

Artificial reefs and fisheries exploitation: a review of the ‘attraction versus production’ debate, the influence of design and its significance for policy

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Accepted 6 February 1996

Abstract

Amidst the growing volume of published research on artificial reefs, one of the key questions concerns their potential for enhancing production over and above merely serving to attract and concentrate fish at specific sites. This paper reviews the ‘attraction versus production’ debate, highlighting the key role of design in determining a reef’s effectiveness. Though some studies have apparently demonstrated that artificial reefs are capable of acting as production enhancers, others have not, for reasons which may be associated with the design of the reef itself. The review identifies a number of lines of enquiry for future research, and argues that while the proper design of a reef is essential to maximise productive potential, this may be of little value in the absence of a management strategy aimed at controlling the build-up of harvesting pressure which some reefs may engender. © 1997 Elsevier Science B.V.

Keywords: Artificial reefs; Production enhancement; Lobsters; Ranching and aquaculture; Resource rent; Fisheries management

1. Introduction

Marine structures, whether man-made or natural, have a recognised potential to attract and concentrate fish (Rounsefell, 1972, Wyche, 1984, Collins and Mallinson, 1984, Bohnsack and Sutherland, 1985, Potts and McGuigan, 1986, Bohnsack, 1989, 1991, Ambrose and Swarbrick, 1989, DeMartini et al., 1989, Bohnsack et al., 1991, Collins et al., 1991a) and to enhance stocks. Whether they act only to attract and aggregate fish or also to increase biomass

is, however, a subject of debate (Solonsky, 1985, Bohnsack and Sutherland, 1985, Bohnsack, 1989, Buckley, 1989, Polovina, 1989, 1990b, 1994, Alevizon and Gorham, 1989, Polovina and Sakai, 1989, Bombace et al., 1990, Kerr, 1992, Seaman, 1996, Harmelin and Bellan-Santini, 1996). For their use as production enhancers, over and above the physical protection that they can and do offer, for example, to spawning grounds from destructive forms of fishing, it is essential to consider whether and how any productive potential can be maximised for exploitable species.

This paper reviews some of the evidence for attraction and production and considers the role of reef design in enhancing productive potential. It

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looks to the future by examining the significance of the 'attraction versus production' debate, the need for future research and the implications for policy. While drawing on evidence from a variety of studies, particular attention is paid to research on the European and American lobsters, *Homarus gammarus* and *H. americanus*.

2. The attraction versus production debate

Productivity in real terms in relation to artificial reef deployment relies on the assumption that artificial reefs provide additional critical habitat which increases the environmental carrying capacity and thereby the abundance and biomass of reef biota (Polovina, 1994, Bortone et al., 1994). The reef potentially provides: substrata for benthic fauna and, thereby, additional food and increased feeding efficiency; shelter from predation or tidal currents (Collins et al., 1991a, Spanier, 1996); a recruitment habitat for individuals that would otherwise be lost from the population; a reduction of harvesting pressure on natural reefs (Randall, 1963, Ogawa, 1973, Stone et al., 1979, Matthews, 1985, Harmelin and Bellan-Santini, 1996). It can also serve to be purely an aggregating device, whereby the behavioural preferences of fish result in aggregation on and around artificial reefs without any increase in biomass (Bohnsack, 1989).

2.1. Benthic biomass

In support of the production debate, artificial reefs have been found to increase the biomass of benthic invertebrates significantly (Sampaolo and Relini, 1994). Compared with infauna prior to emplacement, epifauna on an artificial reef in Delaware Bay was found to be between 147 and 895 fold greater (Foster et al., 1994). It is suggested that these productivity figures reflect the expanding available surface area for benthic faunal use and the trapping of plankton food and other resources by the structure, although increased sedimentation of suspended particles, reef waste products and detached organisms may also contribute (Foster et al., 1994). The availability of propagules and the increased foraging opportunities have been particularly credited with increasing the settlement and resultant biomass of algae and seden-

tary invertebrates on artificial reefs (Borowitzka et al., 1978, Keogh and Downes, 1982). However, growth is modified by the immersion time and such as reef related grazing pressure and environmental parameters (discussed later in the paper) (Dean, 1983, Bailey-Brock, 1989).

Sessile invertebrates and algae serve to attract fish (Anderson et al., 1978, Johnson and Stein, 1979, Dudley and Anderson, 1982, Wallace and Benke, 1984) and, as gut content surveys have demonstrated, provide an essential food source (Johnson et al., 1994). They also give the artificial reef the appearance of a natural reef, providing additional shelter (Wege and Anderson, 1979, Moring et al., 1989). The biogenic structures of these sessile species serve to alter reef topography and heterogeneity, altering the hollows between the blocks and enhancing the essential shelter for juveniles and adults from predation, tidal and wave forces and desiccation (Hixon and Brostoff, 1985, Relini et al., 1994a,b). They also trap sediment particles which reduce the substrate available for hard-bottomed species, while providing additional habitat for species characteristic of soft bottoms (Ardizzone et al., 1989). This stage, Ardizzone et al. (1989) identified as the 'regressive period'.

2.2. Commercial species

Natural reef fish and crustacean abundance also demonstrate a significant dependence on the habitat available (Sale, 1978, Moffitt et al., 1989, Pratt, 1994). On a global and national scale, the geographical scarcity of natural reefs is an obvious limiting factor (Huntsman, 1981, Bohnsack, 1989). Larvae numbers often far exceed the numbers able to settle on a reef (Sale, 1980), which with food eliminated as a direct factor (Shulman, 1984), leaves habitat as the likely dominant factor in limiting reef populations: the 'limited shelter hypothesis' (Randall, 1963, Smith and Tyler, 1972, 1973, 1975, Hixon and Beets, 1989). The shelter provided by the habitat is critical for settlement and the reduction of predation mortality among newly settled juveniles (Shulman, 1984, Doherty and Sale, 1986).

Recruitment to artificial reefs is demonstrated for a wide variety of species, the rate of species recruitment being greatest within the first few months and decreasing with time (Bailey-Brock, 1989). The

Texas Park and Wildlife Department found that new fish populations increased 300 to 1800 times within a few months after reef construction for a reef in 60 ft of water off the Texas coast (Dean, 1983). Over time the occupancy of artificial reefs has been demonstrated to approximate to or exceed those of natural reefs in the neighbouring vicinity, largely irrespective of reef type (tyres, boats, rock, concrete blocks, rubble, pipes) (Ambrose and Swarbrick, 1989). For example, equal numbers of fish and associated species were found on an artificial reef and a natural reef in Florida after only 7 months (Dean, 1983). The biomass on an artificial reef off the Maquevas Island in 1972, monitored by the University of Puerto Rico's Department of Marine Science, was found to be eight times greater than that of a nearby natural reef, although there was a smaller species diversity (Dean, 1983). An enlarged biomass (11 times greater) was also found in artificial versus natural reef comparisons in the Virgin Islands. Here there was an almost comparable species diversity (Dean, 1983). Buckley and Hueckel (1985), Matthews (1985), Ambrose and Swarbrick (1989), Bohnsack (1991), McGlennon and Branden (1994), Branden et al. (1994) and Fabi and Fiorentini (1994) also found similar comparisons between artificial and natural reefs, with Ambrose and Swarbrick (1989) noting a greater biomass density for benthic reef fishes as well as for reef biomass as a whole. The enlarged numbers have been attributed to the different origins of artificial reefs and natural reefs (Dean, 1983). There is evidence, however, that this performance in overall biomass may not always be reflected in individual species. Rounsefell (1972) noted that for lobsters artificial reefs have smaller occupancy levels than those of naturally productive lobster grounds. However, as this paper discusses, this could be a consequence of the design parameters of the artificial reef, especially given evidence of lobster attraction and loyalty to artificial reef structures.

Demonstrating this attraction and loyalty, lobsters (*Homarus gammarus*) and crabs (*Cancer pagurus*) were found on the Poole Bay reef within 3 weeks of deposition (Collins et al., 1992), with a high degree of reef loyalty thereafter. In loyalty trials using tagged lobsters, there was marked preference among lobsters to stay within Poole Bay (Jensen et al., 1992a, Jensen and Collins, 1996). Several individu-

als remained on the Poole Bay reef itself for long periods, although loyalty to any particular reef unit varied from loyalty to one unit to extensive movement between them (Jensen et al., 1992b). The longest period of residence stands at 1050 days (Jensen and Collins, 1996). The lobsters apparently switch between the two modes of behaviour, producing a complex pattern of local movements. Migratory patterns around the Poole Bay artificial reef were found to extend up to 15 km away from the reef (this southwest of the Poole Bay reef, with 3–4 km to the north and 6 km to the south) (Jensen et al., 1992b) with animals potentially leaving the reef site for up to 3 weeks at a time (Jensen and Collins, 1996). However, Jensen and Collins (1996) reported that "most movements averaged over time are less than 4 km in magnitude" (p. 2). Further tagging studies in Bridlington Bay, Aberystwyth and Ardtoe (Bannister, 1992) also demonstrated a small but notable proportion of the lobsters travelling some distance, although the majority again demonstrated marked loyalty, remaining in the vicinity of the release substrate (Bannister and Howard, 1991, Burton, 1992, Bannister et al., 1994).

2.3. Reproduction

In addition to evidence of aggregation, there is also evidence presented of increases in biomass and ongoing recruitment through reproduction. DeMartini et al. (1994) identified that fishes present on a shallow temperate artificial reef and feeding on or immediately near a reef in California had produced tissue through both growth and reproduction, increasing the standing stock biomass by up to 78%. Campos and Gamboa (1989) recorded large egg clusters of typical reef fish (*Chromis atrilobata*) on an artificial reef in Costa Rica. Reproductive activity has also been demonstrated for a number of species on the Poole Bay reef in the UK. Nests have been constructed and defended by the male corkwing wrasse (*Crenilabrus melops*) since 1990 and 50 spiny spider crabs (*Maja squinado*) were identified in July 1990 in a moulting aggregation at the base of one of the reef units (a pattern of behaviour thought to be associated with mating) (Stevcic, 1971). Pairing has been observed on the Poole Bay reef among velvet swimming crabs (*Liocarcinus puber*) and large numbers of hermit crabs (*Pagurus bernhardus*). Whelks

(*Buccinum undatum*) and *Archidoris pseudoargus*, a large nudibranch, have also congregated on the reef to mate and lay eggs (Jensen et al., 1992b).

Berried females of *Homarus gammarus* have been found on the Poole Bay reef since 1990, some reproducing more than once, while other individuals have demonstrated successful moulting (Jensen et al., 1992b, Jensen and Collins, 1996). The capture of small lobsters (27 mm CL) on the reef in 1993 is a further indicator of recruitment (Jensen and Collins, 1995), though it has yet to be determined whether larval lobsters will remain on the site, thereby completing the life cycle. Off Point Judith, Rhode Island, the use of concrete pumice shelters to provide the shelter requirements of lobster eggs and juveniles has demonstrated a significant increase in the resident lobster population (Dean, 1983), which may be indicative of a completed life cycle being achieved here. Dean (1983) uses such evidence to support the proposition that artificial reefs placed near natural reefs do, at first, attract fish from the natural reef, but that they soon develop a life of their own (Dean, 1983).

Unfortunately, as Bohnsack et al. (1994) highlight, “there is no way to [definitively] discern (1) whether fishes that settle or are attracted to artificial reefs would have found suitable habitat if these reefs were not present; (2) whether fishes had a better survival or faster growth at artificial reefs than in natural habitat; (3) whether foraging success and food web efficiency has improved by artificial reefs; and (4) whether habitat is vacated by fishes moving” (p. 821).

2.4. Evidence of productivity

While it is acknowledged that artificial reefs attract and concentrate species, to ascertain whether artificial reefs enhance fish stocks requires direct evidence to prove increased production, such as an increased total regional catch or standing stock in some proportion to the amount of artificial reef material deposited, while accounting for fishing effort, recruitment from surrounding areas and changes in year class strength (Bohnsack, 1989). Laufle and Pauley (1985, Bohnsack (1989) and Campos and Gamboa (1989) highlight that high fish densities, rapid colonisation rates, recruitment and high catch rates are not sufficient evidence. For example, Davis

(1978, 1985) in studying juvenile *Panulirus argus* found that lobsters merely moved from the natural environment to artificial shelters, with no increase in production, an argument supported by Pratt (1994) in identifying colonisation as being limited by the distance of the reef from a source of colonists. Polovina (1990b) also provides evidence, drawn from several studies, that artificial reefs can result in the redistribution of biomass rather than an increase in biomass for mobile species or for species which are not habitat limited. There have been several promising indicators, however. For example, there have been a number of successful bivalve enhancement programmes in the Adriatic Sea using artificial reefs (Fabi et al., 1989) and there are more promising results from trials in the United Kingdom in respect of lobsters (Bannister et al., 1994). Where an increase in productivity is displayed, it is typically species specific and not across the board (Bohnsack, 1989).

The species most likely to benefit in terms of increased biomass are habitat limited, demersal, philopatric, territorial and obligatory reef species. The attraction hypothesis is likely to hold for locations where natural reef habitat is abundant and where species have a high fishing mortality, are recruitment limited, pelagic, highly mobile, partially reef-dependent or opportunists (Bohnsack, 1989). Populations need not always exceed or lie at the carrying capacity of the environment, and hence habitat may not be the only limiting factor on adult population size. (Victor, 1983, Richards and Lindeman, 1987, Doherty and Williams, 1988). Early post-settlement mortality (Bohnsack et al., 1994) and recruitment limitation (a shortage of competent larvae) have also been identified as potentially over-riding factors in limiting adult population size, acting below the threshold of food and space constraints (Williams, 1980, Doherty, 1982, 1983, Victor, 1983, 1986, Sale and Douglas, 1984, Sale et al., 1984, Davis, 1985, Shulman and Ogden, 1987, Doherty and Williams, 1988, Bohnsack, 1989). Bohnsack et al. (1994) express the opinion that artificial reefs are unlikely to significantly increase the population size of such species as are recruitment-limited or subject to heavy fishing mortality.

In terms of enhancing production, the important question may well be production in terms of target

species. Even in Japan, the economic benefits of artificial reef programmes are far from proven, and often negligible, when their contribution to regional productivity is assessed (Bohnsack, 1989, Polovina, 1990b). In Japan such projects are evaluated on the basis of popularity and the value of a particular harvest from the reef against the cost of construction (Grove and Sonu, 1985, Bohnsack, 1989).

3. Artificial reef design and construction

The effectiveness of artificial reefs in increasing productivity depends on the design of a reef structure, in particular whether it meets the specific habitat requirements of individual target species and age groups (Scarratt, 1973, Spanier, 1991, Fabi, 1996, Jensen and Collins, 1996). Despite the number of artificial reefs built and evaluated, and the large body of literature on their effectiveness (Randall, 1963, Turner et al., 1969, Buchanan, 1973, Kanayama and Onzuka, 1973, Walton, 1979, Stone et al., 1979), relatively few studies have been dedicated to determining the relative benefits of different designs for production purposes (Bohnsack and Sutherland, 1985, Delmendo, 1991, Montemayor, 1991, Seaman and Sprague, 1991, Doty, 1994, Gregg, 1995). It is increasingly being recognised that this is one of the major areas where further work is needed: the design, location, planning and evaluation of artificial reefs (Bohnsack et al., 1994) for targeted species and their supporting community structures (Ody, 1989, Ambrose and Swarbrick, 1989, Palmer-Zwahlen and Aseltine, 1994, Kim et al., 1994). In themselves, artificial reefs do not necessarily attract or increase the biomass of desired species nor retain them over long periods. The design of the reef is critical, as is the presence of the desired species in the area (Pratt, 1994, Spanier, 1994). Research needs to establish, for example, whether juveniles (as with lobsters of less than 10 cm total length) prefer habitats similar to adults (Richards and Wickins, 1979) or have different preferences and what those preferences are (Caddy, 1986, Cobb, 1986, Wahle and Steneck, 1991). In respect of *Homarus gammarus*, Barry and Wickins (1992) have started moves in this direction, developing and publishing predictive models for the optimal design of reefs for lobsters.

3.1. Structures

There are a wide variety of structures employed in artificial reefs. Many of the reef structures built during the early 1900s were “a hit-or-miss dumping operation of unsightly scrap material” (Dean, 1983) such as tyres and car bodies. There were a few successes in the 1950s using building rubble and concrete filled beer cases, but there were as many failures (Delmendo, 1991). In Japan, as far back as the 1790s, fishermen placed large wooden and bamboo frames into the sea to increase catches (Dean, 1983). Even today, the deployment of such opportunistic structures remains the more common option in artificial reef construction (Young, 1988, McGurrian and Atlantic States Marine Fisheries Commission, 1989, McGurrian et al., 1989, Seaman et al., 1989, Figley, 1994, Branden et al., 1994, Balgos, 1995). However, there is a growing trend towards dedicated reef designs, with Japan experimenting with moulded concrete blocks as early as 1952, followed by Taiwan and others (Simard, 1995).

Dedicated reef designs use either a single material or several in combination, with the designs varying from simple block structures to complex matrices and mixed shape designs. Low profile concrete pipes, moulded concrete modules in various forms, plastic domes, ‘igloos’, steel cubes and steel reinforced concrete shapes have all been tried (Thierry, 1988, Bell et al., 1989, Collins et al., 1992, Meier and Eskridge, 1994, Blancher et al., 1994, Anon, 1995). Despite the higher initial cost involved with the use of dedicated reef structures and materials, it has become evident that to maximise the potential of artificial reefs “there is a need to integrate biological investigations of species requirements with engineering studies of materials design, placement and performance physically” (Seaman et al., 1989, p. 529; see also McGurrian and Atlantic States Marine Fisheries Commission, 1989).

Concrete has been found to be particularly favourable to reef construction (Sungthong, 1988), gaining interest among a number of artificial reef trials. It is found to be durable in seawater, mouldable to different specifications and, within tropical waters, to have a similar community development to natural coral reefs (Fitzhardinge and Bailey-Brock, 1989). In contrast, fibreglass-reinforced plastic and

PVC have been found to have stability problems, being susceptible to destruction during storms or to being overturned by fishing gear (Bell et al., 1989, Delmendo, 1991, Omar et al., 1994). Examples of some of the structures employed in reef construction are given below. It should be noted, however, that the effectiveness of any of these structures and the materials used in their manufacture depends on their engineering (Myatt et al., 1989, Collins et al., 1995).

Moffitt et al. (1989) used concrete pipes of 30 or 45 cm inside diameter, staked in low profile pyramids of three to six pipes and secured by stainless steel bands and polypropylene line. The pipes contained a centre barrier with holes to maintain water flow and to create a cave like structure. Artificial reefs in the Shimamaki region of Japan used small (0.785 m³ enclosed volume) or large (4.58 m³ enclosed volume) cylindrical concrete modules with several large holes in the sides (Polovina and Sakai, 1989).

Ardizzone et al. (1989, Bombace (1989, D'Anna et al. (1994) and Relini et al. (1994b) utilised reefs of between 100 and 450 concrete cube shaped blocks (2 m × 2 m × 2 m) arranged in low profile pyramids of between five and 14 blocks, with cavities made in the sides and faces of the blocks to increase the surface/volume ratio. This structural arrangement has been supplemented by concrete cages (4 m × 6 m × 5 m) and steel wires stretched between the pyramids for shellfish culture and concrete cylinders around the base of the blocks for shelter provision. The cages were set within a square arrangement of eight concrete pyramids (the pyramids 15 m apart) (Bombace et al., 1994). The structure employed in the Poole Bay experiment also used cubic blocks, each 40 cm × 20 cm × 20 cm, formed into eight conical units, 1 m high by 4 m across, over a 30 m × 10 m area of seabed (Collins et al., 1990, 1991a,b, Jensen et al., 1992b).

Jara and Céspedes (1994) used small hollow concrete cubes (30 cm³) with 20 cm holes in the six sides, stacked two blocks high by three deep and wide. Open-frame concrete-cube modules have also been used, in shallow reef arrangements (1–125 cm³) (Brock et al., 1985, Brock and Norris, 1989, Baine and Heaps, 1992, Fabi and Fiorentini, 1994). Concrete blocks and the pyramid arrangement are seen to have been particularly effective for artificial

reef structures for certain species groups; some pelagic and nekto-benthic fish and some obligatory reef nekto-benthic and benthic species. One of a number of variations on the cube is the igloo, as tested in Chesapeake Bay, which has proven highly attractive for both fish and anglers (Feigenbaum et al., 1989, Meier and Eskridge, 1994).

More complex structures include an artificial reef in Delaware Bay constructed of prefabricated steel-wire reinforced 'Waffle-Crete'[®] panels (2.4 m × 4.9 m × 0.2 m) perforated with 0.2-m-diameter hydrodynamic pressure-released holes. The panels were held together by epoxy coated steel rods creating a module structure 6.1 m in width, 2.7 m high and weighing 20 MT (Foster et al., 1994). Very complex structures include the alveolar structures (12 m³) deployed in a study by Moreno et al. (1994) in Balearic waters and the 'space reef', known as the Porikon reef (Mottet, 1985, Baine and Heaps, 1992). Many of these complex structures, mirroring natural habitats, use a variety of materials and structures.

3.2. Design and abundance

While there are few reports on the comparative effectiveness of these different reef structures or on artificial reef designs for targeted species, several studies have, however, demonstrated a marked preference among different species for particular reef designs and a marked relationship between reef structure and catch volume (Lee and Kang, 1994, Kim et al., 1994, Marinaro, 1995). Studies in Korean waters, for example, have identified dice shaped reef units as being preferred by rockfish, turtle shaped reef units being dominated by demersal fish, while tube shaped structures exhibit intermediate characteristics (Lee and Kang, 1994). For finfish, cylinders with holes along the sides and hollow 'jumbo' structures have been shown to consistently support the highest species diversity, probably due to the hiding spaces, hollow interior spaces, shadow against light, high surface area and protuberances characteristic of these designs (Kuwantani, 1980, Kim et al., 1994, Marinaro, 1995). No comparable survey has been found for benthic species. There are, however, a number of general pointers. The following discussion addresses some of the more general findings of the literature with respect to reef design and aggregation

and production, while also incorporating the requirements of certain example species, particularly, the European lobster.

3.3. Size

Reef size and its influence on the species abundance on artificial reefs is an ongoing debate. Reefs typically range from 1 to 10 m or more in width and height and 1 to 70 t or more in weight (Baine and Heaps, 1992). In Japan, however, some artificial reefs have taken on a different order of magnitude, being of the order of 30 000 m³. Several studies have identified that reef size significantly influences the biomass and the total number of species and individuals (Campos and Gamboa, 1989, Bohnsack et al., 1994, Bombace et al., 1994), with the efficiency of artificial reefs as attractors being far greater when formed into structures rather than disaggregated into pieces (Moffitt et al., 1989). Bombace et al. (1994) and Pratt (1994) reported improvements in capacity proportional to the dimensions of the reef, its volume and the area covered by the reef, with larger reefs (with greater habitat heterogeneity) likely to attract a greater number of persistent species. Ogawa et al. (1977) established a direct relationship between production increase and reef volume up to a critical point of 4000 m³, while Rounsefell (1972) noted that reefs of 25 000–50 000 ft² are required to reach equilibrium and permit propagation. While higher biomass densities accompany larger reefs, such biomass densities are composed of larger but fewer individuals. This has been attributed to the success of larger occupants through competition and predation over smaller individuals (including juveniles) (Bohnsack et al., 1994).

In contrast, smaller reefs have greater fish densities (Bohnsack et al., 1994), in part due to their greater ratio of area of attraction to reef area relative to larger reefs (Ambrose and Swarbrick, 1989). On the basis of these findings, multiple small reefs, providing more individuals and species, have been recommended in preference to a single large reef in respect of overall recruitment (Bohnsack et al., 1994). This is, however, mainly through aggregation, Moffitt et al. (1989) noting the limited value of small reefs as nursery habitats or as a source of increased production. In balance, for fish production, larger

reefs offering increased habitat or increased buffering from adverse environmental conditions may prove more effective (Ambrose and Swarbrick, 1989). For fisheries applications, Bohnsack et al. (1994) accordingly recommend the use of larger reefs.

The size of an artificial reef, however, is also important in relation to the different fish species it is likely to attract (Grove et al., 1991, Bombace et al., 1995). Size is important in the attraction, for example, of transient species (DeMartini et al., 1989), particularly reef height, acting as a visual or audio stimulant or spatial reference (Klima and Wickham, 1971, Jessee et al., 1985, Anderson et al., 1989), its significance increasing with water depth (Molles, 1978). It is also possible that the fish may be able to hear the organisms living on the reef once it has become established (Dean, 1983). The significance of these factors, however, varies between studies, with Moffitt et al. (1989) identifying neither as being particularly significant during their study. For attracting demersal and benthic species, the consideration of reef height (Stephens et al., 1994) may also need to be accompanied by consideration of horizontal spread (Grove and Sonu, 1985); with lobsters, for example, rarely going above 1 m from the seabed, reef capacity will depend somewhat on the spread of the reef (Jensen, A.C. personal communication, 1996). The small extent (30 000 ft²) of an artificial reef (in New Brunswick) of blocks varying in size from 5 to 100 cm diameter and up to 15 cm thick was said to have limited lobster production, the reef failing to support lobsters in comparable numbers to naturally productive areas (Rounsefell, 1972). It is not a simple relationship however, as assemblages can vary significantly across and between reefs of the same size, indicating modification by other factors (Bohnsack et al., 1994).

3.4. Shelter

One of the principal mechanisms by which an artificial reef would increase environmental carrying capacity and biomass within a naturally self-sustaining stock or aid in the survival of an introduced stock is that artificial reef structures can reduce predation on the reefs' residents through the provision of shelter (Bohnsack, 1989, Eggleston et al., 1992).

The structural complexity of reefs, particularly the presence and variety of crevices, has been shown by some studies to contribute significantly to the species composition and biological productivity of reefs (Luckhurst and Luckhurst, 1978, Smith et al., 1979, Chandler et al., 1985, Anderson et al., 1989), although not on its own (Potts and Hulbert, 1994). In contrast, certain fish species and reef populations have been shown to prefer less complex structures (Klima and Wickham, 1971, Risk, 1972, Sale and Douglas, 1984). Sand cavities, the proximity of neighbouring modules and the bio-fouling of exposed surfaces, providing secondary biotic space (Palmer-Zwahlen and Aseltine, 1994), are microhabitat features which influence patterns of colonisation and the resulting assemblages (Bohnsack et al., 1994), specifically attracting certain species. Natural substrata are usually dissected by small to large crevices, with different orientations relative to each other and the water flow and are often comprised of varied rock types with different physical relief, modified by the provision of secondary substrata. Vertical relief within a structure varies water flow, turbulence patterns, sedimentary regimes, light levels, temperature regimes and desiccation stresses, thereby catering for the specific requirements of a diverse community structure.

The design of cavities within the reef and the overall design of the reef is dependent on the target species and their particular biological attributes (Beets and Hixon, 1994). Dean (1983) notes that fish will not venture into dark, closed compartments with only a single exit, preferring objects with many openings in them to provide light and a free flow of water. For small fish, which need a place to rest, the deployment of artificial reef units at right angles to strong currents to provide shelter on the lee side should be considered (Dean, 1983). The European lobster is another species dependent on shelter. Breeding programmes have shown that juvenile lobsters grow faster when suitable shelter is available, probably due to reduced energy expenditure whilst sheltered, among other factors (Richards and Wickins, 1979). The lack of suitable shelter has been attributed as the cause of the predominantly undersized lobsters produced by the Torness artificial reef off Scotland (Todd et al., 1992). The Poole Bay artificial reef, in contrast, produces individuals typi-

cal of an exploited inshore fishery with most animals close to the legal size limit (85 mm carapace length) (Jensen and Collins, 1995). For lobsters in the early benthic phase (EBP), studies of the American lobster have identified the availability of suitable, shelter providing, benthic habitat and density-dependent controls as producing a demographic 'bottleneck' soon after the benthic settlement stage, resulting in mortality and limited adult recruitment (Caddy, 1986, Fogarty and Idoine, 1986, Wahle and Steneck, 1991). Shelter occupancy for small European lobsters in the early benthic phase reduces the high risk of crustacean predation (Stein and Magnuson, 1976), physical disturbance (Howard, 1980, Howard and Nunny, 1983) and/or physiological stress (Bertness, 1981). In fact the strong association of EBP lobsters with shelter suggests that shelter-providing habitat is a necessary prerequisite for recruitment to the benthos (Caddy, 1986, Fogarty and Idoine, 1986, Wahle and Steneck, 1991, Beard and Wickins, 1992).

Adult lobsters also spend most of their time in shelters (Cooper and Uzmann, 1980, Karnofsky et al., 1989a), demonstrating an evident preference for a home shelter (Karnofsky et al., 1989a), using them for protection not only from predators, but also from tidal streams. Larger lobsters are vulnerable to being swept off rocky substrate by strong tidal streams (Addison and Lovewell, 1991). Some individuals occupy the same shelter for periods of up to several months, while others frequently change their shelters. Pre-moult behaviour in the American lobster is particularly characterised by multiple shelter use (possibly to obscure the place of moult from competitors and to discourage other lobsters from inhabiting the immediate vicinity; Karnofsky et al., 1989a). Not being gregarious, shelter and territory are central to their behaviour patterns, with fighting and cannibalism likely in confined conditions (Richards and Wickins, 1979, Cooper and Uzmann, 1980). However, the American lobster can occasionally be found to exhibit multiple occupancy of shelters during the winter months and where there is a scarcity of shelters, which with field observations identifying a marked clustering of shelter locations occupied, indicates some measure of socialisation (Karnofsky et al., 1989a).

In natural habitats, the American and European lobster typically exhibit very similar shelter prefer-

ences, selecting dark shelters close to their body size (even to the point of physical contact) which have two clear openings, free from algal cover, to allow for escape and the maintenance of a lookout (Dybern et al., 1967, Dybern, 1973, Cooper and Uzman, 1980). *Homarus americanus* in its natural setting has been found to occupy eelgrass shelters almost always with two openings: one major entrance and a smaller 'escape door' (Cobb, 1971, Karnofsky et al., 1989a). As Karnofsky et al. (1989a) notes, however, while such general observations can be made, their translation into artificial shelters is not straight forward.

3.5. Shelter and predation mortality

The traditional assumption on which many artificial reefs are built is that obligate reef dwellers are limited locally or regionally by the availability of suitable shelter (Bohnsack, 1989, Hixon and Beets, 1989, Eggleston et al., 1990, 1992), particularly for the recruitment and survival of juveniles (Bell et al., 1985, Matthews, 1989, Gorham and Alevizon, 1989, Spanier et al., 1990); life stages which have quite specialised habitat requirements (West et al., 1994). However, artificial reef projects, especially those aimed at creating recreational or commercial fisheries, provide habitat mostly for adult forms. Since many of these target species are carnivores, and many of the reefs have not been designed with juveniles or smaller species specifically in mind, any potential of the reef for integrated fisheries management is significantly hindered by abnormally high levels of recruitment mortality (West et al., 1994) and post-settlement mortality through interactions between species and adults and juveniles (Smith and Tyler, 1972, 1973, 1975, Gladfelter et al., 1980, Anderson et al., 1981, Gladfelter and Johnson, 1983, Hixon and Beets, 1989). There is significant evidence to suggest that reef fishes, like adult lobsters, prefer hole sizes near their body sizes, with a preference, therefore, among smaller fish for smaller cavity sizes (Randall, 1963, Robertson and Sheldon, 1979, Shulman, 1984). Hixon and Beets (1989) demonstrated that the existence of many large cavities caused an increase in the abundance of large piscivorous fishes, especially where their prey are concentrated in area by the reef (Eggleston et al.,

1990, 1992), which in turn decreased the population of small fishes. The survival rates of prey under this scenario could be higher away from a reef than at the reef site (Eggleston et al., 1994). Scale of both habitat and organisms is crucial to the refuge value of a particular habitat structure.

Bohnsack et al. (1994) identified that for reef fishes the greatest mortality from predation occurred within the first 2 weeks after the settlement of juveniles. Adequate cavity design and complexity are essential if such predation is to be moderated (Bohnsack, 1989). Small holes of only a few cm have been shown to be important for juvenile reef fish survival (Shulman, 1984, 1985, Shulman and Ogden, 1987, Hixon and Beets, 1989, Bohnsack et al., 1994). Reflecting this observation, the addition of physically complex shelter to low, small pontoons in Botany Bay, New South Wales, was found to increase the settlement success of juvenile fish (Hair et al., 1994); results similar to Bell et al. (1985).

Eggleston et al. (1992) presented the results of research into reef predation mortality for the Caribbean spiny lobster *Panulirus argus* Latreille. The trial used artificial lobster shelters of the 'casitas Cubanas' design (a concrete reef bolted to a PVC-pipe frame, maximum size 177 cm × 118 cm × 6 cm) which provided appropriate shaded cover, a low ceiling to exclude large piscine predators and multiple small den openings for the lobsters (Eggleston et al., 1990). The impact of predation was found to vary with lobster size and the degree of protection (the absence or otherwise of a casitas shelter). Larger lobsters (56–65 mm CL) survived better than small lobsters (45–55 mm CL) in relatively exposed sites (protection only being afforded by sparse-to-moderate-density seagrass—*Thalassia*), due to the refuge their relative size affords them (Eggleston et al., 1992). Smaller lobsters had a greater survival rate than larger lobsters in the casitas (Eggleston et al., 1992).

Reflecting size related preferences, reef occupants have been shown to select habitats and to change habitat requirements with age (Bohnsack, 1989): different cavities meeting their shelter requirement at different times. Lozano-Alvarez et al. (1994), quoting Eggleston et al. (1990), reported that a scaling down of casitas size has been shown to enhance the survival of small juvenile lobsters, only predation by

sight being hindered in larger shelters (Spanier and Barshaw, 1994). Once a carapace length of 56–65 mm CL has been reached, medium sized casitas offered lobsters the greatest protection (Eggleston et al., 1992). Studies of *Panulirus argus* and other species (Heck and Orth, 1980) have identified that shelter seeking behaviour reflects the protection characteristics of different sized shelters and the vulnerability of lobsters during different stages of their life cycle, juveniles being particularly vulnerable (Marx and Herrnkind, 1985, Herrnkind and Butler, 1986, Lavalli and Barshaw, 1986, Barshaw and Lavalli, 1988, Ford et al., 1988, Wahle and Steneck, 1991, Barshaw and Spanier, 1994). It is interesting to note that the shelter-seeking behaviour of juveniles is accelerated by the existence of predator odours, with a corresponding decrease in shelter selectivity (Boudreau et al., 1993).

A structural complexity of reef cavity design, aided by reef epifaunal growth and the characteristics of the environment (Lozano-Alvarez et al., 1994) will provide for the shelter requirements for a wider range of species and age groups (Bohnsack, 1989). Clark and Edwards (1994) report that topographically complex artificial reefs, in comparison with more simplistic shapes, are found to have significantly more fish associated with them. The more holes and the greater the predominance of small holes the larger the capacity of the reef in terms of the number of individuals able to find shelter from predation (Hixon and Beets, 1989), the level of significance outweighing any site effects on abundance (Clark and Edwards, 1994). The Poole Bay reef has gone part way to addressing the requirement for complexity, employing a variety of crevices and passages between the blocks to provide shelter for a range of decapod crustaceans. These have been colonised by a range of species (Lockwood et al., 1991).

4. Locational issues

4.1. Depth of installation

Artificial reefs have been operated and evaluated at a wide range of depths from 7 m (Frazer and Lindberg, 1994), 10–11 m (Fabi et al., 1989, Fabi

and Fiorentini, 1994) and 14 m (Ardizzone et al., 1989) to 117 m (Moffitt et al., 1989, Baine and Heaps, 1992). Brock et al. (1985), Brock (1994) and D'Anna et al. (1994) recorded reefs at the 16–20 m depth range. In the USA artificial reefs are generally built in deep offshore waters, very few having ever been built in shallow nearshore waters (Cummings, 1994).

The depth of an artificial reef within a suitable depth range for each species, generally, does not affect the diversity of resident species. The natural recruitment of lobsters has been found to depths of 100 m or more (Richards and Wickins, 1979). For transient populations, however, there is an element of dependency on depth (61 m, 98 m and 117 m) in terms of the aggregated biomass associated with the reef (Moffitt et al., 1989, Ody and Harmelin, 1994). This relationship is identified as being stronger than that between transient fish biomass and structure composition and configuration (Moffitt et al., 1989).

The reef must be located at sufficient depth to minimise the risk of storm damage (Branden et al., 1994), but at the same time maintain access by divers (Lockwood et al., 1991) for reef monitoring, stock enhancement exercises and reef maintenance, and to take advantage of the exchange and mixing of water masses in shallow inshore waters. The mixing of sedimentary nutrients and river runoff in inshore waters is highly productive in terms of phytoplankton and suspended particulate matter. These characteristics have the potential to enhance the productivity of an artificial reef (Bombace et al., 1994).

4.2. Ocean floor type and initial biocensus

Ocean floor type is critical to the locating of an artificial reef: the bottom substrates, storm wave action and currents. The bed must support the weight of the reef material, which requires to remain prominent and locationally and structurally intact (Dean, 1983). Sediment erosion and accretion can undermine or smother seabed structures (Lockwood et al., 1991). Care must be taken to avoid excessive sediment build up. An artificial reef structure within a sand wave field in Delaware Bay built up a 0.75 m sand wave accumulation at its base within a year (Foster et al., 1994), although to be expected in a dynamic shallow area. High sediment loadings in the

water column not only smother the reef structure, reducing its suitability for hard substrate species, but also smother the encrusting epibenthos and reduce light penetration, seriously impeding the effectiveness of artificial reef structures (Rezak et al., 1990).

Several studies have identified the location of an artificial reef in relation to existing hard substrate to be a factor in species diversity and density (Jessee et al., 1985, Ambrose and Swarbrick, 1989). Bombace et al. (1994) found that artificial reefs are particularly effective at sites far from natural hard substrates, with the appearance and increase in catches from the reef of some hard-substrate species of fish and mollusca which had previously been absent or rare in the area. A large gap (60 m) (Frazer and Lindberg, 1994) between reef units, and thereby relatively greater access to soft-bottom food sources, has been shown possibly to influence the structure and abundance of reef-associated faunal assemblages. A similar point was also noted by Seaman et al. (1994) and Alphin et al. (1996) in relation to the concentration and dispersion of artificial reef units. However, the proximity of artificial reefs to existing habitats increases the chance of transient fishes, semi-natural reef fishes and reef fishes inhabiting or encountering the reef, including commercial species (Campos and Gamboa, 1989, Potts and Hulbert, 1994). With close proximity, an artificial reef may become an extension of the existing habitat with possible benefits for fish recruitment (Danner et al., 1994). Stone et al. (1979) noted that a reef placed within 25 m of a natural habitat potentially recruits juveniles without reducing the population of the existing natural reef.

The nature of the bed not only influences the overall species diversity and composition of a reef, it also influences the reef's viability for certain species. The natural recruitment of lobsters is typically found on rocky seabeds with suitable crevices for shelter provision down to 100 m or more, although suitable rocks, stones and artificial structures on sandy substrates can also supply suitable habitats (Scarratt, 1968, Dybern, 1973, Berrill, 1974, Sheekey, 1976), provided that an appropriate food supply, among other factors, is present (Richards and Wickins, 1979). Typical among a lobster's diet are crabs, mollusca, polychaete worms, starfish and fish (Blegvad, 1914, Weiss, 1970, Cooper and Uzmann, 1980). The Poole Bay reef utilises a sandy seabed,

some 3 km from natural rocky outcrops (Collins et al., 1992). Mud bottoms are rarely attractive to lobsters, except in winter when some lobsters will burrow into the mud (Prudden, 1962).

4.3. *Exposure and environmental dynamics*

Little work to date has focused on the environmental factors influencing community structures on artificial reefs. Some work has been undertaken on the structural integrity of reefs under adverse environmental conditions and on the effects of shelter provided by the reef from tidal currents. Certain observations have been made however. Temperature (Hastings, 1979, Lukens, 1981, Sanders et al., 1985), visibility and currents (Sanders et al., 1985) are known to significantly influence the assemblage composition of artificial reefs (Rezak et al., 1990, Bortone et al., 1994). In terms of microstructure, the species composition and evolution associated with artificial reefs varies with the different exposure of each face to light, currents and sedimentation (Vance, 1979, Sebens, 1985, 1988), to which may be added temperature (Rezak et al., 1990), the size of cavities (Beets and Hixon, 1994) and depth (Relini et al., 1994b). In the Poole Bay experiment, a difference could be seen in the species colonising the vertical and horizontal surfaces, faunal species dominating the former and algae on the latter (Jensen et al., 1992b). Riggio et al. (1985), reporting on the progress of a concrete cube artificial reef, noted a dominance of polychaete worms and Polyzoa on the vertical walls in light, while Gastropoda dominated upper horizontal surfaces; largely reflecting a thick algal turf on vertical surfaces and sedimentary deposition on the horizontal surfaces. In shade, sessile invertebrates and low-light adapted algae dominate (Vance, 1979, Sebens, 1985, 1988). The inside faces of the blocks within the pyramids typically give rise to cave communities (Relini et al., 1994b, 1995).

In respect of temperature and salinity, settlement patterns have been shown to be potentially temperature-related (Scarratt, 1968, Wahle and Steneck, 1991) and laboratory studies of juvenile lobsters up to 3 months old have shown that yields can be maximised by adopting salinities of 28–32‰ and a temperature of 20°C (Richards and Wickins, 1979). Growth can also be affected by water quality, genetic

differences, diet and light conditions (Richards and Wickins, 1979). Lobsters, for example, prefer reduced light levels in shelters, potentially interpreted as reflecting differences in microhabitat quality as distinct from purely the intensity of light (Cooper and Uzmann, 1980). The indication is that the onset of settlement is substratum- and quality of shelter-dependent as well as quantity of shelter dependent in lobsters (Botero and Atema, 1982, Cobb et al., 1989, Boudreau et al., 1993). Adult lobsters also display temperature related behaviour, although Karnofsky et al. (1989b) identified this for *Homarus americanus* to be temperature-change related, lobsters hardly moving during winter temperatures of below 5°C and exhibiting increases of activity with rising temperatures in May, June and August and again with decreasing temperatures in October and November.

Currents are often responsible for nutrient and larvae supply to a reef (McAllister, 1981) and the numbers of suspension feeders among reef populations leads to the postulation (Mathews, 1981) that the long axes of an artificial reef should be perpendicular to the prevailing current. The relationship between different hydrodynamic conditions and the growth forms, abundance and diversity of reef species has been noted frequently for natural coral reefs (Loya and Slobodkin, 1971, Loya, 1972, Roberts et al., 1975, 1977, 1981, Murray et al., 1977, Pichon, 1978, 1981, Done, 1983, Baynes and Szmant, 1989), with water circulation and sedimentation shown to affect the abundance and distribution of sessile benthic fauna (Goreau and Wells, 1967, Bakus, 1968, Roy and Smith, 1971, Smith et al., 1971, Loya, 1972, 1976, Maragos, 1972, 1974, Rutzler, 1972, Aller and Dodge, 1974, Roberts et al., 1975, Bak, 1978, Jokiel, 1978, Jokiel and Maragos, 1978, Brown and Dunne, 1980, Baynes and Szmant, 1989).

The position of the structure in relation to currents also influences the distribution of pelagic, demersal and benthic species. Behavioural studies have identified a number of mechanisms which serve to attract fish to artificial reef structures, often related to the presence of the structure and light (Grove and Sonu, 1985, Bohnsack, 1989). The most significant of these are the thigmotactic responses to objects and the instinctive orientation responses (taxes or kinesis) to structures or currents for navigation or to optimise lighting conditions for feeding. Mackerel, sardines

and jacks, and other migratory fish species, have demonstrated a marked attraction by reef structures through the interruption of currents and the presence of vortices: the low frequency vibrations possibly acting as stimuli (Vik, 1982, Bleckmann, 1986). Where the fish actually congregate in relation to such currents is, however, subject to debate (Grove and Sonu, 1985), some are identified upstream and others downstream. The largest volume of fish seems to be attracted at the maximum current flow, as the current amplitude increases (Mori, 1982), with increased speed of flow reflected in fish congregating closer to the reef (Lindquist and Pietrafesa, 1989). Reefs with near vertical sides have been identified as good generators of vortical perturbations, encompassing stagnation zones and lee waves and currents (Bohnsack and Sutherland, 1985).

Not only supplying nutrients, CO₂, O₂, food particles (enhancing food gathering by filter feeders) and removing waste products, water circulation also provides favourable conditions for larval settlement (Crisp, 1955) and reduced sedimentation. At extreme velocities, however, water circulation can cause detachment from the substrate, the reduction or cessation of feeding and poor larval settlement (Baynes and Szmant, 1989). Orientation to minimise the surface area to oncoming oceanic forces will reduce the significance of such velocities (Denny et al., 1985). However, low velocities of water circulation are associated with high levels of sedimentation, harmful to sessile benthic organisms through smothering, abrasion and interfering with their physiological functions (Bakus, 1968, Roy and Smith, 1971, Smith et al., 1971, Maragos, 1972, 1974, Rutzler, 1972, Aller and Dodge, 1974, Loya, 1976, Bak, 1978). Community composition, as a result, varies over the surfaces of the substrate, reflecting variations in water circulation patterns (Goreau and Wells, 1967, Loya, 1972, 1976, Rutzler, 1972, Maragos, 1974, Weinburg, 1978). Horizontal surfaces are more likely to retain sediment and are, therefore, under greater sedimentary stress. Given the potential build-up of sediment on horizontal surfaces in areas of low velocity water circulation and the resultant stress this places on sessile benthic organisms, Baynes and Szmant (1989) propose that sessile benthic growth is maximised by maximising the surface area exposed to laminar current flow and the amount of vertical

substrate. If current shadow is to be minimised then reef orientation should be parallel to current flow (Baynes and Szmant, 1989).

5. Policy implications and conclusions

It is evident that there is a substantial volume of empirical evidence on the biological effects of artificial reefs, some of which appears to support the hypothesis that artificial reefs are capable (in specific circumstances) of enhancing production as well as serving to attract fish. Other studies have failed to support the hypothesis, however, and for this reason the debate on attraction versus production is likely to continue. This is made more likely by the reliability of some of the figures reported for enhanced artificial reef productivity being questioned; for example, reef biomass and density may be overestimated in circumstances where the surrounding sand area is not considered in the calculations (Bohnsack et al., 1994) and errors of estimation are believed to accompany many of the techniques used (Buckley and Hueckel, 1989, Green and Alevizon, 1989). It is evident, however, that the results of the debate are clearer for certain species: potentially future target species.

From the preceding discussion, it is also evident that there is a substantial body of research addressing the design parameters determining a reef's effectiveness in attracting or enhancing the production of marine communities and specific species. Unfortunately, as demonstrated for the *Homarus gammarus* and *H. americanus*, there are many gaps in the knowledge base. There is a need for science to attempt to fill these gaps, particularly in relation to species targeted by artificial reef construction, if the productive capacity of the technology is to be maximised.

One of the key areas of future potential for artificial reefs, subject to a number of policy and legal developments, is for their use as a commercial ranching substrate for key target species. Ranching and aquaculture are increasingly being looked to, globally, as a means of increasing production. With wild catches down and the growing threat of unemployment among fishing communities, artificial reefs are being seen by fisheries managers and fishermen as one of a number of potential production enhance-

ment tools. While Japan has long invested in the commercial potential of artificial reefs, their lead is now being followed by other countries with pressure for the placement of artificial reefs for commercial purposes, whether ranching or enhancement.

Because of its importance in determining the harvest levels from such enterprises, design also becomes a critical factor in the socio-economic determination of the viability of deployment, particularly where the projects are species specific. This is true whether considering reef investment from the perspective of a private commercial organisation (i.e. financial appraisal) or from that of society as a whole (i.e. cost-benefit analysis), as part of the development permission process. Reef design, given its effect on species composition and grazing pressure, is also likely to have a bearing on the outcome of environmental impact assessments (EIAs). These are already required in some form in many countries and full environmental impact assessments are mandatory for certain marine construction projects under such as the European Community's Directive on Environmental Assessments (EEC 85/337).

The determination of optimal design parameters for certain species needs to be one of the key research agendas over the next few years. It will not, however, be the only agenda. While the emphasis of this paper lies with the attraction versus production debate and design issues, it is necessary to emphasise that there are other issues to be addressed if the potential of artificial reefs is to be optimised. For example, the environmental integrity of the materials used in artificial reef construction needs to be more clearly addressed (Pickering, 1996a), along with the management of the structures once in place. The question of ownership and management is likely, over the next few years, to overshadow the current scientific debate of 'production versus attraction'. The reason for this is that, even where a reef can be shown unambiguously to enhance productivity and increase the carrying capacity of the environment, much of the economic benefit generated by a reef-based fishery may nonetheless be lost if exploitative effort is allowed to expand freely in pursuit of the profitable opportunities which are opened up. To use the terminology of economics, the 'resource rent' becomes dissipated (Whitmarsh, 1993, 1996). It is because of the propensity for marine artificial struc-

tures (artificial reefs or fish attracting devices) to increase fishing mortality, and hence reduce the economic returns, that a number of writers (Polovina, 1990a, Waltemath and Schirm, 1995, Fabi, 1996) argue that the deployment of such structures needs to be viewed within an overall management plan. Formulating such a plan may not be straightforward. In theory the loss of economic benefit may be minimised or prevented by the establishment of enforceable property rights to the reef, but the legislative and policy adjustments needed to bring this about may prove a formidable challenge (Pickering, 1996b): one to be explored in subsequent papers.

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