Artificial Habitats for Fisheries Enhancement in the Australian Region

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Introduction

Interest in the construction of artificial reefs in Australia was initially stimulated by the work of Randall (1963) in the Virgin Islands and Carlisle et al. (1964) and later Turner et al. (1969) in California, as well as the early reviews of American and worldwide developments in this field by Stroud and Jenkins (1961), Stroud and Massmann (1966), Unger (1966), and Oren (1968). This interest resulted in the construction, using waste concrete pipes, of Australia's first documented artificial reef in Victoria during the mid-1960's (Anonymous, 1965).

Artificial reef developments in Australia were summarized by Sanders (1974) and Pollard (1976). Although the bibliography on artificial reefs produced by Steimle and Stone (1973) contained only six references to Australian studies, a bibliography listing 137 publications on Australian artificial reefs and fish aggregation devices was published by Pollard and Matthews (1985). Other accounts of Australian developments in this field include a brief review by Pollard (1979) and articles in fishing and conservation magazines by Bowerman (1982), Starling (1983), Deacon (1984), and Hodgson (1986).

This paper outlines in more detail the history and development over about 20 years of projects involving artificial reefs and fish aggregation devices in the Australian region (Fig. 1) and provides information on other artificial fisheries habitat developments in this area.

Multicomponent Reefs

Following the early work on multicomponent reefs carried out in California in the middle to late 1960's (Carlisle et al., 1964; Turner et al., 1969), studies were begun in several Australian states using reefs constructed of similar waste materials.

ABSTRACT—This paper outlines developments over about 20 years in the construction of and ecological research on artificial reefs, fish aggregation devices (FAD's), and other artificial habitats designed to enhance fish populations and fisheries in the Australian region (including New Zealand and Papua New Guinea). Work was initially carried out on multicomponent reefs using a variety of waste materials, as well as some specially constructed concrete and steel structures. Later studies concentrated on single-component reefs, again mainly using waste materials. Although no definitive conclusions were reached on the relative effectiveness of the different materials used, waste motor vehicle tires and derelict ships were generally judged to be the best all-around materials for single-component reef construction in sheltered estuarine and offshore marine environments, respectively, in this region. FAD's comprising polyvinyl chloride pipe spar buoys (or in some areas polyurethane foam floats) attached to railroad car wheel anchors by polyethylene rope and chain, and supporting attractor drapes of synthetic mesh webbing, also proved to be generally successful in this area. Overall conclusions for the Australian region include the predominant use of waste materials in artificial reef construction, which has been primarily aimed at recreational fisheries enhancement; the successful use of FAD's for both recreational and commercial fisheries enhancement; the need for further and better planned research into and monitoring of the effectiveness of both of these enhancement methods; and the need for future research into the effectiveness of unfished "artificial habitat reserves" in enhancing fisheries production from surrounding fished areas.

Victoria

The first documented artificial reef in Australian waters was constructed in October 1965 by the Victorian Department of Fisheries and Wildlife in Port Phillip Bay, near Melbourne. This reef, which was laid in about 20 m of water 8 km off Carrum on the bay's eastern shore, initially comprised around 330 waste concrete pipes, each up to 2.5 m in length and 1.8 m in diameter, weighing in total about 400 metric tons (t). These pipes were barged to the site and sunk on a fine silt bottom over an area of about 4 ha (Anonymous, 1965; Sanders, 1974). Although this reef initially provided good fishing for Australian snapper, *Chrysophrys auratus*, a highly sought recreational species in this area, the concrete pipes gradually sank into the soft substrate and had been scattered over too wide an area to provide a very effective long-term fishing reef. A ferrocement cabin cruiser and a 52 m timber hulk containing about 40 t of concrete ballast were added to this artificial reef in 1967 and 1971, respectively (Sanders, 1974; Beinssen, 1976).

Three multicomponent reefs, each consisting of 100 m^3 of quarry rock, three 1.5 m^3 steel-reinforced open concrete cubes, four 3 m^3 open steel frames, and about 1,000 motor vehicle tires tied in bundles of 8 tires each, were placed on sandy substrates in about 10 m of water in Port Phillip Bay in 1973. These were laid off Mordialloc (near Carrum), Dromana (to the south) and Werribee (to the west), in conjunction with the laying of an ethane pipeline across the bay by Esso-

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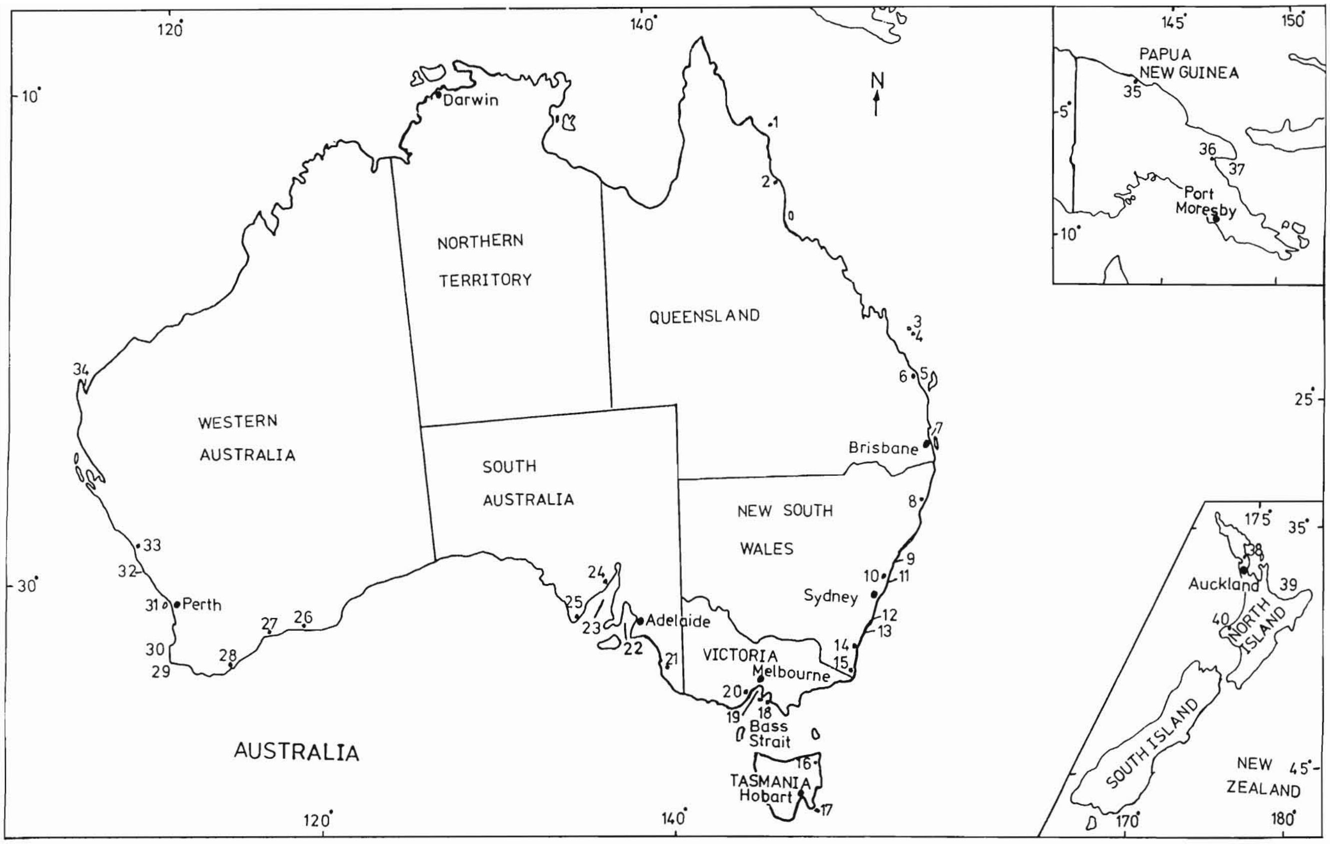

Figure 1.—The main localities in Australia, New Zealand, and Papua New Guinea mentioned in the text. Capital cities (large dots) are named, coastal towns (small dots) are numbered on the landward sides, and other coastal features on the seaward sides of coastlines. Key: 1 = Lizard Island, 2 = Cairns, 3 = Heron Island, 4 = One Tree Island, 5 = Hervey Bay, 6 = Bundaberg, 7 = Moreton Bay, 8 = Coffs Harbour, 9 = Port Stephens, 10 = Newcastle, 11 = Lake Macquarie, 12 = Jervis Bay, 13 = Batemans Bay, 14 = Narooma, 15 = Eden, 16 = St. Helens, 17 = Tasman Island, 18 = Phillip Island, 19 = Port Phillip Bay, 20 = Geelong, 21 = Kingston, 22 = Gulf St. Vincent, 23 = Spencer Gulf, 24 = Whyalla, 25 = Port Lincoln, 26 = Esperance, 27 = Hopetown, 28 = Albany, 29 = Cape Leeuwin, 30 = Cape Naturaliste, 31 = Rottnest Island, 32 = Cliff Head, 33 = Geraldton, 34 = Exmonth Gulf, 35 = Weewak, 36 = Lae, 37 = Huon Gulf, 38 = Leigh, 39 = Bay of Plenty, and 40 = New Plymouth.

BHP Australia[1] (Winstanley, 1972; Sanders, 1974). Diving observations on these reefs showed all of the components except the tires to have been densely settled by mussels, *Mytilus edulis*, within 6 months of their being laid. After 2 years most of the mussels had died off, except those on the steel frames, and the sessile fauna and flora of the remaining reef components were dominated by red algae, sponges, ascidians, and hydroids (Beinssen, 1976).

Like the Carrum reef, these latter reefs supported good populations of Australian snapper (Sparidae), and also ling (Ophidiidae), boarfish (Pentacerotidae), red mullet (Mullidae), beardie and bearded rock cod (Moridae), leatherjacket (Monacanthidae), long-finned sea pike (Dinolestidae) and garfish (Hemirhamphidae), as well as a number of smaller nonangling species. Most of the fish observed on these multicomponent reefs were associated with the tires, which were concluded to "offer by far the most shelter" (Beinssen, 1976).

Locations of these and other Victorian artificial reefs are given by Winstanley (1979), who also commented that, although the concrete pipes, quarry rock, and tires appeared to support the greatest variety and number of fishes sought by anglers, "Development of artificial reefs in Victorian waters has occurred on an ad hoc basis rather than as a planned program, consequently although some observations of established reefs have been made by the Fisheries and Wildlife Division there have not been sufficient resources for systematic monitoring of reef colonisation or for comparison of the effectiveness of different types of materials."

Queensland

Another of the early multicomponent reefs to be constructed in Australian waters, initially consisting of about 50

[1]Mention of trade names of commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

motor vehicle bodies, 1,800 tires, 80 t of concrete rubble and three concrete "fish houses," was laid in 18 m of water off Woody Island in Hervey Bay, southern Queensland, in 1968 by a consortium of local skindiving, angling, boating, and conservation interests. By mid-1973 this reef had been expanded to include some 220 motor vehicle bodies, around 10,000 tires, several derelict wooden and steel barges (between about 25 and 55 m in length), around 400 t of concrete rubble, and 12 concrete "fish houses" (Davie, 1971; Anonymous, 1971, 1973; Pollard, 1976). By 1974 this reef covered an area of some 32 h, and has since been expanded.

After about 5 years, the oldest parts of the Hervey Bay reef were covered with thick growths of soft corals, gorgonians, and sponges, and supported over 70 species of fishes, including many of recreational fishing importance, compared with only 15 fish species observed during preconstruction underwater surveys in this area (Thompson, 1973). Soon after its establishment, a ban on spearfishing on this reef was imposed, though angling pressure on it has apparently remained high. A tentative estimate of this angling pressure for 1973 was ~200 angler hours per week, resulting in an average catch rate of ~0.5 fish per angler hour. The main target species were Australian snapper, tusk fish (Labridae), and sweetlip (Lethrinidae) (Sanders, 1974).

A reef constructed of similar materials, but including a quantity of large (1.5 × 3.5 m and 1.5 × 6.7 m) metal pipes and a number of derelict steel vessels ranging from 20 to 45 m in length, was started in Moreton Bay (just to the north of Brisbane in southern Queensland) in 1968, and added to over subsequent years. At the most recent report this reef comprised some 11 vessels, one tram car, 60 car bodies, 500 tires, 36 steel pontoons, and 7 t of concrete pipes (Underwater Research Group of Queensland, 1985). This reef is located off Cowan Cowan, on the northwestern shore of Moreton Island, on a sandy bottom in around 20 m of water, and was initiated by the Underwater Research Group of Queensland with the assistance (as a training exercise) of a local Citizens Military Forces Water Transport Squadron (Anonymous, 1971; Davie, 1971). A similar assemblage of fish species to that found on the Hervey Bay reef was observed during diving surveys carried out by the Queensland Littoral Society soon after its construction, with approximately 80 species having been observed there by the end of 1970. Conspicuous amonst the fish fauna at the Moreton Bay reef, which is also closed to spearfishing, were very large specimens of estuary cod, *Epinephelus malabaricus*, and giant Queensland grouper, *E. lanceolatus*, observed in 1975 around several of the sunken vessels (personal observation).

Following an advertisement by the Queensland Government Tourist Bureau encouraging visiting anglers to fish the Hervey Bay Reef, the umbrella group (the Maryborough and Hervey Bay Artificial Reef Committee, which included both local angling and skindiving groups) which had initiated the construction of this reef and instigated its closure to spearfishing, also advocated its closure (at least temporarily) to angling. The rationale given was the importance of this reef as a "seeding area" for surrounding waters, and thus its value in "building up the fish population in Hervey Bay" (McDonald, 1973a). Similar comments were subsequently made in relation to the Moreton Bay reef, such that, although "the reef was built to see if fish could be brought back into Moreton Bay . . . the new fish population faced the danger of being fished out before being firmly established" (McDonald, 1973b).

Based on observations of these two Queensland multicomponent reefs, the Queensland Littoral Society concluded that: "Outstanding success had been achieved with rubber tyres bound into lots of five as reef material. Motor car bodies are also successful, despite their short life" (of about 5 years) (Anonymous, 1971).

A further multicomponent reef, comprising a number of derelict launches, many bundles of tires, and a variety of other waste materials, was also constructed in southern Queensland (in Southport Broadwater, just to the south of Moreton Bay) by the Gold Coast Underwater Club in 1972 (Sanders, 1974; Smith, 1976). This reef was also closed to spearfishing, though it apparently provided good angling, and a number of large estuary cod (Serranidae) were observed on it in 1975 (personal observation). Another small multicomponent reef was constructed in Moreton Bay (off Woodgate) using waste bricks, concrete pipes, and old machinery in 1978 (Starling, 1983), but no information on this reef's subsequent effectiveness is available.

South Australia

An unknown number of motor vehicle bodies was placed off Port Broughton in upper Spencer Gulf, South Australia (S.A.), by local angling interests in the late 1960's. However these, in contrast to those placed in Hervey and Moreton Bays in Queensland, were still relatively intact after around 20 years' immersion[2]. No information is available on their effectiveness.

Concrete Module Reefs

The idea of using reefs constructed of small concrete modules for experimental ecological studies in Australia originated from the early work along these lines carried out by Randall (1963) in the Virgin Islands.

Queensland

Experimental work on fish recruitment patterns using reefs constructed of small concrete modules was carried out during 1971 in 3-5 m of water in the lagoon at One Tree Island (at the southern end of the Great Barrier Reef) by Russell et al. (1974). These authors compared two series each of eight reefs (one laid in summer and the other in winter) comprising solid and hollow concrete blocks of dimensions 160 × 60 × 60 cm. These reefs attracted large populations of small coral reef fishes, though no firm results emerged in relation to differences due to habitat structure (Talbot et al., 1978). Comparisons with similar small concrete module reefs in Florida (Bohnsack and Talbot, 1980) showed that reef fishes rapidly colonized such small experimental reefs in both areas, where they also supported similar total numbers of species and families, numbers of species per residence category, and mean numbers of individuals per reef, despite the fact that the Australian locality had approximately twice the

[2]K. Branden, S. A. Department of Fisheries, Adelaide. Personal commun.

species pool available for colonization. Similar concrete module reefs have been used more recently (during the early 1980's) to study predation of juvenile reef fish at Lizard Island on the northern part of the Great Barrier Reef[3].

Western Australia

Concrete shelters were used by the C.S.I.R.O. Division of Fisheries and Oceanography in studies of juvenile western rock lobsters, *Panulirus cygnus*, off Cliff Head, southwestern Western Australia (W.A.), in 1971-72 (Anonymous, 1970a). These shelters were placed in 4.5 m of water about 2 km offshore, but tagged rock lobsters placed on them had reportedly left the reefs by the time they were resurveyed about 1 month later (Chittleborough, 1973).

New South Wales

Although no studies have been carried out to date using small-scale concrete module reefs in New South Wales (N.S.W.) waters, small reefs consisting of pyramidal bundles of earthenware pipes have been used in experimental studies on fish recruitment in Sydney Harbour (Lincoln-Smith, 1978). These small experimental reefs supported larger numbers of "substratum-associated" fishes, in terms of both species present and their abundances, when compared to the flat areas of sea floor upon which the reefs were built. Non-substratum associated fishes were, however, more common in terms of both numbers of species and individuals present over such areas of flat bottom and also around nearby areas of natural reef.

The ecology of fish communities occupying both a natural rocky reef and a large-scale concrete module port revetment wall in Botany Bay, in the southern suburbs of Sydney, were studied by Burchmore et al. (1985) over a two year period between 1977 and 1979. Fish species present were censused bimonthly using a quantitative diver transect method at both sites, and spatial and temporal differences in fish community structure were analyzed. One hundred and two fish species from 50 families were observed, 93 at the natural reef site and 50 at the artificial reef site, with 49 species being common to both. Twenty-five of these species were of some recreational and/or commercial fishing importance, and although the natural reef site supported a larger number of fish species and a higher total abundance of fish, the artificial reef site attracted slightly larger abundances of fishes of economic importance (Burchmore et al., 1985). This result contrasted with the findings of Randall (1963), who found an order of magnitude higher biomass of fish on a concrete block artificial reef compared with a natural coral reef in the Virgin Islands.

Apart from the these small experimental concrete module reefs, and the small-scale use of concrete "fish houses' in some of the multicomponent reefs, no larger-scale specially built concrete "production" reefs have yet been constructed in Australia. Most of the effort has been concentrated on the use of waste materials for reef construction. Although the different multicomponent reefs described consisted of a variety of miscellaneous waste materials, the main single-component reefs have been constructed using waste motor vehicle tires and derelict ships.

Tire Reefs

The idea of using waste motor vehicle tires for artificial reef construction (first adopted in New South Wales in the late 1960's and in South Australia in the early 1970's), originated from an early booklet on this subject by Edmund (1967).

New South Wales

Australia's first documented tire reef was constructed in 1966 by the Newcastle Underwater Research Group using 250 car tires which were sunk, together with a single motor vehicle body, in 8 m of water in Lake Macquarie, a large estuarine coastal lagoon just south of Newcastle in central N.S.W. (Wharton, 1970). However, the car body and the wire used to bind the tires soon rusted away and the tyres were dispersed on the estuary floor. N.S.W. State Fisheries[4] became concerned about the possible future indiscriminate aquatic disposal of waste materials, sought to develop more soundly constructed artificial reefs, and in 1969 chose Lake Macquarie for the construction of several experimental tire reefs.

Four small reefs, each consisting of about 660 car tires, were laid in the northern half of this coastal lagoon in about 10 m of water between October 1969 and July 1970 (Anonymous, 1970b, c; Malcolm and Matthews, 1970). Three such reefs were laid on muddy sand bottoms in areas where the water proved to be too turbid for regular underwater observation, but the fourth, located on a clean sandy bottom near the lake's entrance channel to the sea, proved very suitable for diver observations of its fish fauna. This reef consisted of 22 unanchored triangular-profiled bundles, each of 30 tires (tied into cylinders of 10 and then into pyramidal bundles of 30 using polypropylene rope), placed in an open circle or horseshoe-shaped arrangement on the lake floor (Fig. 2). Fish censuses and observations of this reef's sessile flora and invertebrate fauna were subsequently carried out opportunistically over the following 8 years, with night censuses also being carried out over the last 3 years of the study (Fig. 3).

Studies on this reef included observations on the temporal development and succession of the invertebrate fauna and flora, long-term and seasonal changes in the composition and abundance of the fish community, diurnal changes in fish activity patterns and behaviour, and the residence status and location on and around the reef of various life history stages of the main fish species present.

Overall, 78 species of fishes belonging to 44 families and comprising a total of around 12,500 individuals were observed on the reef during 25 censuses carried out over the study period (Fig. 4). Following an initial 3 year period of primary colonization and "community development", during which a total of 31 fish species was observed at the reef (day censuses only), an additional 25 species were observed during the second, and another 22 species during the third 3-year period of the study (day and night censuses). During the latter two 3-year periods, a total of 72 species was observed by day (averaging 27

[3]G. Anderson, Macquarie University, Sydney. Personal commun.

[4]Now the Division of Fisheries, N.S.W. Agriculture and Fisheries.

species per census) and 50 by night (averaging 24 species per census). The main peaks in species numbers occurred in summer-autumn and the main troughs in winter-spring during the latter 6-year period.

The ten most "common" species on this reef (based on a multiple of their estimated total abundance and their frequency of occurrence) included three scorpidids, a monacanthid, an apogonid, a carangid, two plotosids, a dinolestid, and an enoplosid. The most heavily represented family was the Serranidae, followed by the Monacanthidae, Pomacentridae, Labridae, Carangidae, Scorpaenidae, Tetraodontidae, and Chaetodontidae. Although most of the species observed were of Peronian (south-central eastern Australian warm temperate, here including widespread) zoogeographic affinities, 20 species (mainly present during summer-autumn) were found to be of Solanderian (northeastern Australian tropical) affinities, and no Maugean (southeastern Australian cool temperate) species were observed. Among the 25 species present which were judged to be of economic value, the ten most abundant belonged to the families Carangidae (2 spp.), Dinolestidae (1 sp.), Monacanthidae (1 sp.), Kyphosidae (1 sp.), Sparidae (3 spp.), Gerreidae (1 sp.), and Cheilodactylidae (1 sp.). The succession of dominant sedentary invertebrate fauna on the reef comprised barnacles, mussels, and then sponges, in that order (Fig. 5). The tires and their attachment ropes were found to be in generally sound condition after 9 years' immersion (Pollard et al., 1987).

Similar small tire reefs were subsequently laid in a number of other locations in N.S.W. during the mid 1970's, including Batemans Bay (on the mid south coast), Port Stephens (on the mid north coast), and Port Hacking (just south of Sydney). Only the latter reef was monitored, and in this case, although the tire bundles used were constructed with a higher profile (each comprising 10 cylinders of 10 tires, attached with plastic packaging strap and polythene buckles), it was subsequently found that this site was too deep (about 25 m) and too far upstream in the estuary to provide effective habitat for a variety of estuarine fish (Fig. 6). Only 25 species were observed over the next 2 years[5].

Figure 2.—Tire reef units being laid in Lake Macquarie, 1970.

Figure 3.—Diver recording biological data on Lake Macquarie tire reef, 1975.

South Australia

Another study using tire reefs was carried out in Gulf St. Vincent near Adelaide by the S.A. Department of Fisheries in the early 1970's (Sanders, 1974). The first of these reefs was constructed on a sandy bottom in around 10 m of water about 4 km off Henley Beach (near Grange) in 1970, and consisted of about 15,000 tires which had been slit and tied with plastic packaging tape into cylindrical bundles of around 8-10 tires. Unfortunately, this reef, in which no anchoring was employed, was largely dispersed and buried during a one-in-thirty-year storm less

[5]D. Pollard and J. Matthews, N.S.W. Fisheries Research Institute, Cronulla. Unpubl. data.

Figure 4.—School of blackfish, *Girella tricuspidata*, around Lake Macquarie tire reef, 1975.

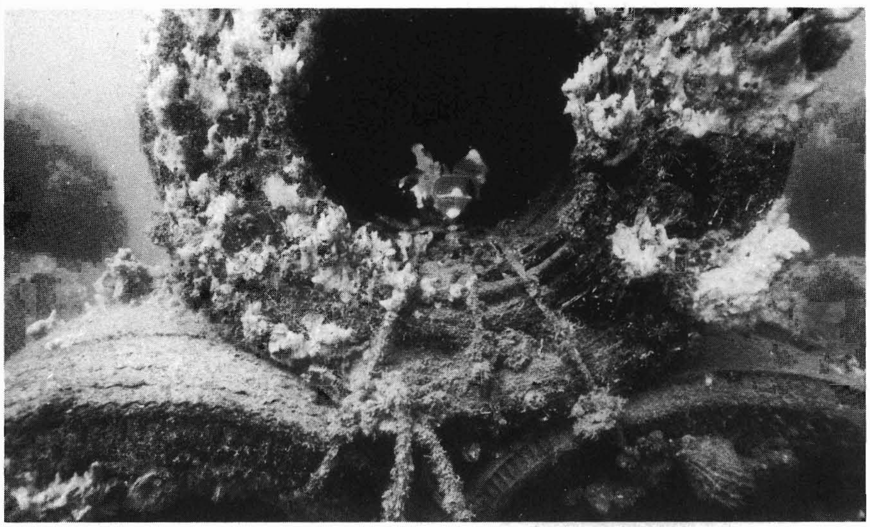

Figure 5.—Sponges and other encrusting organisms on Lake Macquarie tire reef, 1975.

than a year after being laid. A second reef comprising some 25,000 tires was subsequently laid, also near Adelaide, on a sandy substrate close to a natural calcareous reef in about 18 m of water about 5 km offshore from Glenelg in 1973. This reef was also partially dispersed over subsequent years by winter storms (Olsen et al., 1976).

In general, the dominant attached fauna and flora on the tires of both reefs comprised oysters and encrusting serpulid polychaete tubeworms, together with some ascidians and a variety of algae (the latter forming about 60 percent cover on the remaining tires of the Grange reef after about 3 years). Although 6 fish species were observed on the Grange reef about 6 months after it was laid and before it was dispersed by storm damage, only 3 species were observed on its remains during the following 3 years. About 17 fish species (including 5 or 6 of some economic importance), however, were observed on the Glenelg reef about 1 year after its construction, and 27 species after 4 years (Branden, 1976). This greater diversity of fish may have been due to this reef's location close to an area of natural reef. The latter artificial reef was also reported to be popular among sport fishermen, some of whom claimed to have taken good catches of King George whiting (Sillaginidae) and Australian snapper from it (Olsen et al., 1976).

Olsen et al. (1976) concluded from the above studies that: "Overall, the results from both reefs suggest that the provision of shelter by the tires is more important than the development of an attached community of organisms on them (which may be a source of food) in attracting fish to the artificial structure."

Following the placement of the first tire reef off Grange in 1970, several smaller tire reefs were laid by local fishing groups under the supervision of the S.A. Department of Fisheries at other South Australian locations near Whyalla (5,000 tires in 1971), Port Lincoln (2,000 tires in 1972), Kingston (700 tires in 1972), Port Vincent (1,400 tires, date unknown), and Robe (number of tires and date unknown) (Sanders, 1974; Olsen et al., 1976), though no information appears to be available on the subsequent effectiveness of these reefs. Another tire reef was laid in about 15 m of water near Whyalla in 1983, which comprised around 50 t of large earth-moving machinery tires (each weighing over 200 kg) together with about 10 t of waste concrete pipes (Daniels, 1984), though again no reports are available as to this reef's effectiveness.

The most recent tire reef program in South Australia, and so far Australia's largest in terms of both the numbers of tires laid and its cost, has been that carried out by the S.A. Department of Fisheries between 1984 and 1986. During this period around 7,000 "tetrahedron module units" were constructed, each comprising 28 ventilated tires secured by polyester tape and stainless steel crimp seals, with the nine basal tires being weighted with concrete. These tire reef units, each weighing around 250 kg, were placed at 7 sites of low fish abundance at depths of at least 15 m (to avoid storm surge damage) in both Spencer Gulf and Gulf St. Vincent. They were constructed using unemployment relief labor at a total estimated cost of $A1.2 million (Branden and Reimers, 1987).

By late 1987 almost 70 species of fishes had been recorded on these reefs, about half of which were spcies of some recreational and/or commercial fisheries value, including such highly sought angling species as Australian snapper and King George whiting. So far about 60 species of algae have been identified on the reefs, and algal succession is also being studied using removable tire-rubber panels placed on them at 2-month intervals[2].

Other Australian States

Apart from the use of tires in the multicomponent reefs described above in both Queensland and Victoria, a small reef comprising 80 tires was also constructed on a flat sandy bottom off Rottnest Island near Pearth in southwestern W.A. by the Underwater Explorers Club of W.A. in 1971, with the aim of providing home sites for rock lobsters (Sanders, 1974). Another reef of 2,000 tires was also placed in about 10 m of water off Portarlington in Port Phillip Bay near Geelong, Victoria, by the Barwongrove Skindivers Club in 1973 (Beinssen, 1976). No further information is available on the effectiveness of either of the latter two reefs, or of another small tire reef laid near Rous Light in Moreton Bay, Queensland, by a local trailer boat club in 1975 (Starling, 1983).

New Zealand

Russell (1971, 1975) constructed a small experimental tire reef near Leigh off the northeastern coast of New Zealand during the early 1970's and found it to support a very high fish biomass, equivalent to 10-14 times the standing stock of nearby natural rocky reefs. The bulk of this biomass was accounted for by a species of red mullet which "aggregated in large numbers around the reef"... but "fed mainly by grubbing about on the surrounding sand" (Russell, 1976). From this study, and the observations of other workers in California and Hawaii, Russell noted that such "peripheral-living" sand-dwelling species were often important components of artificial reef fish populations, and in consequence suggested that large numbers of small reefs (which would maximize the available ecotone areas) may prove to be more effective than smaller numbers of larger ones (Russell, 1976).

Figure 6.—Tire units being barged to Port Hacking artificial reef site, 1977.

Ship Reefs

Although sunken boats and barges had been used previously in several of the multicomponent reefs described above (e.g., in Port Phillip Bay in Victoria, and Moreton and Hervey Bays and Southport Broadwater in southern Queensland) during the late 1960's and early 1970's, the first large offshore reef consisting entirely of derelict ships was commenced in N.S.W. waters off Sydney in the mid 1970's (Pollard, 1976).

New South Wales

The first of the vessels, an 88 m Sydney Harbour ferry, was sunk on a flat sandy bottom in about 45 m of water about 3 km offshore from Narrabeen in the northern suburbs of Sydney in May 1976 (Anonymous, 1976). A 67 m linseed oil tanker was added to the reef site in December of that year, and about another 10 vessels ranging from 20 to 75 m in length were added between that time and the early 1980's (Fig. 7). By 1979, divers from N.S.W. State Fisheries had noted 25 species of fish on this reef, ranging from small baitfish such as yellowtail, *Trachurus novaezelandiae*, to 15 kg yellowtail kingfish, *Seriola lalandi*, and similar-sized mulloway, *Argyrosomus hololepidotus*. Recreational and commercial fishermen using lines and traps, respectively, reported good catches of the latter two species, plus Australian snapper, teraglin (Sciaenidae), and several other species, from this ship reef during the late 1970's (N.S.W. State Fisheries, 1979) (Fig. 8).

In addition to diving surveys of some of the ships comprising this reef, which lies in 45-55 m of water, and hence near the limit of convenience for scuba diving surveys of sufficient duration, the reef has also been surveyed using the small manned research submarine *Platypus* (Anonymous, 1982a), and also an unmanned robot submersible, the "TREC" (Tethered Remote Camera), equipped with color video cameras and a remotely controlled arm and claw (Anonymous, 1984).

Other Australian States

Apart from the various artificial reefs containing derelict vessels mentioned above and the many accidental shipwrecks scattered around the Australian coastline which have proved to be excellent fishing spots, a number of other vessels have been

Figure 7.—Sinking of the linseed oil tanker *Meggol* at the Narrabeen artificial reef site, 1976.

Figure 8.—Schools of trevally, *Pseudocaranx dentex*, and mulloway, *Argyrosomus hololepidotus*, and a solitary white ear, *Parma microlepis*, in the hold of the sunken ferry *Dee Why* at the Narrabeen artificial reef site, 1979.

sunk for this specific purpose in Australian waters. These include a 74 m bucket dredge sunk in ocean waters at 20 m depth off Phillip Island, Victoria, in 1976 (Winstanley, 1979); a 39 m Vietnamese refugee boat and a 35 m pontoon sunk in Darwin Harbour, Northern Territory, in 1982 (Starling, 1983); and two 43 m hopper barges sunk in about 20 m of water off Glenelg and Ardrossan in Gulf St. Vincent, South Australia, in 1984 (Branden, 1984). Little information is available on the success of these latter ship reefs, though at Glenelg, boarfish, leatherjackets, trevally (Carangidae), and a number of other smaller species of fishes were observed by divers about a month after sinking (Branden, 1984).

Fish Aggregation Devices

Initial experiments with surface and midwater fish aggregation devices (FAD's) in Australian waters were inspired by the early observational studies on fish attraction to floating structures by Gooding (1965) and Gooding and Magnuson (1967) in Hawaii, and subsequent experimental work on FAD's by Wickham et al. (1973) and Wickham and Russell (1974) in the Gulf of Mexico off Florida.

New South Wales

The first known experiments with FAD's in Australia were carried out by J. Matthews of N.S.W. State Fisheries and the author in 1978. Attempts were made at this time to place a tent-shaped attractor consisting of a polyvinyl chloride (PVC) pipe frame covered with white vinyl cloth beneath the buoy (a foam-filled Boeing 707 aircraft tire) which had been attached by chain to the hull of a sunken ferry to mark the position of the Narrabeen Ship Reef (see above) for the benefit of anglers and divers. Although this FAD (similar to that illustrated in Matthews, 1973) was of generally similar construction to those used by Wickham et al. (1973) in the Gulf of Mexico, it was rapidly broken up by the strong current which often prevails in this area.

As the marker buoy was also lost soon afterwards (again probably due to the strain on it from the current), a replacement spar buoy constructed of 20 cm diameter PVC pipe was attached to the ferry using wire cable in 1979. Another attractor, constructed of a stronger PVC pipe frame within which was stretched a rectangle of black plastic mesh, was attached in midwater beneath this buoy. This FAD was observed to attract schools of small scads (Carangidae) and other baitfish, as well as numbers of large yellowtail kingfish, before both it and the buoy to which it was attached were lost some months later, in this case apparently due to human interference.

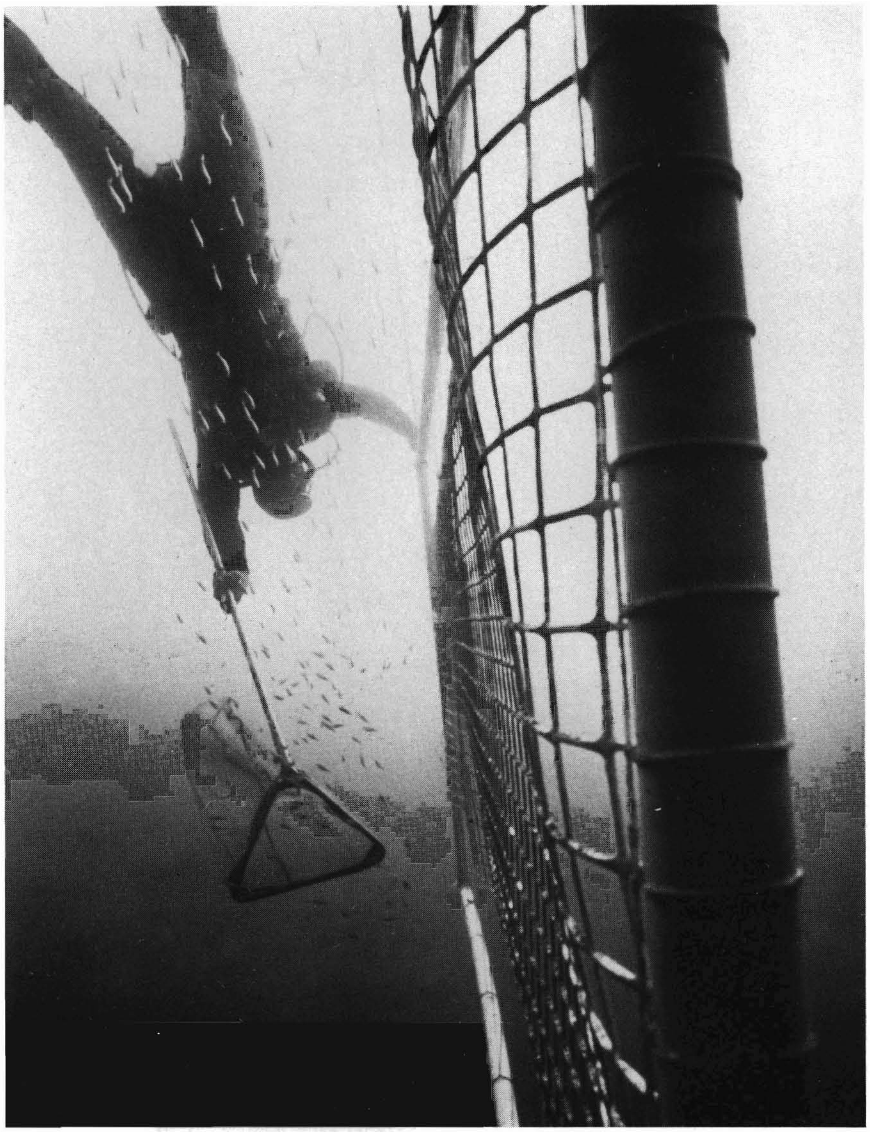

Figure 9.—Diver sampling baitfish schooling around midwater FAD attractor drape, 1980.

A further experimental FAD was constructed in 1980, comprising a 4 × 15 m rectangle of black plastic mesh suspended at 4 m depth below a buoy constructed of 2 × 200 liter foam-filled oil drums. This FAD was placed about 30 km offshore from Sydney in about 180 m of water (Anonymous, 1980) (Fig. 9). Three similar FAD's were subsequently placed off the southern N.S.W. coastline in the vicinity of Jervis Bay (1) and Eden (2) in 1981, with the aim of attracting commercial quantities of southern bluefin tuna (Scombridae). These FAD's consisted of 13 × 18 m polyethylene netting "flags" (or a 9 m long netting cone in the case of the Jervis Bay site) attached 10 m below similar buoys (i.e., 2 × 200 liter foam-filled oil drums attached end to end, and in this case surrounded by a collar of foam-filled PVC pipes to provide extra flotation). These buoys supported a conical battery compartment, a radar reflector, and a flashing amber light triggered by a photosensitive switch, and were attached to 500 kg concrete anchor blocks by 300 m of PVC-covered 6 mm galvanized wire and a short ground chain (Fig. 10). Unfortunately, all of these FAD's had disappeared within several months of their placement and before their fish attraction potential could be adequately assessed and monitored (Matthews and Butcher, 1983). Although no southern bluefin tuna were reported, anecdotal evidence from both recreational and commercial fishermen suggested that they were successful in attracting a number of other pelagic fish species, including scads and yellowtail kingfish.

Further experiments were carried out

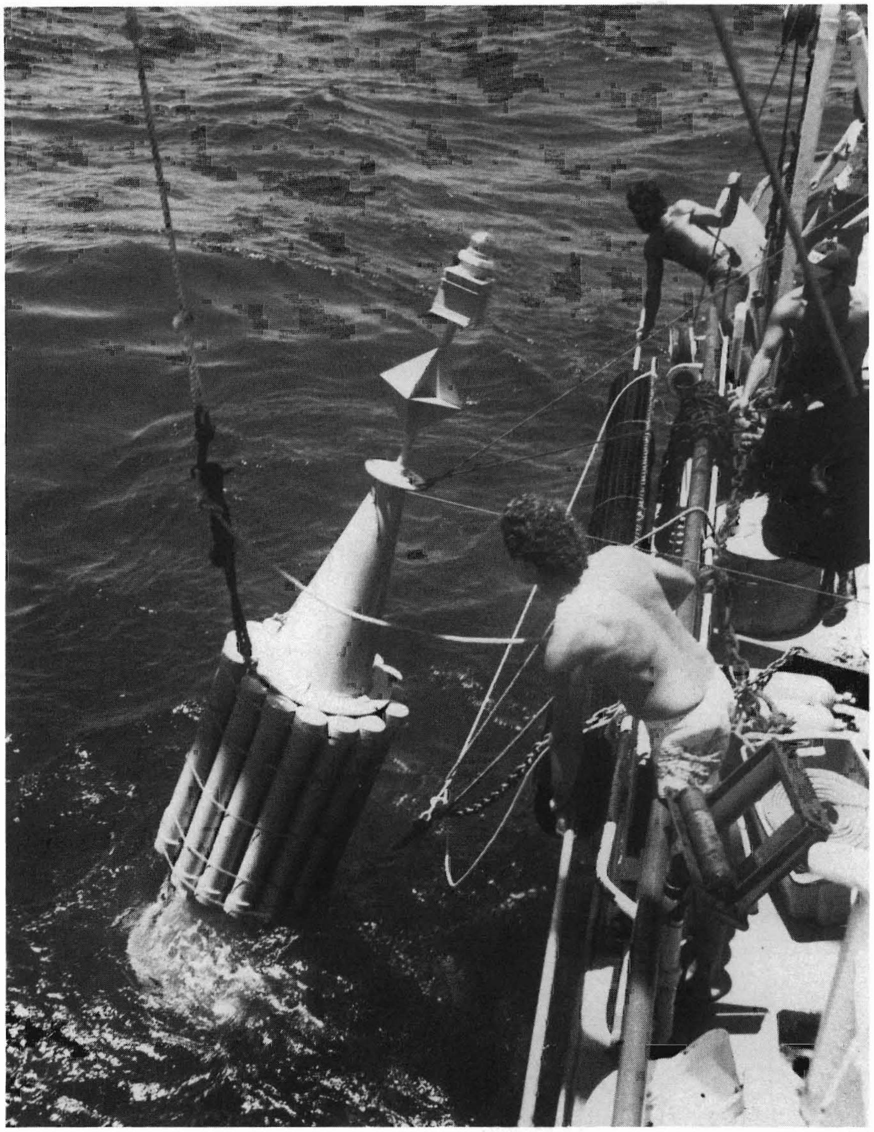

Figure 10.—FAD being deployed from FRV *Kapala*, 1979.

by J. Matthews in 1982 using buoys constructed of 3 × 200 liter foam-filled oil drums mounted side by side in a hardwood frame with a counterweight beneath. These buoys had the same radar reflection and lighting arrangement as the above, were attached to a 1,050 kg concrete anchor, and supported an attractor drape of plastic strapping woven into netting. These FAD's were placed off Sydney (3), Port Stephens (1), and Narooma (1), but again most of them were lost within about 3 months of placement. However, before their loss (which was again attributed to the strong current, heavy swell, and possibly also shipping in this offshore area), diving and trolling surveys on some of these FAD's showed good populations of small baitfish (mainly scads) and also such popular angling species as yellowtail kingfish and dolphin fish (Coryphaenidae). Amateur anglers also reported catches of these two species, as well as albacore, yellowfin and skipjack tunas (Scombridae), and sharks, and also sightings of marlin (Istiophoridae) around these FAD's before they were lost.

Developments in this FAD program since 1983 have involved a return to the use of current and swell-resistant spar buoys, since the 2 and 3 × 200 liter oil drum designs, which had reputedly proven successful overseas, had consistently failed in the strong current and high shipping activity areas where they had been deployed off the N.S.W. coastline. These spar buoys are constructed from 6 m lengths of 315 mm diameter heavy duty PVC pipe filled with polyurethane foam for floatation. Concrete (~70 kg) is poured into the bottom ends of the pipes for ballast, aluminium foil placed in the top ends for radar reflection, and end caps attached using PVC glue and 18 mm diameter steel center rods threaded at the top end and bent to form a ring at the bottom. The mooring assembly consists of a ~450 kg railroad car wheel as the anchor, 10 m of ground chain, ~1.2 times the water depth of 28 mm polyethylene rope, and 10 m of top chain attached to the buoy via a swivel. All connections are made using hammerlocks and hard eyes. The attractor drape, which comprises a 10 × 2 m section of 45 mm welded cross-strip plastic webbing, is attached to a light chain and thence to the mooring system at the selected depth[6].

Nine of these FAD's, several of which lasted for more than 6 months, were deployed off Sydney during 1983-84, and fish species attracted to them included a variety of small baitfish, yellowtail kingfish, rainbow runner (Carangidae), dolphin fish, yellowfin and skipjack tunas, and sharks (Matthews and Butcher, 1986) (Fig. 11).

The most recent FAD to be located in N.S.W. waters by the Fisheries Research Institute was placed in 75 m depth off Coffs Harbour, in the north of the state, during 1986. Although this FAD, which was of similar design to the above, was lost within 6 months of its placement, it was observed to attract large numbers of a variety of fish species, including yellowtail kingfish, rainbow runner and amberjack (Carangidae), cobia (Rachycentridae), dolphin fish, various species of sharks, leatherjackets, and small baitfishes. One notable catch by two members of a local sportfishing club at this

[6]J. Matthews, N.S.W. Fisheries Research Institute, Cronulla. Personal commun.

FAD "resulted in 158 dolphin fish being tagged and released in one session" (Anonymous, 1986).

Western Australia

A number of FAD's were placed at four locations off Esperance and Hopetown in southwestern W.A. in 1980-81 by the W.A. Department of Fisheries. The buoys for these comprised 3 × 200 liter foam-filled oil drums in steel frames supporting lights and radar reflectors, and were attached to 1,500 kg concrete anchors in 120-200 m depths using polypropylene rope and chain. Attractor drapes, which were hung from the buoys, comprised 15 m lengths of rope attached by wooden crossbeams and supporting rope-fiber bundles. Problems were experienced with buoys breaking up and dragging their anchors, but commercial fishermen made good catches of southern bluefin tuna around them by pole and line live-bait fishing, as well as catching some bigeye and skipjack tunas and sharks (Anonymous, 1981a, b). The estimated minimum contribution of these FAD's to the total tuna catch of this area in 1980-81 was 34 percent (Starling, 1983).

Although all of these FAD's eventually broke away, one lasted for 18 months. The buoys used were subsequently changed to fiberglass-coated high-density polyurethane blocks and the anchors to two railroad car wheels attached in tandem, and nine of these newer-design FAD's were placed off the south coast between Albany and Esperance during 1983. A further 10 were deployed off the south coast in 1984, in addition to one at Cape Leeuwin, one at Cape Naturaliste, and three off Exmouth Gulf. Unfortunately, "feedback from professional and amateur fishermen on the success of this programme has been disappointing" (Anonymous, 1987).

In addition to the above FAD's, which were placed primarily for the benefit of commercial tuna fishermen by the W.A. Department of Fisheries, amateur fishing groups in that state have also placed a number of FAD's off Rottnest Island, near Perth, since the early 1980's. Good catches of dolphin fish and tunas have since been made around these structures (Starling, 1983; Roennfeldt, 1984).

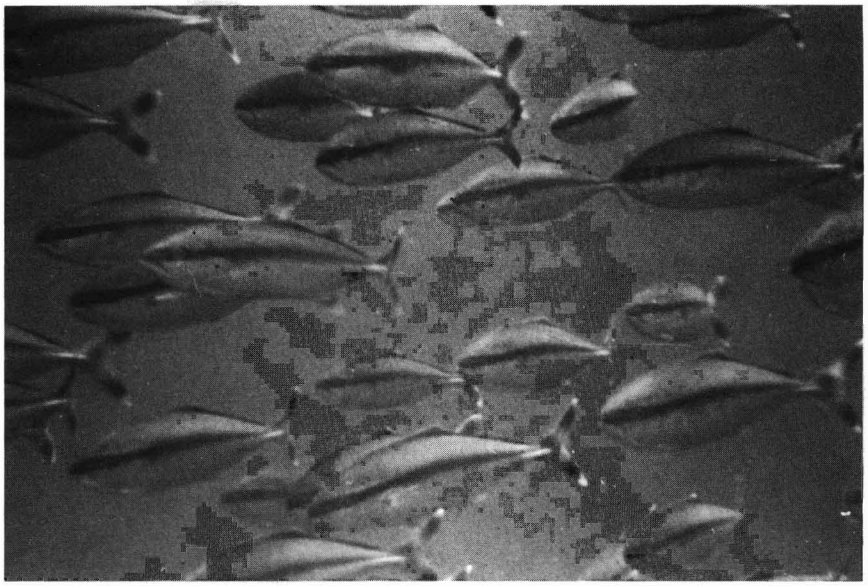

Figure 11.—Yellowtail kingfish, *Seriola lalandi*, schooling around a FAD off Sydney, 1983.

Queensland

Although a FAD was reportedly placed off Moreton Island in southern Queensland by amateur angling interests in 1981 (Orr, 1981; Bowerman, 1982), no information is available as to its success. However, during 1982 three further FAD's were placed off Bundaberg, further to the north, and these reportedly provided good fishing for yellowfin tuna and Spanish and school mackerels (Scombridae), black marlin and sailfish (Istiophoridae), and cobia (Rachycentridae) (Starling, 1983).

Two more FAD's were placed over a shallow seamount about 80 n.mi. off Cairns in the north of this state during 1982 to attract tuna for commercial handline and pole fishing in that area. The buoys used were of fiberglass-covered polystyrene supporting masts with radar reflectors and flashing lights, and under which were suspended drapes comprising 2 m lengths of plastic binding tape inserted into the lay of 20 m of "terryprop" rope (Anonymous, 1982b). No reports have been received on the effectiveness of these FAD's, or on a number of others placed in southern Queensland waters by local angling interests since that time (Steptoe, 1984).

Tasmania

A FAD of similar design to those used off Cairns was placed in ~150 m depth off Tasman Island in southeastern Tasmania in 1982 to attract southern bluefin and skipjack tunas (Anonymous, 1982c), although no report as to its success has yet been published. A further FAD was placed in 110 m depth off St. Helens in northeastern Tasmania in 1983, and although no details of its construction are available, good catches of albacore and skipjack tuna and sightings of southern bluefin tuna and marlin were subsequently made in the area (Wilson, 1983).

Other Australian States

A single experimental FAD, consisting of an inverted cone of netting about 5 m deep and suspended in midwater, was placed by the S.A. Department of Fisheries in 23 m depth off Onkaparinga Head in Gulf St. Vincent, just south of Adelaide, in 1982 (Gartside and Branden, 1983), but no reports of its effectiveness have appeared to date.

Although no FAD's have yet been constructed in Victorian waters, the Victorian Department of Fisheries has been monitoring fish populations around oil production platforms in Bass Strait (which provide excellent nonpurpose built fish attractors) in relation to the possible future development of FAD's, and also the possible eventual use of these platforms as artificial reefs, in this area.

New Zealand

The first FAD to be placed in New Zealand (N.Z.) waters was located off Mayor Island, in the Bay of Plenty to the south east of Auckland, in 1982, and consisted of "a lattice of aluminium tubes with a 20 metre length of net hung beneath it, the net being laced with streamers of blue plastic parcel strapping." Although this FAD was constructed by a commercial fishing company with the aim of aggregating small schools of skipjack tuna present in this area for purse-seining purposes (Anonymous, 1982d), no information as to its success has subsequently been reported. Other FAD's have since been deployed in N.Z. waters by sportfishing clubs, such as that located in the North Taranaki Bight near New Plymouth (Baty, 1988), though again no information on their success is available.

Papua New Guinea

The use of small-scale fish aggregation devices by artisanal fishermen in Papua New Guinea (P.N.G.) was reported on by Frusher (1986). In this study by the Fisheries Research and Surveys Branch of the P.N.G. Department of Primary Industry, two FAD's were deployed in 160 and 390 m of water along the northern coastline near Wewak in 1984. These consisted of two or three 200 liter foam-filled oil drums welded in an angle-iron frame and anchored by rope and chain to discarded engine blocks. No information was given on attractor drape materials or design. Although the shallower of the two FAD's "proved unsuccessful both in the amount of fish it aggregated and the consistency with which they were aggregated," the deeper (390 m) FAD "provided consistent troll catches averaging 12 kg/hr/vessel, with several catches exceeding 40 kg/hr/vessel." This deep-water FAD tripled the annual harvest of tunas by artisanal fishermen in the Wewak area. However, the fish caught around the FAD were significantly smaller than those normally caught in the artisanal fishery. Frusher (1986) also commented that, "while FAD's appear as a bonus to P.N.G. artisanal fishermen, their harvest of juvenile fish is of concern," and that "the harvesting of (juvenile) tunas at FAD's may remove a built in safety margin that prevents growth overfishing."

A similar low-cost, low-maintenance FAD was placed in 90 m of water in Huon Gulf, northeastern P.N.G., in 1982 (and replaced in 1983), also to assist artisanal fishermen. Dried coconut fronds were attached as the attractor drape and found to be effective in attracting a variety of small baitfish species, as well as whaler sharks (Carcharhinidae), dolphin fish and tunas. The 1983 replacement FAD lasted for 22 months, and although it reduced travelling time and fuel costs, the local village fishermen were apparently not motivated enough to maintain it by regularly replacing the coconut frond drapes (Quinn, 1987).

Portable Fish Attractor

Although not a FAD in the more traditional sense, a recent Australian development termed a "fish magnet" also warrants some mention in the general category of surface fish attraction devices. This portable fish attractor consists of an inverted truncated cone-shaped structure made of heavy-duty polyethylene plastic with panels of reflective material on its submerged surfaces. Inside is mounted a rechargable battery operating a small pump which sprays water from an adjustable hose nozzle mounted above water level. When launched from a boat and floating in the water, "wave action causes the 12 mirrored panels to flash sunlight deep underwater—simulating the flanks of surface fish—while water spraying from its angled nozzle spins the buoy causing random splashing on the surface." This action is claimed to "simulate the surface disturbance of a school of anxious baitfish," and thus attract such "hungry and curious fish" and "large predators" as marlin, kingfish, dolphin fish, and various species of tunas (Anson-Smith, 1987).

Artificial Habitats for Spawning and Recruitment

Although they may not fall under the strict definition of artificial reefs or FAD's, brief mention will also be made here of a variety of artificial structures that have been used in Australian waters for small-scale experimental and other scientific studies on juvenile fish and crustacean recruitment and fish spawning.

Artificial Aquatic Vegetation

"Artificial seaweed" collectors have been used to collect the puerulus larvae (i.e., the last pelagic stage) of the western rock lobster for commercial catch prediction purposes in Western Australia since 1969 (Phillips, 1972). These collectors comprise a triangular tent-shaped structure of gray PVC sheet mounted in an aluminium frame, to which is attached seagrass matting and numerous tassels of man-made "tanikalon" fibers. They are deployed (suspended at the surface) at various points along the coastline of southwestern W.A. where the puerulus larvae, which collect among the fibers, are sampled at regular intervals. By counting the puerulus larvae which have settled, a relatively reliable estimate of the abundance of recruits to the fishery 4 years later can be made (Phillips, 1987).

Bell et al. (1985, 1987) have used "artificial seagrass units" (ASU's) to study the recruitment of postlarval and juvenile fishes and crustaceans to estuaries in the vicinity of Sydney, N.S.W. These ASU's were constructed by attaching 550 bunches each of 10 plastic "leaves" (each leaf" being 280 mm long and containing small air bubbles for floatation) to 7 m^2 panels of galvanized steel mesh using monel metal staples, giving each unit an overall leaf density of 800 m^{-2}. Twenty-four such ASU's were submerged near natural *Zostera capricorni* seagrass beds for 6 weeks, and the fish and crustaceans inhabiting them were collected using fine surrounding nets and the ichthyocide rotenone. These faunal assemblages were then compared with those collected from comparable areas within the adajacent natural seagrass beds. The ASU's yielded fewer species, but there was no significant difference in the number of individuals present. However, relative abundances of species were generally similar in the two habitats, and it was concluded that the artificial seagrass attracts vagile macrofauna typical of real seagrass, with the difference in species numbers present probably being due to the lack of time available for the ASU's to accumulate the full suite of species present in the natural seagrass (Bell et al., 1985).

Later experiments were also carried out using similar ASU's to determine whether settling fishes discriminated between artificial seagrass with dense and sparse leaves. From these it was concluded that the relative abundances of juvenile fishes in isolated ASU's were not due to settlement preferences based on physical complexity of the seagrass habitat (Bell et al., 1987). Artificial seagrasses are also currently being used in ecological studies on the distribution and community dynamics of algae and invertebrates typically epiphytic on the seagrass *Amphibolus* in southwestern W.A. (Murdoch University, 1985).

Similar artificial macrophyte beds have also been used as "traps" in brackish and freshwater upper estuarine habitats during studies of juvenile Australian bass (Percichthyidae) recruitment in the Hawkesbury River system just to the north of Sydney. Although these units were successful in attracting a variety of small freshwater fishes, they were not judged to be very practical over longer time periods as they quickly became fouled by debris which was washed downstream[7].

Rock Shelters

Working in the freshwater riverine environment, Koehn (1987a) compared populations of river blackfish (Gadopsidae) in a stretch of the Ovens River, northeastern Victoria, which had been "seeded with large rocks," with populations in both an adjacent unmodified section and a section of the river containing willow debris. Numbers of blackfish were about nine times greater in the section containing the artificially placed rock habitat (and six times greater in that containing the willow debris) than in the adjacent unmodified section. Although Koehn noted that there appeared to be no previous documentation of the use of instream structures in attempts to enhance freshwater fish populations elsewhere in Australia, he concluded: "Overall the study highlights the importance of instream cover" . . . and "shows that the use of artificial habitat structures to increase cover can dramatically increase fish populations."

Although they may not strictly qualify as artificial reefs, small pieces of eroded coralline limestone rock ("D-units") were used in comparative studies of reef fish recruitment to live coral colonies ("L-units") of similar size off Heron Island (at the southern end of the Great Barrier Reef, Queensland) by Sale and Dybdahl (1975). Greater number of species and individuals were collected (each 4 months over 2 years) from the L-units than the D-units, and although 5 common species preferred the L-units over the latter, most species did not make this discrimination. These authors concluded that, with the exception of the above 5 species, ". . . the distribution of species among units is a result of chance colonisation, not of a systematic partitioning of the living space provided."

Artificial Habitats for Spawning

With regard to artificial habitats for fish spawning, different configurations of PVC pipes have been used experimentally to provide spawning cavities for river blackfish (Gadopsidae) in freshwater stream environments in Victoria (Koehn, 1987b), and for collecting the breeding adults, eggs and larvae of introduced oriental gobies (Gobiidae) in estuaries on the N.S.W. central coast[8].

Discussion

Having outlined in some detail the history and development of various artificial fish habitat projects in the Australian region over the past 20 years or so, it is considered appropriate here to summarize some of the main problems encountered and lessons learned and to discuss possible future developments.

The most suitable materials for artificial reef construction in this region appear to vary with both the area (e.g., latitudinally) and the habitat type (e.g., estuarine vs. open ocean). For instance, while motor vehicle bodies had a life expectancy of <5 years in the subtropical waters of southern Queensland (Anonymous, 1971), in cooler temperate areas, such as the South Australian gulfs, they were found to remain substantially intact for at least 20 years[2]. In enclosed waters (e.g., estuaries and sheltered bays) bundles of motor vehicle tires appeared to provide the most suitable shelter for fish when compared with a variety of other waste materials used in the construction of multicomponent reefs (e.g., Anonymous, 1971; Beinssen, 1976). However, without substantial attachment and anchoring, such tire reefs were rapidly broken up and dispersed in more exposed situations, e.g., the South Australian gulfs (Olsen et al., 1976). In N.S.W. at least, initial studies indicate that tire reefs in the lower, more marine dominated areas of estuaries (Pollard et al., 1987) appear to support higher diversities and densities of fishes than those located in more upper estuarine situations[5].

Some of the obvious advantages of using waste tires for reef construction include their ready availability (usually obtainable free and in large quantities), their bulk to weight ratio (and thus ease of handling and transport), their durability, and their nontoxic composition. They are also easily and cheaply attached to each other in a wide variety of configurations (e.g., using plastic packaging strap, or in more severe environments, polypropylene rope), and they provide a suitable substrate for a wide variety of sessile invertebrates and algae as well as a structurally complex habitat for fish (Beinssen, 1976; Pollard et al., 1987; and Branden[2]).

The most suitable material for reef construction in exposed or offshore areas appeared to be derelict vessels. These have proven very successful off the central coastline of N.S.W., where they are fished regularly, with good catches being taken by both recreational and commercial fishermen (N.S.W. State Fisheries, 1979). Derelict vessels have not been difficult to obtain in the vicinity of larger port cities (such as Sydney), and have usually been prepared (e.g., cleaned of oil and floatables) and transported free to the sinking site by the owners, who are eager to dispose of them cheaply. Care needs to be taken that they do not form a hazard to navigation, for which the reef-building authority could be held responsible. In

[7]J. Harris, N.S.W. Fisheries Research Institute, Cronulla. Personal commun.

[8]D. Pollard and R. Talbot, N.S.W. Fisheries Research Institute, Cronulla, Unpubl. data.

this regard, the Commonwealth Department of Transport requires 33 m depth of clear water above any vessel sunk in open ocean waters around Australia for this purpose.

Other materials which have been used successfully for reef construction in this region include large concrete pipes, quarry rock, and, in a few cases, specially constructed concrete "fish houses" and steel box frames (Beinssen, 1976). All of these materials, however, and especially when used in enclosed waters, need to be laid on very firm substrates to avoid their becoming buried. They should also be arranged on the bottom in relatively high-profile structures to be most effective in attracting and supporting significant populations of fish (Beinssen, 1976). Although specially constructed concrete "fish houses" (generally based on Japanese designs) have been used on a small scale in both subtropical and temperate areas (e.g., Davie, 1971; Beinssen, 1976), they have generally not proven to be superior to tire bundles of similar size, are more costly, and are more difficult to transport and handle.

It can thus be concluded that because of their generally low cost, ready availability, effectiveness, and relative ease of handling, waste materials, and particularly motor vehicle tires and derelict vessels, have proven to be the most popular reef building materials used in the Australian region. Although they may also prove successful, specially constructed concrete structures have been used mostly in small-scale experimental reefs constructed specifically for scientific research purposes (e.g., Russell et al., 1974).

The greatest successes to date with surface and mid-water fish aggregation devices have been achieved with either spar buoys constructed of foam-filled PVC pipe or very light and buoyant floats constructed of polyurethane foam. The former have proven to be the more suitable in high current flow areas, such as off the N.S.W. coastline (Matthews and Butcher, 1983), and the latter in other areas of lesser current flow (e.g., Anonymous, 1982b, c; Starling, 1983).

Surprisingly large anchors (up to about 1,000 kg) have been required in some areas, though railroad car wheels of around half that weight, which appear to be superior to concrete blocks, have been used successfully together with spar buoys off the N.S.W. coastline. Although both plastic-coated wire cable and chain have been used, the most successful attachment material between anchor and buoy has proven to be polyethylene rope (of either relatively short scope or weighted in places to prevent it from floating on the surface and becoming entangled in ships' propellors), together with top and bottom chains, swivels, and "hammerlock" connections.

The most successful attractor drapes appear to be "flags" of various types of synthetic mesh webbing or netting suspended within 20 m of the surface, although palm fronds suspended at or near the surface have proven both very convenient and effective in tropical areas (e.g., Quinn, 1987).

The most common groups of fishes attracted to FAD's in the Australian region, apart from a variety of pelagic bait fishes, have included various species of tunas (Scombridae) in all areas, and yellowtail kingfish (Carangidae), dolphin fish (Coryphaenidae), and various billfishes (Istiophoridae) in warm temperate to tropical waters.

In the area of portable fish attractors, the "fish magnet" (Anson-Smith, 1987) appears to show considerable promise in attracting surface-feeding fish, although its effectiveness has yet to be fully evaluated. It could also be further adapted to exploit a number of other forms of sensory stimulations of these fish, including for instance a "berley" (or "chum") slick, flashing underwater lights for night fishing, sonic attractors, etc.

Apart from the use of small concrete modules and similar artificial reef structures in experimental scientific studies (e.g., on fish recruitment), artificial vegetation (e.g., seagrass; Bell et al., 1985, 1987) also shows promise for this type of work, as do small-scale rock shelters (e.g., Sale and Dybdahl, 1975), and individual artificial spawning habitats (e.g., of PVC pipe; Koehn, 1987b), in both the inshore marine/estuarine and freshwater environments. Comparisons of natural vs. artificial reef habitats have also provided useful information on the functional ecology of these systems in the former environment (e.g., Burchmore et al., 1985).

In spite of the few relatively small-scale studies on fish recruitment and the natural-artificial reef comparisons mentioned above, and apart from the one relatively long-term ecological study of the fish assemblage inhabiting a tire reef in a N.S.W. estuary (Pollard et al., 1987), most evaluations on the effectiveness of artificial reefs and FAD's constructed in the Australian region have been based on rather haphazard observations. There is a need for more extensive and properly designed biological monitoring programs not only in Australia (e.g., Winstanley, 1979) but worldwide. As pointed out by Bohnsack and Sutherland (1985): "Due to inadequate long-term monitoring, critical knowledge about why artificial reefs work or do not work is lacking."

Some more general and summary observations based on the Australian developments described above include the following:

No large-scale "purpose built" structures (e.g., specially constructed concrete "fish houses," as used in Japan) have so far been used in production (as opposed to experimental) artificial reefs in Australia, where the emphasis has been primarily on the use of cheap and easily obtainable waste materials. Fortunately, there seem to have been few attempts to use artificial reef construction as an "excuse" for the disposal of unwanted waste materials in Australian coastal waters. Most of the production reefs constructed have been primarily for the benefit of recreational fishermen, though a number of FAD projects have been aimed at enhancing commercial (particularly tuna) fisheries.

Resources (particularly staff and funding) for artificial habitat research in the Australian region have been very restricted (compared with, even on a per capita basis, the United States and Japan). The trends in research interest up to the early 1980's were outlined by Pollard and Matthews (1985), with the majority of the publications on multi-component and tire reefs appearing around the early to mid 1970's, those on ship reefs in the late 1970's, and those on

FAD's in the early 1980's. Very little work, except for that on tire reefs in South Australia by Branden and Reimers (1987), has been carried out in Australia since that time.

At present there is no environmental "mitigation" legislation in force in Australia (e.g., along the lines of that presently applying in California: Duffy, 1985; Grant, 1987) which could provide a much-needed boost to artificial fisheries habitat construction and research here. The success of such programs in Australia to date, as in earlier times in the United States (Stone et al., 1987), has generally depended much more on the energy, enthusiasm, improvisation and initiative of those carrying them out than on specialised technical expertise and adequate funding.

In the future, with well planned and adequately funded research, it should be both technically and practically possible to design economical artificial reefs and FAD's which will be successful in attracting balanced assemblages of fishes, including harvestable populations of species of economic importance to both recreational and commercial fisheries, for use in different habitat types found around Australia.

One possibility for longer term fisheries conservation, which was discussed at the concluding session of the Fourth International Conference on Artificial Habitats for Fisheries in Miami in November 1987, is the creation of artificial habitats which might be maintained unfished. These "artificial habitat reserves" should provide protected nursery or "seeding" areas for fishes which, with increasing population numbers, would "spill over" into surrounding fished areas, thus enhancing the overall production of fisheries in the region. Before this could be successfully implemented, however, further research is needed to determine the extent to which different types of artificial habitats increase the overall biomass, rather than just concentrating populations, of economically useful species.

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