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Artificial habitats for benthic dwelling lobsters - analysis of 5 decades of research

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Abstract

Adult lobsters of the families Palinuridae, Nephropidae and Scyllaridae are important fisheries resources in tropical and temperate waters. They are nocturnally active and shelter during the day presumably as an anti-predatory adaptation. Recognizing that the need for shelter is paramount, current studies are aimed at development of artificial reefs (ARs) that imitate the natural shelters of lobsters, particularly those inhabiting hard substrates, and provide appropriate sheltering needs for relevant benthic ontogenetic stages. A review of the literature from the past 5 decades suggests that interest in developing ARs for lobsters has increased. Much of this increase in research efforts stems, on one hand, from a better understanding of the recruitment processes of several important commercial lobster species and, on the other hand, from the decline of many commercial lobster populations due to overfishing, diseases, man-made destruction of environment, and other natural phenomena. Most AR studies on lobsters are limited to a small number of species, confined locally, and are conducted only in the short term. Thus there is presently insufficient evidence to argue that these ARs are effective at increasing survival of lobsters at the population level and do little more than aggregate individuals on the reef. Long-term, large-scale, quantitative field studies of ARs of the commercially/ecologically most important lobster species are needed. Such studies will enable understanding of the actual role of these man-made structures in fisheries management and conservation of lobsters.

Keywords: Lobsters, artificial reefs, man-made reefs, *casitas, pesqueros*, enhancement

Introduction

Lobsters in the infraorders Palinura and Nephropida represent an important worldwide food resource, with the species that support the majority of the total world lobster fishery coming from three families: clawed lobsters (Nephropidae), spiny lobsters (Palinuridae), and to a much lesser degree, slipper lobsters (Scyllaridae) (Spanier and Lavalli, 2007; Herrnkind and Cobb, 2008). All fished species of lobsters are considered luxurious delicacies and are among the most costly of all seafood products (e.g., Wallace, 2004). Reported global fisheries production of lobsters in 2007 was 226,805 metric tons, of which clawed lobsters made up 70%, spiny lobsters made up 28%, and slipper lobsters contributed less than 2% (FAOSTATS, 2010). Demand for lobsters has increased as expressed by an increase in prices and value (FAOSTATS, 2010; Fig. 1). Such demand has resulted in increased fishing effort and pressure on commercial lobster populations as seen by the three-fold increase in crustacean production between 1950 and 2008 (FAOSTATS, 2010; Fig. 1) and a 2.4-fold increase in worldwide exports between 1986 and 2006 (FAOSTATS, 2006). Unfortunately, overfishing of local stocks and even collapses of lobster fisheries for certain species have become a more frequent phenomenon. For example, sharp declines seen in stocks of *Homarus gammarus* in Norway (van der Meeren, 2003), *H. americanus* along the Atlantic coast of Canada (Garnick, 1989), the Tasmanian rock lobster, *Jasus edwardsii* (Bradshaw, 2004), the Caribbean spiny lobster (*Panulirus argus*) in the southern Florida fishery (Bertelsen and Matthews, 2001), and the Mediterranean slipper lobster, *Scyllarides latus*, along the Mediterranean coasts of Europe (Spanier, 1991; Pessanni and Mura, 2007) and in the Azores Islands (Martins, 1985) (and see other reports in the present volume). All of the above point to the unsustainability of current fishing practices, in terms of both technological advances that make increased fishing effort possible and in numbers of fishers pursuing these resources.

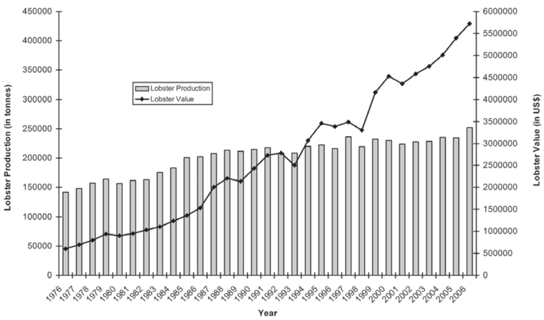

Fig. 1. FAO Commodity trade and production values in US Dollars (line) and production value of quantity (bars) for lobsters in all forms (live, frozen, tails). From FAO-fisheries and aquaculture information and statistics service, 31 July 2010

In some cases, overfishing of one or more species of one family of lobster increases fishing pressure on another family. As a result of the depletion of the local spiny lobsters *Panulirus penicillatus* and *P. gracilis* in the Galapagos Islands, fishing pressure has increased on *S. astori* (Hearn, 2006; Hearn *et al.,* 2007). Likewise, a 50% drop in recruitment to fisheries of *P. marginatus* in Hawaii since 1989 resulted in subsequent overexploitation of the Hawaiian slipper lobsters (*S. squammosus, S. haanii, Parribacus antarcticus*) and spiny lobsters (*P. marginatus, P. penicellatus*) (Polovina *et al.,* 1995). Overfishing of lobsters in some localities in India (e.g., Mumbai, Veraval) caused collapses of the fisheries of the slipper lobster, *Thenus orientalis* and spiny lobster *Palinurus polyphagus* (Radhakrishnan *et al.,* 2007). These examples combined with state and/or federal fisheries management models of stock production suggest that natural lobster populations have been harvested to an apparent worldwide maximum and that most commercial lobster fisheries are operating at or above maximum sustainable yield (Herrnkind and Cobb, 2008).

In addition to fishing effects, some species of lobsters have experienced dramatic declines due to harmful natural environmental events or anthropogenic effects. These include the mass mortalities of *Jasus lallandii* along the west and south coasts of South Africa that were due to low-oxygen conditions (Cockcroft, 2001); the significant mortalities suffered by Long Island Sound *H. americanus* lobsters that were attributed to higher water temperatures and the resultant hypoxia, heavy metal poisoning, pesticides, and alkyphenols (possible endocrine disruptors) (Biggers and Laufer, 2004; Pearce and Balcom, 2005; Tlusty *et al.,* 2007; Vogan *et al*., 2008 and references therein); the decline in catches of *P. argus* in Yucatan, Mexico (Briones-Fourzán *et al.,* 2000) as well as in Florida (Hunt, 2000) because of loss of habitat from severe hurricanes and loss of sponges that provided shelter for early benthic stages (Butler *et al.,* 1995); and the ~45% drop in landings of *P. argus* as the result of a new pathogenic virus (PaV1) (Shields and Behringer 2004; Li *et al.,* 2008). Environmental disasters, such as an oil spill, can cause considerable loss of lobsters within a population (e.g., the oil spill in Narragansett Bay, Rhode Island, USA in 1989; Castro *et al.,* 2001). These natural and man-made events have profound effects on local populations which take years to recover, and recovery is slowed when the remaining population continues to be commercially exploited (see other recent examples in the present volume). Likewise, natural events, such as algal blooms, excessive river run-off during heavy rains, storm changes in shallow benthic environments, and/or thermal changes via climate change, can also negatively impact established lobster populations and cause redistribution of the lobsters comprising those populations to other areas; such changes may be short- or long-term in nature. Where such perturbations to the environment have occurred, the use of artificial reefs (ARs) may help ameliorate such effects by attracting lobsters back into the area more quickly or providing suitable habitat for benthic recruitment of settling forms.

The present article reviews scientific and technical publications dealing with lobsters and ARs by focusing on three lobster families that have considerable commercial importance. It examines the current state of knowledge of what types of structures are most successful in attracting benthic adult and juvenile stages of lobsters, discusses whether such structures are effective at increasing local populations and/or enhancing production of lobsters or merely act to redistribute and concentrate lobsters into a particular area, and provides suggestions that can be used for future work on ARs specifically aimed at improving lobster populations.

Artificial reefs (ARs) and their effects

Artificial reefs (ARs) have been used for a variety of marine organisms and a considerable body of research has been devoted towards an understanding of what makes them attractive to target species. The desired effect of ARs is to increase long-term abundance and productivity of the target species, and this effect differs from a simple local attractive effect only in terms of time and space. As a result, when assessing the efficacy of ARs, experimental resolution has to be fine enough to enable detection of differences between a mere attractive effect that aggregates and concentrates species and a true and permanent increase in abundance of species in the local area (*i.e.,* a production increase) (Seaman, 2000). Experiments also have to last long enough to observe the limits of AR effects. This is easier said than done as proper replication with interspersed controls can be difficult to set up in the space set aside for an AR (Brickhill *et al*., 2005).

When ARs are deployed, three main types of effects on local fauna may take place: (1) biomass redistribution, (2) aggregation, which increases only the exploitable biomass, and (3) an increase in total biomass via production (Polovina, 1991). Biomass redistribution assumes that immigration to the reef will ultimately be balanced by emigration from the reef to formerly occupied sites as overall numbers of lobsters increase and/or by settlement into former grounds as space becomes available. In contrast, the aggregation hypothesis predicts that the loss incurred to the natural habitat by individual emigrating to the AR will not be augmented by new arrivals generated by AR production or by the opening up of space for new recruits. The production hypothesis, however, predicts mitigation for the fauna attracted to the AR by new arrivals to the natural habitat and also suggests positive effects of faunal export to and from the AR, which may eventually serve as an enhanced gene pool for the local population. Which effect(s) will take place depends on ecosystem components present and the manner in which humans impact those components (e.g., fishing pressure and habitat degradation). Many post-deployment surveys of ARs have reported the presence of local fish aggregations, but little direct evidence points to permanent increases in total population size or fish stock (Polovina, 1991; Pickering and Whitmarsh, 1996; Bohnsack *et al.,* 1997; Osenberg *et al.,* 2002). Hence, some believe that ARs simply represent another location in which species could suffer overexploitation by fisheries (Brickhill *et al.,* 2005).

Although increased production of local populations is the stated goal of ARs, attractiveness/aggregation to benefit fisheries is also sought as a major result, which is one of the foremost criticisms of deploying ARs (Bohnsack *et al.,* 1997; Grossman *et al.,* 1997; Lindberg, 1997; Bortone, 1998, 2008 and see discussions in Seaman, 2000). Proposals presented by entities within the more than 30 countries deploying ARs state that the main purpose of these reefs is fishery related (Jensen 2002; Bortone, 2008). Benefits for conservation of species and habitat restoration were occasionally mentioned, but tended to be overstated and were secondary to fishing enhancement. As more and more ocean species become depleted, these biases towards aggregating species for easier human exploitation may shift our thinking about the role ARs can play in restoration of depleted populations.

In general, site-specific and species-specific approaches in the design and deployment of ARs are necessary, because the mechanisms underlying recruitment to an AR, with either attractiveness or production playing a role, vary across a wide range of factors. For lobster (as well as other crevice dwelling organisms), this means study designs for ARs need to incorporate monitoring of the enhanced sheltering opportunities provided in the reef compared to that of the natural environment, as well as monitoring spatial and temporal aspects of the shelters that are important to particular life history stages.

General importance of ARs to benthic lobsters

Various man-made structures, not originally designed or deployed to attract lobsters, such as ship wrecks, have been known for decades to attract these large crustaceans. (e.g., Howard, 1980; Werz, 2007). Other artificial structures such as breakwaters, jetties and canal walls have attracted considerable numbers and wide size ranges of lobsters (Relini, 2000; Barnabé *et al.,* 2000). Fishermen, knowing of the tendency of lobsters to be attracted to these unintended ARs, have set their traps and lobster pots in these locations to increase their lobster catch. Divers have also known about the concentration of lobsters in ship wrecks and preferred to work in these man-made sunken structures when diving for lobsters (Berg, 2009). Even lobster pots can be considered a type of AR since the majority of lobsters move freely in and out of these traps (Jury *et al.,* 2001).

ARs designed to attract other taxa have also attracted lobsters. In Japan, ARs called “tsukiiso” were constructed for sessile organisms, but attracted spiny lobsters as well, no doubt due to the food sources available on these reefs (Sahoo and Ohno, 2000). Despite the attractive nature of these structures, they are not necessarily ideal ARs for lobsters and do not always imitate natural lobster dens, or provide appropriate shelters for all benthic stages of lobsters (juvenile to adult). Hence, proper design of ARs for lobsters needs to account for particular ontogenetic stages and their needs.

To design and deploy effective ARs, one needs detailed information on individual species, particularly with regard to habitat preference and food resource needs. Lobsters are found in all oceans along the continental shelf and upper continental slope (Holthuis, 1991, 2002; Phillips, 2006; Webber and Booth, 2007). Information on adult habitats is readily available for commercially important species of clawed, spiny, and slipper lobsters, but is less available for species that are captured as by-product of other fisheries, caught only in recreational fisheries, or are unexploited. From what is known, adult lobsters use a variety of habitats, ranging from those in the shallower waters of the continental shelf that provide complex structure via rocks, boulders, ledge, and coral outcroppings to those in deeper habitats of the continental shelf or slope that provide no structure (mud, sand) (Holthuis, 1991). Some species are well adapted for digging and burrowing and can actively manipulate the substrate to suit their needs; other species simply find crevices in which to shelter.

Within photic zones of the continental shelf, fished species of adult and juvenile lobsters increase activity levels at dusk to forage during nocturnal hours, and then gradually decrease activity around dawn (Kanciruk and Herrnkind, 1973; Atema and Cobb, 1980; Ennis, 1984, Herrnkind, 1980; Lipcius and Herrnkind, 1985; Jones, 1988; Karnofsky *et al.*, 1989; Spanier and Almog-Shtayer, 1992; Childress and Herrnkind, 1994; Smith *et al.,* 1999; Martinez *et al.,* 2002; Lavalli *et al.,* 2007). Benthic, continental shelf adult and juvenile lobsters prefer to shelter in complex substrates (Cobb, 1971; Botero and Atema, 1982; Marx and Herrnkind, 1985; Jernakoff, 1990; Sharp *et al.,* 1997; Ratchford and Eggleston, 1998; Robertson and Butler, 2003) or bury in soft sediments during daytime hours (Lavalli and Barshaw, 1986; Jones, 1988; Faulkes, 2006). However, little is known about the activity of deep water lobsters. These diverse sheltering behaviors are assumed to be predator avoidance adaptations (Roach, 1983, Johns and Mann, 1987; Barshaw and Lavalli, 1988; Eggleston *et al.,* 1990, 1992; Smith and Herrnkind 1992; Wahle, 1992a, Wahle and Steneck, 1992; Barshaw *et al.,* 1994) and may be altered or relaxed where predators are absent or rare (Barshaw and Spanier, 1994a) In situ tethering studies of lobsters in and out of shelters also strongly suggest that activity levels and sheltering behavior are the result of predation (Wahle and Steneck, 1992; Barshaw and Spanier, 1994b). Thus, human activities that impact the presence of predators or the occurrence of suitable habitat in which to shelter can have profound effects on the behavior and survival of lobsters comprising local populations (Caddy, 2008). However, the sheltering needs of lobsters differ not only amongst the three families that suffer the majority of fishing exploitation, but also within those families. Hence, it is necessary to understand the differences in habitat requirements for individual species within each of the families to appropriately design effective ARs.

ARs for nephropid lobsters (*Homarus* spp.)

Clawed lobsters are found in wide variety of habitats largely because of their ability to burrow into substrates or to fit into crevices. Inshore populations of all benthic phases are found on mud, cobble, bedrock, peat reefs, eelgrass beds, and within sandy depressions (Thomas, 1968; Cooper, 1970; Cobb, 1971; Cooper *et al.,* 1975; Hudon 1987; Able *et al.,* 1988; Heck *et al.,* 1989; Wahle and Steneck 1991; Lawton and Robichaud, 1992). Offshore populations are found in mud, bedrock, within sandy depressions, or in clay (Cooper and Uzmann, 1980). Within their geographical range, clawed lobsters have a wide temperature tolerance (-1 to 30.5° C) and, while considered stenohaline organisms, are broadly tolerant of salinities ranging from those of coastal and offshore habitats (> 25 ppt) to estuarine areas (Thomas, 1968; Harding, 1992). Habitat preferences of *H. gammarus* are narrower than those for *H. americanus* and consist mostly of rocky/cobble or boulder habitats to mud/clay substrates in which the lobsters can burrow (Dybern, 1973; Cooper and Uzmann, 1980). The European lobster seems to actively avoid sheltering where algae conceal crevice openings (Dybern, 1973).

American clawed lobsters: The fundamental idea behind the philosophy of using ARs for clawed lobsters is that near-shore shelter is a limiting factor affecting the distribution and abundance of fishable lobsters (Stewart 1970; Cobb 1971; Scarratt 1973; Briggs and Zawacki 1974; Fogarty and Iodine 1986; Richards and Cobb 1986; Steneck 2006). While American clawed lobsters range along the Canadian-United States coast from Labrador and Newfoundland, Canada to Cape Hatteras, North Carolina, they are most common in the Gulf of Maine in the U.S. and in the Gulf of St. Lawrence and close to Nova Scotia in Canada. This distributional pattern is likely the result of glacial deposits left from Pleistocene glacier advances and retreats that left heavy concentrations of gravel in a broad arc around the periphery of the Gulf of Maine and the inner rocky shelf near Nova Scotia, as well as in and between isolated banks in the gulf (Pratt and Schlee, 1969). As a result, clawed American lobsters have limited shelter-providing habitat throughout most of their range. ARs may therefore represent a means by which local abundance might be increased on featureless sediment. As opposed to studies with spiny and slipper lobsters, much of the early work on ARs for clawed lobsters has focused on temporarily altering the distributional pattern of lobsters by supplying shelter-providing structure on barren substrates rather than attempting to understand the components that make an AR site successful and the features that make the AR particularly appealing to lobsters.

One of the earliest attempts to construct ARs for *Homarus americanus* consisted of a naturalistic reef covering nearly 3,000 m^2 that was made of sandstone rocks up to 1 m in size, assembled on a sandy bottom mixed with small cobble in Northumberland Strait, Canada, 2.5 km away from the nearest known good lobster habitat (Scarratt 1968, 1973). Colonization by lobsters was slow throughout the first two years, with a lower biomass than found in nearby areas, but the lobsters that recruited to the AR were, on average, of larger size than in surrounding areas. Seven years after the deployment of the AR, the biomass of immigrant lobsters exceeded that of nearby natural areas, with a similar, wide size distribution of all life history phases (Scarratt, 1968, 1973).

Non-natural materials have also been used to create ARs. One AR (Kismet Reef), 457 m long × 46 m wide, consisting of two submerged barges and bundled tires was deployed on a sand and gravel bottom in 6-7 m of water in Great South Bay, New York and another (Fire Island reef), 1.6 km long × 0.2 km wide, consisting of rock and building rubble was deployed in deeper waters (21 m) in the Atlantic (Briggs and Zawacki, 1974). These ARs were originally designed to attract and increase the biomass of finfish, but also attracted lobsters. Differences amongst the sites existed with the oceanic AR attracting larger, offshore individuals in a 1:1 sex ratio and the Great South Bay AR primarily attracting sub-adult males (Briggs and Zawacki, 1974).

In what was one of the first attempts to match reef characteristics with behavioral preferences of lobsters, Sheehy (1976, 1977) designed shelter units for *H. americanus*, based on work by Cobb (1971). His pumice concrete shelters consisted either of two-piece, single chamber crevices (39.5 cm wide × 14 cm high × 39 cm deep) or a single smaller crevice (39.5 cm wide × 14 cm high × 19.5 cm deep) (Fig. 2A). They were deployed in Rhode Island, USA on a featureless sand substrate about 0.6 km from the nearest lobster supporting habitat. Within a week, lobsters preferentially moved into the shelters that were oriented with the openings perpendicular to the current. A year later, lobsters ranging from postlarvae to egg-bearing females resided on the reef and multiple occupancy of shelters rose to 35%. Lobster biomass in the ARs was higher than on nearby natural lobster ground. Later triple units (60.5 cm wide x 19.5 cm high x 39.5 cm deep with three 11 cm wide openings spaced 6.5 cm apart, Fig. 2B) were deployed and were occupied at a higher rate than similar volume single units; however, these units were difficult for divers to handle and space. A more stable, half-cylinder, single chamber unit with a curved roof design (40.6 cm wide × 14 cm high × 40.6 cm deep, Fig. 2C) was subsequently developed and these were deployed at six different sites with bimonthly monitoring over two years

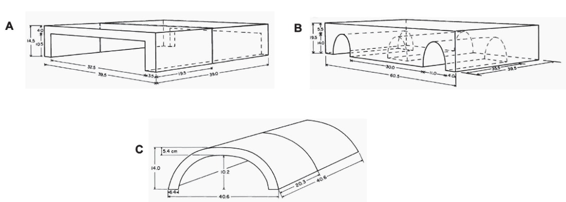

Fig. 2. Artificial habitats for American clawed lobsters. (A) two-piece single unit shelter; (B) triple unit shelter; (C) high stable, half cylinder single unit shelter (from Sheehy, 1976, 1977 used with permission)

(Sheehy, 1977). Overall occupancy of shelters was highest during winter months and multiple occupancy peaked in winter. Multiple occupants typically consisted of smaller individuals with a greater proportion of claw loss. While Sheehy's earlier study (1976) suggested that spacing interval of the units was important and affected the size of lobsters recruiting, his latter study (1977), demonstrated no such interaction between spacing and lobster size. However, large lobsters occupied the periphery of all ARs, while smaller lobsters occupied the units within the AR and 1 m was suggested as the minimum spacing between units (Sheehy 1977). Recent studies by Steneck (2006) using artificial shelters composed of hemicylindrical PVC pipe (20.3 cm wide × 47.7 cm long) demonstrate effects more similar to Sheehy's (1976) work, and suggest that 1 m spacing, while increasing population densities significantly, had a greater proportion of empty shelters, a higher incidence of aggressive interactions, and primarily attracted lobsters of smaller sizes. Differences between Sheehy's (1977) and Steneck's (2006) results may have been caused by differences in sheltering material—one using concrete structures more similar to natural substances and one using a smooth, non-naturalistic substance that was not conditioned prior to deployment, such that the material could have impacted the behavior of the lobsters. Hence, further work is needed here to better understand the dynamics involved in the spacing of individuals with different materials before appropriate ARs can be deployed for sub-adult and adult clawed lobsters. Nevertheless, analysis of communities pre- and post-deployment demonstrated that the ARs increased area productivity rather than simply attracting individuals from other locations. In addition, the ARs increased the carrying capacity of featureless bottom in that both food and shelter was increased for a variety of organisms, including predators of lobsters and all benthic life history phases of lobster (adult, juvenile, and settlers) (Sheehy, 1977).

Similarly, Bologna and Steneck (1993) found that artificial kelp beds (made of black construction-grade plastic cut into strips to mimic live kelp fronds and mounted onto steel bars embedded in featureless substrate) attracted densities of sub-adult lobsters similar to those found in live kelp beds that were transplanted into featureless terrain, and that both live and artificial kelp beds had significantly higher densities of lobsters than did adjacent featureless terrain. Both live and artificial beds were immediately attractive, with lobsters colonizing the bed within 24 hrs. However, as the size of the beds increased, lobster density decreased and density was strongly and positively influenced by the perimeter-to-area relationship of the kelp bed, with perimeter length being the important factor (i.e., an edge effect). Bologna and Steneck (1993) concluded that kelp beds, or even artificial beds, had the capacity to affect local lobster population densities by concentrating individuals along the edge of the bed and could, therefore, increase local carrying capacities of featureless habitats. Given that the Japanese have developed ARs for kelp, deployment of such ARs in the western Atlantic could also have a positive impact on lobster populations. Other studies that show positive effects on enhancing lobster density include the AR that was constructed after the 1989 oil spill in Rhode Island. This AR attracted large juveniles and adults within three months of construction and increased their density over a period of two years (Castro *et al.,* 2001). Despite these successes in increasing lobster density and species biomass, Sheehy (1976, 1977) cautioned that AR site location should be carefully selected, as grain size, water depth, wave activity, and current conditions all have important ramifications for long-term stability of the AR components.

Pursuant to some of Sheehy's (1976, 1977) suggestions, laboratory tests (Miller *et al.,* 2006) examining the effects of shelter type, substrate on which the shelter resides, and area effects of a shelter pile were recently conducted to determine how these factors influence the ability to shelter and the density of sub-adult and adult lobsters in two sizes ranges (50-59 mm CL and 70-79 mm CL or 82-89 mm carapace length). Comparisons between low entrance concrete bricks (37 mm high × 110 m wide) and high entrance bricks (57 mm × 110 mm wide) on a sand-gravel substrate demonstrated that lobsters of any of the size groups tested required the high entrance bricks to be able to occupy shelters without having to excavate substrate (a time-consuming task), but could occupy the low entrance bricks after excavation. However, smaller lobsters had more difficulty than larger lobsters in the excavation process. When presented with rock piles on a sand-gravel bottom versus a hard-bottom, the size of the rocks impacted ability to shelter, but generally speaking, smaller lobsters (50-59 mm and 70-79 mm carapace length) occupied piles on the soft bottom and excavated into the sand-gravel under the rocks. Coarseness of the sand-gravel affected time to excavate and influenced shelter occupancy, such that smaller lobsters could more easily excavate smaller grained (1-2 cm) substrate than larger grained substrate (3-5 or 6-8 cm). Finally, larger diameter piles of rocks, with fewer rock layers, resulted in higher densities of lobsters.

Additional studies have attempted to enhance American lobster populations using ARs in the field (Hruby, 2009), but none has had any significant impact on fisheries. As a result of the failure of prior attempts to significantly enhance production for fisheries or to mitigate effects of habitat loss or degradation, Barber *et al.* (2009) developed a systematic model for AR site selection that specifically targeted *H. americanus* prior to deploying cobble/boulder ARs as part of a mitigation project for habitat loss due to a gas pipeline. Their model included seven steps: (1) exclusion mapping to select several target areas, (2) depth and slope verification, (3) surficial substrate assessment, (4) ranking of sites based on analysis of biological and physical parameters, (5) the use of visual transect surveys to determine grain size and pre-deployment fauna, (6) benthic airlift sampling at target and reference natural cobble sites to compare densities of mobile benthic macrofauna, and (7) consideration of natural postlarval supply as determined by settlement collector deployment developed by Incze *et al.* (1997). The results of this stepwise analysis allowed the selection of a site that had low sedimentation rates, suitable slope and depth, appropriate bottom substrates to support the weight of an AR, natural postlarval supply, and low species diversity before reef deployment. Thus far, the AR has successfully recruited larvae and postlarvae of various invertebrate species, including lobster, and species diversity is approaching that of natural reefs nearby (Barber *et al.,* 2009). This approach is consistent with Sheehy's (1977) advice on site selection and holds great promise for actually increasing production and enhancing natural population levels at such ARs.

European clawed lobsters: European clawed lobsters, *H. gammarus*, have also been the target of licensed ARs projects in the United Kingdom. The Torness AR, constructed from quarried rocks, was deployed off the southeastern Scottish coast in 1984 (Todd *et al.,* 1992). Although this AR was reported to enhance the local lobster population, the authors stress the importance of an extended survey period in assessing its long-term effect on the population. The Poole Bay AR in the U.K. was deployed in 1989 as a materials test experiment. The AR originally consisted of units made from blocks of stabilized pulverized fuel ash (PFA), placed in 10 m × 30 m arrays of eight conical 4 m × 1 m piles on a 12 m deep sandy bottom 2 km away from the nearest natural lobster habitat. In 1998, tire modules were added. Lobsters were found in the AR three weeks after deployment (Jensen *et al.,* 1994, 2000a, b; Jensen, 2002). Berried females recruited into the AR two years after its deployment, and small juveniles were found on the AR three years later (in 1993) (Jensen and Collins, 1995). Some lobsters were repetitively tagged and recaptured on the AR system for over four years (Smith *et al.,* 1999). Electromagnetic telemetry of lobsters detected predominantly nocturnal movements between and among the eight AR units, with more frequent movements in spring and summer than in winter. Smaller lobsters moved more frequently than larger individuals in early and late autumn (Smith *et al.,* 1999). Despite these successes in recruiting all benthic life phases of lobster, Smith *et al.* (1999) stated that the Poole Bay AR did not support a sufficiently large enough population of lobsters to undertake any kind of fishery stock assessment.

The Loch Linne AR, constructed on the west coast of Scotland from 2001 to 2006 at a depth of 10-20 m, consisted of 30 separate reef modules clustered into eight groups and has been specifically designed for the purpose of understanding how reef construction and species interact (Sayer and Wilding, 2002; Wilding and Sayer, 2002), rather than solely for the purposes of increasing abundance of local macrobenthic, epifaunal, and infaunal populations. Each reef module contains 4,000 blocks of two types (solid and ones with two voids for nesting spaces) constructed in a conical pile 3-4.5 m in height and 10-15 m in diameter. The different kinds of blocks were deployed in different hydrological conditions and different sediments (cobble, silty-sand, and muddy) to study colonization and habitat utilization at different scales and habitat complexity. A monitoring program was put in place in 1998 pre-deployment and currently continues. Fixed belt transect surveys conducted monthly over a calendar year (2003-2004) demonstrated that there were no differences in animal abundance and diversity among the groups of reef modules and natural reefs in summer, autumn, or winter, but in spring, the simple reef modules (those with solid blocks) had less abundance and reduced diversity compared to the complex reef modules (blocks with voids) and the natural reef (Hunter and Sayer, 2009). Overall abundance of obvious fish and macro-invertebrates was 2-3 higher on the complex block AR modules than in either the simple block AR modules and nearby natural reefs (Hunter and Sayer, 2009). However, lobsters were not found within the belt transects on either the AR or the natural reef, even several years after deployment of the first six groups of blocks were in place (Hunter, 2010, personal communication).

France has experimented with a number of AR materials on both its Atlantic and Mediterranean coasts. Earliest materials consisted of old car bodies and tires, followed by use of concrete structures in various types of shapes (Barnabé *et al.,* 2000). Atlantic coast reefs had serious problems of siltation and were difficult to survey by divers; thus, those projects were largely abandoned and replaced by more intensive efforts in the Mediterranean. While hydrological and geological differences divide France's Mediterranean coast into east and west sections and these differences affect colonization at the deployed reefs, France has, nonetheless, deployed six ARs, representing 19,840 m^3 along its east coast (the Provence-Alpes-Cote d'Azur region) and seven reefs representing 19,226 m^3 along its west coast (the Languedoc–Roussillon region). The east coast ARs have been deployed largely to mitigate habitat degradation (damaged seagrass beds) due to coastal development, while the west coast ARs have been deployed at the request of artisanal fishermen to protect their static fishing gear and long-lines from illegal trawling. Only a few were deployed to increase biological production (Barnabé *et al.*, 2000). As in the Atlantic, Mediterranean ARs deployed in the late 1960's consisted of old cars; these were followed by tire ARs in the late 1970's and 1980's. By the mid-1980's, more preplanning went into both deployment and material selection, such that industrially made concrete ARs became the norm and these were designed into specific modules to fit into predetermined configurations. The AR program of the east coast ended in 1989, although in 1997 a new AR of concrete telegraph poles was deployed. West coast ARs were deployed in 1985 and 1988 and again in 1995 (Barnabé *et al.,* 2000).

Two west coast ARs, in particular, have attracted lobsters. The first was deployed in 1985 for the purpose of providing an obstacle to trawling; this AR consisted of 410 modules of a "sea-rock" type (flat topped, pyramidal concrete structure with voids on the pyramidal faces, Fig. 3A) covering 640 m^3. Extensive colonization by oysters, mussels, fish, octopus, and lobsters was reported by Tocci (1996) for this AR. The second AR was deployed in 1995 to protect a molluscan culture zone and this AR was constructed from two concrete pipes, one of 1 m diameter that fit into another of 1.9 m diameter, each of 2.5 m length, weighing 8.5 tonnes (Fig. 3B). Units were spaced 200 m from each other; sixty units were placed off Marseillan in 1992 and 200 units were placed off Agde in 1995. The units in Marseillan have attracted mussels, oysters, conger eel, sea bass, and numerous lobsters (Barnabé, 1995), while those in Agde have mainly attracted mussels and conger eels (Barnabé *et al.,* 2000). These differences amongst ARs in their attractiveness to lobsters indicates that even when the same materials are used in different locations, some nearby population of lobster must be present for immigration into the reef to occur. Thus, if lobsters become the target species for AR projects, basic information about their distribution must be presented before choosing appropriate AR sites.

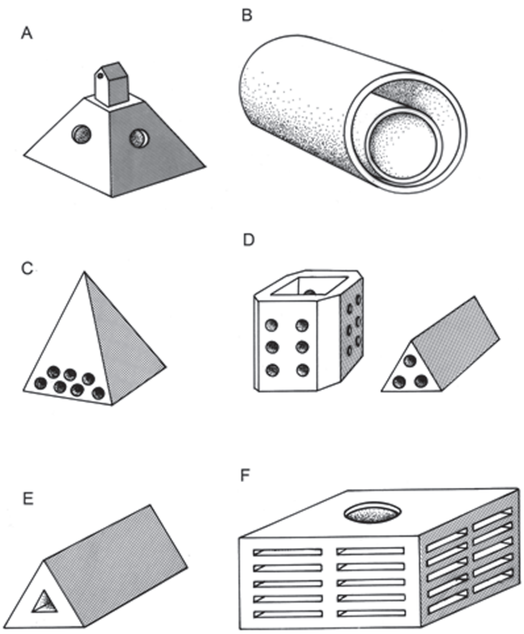

Fig. 3. French and Japanese concrete artificial habitats for lobsters. (A) sea rock type block used as a trawling obstacle; (B) pipe-within-pipe module used for protection of mussel beds and as a trawling obstacle; (C) pyramidal concrete block (70 cm) used for both spiny lobster reef and agar-agar cultivation in Shizuoka Prefecture; (D) blocks used by Shizuoka and Nagasaki Prefecture for lobster reefs; (E) triangular concrete block used in Wakayama Prefecture; (F) large rectangular block used by Shizuoka Prefecture (redrawn by R. Pollak from Barnabé *et al*. 2000 and modified from Fishery Civil Engineering Study Association 1982)

Spiny lobster ARs

Adult spiny lobsters are widely distributed in tropical, subtropical, and temperate zones of all oceans, and occur from the intertidal to depths approaching 1000 m (Holthuis, 1991). Usually, different genera do not co-occur, having distributions that are distinctive both in latitude and depth (Butler *et al.,* 2006); however, species within a genus often do co-occur in a particular region (i.e., *Panulirus argus* and *P. guttatus* in the northern Caribbean), but are generally segregated by habitat and behavior

(Berry, 1971; Lozano-Álvarez and Briones-Fourzán, 2001; Briones-Fourzán *et al.,* 2006). This would be the case in the Indian Ocean where 10 species are present (Phillips and Melville-Smith, 2006) or in southern Africa where seven genera co-occur (Berry, 1971).

Habitats of spiny lobsters are very diverse and vary according to life history stage and behavior (solitary versus social species) – lifestyles include shallow, semi-social, residential dwellers on coral reefs to gregarious, migratory species that live on open soft substrates at both shallow depths and depths greater than 300 m (Butler *et al.,* 2006). Of the better studied genera, *Jasus* lobsters are mainly rocky reef dwellers, but can be found in various substrates from the intertidal to 200 - 400 m (MacDiarmid and Booth, 2003; Booth 2006). *Panulirus* lobsters are common in rocky and coral substrates, although some are found on soft muddy bottoms. Generally, most species inhabit substrates where food, micro-caves, and natural protective holes are numerous (Groeneveld *et al.,* 2006).

Compared to clawed and slipper lobsters, there is a wealth of information on ARs for spiny lobsters that mainly arises from studies on one commercial species – the Caribbean spiny lobster, *Panuilrus argus*. Extensive field and laboratory research on the behavior and ecology of various life history phases of this species have focused on habitat preferences and natural shelter selection. These studies have provided a baseline data for construction of appropriate artificial shelters for this species and, generally, such data are lacking for other species of spiny lobster.

Sheltering in natural structures has been studied in several species of spiny lobsters. *Palinurus*, *Panulirus* and *Jasus* spp. typically seek shelter in crevices in rocks, corals, sponges, or under ledges or vegetation (Kanciruk, 1980; Spanier and Zimmer-Faust, 1988; MacDiarmid, 1994; Childress and Jury 2006). Many spiny lobster species have an ontogenetic habitat shift from the postlarval settlement habitat of algae, kelp, or seagrass (at 6-15 mm carapace length for *P. argus*) to benthic crevices as larger benthic juveniles (~15-30 mm carapace length for *P. argus*), subadults, and adults (Butler and Herrnkind, 2000; Butler *et al.,* 2006; Childress and Jury 2006). Some species that demonstrate ontogenetic habitat shifts often share a den with conspecifics upon migration to the benthos and continue to do so as they grow larger and larger (e.g., Cobb, 1981; Zimmer-Faust and Spanier, 1987; Eggleston and Lipcius 1992; Eggleston *et al.,* 1992, Mintz *et al.,* 1994; MacDiarmid, 1994) even when natural dens are plentiful (see review by Nevitt *et al.,* 2000). Other species, however, do not exhibit such ontogenetic habitat shifts, and settle directly onto adult habitat; often these are the obligate dwelling coral reef species (i.e., *Panulirus guttatus* (Sharp *et al.,* 1997; Robertson and Butler, 2003).

Spiny lobsters prefer dens that have shaded cover with multiple entrances and avenues of escape (e.g., Spanier and Zimmer-Faust, 1988; Eggleston *et al.,* 1990). Predators can influence specific preferences, such that lobsters become less choosey in the presence of a predator (Gristina *et al.,* 2009). For species with ontogenetic habitat shifts, the attraction of dens is further increased if conspecifics are present (Zimmer-Faust and Spanier, 1987; Ratchford and Eggleston 1998) and it is thought that conspecific odors help shelter-seeking lobsters locate appropriate dens more quickly ("guide effect") (Zimmer-Faust and Spanier, 1987; Childress and Herrnkind 1994, 1996, 2001). Hence, for social spiny lobsters, ARs have to incorporate the ability of multiple individuals to co-den in crevices, something that is not necessary for clawed lobsters or solitary species of spiny lobsters.

ARs for spiny lobsters have been designed specifically to concentrate individuals for fishing purposes, to increase lobster population productivity, or to mitigate population loss arising from lack of shelter (Herrnkind and Cobb, 2008). Use of ARs for ease of harvesting by concentrating individuals in the AR has occurred in Cuba and Mexico for *P. argus* (Cruz *et al.,* 1986; Cruz and Phillips, 2000; Briones-Fourzán *et al.*, 2000, Briones-Fourzán *et al.,* 2007), while attempts to increase productivity of populations have occurred in Japan and Mexico focusing primarily on *P. japonicus* (and several other species found in Japanese waters) and *P. argus*, respectively (Nonaka, 1968; Nonaka *et al.,* 2000;

Briones-Fourzán *et al.,* 2000, 2007). In all cases using ARs for mitigation of the loss of local shelter that subsequently depressed populations (Davis 1985; Butler *et al.,* 1995; Herrnkind *et al.,* 1999) or to better understand the ecological role of shelter, studies have focused on *P. argus* (Eggleston *et al.,* 1990; Butler and Herrnkind 1992, 1997; Lozano-Alverez *et al.,* 1994; Mintz *et al.,* 1994; Cruz *et al.*, 2007). In several cases, ARs have also been used as replicable collecting devices for population sampling (Cruz *et al.,* 1986; Behringer and Butler, 2006) and have again focused on *P. argus*. Traditional ARs *(casita*s) have also been used as a replicable sheltering device to evaluate and compare the distribution and abundance of small juvenile lobsters in Mexico's Caribbean shallow waters (Arce *et al.,* 1997). Likewise, Behringer *et al.* (2009) used artificial structures (concrete partition blocks) to assess the relative abundance of juvenile *P. argus* in different habitats, and to determine how diseased animals were spaced relative to healthy animals.

Japan began experimenting with bamboo-framed structures as ARs for spiny lobsters as early as the late 1700's, and then, based on successes in increasing local catches of fish, moved on to use old boats, sand bags, and cut stones. In the 1930's, the government began experimenting with concrete blocks and in the 1950's almost exclusively used such blocks for government subsidized AR projects (Oshima, 1964) although additional materials have been explored and used (steel, old tires, ceramic products/earthen pipes, and synthetic resin products, old boats, old buses). Each prefecture in Japan has its own preferred reef material (see Fig. 3C-F for examples), but in some cases, simple stone beds and piers have been deployed in communities of agar-agar seaweed for spiny lobster grounds (Nonaka *et al*., 2000). Despite decades of work to actively enhance productivity of lobster via these ARs, the catch consists of otherwise dispersed lobsters attracted to the ARs, which are located in previously poor fishing grounds, and does not represent an increase in population recruitment or in the local stock (Nonaka *et al.,* 2000). Polovina (1989) argues that the real benefit of these ARs is not an increase in production, but an aggregative effect to localize fishing activities such that traditional small fishing vessels within Japanese fishing communities can remain economically viable.

Similarly, ARs deployed for *P. argus* have been used to concentrate the lobsters and enhance fishery catches. Due to the exceptional commercial importance of this species of lobster, considerable research has been conducted on the design of attractive artificial structures. For more than 60 years now, Cuban and Mexican fishermen increase the catch of the Caribbean spiny lobsters using a simple, inexpensive, durable and easily harvested artificial shelter called *pesquero* (Cuba, e.g., Cruz and Phillips, 2000) or *casita* (Mexico, e.g., Briones-Fourzán *et al.,* 2000). These shelters are modified from the indigenous fishermen's earlier design. Originally, Cuban ARs were shelter providing structures constructed with mangrove branches 8-12 cm in diameter, with parallel sticks creating three to four layers forming a 4 m^2 raft-like formation (Fig. 4A). These were positioned on shallow substrates where natural shelters were scarce and currents were mild. A single *pesquero* could concentrate as many as 200 lobsters, which were then captured by divers using encircling nets; in this way, an estimated average of 16 t of marketable lobsters could be acquired per diver per year (Cruz and Phillips, 2000). After it became illegal to cut mangroves in Cuba, other low-priced, durable building materials were used, including PVC pipes, all-cement structures, and ferrocement shells mounted onto two wooden branches (Fig. 4B). These devices were placed in accessible coastal waters, and have revolutionized lobster fishing, as well as fishery management in the region. Hundreds of thousands of these artificial shelters have been used successfully for spiny lobster fishing mainly in Cuba and Mexico, but also in the Bahamas, U.S. Virgin Islands, Florida, Africa and elsewhere (Herrnkind and Cobb, 2008). Lobster fishermen believe that, in addition to enhancing fisheries, *casitas/ pesqueros* increase lobster populations by helping individual lobsters find shelter rapidly and co-defend against natural predators (Moe, 1991; Briones-Fourzán *et al.,* 2000) via collective prey vigilance and collective defense (Herrnkind *et al.,* 2001). These authors also hypothesized that when numerous *casitas* are placed in habitat lacking in natural shelter, lobsters feed more efficiently and have longer access to their prey because they can exploit food resources over extended areas and still find shelter rapidly if needed, thereby growing faster (Briones-Fourzán *et al.,* 2000). Herrnkind (1977) proposed a model in which local residency was affected by both food and shelter, and increased in duration when both food and shelter were common. Hence, the placement of numerous shelters in shelter-less or shelter-limited habitat, may help to increase the local carrying capacity of spiny lobsters.

A

B

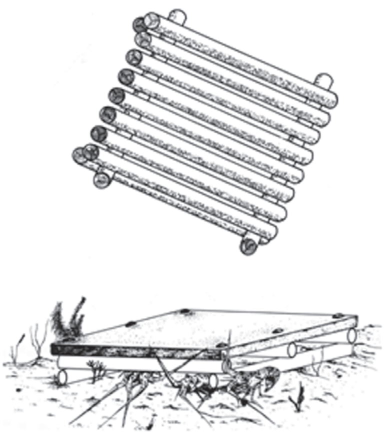

Fig. 4. (A) A typical Cuban *casita/pesquero* for fishing of the Caribbean spiny lobsters, *Panulirus argus.* (B) *A casita/pesquero* (177 cm length, 118 cm width and 6 cm, height of opening) constructed with a frame of PVC-pipe and a roof of cement (redrawn by R. Pollak from from National Research Council 1988 and Eggleston *et al*., 1992, used with permission)

Briones-Fourzán *et al.* (2000) emphasized that *casitas/ pesqueros* were most effective in shallow water habitats lacking natural crevices, such as sea grass. These habitats are frequently next to nursery grounds where juveniles continually emerge as they outgrow the initial algal settlement habitat, become nomadic, and traverse the coastal shallows to forage, while taking up residence in natural or artificial crevices (Herrnkind, 1980; Kanciruk, 1980; Lipcius and Eggleston, 2000; Herrnkind and Cobb, 2008). Used in this manner, *casitas/ pesqueros* may very well increase production of lobster populations as juveniles emerging from algae will readily and quickly find shelter and reduce the time they are walking over seagrass beds or other featureless terrain—a situation that would expose them to predation (Herrnkind *et al.,* 2001). However, the benefits to local fishermen may then be delayed as these structures act primarily as grow-out facilities. Since settlement and juvenile habitats are in shallow water while reproductive adult habitats are in deeper water (Kanciruk and Herrnkind, 1976; Lipcius and Herrnkind, 1987), most of the lobsters in the *casitas/ pesqueros* are below the minimum fishery size limit (Herrnkind and Cobb, 2008). In bays and other inshore areas, egg-bearing females rarely occupied these structures, making up only 0.4 % of 2,500 females in *casitas* in Bahia de la Ascension, Mexico (Briones- Fourzán *et al*., 2000). Thus, stakeholders should be aware that the purpose of shallow water *casitas/ pesqueros* may differ greatly from the purpose of deeper water *casitas/ pesqueros* and fishermen should be encouraged to only fish in those structures that are designed to attract legal sized adults.

In addition to enhancing production and/or concentrating individuals for fishery purposes, AR blocks and *casitas/ pesqueros* have been used to mitigate habitat loss. Davis (1985) used hollow pyramids made of standard 2-hole concrete blocks to mitigate crevice loss for the more than one thousand juvenile *P. argus* displaced by rock-fill during marina reconstruction. Lobsters moved into the pyramids and remained there over a 14-month period. Similarly, in 1991-1993 during a mass sponge die-off from a cyanobacteria bloom in Florida Bay, Herrnkind *et al*. (1997a,b, 1999) experimentally deployed a 1-hectare array of 240 double-stacked, three-hole concrete partition blocks (10 cm × 20 cm × 40 cm) as potential mitigation for loss of sponge crevices. Almost all large, crevice-bearing sponges supplying about 70 % of dens for small juvenile lobsters (< 50 mm carapace length) were destroyed over several hundred square kilometers (Butler *et al.,* 1995). Herrnkind and Butler (1986), Herrnkind *et al.* (1997a, b) and Smith and Herrnkind (1992) found that in the absence of proper nearby crevices, the rate of predation of small juveniles (15-25 mm carapace length) emerging from the algae-dwelling stage was extremely high. Childress and Herrnkind

(1994) and Herrnkind *et al.* (1997a, b) demonstrated that block crevices were as attractive and protective as sponge and other natural crevices. Three months after deployment of the blocks, numbers of newly recruited post-algal juveniles in the blocks surpassed that on the sponge-less control sites and was similar to the numbers on sponge-rich sites. This situation continued, with some seasonal fluctuations, for an additional nine months. Analysis of microwire tag recapture data also supported both the idea that shelter was a key to survival of the small juveniles and that large numbers of settlers were required to strongly affect the ultimate numbers of surviving juveniles (Herrnkind and Cobb, 2008). Similarly, Briones-Fourzán and Lozano-Álvarez (2001) demonstrated that small, scaled down *casita*-like artificial shelters designed for post-algal juveniles were rapidly colonized by considerable numbers of late algal and early post-algal juveniles when placed in a crevice-poor, vegetated lagoon at Puerto Morelos, Yucatan, Mexico. Deployment of *casitas* resulted in a six-fold increase in juvenile density and a seven-fold increase in biomass compared to control sites lacking natural crevice shelter (Briones-Fourzán *et al.,* 2006). Tag–recapture experiments revealed that this level of enhancement was achieved not by promoting individual growth, but by increasing survival, persistence, and foraging ranges of small and large juveniles. Briones-Fourzán *et al.* (2006) suggested that *casitas* both mitigated lack of natural shelter and increased sociality, allowing for cohabitation of smaller, more vulnerable juveniles with larger conspecifics that have greater defensive abilities.

The results of these mitigation experiments in Florida and Mexico demonstrate that shelter availability influences local population recruitment by reducing post-settlement predation mortality (Herrnkind and Cobb, 2008). These authors emphasized the importance of correctly understanding the ecological processes and population consequences of *casitas/pesqueros*—an understanding that comes about only by experimental work examining the effects of the shelter in different habitat conditions with different life history stages of lobster. Such studies have been conducted on *P. argus*, but are generally lacking for other spiny lobster species. Field studies using *P. argus* showed that shelter selection by large juveniles and adults depended on lobster size, shelter dimensions, and lobster density (Eggleston and Lipcius, 1992, Ratchford and Eggleston, 1998). When large juveniles and adult *P. argus* were experimentally tethered in place, they survived significantly better in a *casita* than just outside the AR or far away in open seagrass (Herrnkind and Cobb, 2008). The limited opening and height of the *casita* roof either prevented entry by predators of large lobsters or restricted an effective attack by the predator (e.g., triggerfish) within the shelter (Lozano-Alvarez and Spanier, 1997). Under experimentally high predation risk, lobsters grouped together in higher densities and within larger shelters so that more conspecifics could be accommodated, suggesting theoretical benefits from increasing collective defense and/or dilution effect (Herrnkind *et al.,* 2001). However, the same aggregation benefit does not necessarily hold for post-algal phase lobsters when tethered together (Butler *et al.,* 1997; Childress and Herrnkind, 2001). Mintz *et al.* (1994) found that juvenile lobsters tethered in smaller, artificial sponge dens that could hold relatively few individuals had similar survival rate to those in *casitas*, suggesting that ARs need to be appropriately scaled for the life history stage targeted (Eggleston *et al.,* 1990).

Herrnkind and Cobb (2008) suggested that the most convincing argument for the protective role and enhanced survivorship of *casitas* would be a direct comparison showing higher long-term (months) survival by *casita* resident lobsters versus same-aged lobsters roaming about large areas of sparse natural shelter. This requires sufficient knowledge of the abundance and distribution of lobsters in the absence of *casitas*. Current evidence strongly suggests that *casitas* may enhance populations by protecting shelter-seeking, post-algal juveniles when ready shelter is not otherwise available. However, at present, research results do not provide any clear-cut evidence that *casitas* provided enhancement of lobster survival from natural predation at the population level.

In addition to the benefits mentioned above, *casitas* can also be useful in fishery management. Cruz *et al.* (1986, 1995) used arrays of small ARs constructed of 60 standard concrete blocks to successfully predict commercial catches in subsequent years. This monitoring approach has since been incorporated into fishery management models and additional research projects (Baisre, 2000). In a later study, Cruz *et al*. (2007) suggested that introduction of ARs might help reduce natural mortality of post-pueruli and juveniles and increase recruitment to fishing areas, much as has been seen in Florida and Mexican work (described above). Eventually, understanding the level to which survival of small juveniles is enhanced from algal-phase to fishery recruitment, may allow the development of predictive indices based on collection of algal-phase lobsters via Witham-like collectors, as has been done in *Panulirus cygnus* fisheries (Phillips, 1986).

A few ARs in the Mediterranean have recruited European spiny lobsters, *Palinurus elephas*. Relini *et al.* (2007) reported that limited numbers of *P. elephas* recruited to custom-designed concrete modules deployed in the Ligurian Sea, Italy. Sinis *et al.* (2000) listed *P. elephas* among species caught with experimental fishing on ARs in Chalkidiki, North Aegean Sea, Greece. A recent laboratory experiment on shelter preference demonstrated how shelter shape, size, and substrate slope affect the choice of *P. elephas* juveniles, enhancing their protection and survival rate (Gristina *et al.,* 2009). Thus, it seems as though ARs may become more prevalent for other species of spiny lobster in the near future. In addition, since spiny lobsters move freely in and out of lobster pots (Phillips, personal communication, 2010) these fishing devices can also be considered ARs.

Nonetheless, Briones-Fourzán *et al.* (2000) and Herrnkind and Cobb (2008) point out that there are some possible negative effects of artificial structures. These man-made habitats are large enough to attract predators (e.g., crabs, octopus, groupers, sharks, and triggerfish) that prey on juvenile lobsters, particularly small individuals (Mintz *et al.,* 1994; Arce *et al.,* 1997; but see Lavalli and Herrnkind, 2009 showing that smaller animals were not necessarily the most vulnerable). Some of these predators (e.g., octopus) may be able to enter the artificial devices and prey on the lobsters there, while others (e.g., triggerfish) may be able to pull lobsters from the shelters by grabbing onto the long antennae (Weiss *et al.,* 2008). Some smaller predators can even compete with the lobsters for shelter (Butler and Lear, 2009). ARs that concentrate high numbers of lobsters may make otherwise scattered lobsters more vulnerable not just to predation by natural predators (see review by Briones-Fourzán *et al.,* 2000), but also to overfishing. Additionally, crowding of lobsters in *casitas*/*pesqueros* may facilitate the spread of diseases and parasites (Shields and Behringer, 2004; Behringer *et al.,* 2008; Li *et al.*, 2008), although evidence to date indicates that healthy lobsters are capable of detecting infected conspecifics and then avoid contact with them (Behringer *et al.,* 2008). Finally, Davis (1981) argued that where many inhabitants of the AR are undersized for the fishery, repeated handling during incidental capture in fishing gear might cause injury and reduce growth or delay maturity.

Slipper lobster ARs

Adult and sub-adult slipper lobsters are distributed in a variety of geographical regions and can be found in temperate, subtropical, and tropical parts of all oceans and adjacent seas with latitudinal ranges from 4°S-45°N lat. and depths of 0 to at least 800 m (Holthuis, 1991, 2002; Brown and Holthuis, 1998; Webber and Booth, 2007). These latitudinal and depth variations are associated with differences in several environmental factors such as temperature, light, salinity, and pressure. Benthic adults and sub-adults are also found in a variety of habitats, from featureless flat soft substrates such as mud, sand, and shelly sand, to rubble, macroalgae, sea weed, and sedentary invertebrates (such as sponges and branching corals), to harder and complex substrates such as rocky outcrops and coral reefs (Lavalli *et al.,* 2007; Webber and Booth, 2007). One can divide the substrate habitats of slipper lobsters into two groups: those that are complex, such as rocks, coral reefs, rocky caves, and which are attractive to species of *Acantharctus, Arctides*, *Scyllarides,* and *Scyllarus*. The second substrate group is non-complex and featureless, such as sand or mud, and these are attractive to species of *Thenus*, *Ibacus* and *Evibacus* *princeps* (Jones, 2007; Haddy *et al.,* 2007; Lavalli *et al.*, 2007; Radhakrishnan *et al.,* 2007). *Parribacus* spp. seems to dwell in both complex (coral, stone, or shore reefs) and plain substrates (Lavalli *et al.,* 2007; Sharp *et al.,* 2007). Therefore, AR development for slipper lobsters needs to be species/ genera - specific to work with these substrate preferences.

In a series of field and laboratory studies with natural and artificial dens, including ARs, Spanier and his colleagues examined the shelter preferences of the Mediterranean slipper lobster, *S. latus* (Spanier *et al.,* 1988, 1990, 1991, 1993; Spanier, 1994; Spanier and Almog-Shtayer, 1992; Spanier and Lavalli, 1998, 2006). In laboratory choice tests, using opaque or transparent plexiglass pipes for shelters, lobsters significantly preferred horizontal opaque to transparent shelters of the same shape and size and preferred horizontally-oriented dens with low light levels to vertically-oriented dens where light levels were higher. They also preferred medium-sized shelter diameters (20-30 cm) that were opened on both ends (Spanier and Almog-Shtayer, 1992). These preferences were also evident in natural dens (Spanier and Almog-Shtayer, 1992, Spanier *et al*., 1993; Spanier, 1994). During daylight hours, light in natural, horizontally-oriented shelters was 10-20 times less than that in the open reef habitat. Spanier and Almog-Shtayer (1992) suggested that these shelter preferences were anti-predator adaptations. Horizontally-oriented shelters supplied shade and reduced visual detection by diurnal predators. Small shelter openings also supplied shade but, in addition, increased physical protection against large diurnal predators, especially fish with high body profiles, such as the gray triggerfish, *Balistes carolinensis*. Multiple shelter openings enabled escape through a “back door” if a predator was successful in penetrating the den. Lobsters could then escape by using their fast tail-flip swimming capability (Spanier *et al.,* 1991; Spanier and Almog-Shtayer, 1992).

Sheltering preferences were examined in ARs constructed of used tires weighted with concrete in their lower parts and arranged in various configurations that were deployed at 20 m water depth on a flat substrate of the Mediterranean coast of northern Israel (Fig. 5). Again, lobsters preferred horizontal shelters with a medium-sized diameter and multiple openings—those found between adjacent horizontally arranged tires—rather than the large, central hole of the tires themselves (Spanier *et al,.* 1988, 1990; Spanier and Almog-Shtayer, 1992). When the additional “back doors” of these dens were experimentally blocked, lobsters stopped using the single-opening dens. Additional work on the effectiveness of crevices provided within ARs as protection against predators demonstrated that predation by the gray triggerfish, a high-body-profile, large, diurnal fish, was significantly less on lobsters tethered in the ARs compared to those tethered in open areas (Barshaw and Spanier, 1994b). Thus, the ARs, if properly constructed to provide appropriate shelter for lobsters, could serve as a means by which to concentrate slipper lobsters in featureless terrain.

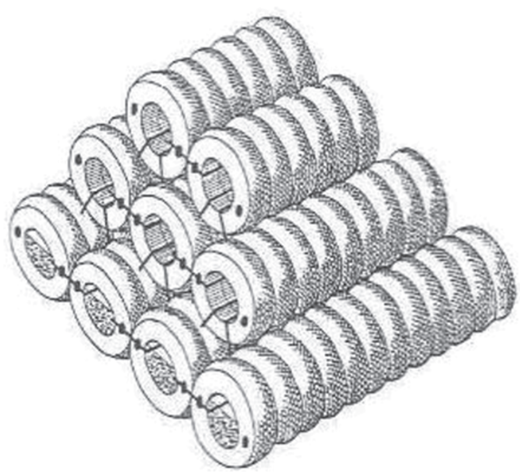

Fig. 5. An artificial habitat that successfully recruited Mediterranean slipper lobster, *Scyllarides latus*. The man-made structure was made of used car tires (32 cm inner diameter, 65 cm outer diameter and 17 cm tire width) connected with 18 mm steel bars and weighted with concrete poured into the lower part of the first row of tires (from Spanier *et al.* 1988, used with permission)

Following the success of the tire reefs in attracting lobsters, four small experimental ARs were designed and constructed according to the sheltering preferences of *S. latus* (Edelist and Spanier, 2009). Each AR was 1.2 m sided, cubical, steel reinforced, concrete structure, weighing 1500 kg in water and fitted with 16 sections of 25 cm diameter polyethylene pipes opened on both sides. The ARs were deployed on extremely flat hard bottom ground with as little complexity as possible in 20 m depth off the coast of Haifa, Israel and were successful in recruiting Mediterranean slipper lobsters which were observed frequently during the lobster season (Fig. 6). These initial successes suggest that ARs might be a useful tool to aggregate slipper lobster species in areas where they occur but where shelter-providing habitat is lacking, as has been done for clawed and spiny lobsters. However, given the wide diversity of habitats exploited by slipper lobsters, researchers need to pay close attention to habitat preferences for the target slipper lobster species, as not all reside in complex substrates.

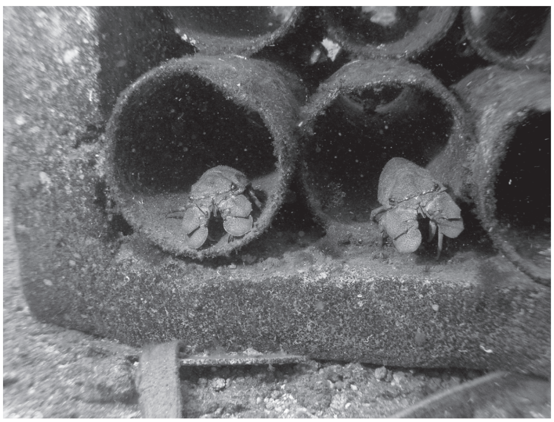

Fig. 6. Mediterranean slipper lobsters recruited to an experimental artificial habitat (1.2 m sided cubical steel reinforced concrete structures, weighing 1500 kg in water and fitted with 16 sections of 25 cm diameter polyethylene pipes opened on both sides), designed and constructed according to the behavioral-ecological preferences of *Scyllarides latus* for shelter and deployed on a flat rocky substrate in the southeastern Mediterranean (Photo by S. Breitstein, used with permission)

Artificial habitats and lobster enhancement, MPAs and AR Ownership

Artificial reefs could be used to provide habitat for artificially stocked lobsters, particularly as commercial lobster aquaculture programs are generally economically unfeasible. Given that a number of spiny lobster species have now been successfully cultured to the puerulus stage (e.g., Booth, 2006, Groeneveld *et al.,* 2006; Phillips and Melville-Smith, 2006), some scyllarids are cultured to the nisto and later juvenile stages (Mikami and Kuballa, 2007), and clawed lobsters are easily raised to juvenile stages (see review by Nicosia and Lavalli, 1999), aquaculture could provide stock for reseeding and enhancement of the wild populations (and fishery). Such restocking can be successful if suitable ages/stages of lobsters are seeded (see reviews by Bannister *et al.,* 1989; Cook, 1990; Tveite and Grimesn 1990; van der Meeren and Næss, 1993; Bannister, 1998; Nicosia and Lavalli, 1999) and appropriately designed artificial structures are supplied to the predator-sensitive early stages as demonstrated in the field study of Butler and Herrnkind (1997) with *P. argus*. Additionally, biological research on the target species needs to be conducted beforehand to understand behavioral deficits that arise under culturing conditions and to compensate for those (see Agnalt *et al.,* 2007; Svåsand, 2007; Oliver *et al.,* 2008 for examples of such studies). In addition, sea-cage culture (ongrowing) of juvenile and sub-adult spiny lobsters may have potential and has been used in some parts of the world (mostly Asia and Mexico) with mixed results, due largely to reduced growth, increased mortality from poor water quality or infection, and increased aggressive encounters amongst individuals of some species, as well as the high cost of collection of pueruli and juveniles (Creswell 1984; Assad *et al.,* 1996; Lozano-Alvarez, 1996; Brown *et al.,* 1999; Jeffs and James, 2001, and see reviews of growout attempts by Booth and Kittaka 2000 and Williams 2009, as well as additional reports on growout projects in southeast Asia in the present volume). In Tasmania and Australia, fishermen can take pueruli and young juveniles for ongrowing in lieu of fishing their quota and in Australia, but they must return 50% of those animals to the sea the following year. However, thus far, the collection costs have been high, aquaculture aspects have been difficult, and the production of legal-size lobsters has been low (Booth, 2006). It is likely, therefore, that while some parts of the world will employ such enhancement projects combined with ARs, these efforts will be the exception rather than a common practice.

Recently, there has been an increasing interest in Marine Protected Areas (MPAs) to protect and conserve populations of marine organisms, especially fish. MPAs combined with the use of ARs could be used as a management tool for lobsters (e.g., Childress 1997; Goñi *et al*., 2001, 2006; Follesa *et al.,* 2008; Pettersen *et al.,* 2009). Such marine reserves can be used to help protect endangered or overfished populations and to create a sanctuary for reproductive populations (e.g. Bertelsen and Matthews, 2001). Despite the nomadic or migrating nature of some adult lobsters (e.g., Spanier *et al.,* 1988; Herrnkind and Cobb, 2008), MPAs can be effective for sub-adults and adults lobsters, provided that they are not too small in scale (see Eggleston and Dahlgeren, 2001; Stockhusen and Lipcius, 2001), are properly managed and protected, and contain the proper natural habitats for respective life history stages or have featureless habitat complemented by deployment of ARs. In the species that have limited movements for foraging and/or reproduction, MPAs, even if relatively small, may help enhance over-exploited stocks (Goñi *et al.,* 2001). Whether MPAs are large or small, researchers caution that the population structure of the protected species should be understood before establishment of such entities occurs (Cannas *et al.,* 1998; Tuck and Possingham, 2000).

One of the most important aspects of using ARs for lobster fisheries is the question of ownership of a site. Those entities that construct and deploy the ARs naturally desire to be the lone beneficiary of their investment. The identification of the stakeholder groups, allocation of rights, ownership (including possible lease/purchase agreements of the sea bottom), and the acceptance of potential liability (due to effect of intact and especially of disconnected ARs that can be swept away in severe weather conditions) can be controversial issues (Sayer and Wilding, 2002) with different solutions arising in different countries (Jensen, 2002). Briones-Fourzán *et al.* (2000) described one solution along the Caribbean coast of Mexico—that of local lobster fishermen co-operatives that constituted a form of limited entry. Such utilization of community-based, common property resources can facilitate sustainable use of ARs in the spiny lobster fishery. However, Briones-Fourzán *et al.* (2000) point out that such a co-operative arrangement does not necessarily imply a limited fishing effort. Although the number of fishermen in the co-op is limited and has even decreased in recent years, deployment of more *casitas*, made of better material, and operation of faster boats may enhance the co-operative fishing performance. Generally speaking, most countries today have developed a set of licensing procedures and protocols for development of ARs to deal with such ownership and usage issues, but often the liability issues are not well covered.

Conclusion and recommendations

A review of the literature in the last five decades (Fig. 7) indicates a continuous increase in the number of studies on ARs for lobsters from the 1960's onward, with a considerable boost in the 1990's. This increase stems, on the one hand, from improved knowledge of recruitment processes of a relatively small number of important commercial lobster species and, on the other hand, from the decline of many commercial lobster populations and the need to enhance and/or manage their fisheries. The results of these studies indicate that ARs that are species specific and appropriately designed for particular life history stages seem effective in recruiting lobsters

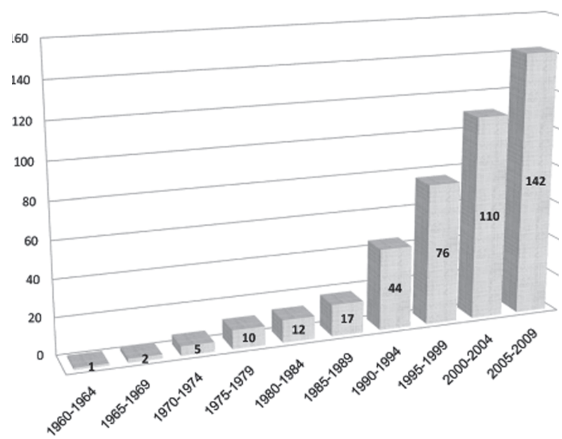

Fig. 7. Results of a literature survey of publications: accumulated publications in five-year periods over five decades, on artificial habitats and lobsters (based mainly on publications in English, or with English abstracts, in refereed scientific journals and books, conference proceedings and official reports)

and substituting for natural habitat (damaged, diminished, destroyed, or missing). Despite evidence that ARs are attractive to clawed, spiny, and slipper lobsters, they have been in wide use for fisheries and management only in one species, *Panulirus argus*, in the form of *casitas/pesqueros*. Although there are several indications that these structures and a few other types of ARs for lobsters may enhance populations locally, the long-term effectiveness of these ARs in enhancing commercial catches by aggregation and/or enhancement of production at the population level is still questionable. Only long-term and large-scale studies comparing populations of lobsters (of the same species, sex ratio, and size range) with and without man-made habitats can supply clearer answers. Such studies should, perhaps, be done in MPAs to control for the harvesting effect by man (although the removal of human predators may mean increased activity of other natural predators). To allow for generalizations, future studies on ARs and lobsters should be expanded to a variety of lobster taxa and geographical regions and incorporate broad ecological theories such as the habitat selection theory (e.g. Rosenzweig, 1981) and ideal free distributions (e.g. Kacelnik *et al.,* 1992). Issues such as residency time, home range, homing, emigration, and predator-prey interactions should be investigated.

Natural mortality drops sharply with growth of a lobster ("size refuge", e.g., Butler *et al.,* 2006) but man-made mortality (i.e., fishing) increases with growth above a given legal size. Are ARs just a tool to concentrate lobsters for more efficient harvest (Herrnkind *et al.,* 1997b) and, if deployed more extensively, would they even increase human predation as has been argued by Polovina (1991)? The answer is probably yes and no. If ARs play a role in increasing the survival of lobsters that otherwise are lost due to natural predation because of lack of shelter, then such lobsters will add to the population and increase production of the environment. At some point in the growth of a lobster, they will reach a "size refuge" (Butler *et al.,* 2006) from natural predators, but will be subject then to predation by humans upon attaining legal harvestable size. The important question is does the gain in production (from reducing natural predation) balance or exceed the loss from fishing at an appropriately designed AR? This question requires further research and must be answered by taking into consideration the inter-relationship of multiple predator effects on lobsters.

Even if future studies indicate that ARs act merely as another fishing device, they can still be useful in lobster fishery management, provided that proper legal and socio-economic regulations are established and enforced (e.g., the case of lobster fishermen co-operatives along the Caribbean coast of Mexico described by Briones-Fourzán *et al.,* 2000).

Although some AR applications have been used for fisheries, few applications were directed towards the use of lobster ARs for eco-tourism and conservation. Aesthetic ARs for lobsters can be attractive for (non-fishing) eco-tourism by SCUBA divers and thus may alleviate harmful diving pressure on sensitive natural habitats (such as coral reefs). In view of the recent decline of quite a few lobster populations and the deterioration of their natural habits (see reports in the present volume), the use of ARs for conservation of lobsters and mitigation of their habitats is called for.

In addition, depletion of populations of lobsters by overfishing or environmental damage can be mitigated by creating sanctuaries (MPAs) for reproductive populations supplied with proper artificial habitats. Since several lobster species are reared today in captivity, these steps can be supplemented by stock enhancement of juvenile stages to be released (in the right season and time of the day) at an MPA with the appropriately designed ARs for the stocked stages. Re-stocking and enhancement of natural population by hatchery-reared lobsters from wild stock females should be done only after validating that it actually enhances production and does not simply displace natural stocks—employing ARs designed specifically for this purpose can help ensure this.

Several lobster scientists have also pointed out some potential disadvantages of concentrating lobsters in ARs, particularly with respect to disease. These suggestions should be tested carefully in designed field and mesocosm experiments (like those described in Lavalli and Herrnkind, 2009) so that the use of ARs can be better understood. Finally, ARs are deployed in areas that generally have low densities of the target species, but this does not mean that these areas are not productive grounds for other species. The impact that ARs have on ecosystems within these areas needs to be better understood so that we do not obtain enhancement of one species at the detriment of many others.

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