report on the use of concrete scale models (1:30) of reefs tested in laboratory wave channels for stability and scour performance; this work is incorporated in a "stability chart" used to match design, installation and settling parameters to water depth and wave conditions in Turkey. Both physical and mathematical modeling are distinct advantages to engineering research.

In contrast to physical and engineering research, ecological modeling and forecasting have been infrequently addressed in studies of artificial reefs. Recent work by Pitcher *et al*. (2002) considered over 250 species of fish at Hong Kong to develop an ECOPATH model of trophic flows among functional groups in the ecosystem and an ECOSIM simulation of biomass fluxes in response to fishing. This in turn led to an ECOSPACE evaluation of biomass and fishery responses to various possible management scenarios, with one conclusion being: "While small protected areas with human-made reefs achieve little to avert collapse of the fisheries or a shift towards catches of low-value species, larger protected areas can do much to restore valuable fisheries for reef-associated fish" (p. S17). Osenberg *et al*. (2002), meanwhile, proposed both a mathematical model concerning the effects of multiple processes on reef fish dynamics, and experimental approaches to address what they define as a gap in information: "We know of no study that has quantitatively compared production (or fish abundance) of replicate natural reefs with and without nearby artificial reefs and partitioned the total production between them" (p. S218).

The lack of study of the effects of artificial reefs on surrounding benthic ecosystems was indicated by Fabi *et al*. (2002), whose research in 1997–1999 on a group of 29 five-module (8 m^3 each) concrete reefs built in 1987 and a nearby sandy-muddy area of the central Adriatic Sea (11 m depth) documented 166 invertebrate taxa. Infauna were removed by a suction sampler operated along transects internal and external to the reefs. Differences included accumulation of organic matter inside the reef, which favored deposit and suspension feeders such as polychaetes; molluscs were dominant externally.

A small body of recent literature specifically concerns the influence of attributes of habitat upon biological assemblages at artificial reefs. The subject of design is particularly amendable to manipulative experiments. One of the most expensive and largest (61 ha) artificial reefs in the United States is intended to mitigate for loss of kelp (*Macrocystis pyrifera*) in Southern California. Deysher *et al*. (2002) summarize a set of design specifications for establishing sustainable kelp populations derived from a five-year pilot study at a 9-ha site. The attribute of relief, for example, is most conducive to kelp cover when it is "low" instead of either "very low" or "high." Optimal depth is 12–14.5 m. Importantly, these and other studies (e.g., Reed *et al*. 2006) draw heavily on ecological knowledge of the species of concern, to account for effects of disturbance and grazing upon plant survival as a means of designing reef profile. Finally, this work is notable for establishing two success criteria, i.e., four adult kelp plants per 100 m^2, and "similarity" of invertebrate and fish assemblages to natural reefs, as a means of evaluating performance of the artificial reef to meet its objectives.

Broadly speaking, "complexity" of habitat is repeatedly identified as a key attribute that in turn dictates biological diversity on an artificial reef. Miller (2002) gave an example of experimental reefs with relatively "greater availability and heterogeneity of refuge space" as supporting more fishes, in a situation where predation was a mechanism limiting fish abundance (Eklund 1997).

In studies of concrete module-based control (deployed 1986) and experimental (deployed 1987, modified 1991) reefs, Charbonnel *et al*. (2002) in 1987–1989 and again in 1997–1998 conducted visual censuses which determined that total number of fish species doubled (to 36) on the experimental reef after addition of complexity, as did the mean number of species per census (18.9), while total wet weight biomass increased significantly. The authors suggest that increased availability of shelter may be the most important factor involved, and note that increased food is available at the reef and in surrounding habitat. They further conclude that the original design of the reefs lacked effectiveness in meeting the ecological requirements of the local demersal fish fauna, an indication of the need to carefully consider reef design before deployment to enhance fisheries.

One prominent *de facto* artificial reef in the nearshore Pacific Ocean off Santa Barbara, California, U.S.A. is an accumulation of metal debris left on the seabed after drilling of exploratory and production oil wells. Based on analysis of videotapes from 130 objects Caselle *et al*. (2002) assessed fish assemblage composition as related to morphology of structure. They found that vertical profile positively affected abundance for two of four rockfish (*Sebastes*, Scorpaenidae) species studied, and that shelter positively affected species richness.

A study specifically addressing artisanal fisheries in Algarve, Portugal used nighttime gillnet samples (256 net sets over 14 years) to compare yield at artificial reefs (of 2.7 m^3 units) and control sites (Santos and Monteiro 2007). Overall, catch at artificial reefs always exceeded control sites, with benthic species more abundant than nekto-benthic and then pelagic fishes. The authors note that ecologically the artificial reefs support the same "relative proportion" of these three functional groups as is found on natural/control reefs. The study concludes that the artificial reefs contribute to improved local artisanal fisheries. The occurrence of benthic species on the Algarve reefs meets one of the characterizations for species likely to inhabit artificial reefs listed by Bohnsack (1989); other life history characteristics include territoriality, philopatry and habitat limitation.

6. Artificial Reef Applications in a Management Context

The use of artificial reefs in mainstream fishery and aquatic science has become more accepted, even as healthy skepticism remains. The historical lack of evaluative studies and experimental manipulations of course have justified concerns for applying reef technology. Fabi *et al*. (2002, p. S343) state that "Artificial reefs are commonly used around the world as fishery-management tools and to replace habitat losses caused by human impacts." Santos and Monteiro (2007) state that they "have become important elements of integrated fisheries management plans" (p. S25). In both cases these authors have been studying reef systems for over a decade. Conversely, Jensen (2002) states: "Artificial reefs are still seen by most managers of the marine environment and/or fisheries in Europe as an ineffective and expensive technology" (p. S9). He refers to concerns for overexploitation of aggregated adult fishes, but also to gaps in communication by experts to explain actual and potential applications.

Artificial reefs are deployed in coastal ecosystems for aims such as physical protection against illegal trawling, restoration of habitat, enhancing biodiversity, improving fishing catch, research on materials and designs performance, and environmental observation, as enumerated by Relini *et al*. (2007). These authors reported on one of the richest datasets for artificial reefs anywhere: From research over 30 years in the Gulf of Genoa, Italy, which has resulted in about 100 technical publications, they conclude that reef deployment successfully achieved increase of species richness and biomass, and protection against otter trawling in sensitive habitat. The long time-series of data contributes to a finding of functional equivalence between artificial reefs and natural rocky reefs.

Because of the localized and seemingly small scale of many deployments of artificial reefs it is important to keep in mind the community and cultural characteristics of key groups of stakeholders. A response to destruction of habitat and overfishing in many areas of the world is typified by artisanal and subsistence fishing interests in India to revitalize longstanding utilization of small artificial reefs. The situation described for Kerala by d'Cruz *et al*. (1994) is noteworthy because the local populace was strongly motivated to regulate fishing activity and access to sustain long-term harvest, and because the investigations closely incorporated local citizens into project planning and data gathering. Understanding the social framework of the community was a prime concern of the study. Similarly, in an urban setting, Ditton *et al*. (2002) observed a trend in natural resource management "towards an understanding of, and planning for, resource users and their recreational experiences rather than simply being concerned with biological enhancements" (p. S186), and reported the response of sport divers in Texas, U.S.A. that they would most prefer large naval ships as a reef material, instead of other structures such as concrete blocks. In fact 82% of divers with this preference indicated that they would increase their diving if a ship was deployed at their favorite dive site. Sensitivity to local needs is reflected in commercial fishing development, as well, as reported for Japan by Simard (1995).

Despite a trend toward increasing use of specially designed and fabricated reef structures worldwide, certain "materials of opportunity" (i.e., surplus and waste manufactured items of considerable size) will continue to be proposed. Managers of natural resources need to be prepared to deal with them objectively. Of particular note is the situation in which obsolete oil and gas production platforms are already used, or proposed for decommissioning and redeployment, as fishing enhancement structures. Eight of 55 papers published from the 1999 international conference on artificial habitats address petroleum platforms, as examined in a conference session, and offer benchmark information about fisheries potential. One of the papers, by Cripps and Aabel (2002), identifies 39 possible impacts of "rigs" being used as reefs including biological factors such as redistribution of biomass, overfishing and changes in infauna, as well as legal and operations issues. This approach is relevant to planning of artificial reefs generally. (For the Norwegian reef addressed by these authors, a protection strategy for platform use was deemed to have more benefit than a fishing strategy.)

A key element of understanding how artificial reefs can be used as an integrated management tool (Jensen 2002) is the ability to evaluate their performance. Preceding sections have focused on physical and biological aspects. Socio-economic assessment is also important, but its implementation has lagged. Milon *et al.* (2000) decry the "general lack of reports or studies about the demand for artificial reefs and the socioeconomic efficiency of these projects." Such studies remain limited. Positive effects from the sinking of a naval ship in the Florida Keys National Marine Sanctuary (USA) were determined in testing of a hypothesis by Leeworthy *et al.* (2006) to include both reduction of diver pressure on nearby natural reefs and expansion of the local economy as measured by growth of income and employment in dive charter businesses. In a progression from biological to economic assessment at artificial reefs in Portugal, Ramos *et al.* (2006) found that commercial fishing regularly occurred at the Olhao Reef System and that an income significantly higher than the national minimum wage was realized,

Marine ranching has been emphasized in eastern Asia, and the additional concept of stocking hatchery-reared fishes onto artificial reefs developed there. The concept has been extended to southern Europe, where trials with two species of Sparidae show promise as part of an integrated plan to enhance local artisanal fisheries (Santos *et al.* 2006).

7. Discussion and Outlook

As with other practices of Fishery Science, artificial reefs must be used in a science-based fashion and administered, evaluated and enforced realistically. A precautionary approach toward artificial reef development is common among scientists and administrators. The advent of a multi-disciplinary research base has enhanced the adoption of some reef practices, and the dismissal of others. Key advances in this field include maturation and subsequent analyses of long-term databases to address fundamental ecological issues (e.g., production); specification of physical, biological and socio-economic design criteria (e.g., habitat complexity) to enhance performance of reefs consistent with measurable resource management aims and success criteria; and in a few cases the "scaling-up" of reef size either for research (e.g., Loch Linne, Scotland reef of 42,000 tonnes) or to influence larger spatial areas for fisheries (e.g., Algarve, Portugal reefs involving 35 km^2; Jensen 2002).

Scientifically, advancement of this field will be furthered by: (1) understanding of the basic biology of reef organisms; (2) tying design criteria to life histories of reef organisms; (3) development of long-term databases from individual sites; (4) comparison of reef sites across appropriate spatial gradients; (5) continuing expansion of manipulative experiments; (6) pilot studies as cost-effective precursors to large reef developments; (7) inter-disciplinary studies; (8) cooperative studies across regional and national boundaries; (9) fishery and ecosystem modeling; and (10) specification of success criteria and evaluation of reef performance against measurable objectives. Meanwhile, communication between scientists and the managers of resources is essential to foster understanding of potential and limits to reef technology, and expedite information transfer. A model of expansive regional cooperation is seen in the European Artificial Reef Research Network, which has promoted formulation of common research priorities and documentation of scientific and management progress (e.g., Jensen 2002). Continuing the series of international conferences, expanding technical education courses for professionals on reef design and management, and conducting a review and synthesis of published reviewed technical literature on reef ecology and influences all would strengthen this field.

References

Bohnsack JA. Are high densities of fishes at artificial reefs the result of habitat limitation or behavioral preference? *Bull. Mar. Sci.* 1989; **44**(2): 631–645.

Caselle JE, Love MS, Fusaro C, Schroeder D. Trash or habitat? Fish assemblages on offshore oilfield seafloor debris in the Santa Barbara Channel, California. *ICES J. Mar. Sci.* 2002; **59**: S258–S265.

Charbonnel E, Serre C, Ruitton S, Harmelin J-G, Jensen A. Effects of increased habitat complexity on fish assemblages associated with large artificial reef units (French Mediterranean coast). *ICES J. Mar. Sci.* 2002; **59**: S208–S213.

Chou W-R, Tew KS, Fang K-S. Long-term monitoring of the demersal fish community in a steel-slag disposal area in the coastal waters of Kaohsiung, Taiwan. *ICES J. Mar. Sci.* 2002; **59**: S238–S242.

Collins KJ, Jensen AC, Smith IP. Oxygen fluxes of enclosed reef epibiota communities. *ICES J. Mar. Sci.* 2002a; **59**: S94–S99.

Collins KJ, Jensen AC, Mallinson JJ, Roenelle V, Smith IP. Environmental impact assessment of a scrap type artificial reef. *ICES J. Mar. Sci.* 2002b; **59**: S243–S249.

Cripps SJ, Aabel JP. Environmental and socio-economic impact assessment of Ekoreef, a multiple platform rigs-to-reefs development. *ICES J. Mar. Sci.* 2002; **59**: S300–S308.

d'Cruz T, Creech S, Fernandez J. Comparison of catch rates and species composition from artificial and natural reefs in Kerala, India. *Bull. Mar. Sci.* 1994; **55**(2–3): 1029–1039.

Deysher LE, Dean TA, Grove RS, Jahn A. Design considerations for an artificial reef to grow giant kelp (*Macrocystis pyrifera*) in Southern California. *ICES J. Mar. Sci.* 2002; **59**: S201–S207.

Ditton RB, Osburn HR, Baker TL, Thailing CE. Demographics, attitudes and reef management preferences of sport divers in offshore Texas waters. *ICES J. Mar. Sci.* 2002; **59**: S186–S191.

Duzbastilar FO, Lok A, Uas A, Metin C. Recent developments on artificial reef applications in Turkey: hydraulic experiments. *Bull. Mar. Sci.* 2006; **78**(1): 195–202.

Eklund AM. The importance of post-settlement predation and reef resources limitation on the structure of reef fish assemblages. *Proc. 8th International Coral Reef Symposium* 1997; **2**: 1139–1142.

Fabi G, Luccarini F, Panfili M, Solustri C, Spagnolo A. Effects of an artificial reef on the surrounding soft-bottom community (central Adriatic Sea). *ICES J. Mar. Sci.* 2002; **59**: S343–S349.

Fabi G, Manoukian S, Spagnolo A. Feeding behavior of three common fishes at an artificial reef in the northern Adriatic Sea. *Bull. Mar. Sci.* 2006; **78**(1): 39–56.

JNCFDA (Japan National Coastal Fishery Development Association). Manual for Designing Structures for Coastal Fishing Ground Development Project. 1984; 359 pp. (in Japanese).

Jensen AC. Artificial reefs of Europe: perspective and future. *ICES J. Mar. Sci.* 2002; **59**: S3–S13.

Kakimoto H, Okubo H. General study on the artificial reefs of Niigata Prefecture and realizations. Niigata-ken Suisan Shikenjo: Fisheries Experimental Station of Niigata Prefecture, Japan; 1985. 327 pp. (in Japanese).

Kim CE, Kim HS, Baik, C, Kakimoto H, Seaman W. Design of artificial reefs and their effectiveness in the fisheries of eastern Asia. American Fisheries Society Symposium (in press).

Leeworthy VR, Maher T, Stone EA. Can artificial reefs alter user pressure on adjacent natural reefs? *Bull. Mar. Sci.* 2006; **78**(1): 93–101.

Miller MW. Using ecological processes to advance artificial reef goals. *ICES J. Mar. Sci.* 2002; **59**: S27–S31.

Milon JW, Holland SM, Whitmarsh DJ. Social and economic evaluation methods. *In*: Seaman W (ed). *Artificial Reef Evaluation*. CRC Press. London. 2000; 165–194.

Osenberg CW, St. Mary CM, Wilson JA, Lindberg WJ. A quantitative framework to evaluate the attraction-production controversy. *ICES J. Mar. Sci.* 2002; **59**: S214–S221.

Pitcher TJ, Buchary EA, Hutton T. Forecasting the benefits of no-take human-made reefs using spatial ecosystem simulation. *ICES J. Mar. Sci.* 2002; **59**: S17–S26.

Pondella DJ, Stephens JS, Craig MT. Fish production of a temperate artificial reef based on the density of embiotocids (Teleostei: Perciformes). *ICES J. Mar. Sci.* 2002; **59**: S88–S93.

Ramos J, Santos MN, Whitmarsh D, Monteiro CC. Patterns of use in an artificial reef system: a case study in Portugal. *Bull. Mar. Sci.* 2006; **78**(1): 203–211.

Reed DC, Schroeter SC, Huang D, Anderson TW, Ambrose RF. Quantitative assessment of different artificial reef designs in mitigating losses to kelp forest fishes. *Bull. Mar. Sci.* 2006; **78**(1): 133–150.

Relini G, Relini M, Torchia G, Palandri G. Ten years of censuses of fish fauna on the Loano artificial reef. *ICES J. Mar. Sci.* 2002; **59**: S132–S137.

Relini G, Relini M, Palandri G, Merello S, Beccornia E. History, ecology and trends for artificial reefs of the Ligurian sea, Italy. *Hydrobiologia* 2007; **580**: 193–217.

Santos MN, Monteiro CC. A fourteen-year overview of the fish assemblages and yield of the two oldest Algarve artificial reefs (southern Portugal). *Hydrobiologia* 2007; **580**: 225–231.

Santos MN, Lino PG, Pousao-Ferreira P, Monteiro CC. Preliminary results of hatchery-reared sea breams released at artificial reefs off the Algarve coast (southern Portugal): a pilot study. *Bull. Mar. Sci.* 2006; **78**(1): 177–184.

Schroepfer R L, Szedlmayer ST. Estimates of residence and site fidelity for red snapper *Lutjanus campechanus* on artificial reefs in the northeastern Gulf of Mexico. *Bull. Mar. Sci.* 2006; **78**(1): 93–101.

Sheng YP. Physical characteristics and engineering at reef sites. *In*: Seaman W (ed). *Artificial Reef Evaluation*. CRC Press, London. 2000; 51–94.

Simard F. Reflexions sur les recifs artificiels au Japon. *Biologia Marina Mediterranea* 1995; 99–109. (Not seen.)

Stephens J, Pondella D. Larval productivity of a mature artificial reef: the ichthyoplankton of King Harbor, California, 1974–1997. *ICES J. Mar. Sci.* 2002; **59**: S51–S58.

Yamane T. Status and future plans of artificial reef projects in Japan. *Bull. Mar. Sci.* 1989; **44**(2): 1038–1040.

Appendix 1. Identity of 48 countries and territories with artificial reef development as reflected by oral and poster presentations at international conferences, 1987—2005.

Country/Territory	Year and location of conference				
	1987 United States	1991 United States	1995 Japan	1999 Italy	2005 United States
Australia	X	X	X		X
Bangladesh			X		
Belgium					X
Brazil				X	X
Canada	X	X	X	X	
Chile		X			
China			X		X
Colombia					X
Costa Rica	X				
Cote d'Ivoire	X	X	X		
Cuba		X	X		
England		X	X	X	X
France			X	X	
Germany	X			X	X

Appendix 1. (cont.)

Country/Territory	Year and location of conference				
	1987 United States	1991 United States	1995 Japan	1999 Italy	2005 United States
Greece				X	
Guatemala	X				
Hong Kong			X	X	
India	X	X	X		
Indonesia	X				
Israel	X	X		X	X
Italy	X	X	X	X	X
Jamaica	X				
Japan	X	X	X	X	X
Korea		X	X		X
Malaysia		X	X		
Maldives	X	X			
Mexico	X	X			X
Monaco	X	X		X	
Nigeria		X	X		
Norway			X	X	
Oceania	X	X			
Philippines	X	X	X		X
Poland				X	
Portugal		X	X	X	X
Puerto Rico			X		
Romania	X				
Russia		X	X		
Scotland	X		X	X	X
Senegal			X		X
Spain		X	X	X	X
Sri Lanka	X	X	X		
Sweden			X		
Taiwan	X	X	X	X	X
Thailand	X				
Turkey				X	X
Ukraine			X	X	
United States	X	X	X	X	X
Virgin Islands	X	X			
TOTAL	24	25	28	20	20