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POLLUTION OF CORAL REEFS

by

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Contents

1.	Coral Reefs and their Importance	Page 343
2.	Some Features of the Coral Reef Community that have Particular Relevance for Pollution Studies	344
3.	Pollution	345
4.	The Types of Pollution Affecting Coral Reef Communities and Control of each Type	346
4.1	Sedimentation	346
4.2	Dredging, filling and mining	347
4.3	Chemical pollution	348
4.4	Sewage pollution	349
4.5	Thermal pollution	350
4.6	Effluents from desalination plants	351
4.7	Oil pollution	351
4.8	Blasting and nuclear weapons testing in coralliferous areas	353
4.9	Collection of elements of reef biota	354
4.10	Population explosions of *Acanthaster planci*	356
4.11	Alien species	357
4.12	Tourism	357
5.	Detection of Pollution and the Need for Marine National Parks and Research Laboratories in Coralliferous Areas	358
5.1	Detection of pollution	358
5.2	Marine national parks	358
5.3	Research stations	358
6.	Destruction and Recovery of Coral Reef Communities	358
7.	Conclusions	361
8.	References	363

1. CORAL REEFS AND THEIR IMPORTANCE

Human activities have produced devastating effects on terrestrial ecosystems and it should come as no surprise that shallow-water marine ecosystems are now threatened. However, some of these marine ecosystems, such as coral reef ecosystems, are usually covered by several metres of water and hidden from the view of all but skin and scuba divers. Few reefs are under continuous observation by scientific personnel and little attention has been given to the impact of man on coral reefs. Hence, it is not generally realized that, during the last decade, a massive destruction of the hard coral cover of numerous reefs in the vast Indo-West Pacific region has occurred and that this destruction could be man-induced.

Coral reefs are rigid shallow-water structures formed from the calcareous skeletal remains of corals, coralline algae and other organisms. Usually, the remains are compacted to form reef limestone. The limestone carries a veneer of living organisms which constitute the coral reef community. Coral reefs are important for many reasons. They may be regarded as wilderness areas, places for natural adventure and recreation. Such areas become fewer each year on our crowded planet as human populations increase. As yet, their full potential as tourist attractions and recreational centres has not been realized. Few terrestrial areas can rival the beauty and interest provided by coral reef communities. Scuba and skin

diving, fishing, swimming, fossicking at low tide on reefs, examination and photography of the diverse fauna and flora of reefs, sailing and boating among reefs and exploring of islands situated on reefs are among the recreational activities that coral reefs have to offer.

Toxic products from terrestrial plants - e.g. morphine, atropine, curare, strychnine, digitalis, etc. - have for long been used in medicine and studies of the pharmacological activities and chemical structure of these products have enabled hundreds of new drugs to be synthesized. The clinical use of penicillin and other anti-microbial compounds derived from fungi has revolutionized the treatment of certain diseases. In recent years it has become apparent that a wide variety of toxic compounds including anti-microbial compounds is elaborated by marine organisms, especially those found on coral reefs (Endean, 1966). The possibility that new therapeutic drugs can be developed from some of these toxic products is currently being investigated.

Then again, coral reef communities are among the most biologically productive of all natural communities (Odum, 1971; Johannes, 1975). The potential of such communities to provide food has not been fully explored. Even the exploitation of obvious food sources such as fish and crustaceans has not been properly investigated. Because of the phenomenal increase in the world's human population that is now occurring, it is vital that optimal use should be made of all renewable food resources.

High grade lime for constructional activities, manufacturing, treatment of ores, and for agriculture, is present in enormous quantities on coral reefs. Some of this lime could be removed in some cases without appreciable damage to coral reef communities.

It is not generally appreciated that coral reefs possess a vast bacterial flora which together with benthic animals remove organic materials from sea [illegible]er. Accordingly, coral reefs act as gigantic filters helping to purify sea water (Sor[illegible] [illegible]ersonal communication). Moreover, as pointed out by Johannes (1975), coral reefs act as [illegible]iring breakwaters which give protection to thousands of kilometres of continental co[illegible]nd which permit the continued existence of hundreds of islands.

In view of the importance of coral reef ecosystems it behoves us to combat all major threats to these biocenoses. However, it is only recently, thanks to the pioneering work of R.E. Johannes, that the real nature of these threats has become apparent. We can but hope that the view of Voss (1973, p. 47) that "an unprejudiced observer might well be fearful that in the not-too-distant future our children may be able to learn about the coral reefs only from books and documentary films, for one of nature's unique habitats will have vanished from the face of the earth" proves to be unduly pessimistic and that by taking urgent action to counter current threats to coral reef communities we can ensure their continued existence.

2. SOME FEATURES OF THE CORAL REEF COMMUNITY THAT HAVE PARTICULAR RELEVANCE FOR POLLUTION STUDIES

Coral reef communities are famed for their biological complexity. They possess large numbers of plant and animal species. For example, approximately 100 species of coral and 700 species of fish have been recorded from the shallow waters of the reef flat at Heron Island, Great Barrier Reef (Jones and Endean, 1967). The species richness of such communities is generally attributed to a high incidence of coevolved relationships and complex interactions (Glynn, 1973; Ehrlich, 1975). These tend to evolve in tropical environments where steady and predictable physico-chemical conditions have persisted over long periods of time.

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Many species present are highly specialized (e.g. many of the coral associates described by Patton, 1976) and contribute to the uniqueness of the coral reef community. However, generalists are also well represented. Despite the structural complexity of the mature coral reef community, population sizes of individual species are essentially stable (Grassle, 1973; Ehrlich, 1975). This stability apparently stems from the operation of a multiplicity of homeostatic mechanisms that have been acquired during the evolutionary history of coral reef communities. These mechanisms depend on the existence of a great number of complex interactions in the species-rich community. Indeed, the coral reef communities of the Indo-West Pacific region are said to be biologically accommodated (Sanders, 1968) because biological interactions such as competition, predation, symbiosis, etc., play key rôles as determinants of community structure. By contrast, Eastern Pacific coral reef communities which are depauperate in species are said to be physically accommodated because physical factors such as extent of wave action play more important rôles than biological factors in determining community structure.

It should be appreciated that, although biologically accommodated coral reef communities have evolved mechanisms that resist change induced by normal events that have operated continuously or intermittently for millennia, they may not be buffered against perturbations induced by novel factors. Certain human activities may constitute such novel factors against which they have no defenses. As a result, catastrophic destruction of the communities may occ[illegible] course, localized destruction of corals and their associates as a result of the ope[illegible] normal physical and biological factors occurs regularly on all coral reefs and is app[illegible]sponsible for the spatial heterogeneity found on coral reefs (Endean, 1976). Occasionally [illegible]ruction of the biota caused by a natural agency such as a severe tropical storm is exte[illegible]e but, as pointed out by Endean (1976), it would appear that in the past catastrophic destruction of coral reef communities was a rare event and that these communities "in some areas at least, have had a long history of continuous development although the communities have moved laterally from time to time because of eustatic changes in sea level".

Although corals play basic rôles in the construction and maintenance of coral reefs thereby creating conditions favourable for the development of complex communities, other organisms also play important rôles in the structuring and maintenance of these communities. Some of these organisms may occupy key positions in food webs and their selective elimination could have profound effects on the entire coral reef community. Attention should therefore be given to the possibility that the deleterious effects of certain forms of pollution might be exerted more decisively on elements of the biota other than corals. Also, some organisms might be more sensitive indicators than corals of the existence of particular forms of pollution.

Many coral reefs are separated from other coral reefs by sizeable stretches of water. Indeed many coral reefs may be regarded as "oases in the oceanic desert" (Sorokin, 1973). Coral reef communities on each reef are essentially distinct entities although community structure may be similar for reefs in particular geographical areas. Gene flow among populations of most species on the different reefs is maintained by transport of sexual products and larvae by currents. In a few cases, species migrate from one reef to another.

3. POLLUTION

Pollution has many forms and may be defined in a number of ways. Most definitions make some reference to the potentially adverse effects of pollution on the environment for, if unchecked, pollution will produce environmental changes that are generally regarded as injurious to human welfare. Usually, attention is focussed on chemical pollution of air and water as pollution of this type, if excessive, produces deleterious effects that can readily be appreciated by laymen and politicians as a result of contamination of the air they breathe or the water they drink. Frequently, the adverse effects of pollution on organisms other than humans appears to be regarded as being principally of academic interest. Yet the most pressing of all environmental problems is the destruction that is occurring of natural eco-

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systems regarded by Ehrlich (1974) as the life-support systems of our planet. In the main, humans are responsible for the destruction of these natural ecosystems, and all forms of human activity that cause significant damage to these ecosystems can be regarded as pollution. These human activities certainly include the release of toxic chemicals into the environment but other forms of human activity may currently be having a greater effect on some ecosystems such as coral reef ecosystems.

Ecosystems are comprised of discrete communities and, as far as coral reef communities are concerned, pollution could be defined, with advantage, as the introduction into their environment of substances, organisms or human activities of various kinds that either render existing homeostatic mechanisms ineffective or so upset them that significant adverse change in community structure occur. Of course, there could be argument about the amount of change that must occur before it is considered significant. Also, there could be argument about whether particular changes in community structure are, in fact, adverse. However, in many cases, the damage resulting from pollution is obvious and unequivocal as when complete breakdown of community structure occurs. In such cases, the attendant reduction in faunistic diversity, the drab appearance of the reefs involved and the associated economic loss when reef fisheries or tourism are affected are regarded by most people as adverse changes.

4. THE TYPES OF POLLUTION AFFECTING CORAL REEF COMMUNITIES AND CONTROL OF EACH TYPE

4.1 Sedimentation

It is well known that coral colonies can be killed as a result of material such as mud or sand falling on them from above or as a result of an encroachment of accumulated sediment from below. Indeed most species of coral are unable to withstand burial under sediment for periods longer than one or two days (Mayer, 1918, 1918a; Edmondson, 1928). Large quantities of coral sand and rubble are sometimes deposited on living coral colonies during severe tropical storms resulting in large-scale mortalities of colonies so buried. For example, during a cyclone in March 1972 sections of the reef crest and adjacent areas on the northern side of Heron Island, Capricorn Group, Great Barrier Reef, were blanketed with coral sand which buried numerous coral colonies. Some of the buried colonies were uncovered 14 days subsequently and their flesh was found to be putrefying (R. Endean and P. Alderslade, unpublished). Under less extreme conditions than those associated with tropical storms sediment deposition and accumulation can still be responsible for substantial coral mortality. However, the threat posed by sediment varies with particle size and with the species of coral involved. It has been known since the work of Marshall and Orr (1931) that colonies belonging to species possessing large polyps are generally more successful at ridding themselves of sediments than colonies belonging to species that have small polyps. Recently, Hubbard and Pocock (1972) showed that differences in the extent to which sediment was rejected were related to distentional capacity of polyp and calyx geometry as well as to polyp size. Moreover, they showed that these differences were also related to particle size. In studies involving 6 size classes of sediment and 16 species of reef corals, they showed that silt, the smallest size class used, was the only size class removed by all species of coral.

Dramatic increases in the amount of sediment carried to coastal waters by rivers and streams have occurred in some coralliferous areas in recent years as a result of unplanned agriculture and deforestation leading to accelerated erosion of land surfaces. The possibility that increased sedimentation stemming from this cause would have an adverse effect on corals growing in the Low Isles region of the Great Barrier Reef was raised by Fairbridge and Teichert (1948). As pointed out by Johannes (1975) high islands and continental land areas fringed by coral reefs are frequently areas of high rainfall and lush vegetation and are particularly susceptible to erosion when the vegetation is removed in such areas. Apart from an increase in the sediment load carried from eroded land by streams, larger volumes of fresh water than usual may pass down the streams to the shoreline where coral

reefs occur. Marked fluctuations in salinity are inimical to the survival of corals (Endean, 1976).

Since 1945 the watershed about Kaneohe Bay, Oahu, Hawaiian Islands, has been subjected to increasing urbanization associated with an almost ten-fold increase in population size (Banner, 1974). As a result, there has been an increase in the freshwater run-off from the watershed during storms and there is evidence for a great increase in the amount of sediment carried into the bay annually, much of the sediment arising from newly bulldozed land. Although there has been a heavy mortality of corals in Kaneohe Bay since 1950, the actual extent that sedimentation has contributed to this mortality is unknown.

Deforestation associated with land development projects for agriculture, tourism and housing constructions has been carried out at an increasing rate over the past ten years on almost all parts of Okinawa (Nishihira and Yamazato, 1974). As a result, a heavy sedimentation of red clay particles is occurring on the shallow coral reefs in many areas and coral mortality has been extensive. Devastated areas of reef continue to expand.

With respect to mitigation of the deleterious effects of heavy sedimentation on coral reef communities, it is essential that new agricultural projects and other developmental projects involving extensive deforestation near shorelines in coralliferous areas should be carefully sited and planned so as to minimize erosion of land surfaces. Soil conservation techniques appropriate for the area concerned should be practised and attention should be given to restricting the sediment loads carried by streams and rivers discharging near coral reefs. Possibly, a system of dams and irrigation canals that would slow stream velocities and hence lessen the sediment load carried would be found useful in some instances.

4.2 Dredging, Filling and Mining

Coral reefs are considered by some to be renewable resources that should be mined systematically. However, direct mining of reef limestone poses hazards. Inevitably, a great deal of mechanical damage will be inflicted on the biota of reefs, and reef habitats will be altered as a result of the mining activities themselves. Lulofs (1973) has described how in Malaysia dislodged coral colonies are dragged across reefs before being winched aboard vessels. In some cases the amount of coral removed from reefs is substantial. It has been estimated for example that 60 000 m^3 of coral stones are removed annually from coral reefs in the Gulf of Mannar and Palk Bay, India (Mahadevan and Nayar, 1972) and Walker (1962) has commented on the over-exploitation of reef corals in Mauritius. Then too, the stirring up and translocation of sediment during the removal of reef limestone could result in extensive damage to an area of reef many times greater than the actual area of mining operations.

Mining in terrestrial locations can have adverse effects on adjacent coral reefs if spoil is introduced into the ambient sea water as has occurred at one sea-shore locality at Okinawa where ballast from a quarry is washed with sea water (Nishihira and Yamazato, 1974).

Spoil from dredging activities in the vicinity of Townsville Harbour, Queensland, Australia, released over several years into waters near Magnetic Island has caused destruction of many of the coral colonies that formed fringing reefs around the island (Brown, 1972; Endean, 1976). Tabular acropores were particularly susceptible to the rain of fine sediment produced when the spoil was dumped. It was noted that algae invaded many areas after destruction of part of the coral cover and precipitated further destruction by trapping sediment.

Dredging operations associated with reclamation works on the adjacent reef flats have been responsible for heavy coral mortality at various localities on both the eastern and western coasts of Okinawa (Nishihira and Yamazato, 1974). Destruction of coral reef communities caused by dredging has been observed at Johnston Island (Brock et al., 1966) in Singapore (Johnson, 1970), the Seychelles (Vine, 1972), American Samoa (Sverdloff, 1973) and at Guam (Marsh and Gordon, 1974).

A channel and swing basin which served as a harbour was excavated from the reef flat at Heron Island, Great Barrier Reef, in 1967. Bund walls were raised around the perimeter of the channel and swing basin to prevent excessive drainage of water from the reef flat at low tide (water is normally dammed on the reef flat by the reef crest at low tide). However, a series of cyclones in the early 1970s made breaches in the bund walls thereby causing an abnormal lowering of water level at low tide on the reef flat in the vicinity of the harbour. This, in turn, led to a large-scale mortality of the upper portions of coral colonies, particularly large Acropora colonies, near the harbour.

In view of the foregoing, it is apparent that dredging, filling and mining activities in coral reef waters should be undertaken with great caution only after a careful assessment of the likely effects, bearing in mind local conditions, of such activities on coral reef communities. Particular attention should be given to the possibility that such activities, especially those involving filling, could interfere with established drainage patterns in lagoons or within reef flats. Obviously, spoil from dredging activities should not be dumped on coral reefs or in situations where the spoil could readily be carried by surface currents or tidal flow to coral reefs.

In conjunction with feasibility studies normally undertaken in connexion with projected mining ventures, environmental impact studies involving biologists and engineers should be made. If properly handled, the dredging of unconsolidated coral sands at some localities could create fewer environmental problems than mining the consolidated reef limestone. Dredging could be carried out when tides and currents were such that sediments would be carried away from coral reef communities. The use of a modified suction head that could be buried in the sand (see Johannes, 1975) would restrict the amount of sediment stirred up. Sufficient amounts of coral sand could be left to maintain reef profiles and to ensure that an adequate stock of sand-dwelling species is available to colonize sand masses as they reformed. Careful monitoring of the effect of the dredging operations on the coral reef community should be carried out by trained biologists.

4.3 Chemical Pollution

As pointed out by Halstead (1972) shallow water tropical insular regions are particularly susceptible to chemical pollution. These are regions where coral reefs occur. However, the extent of chemical pollution in these regions has not been studied. Few data are available on the nature of chemical pollutants occurring in coral reef waters or on the effects of these pollutants on the biota of coral reefs.

There is a dearth of information on heavy metal pollution in coral reef areas. Levels of heavy metals in sediments and marine organisms have been determined in Pearl Harbour, Hawaii, by Evans et al. (1972) and the distribution of heavy metals in groupers from reefs in the Gulf of Mexico and in the Bahamas has been studied by Taylor and Bright (1973). The results of copper toxicity tests on a number of reef-associated marine organisms from south Florida have been discussed by Chesher (1975). It should be noted that copper is an important toxic contaminant of the effluent of desalination plants which are proliferating in coral reef areas. The effects of the release into marine water of effluent containing tailings from treatment plants at the large Bougainville copper ore plant on marine fishes is being monitored by environmental officers attached to Bougainville Copper (J. Powell, personal communication).

Mercurial compounds are used in agriculture in many tropical countries. In Queensland, mercurial compounds are used as fungicides and nematocides associated with the sugar cane industry. It would be of interest to examine the mercury content of the organisms growing on flats near the mouths of rivers and creeks draining from sugar cane growing areas.

It is well known that pollution of the world's oceans by man-made organic chemicals, particularly DDT, has occurred. DDT has been extensively used in coral reef areas where agriculture is carried out on a significant scale or where large human populations occur

(Chesher, 1969, 1969a; Randall, 1972). Other chlorinated hydrocarbons such as Dieldrin and Endrin which are more toxic for fishes and other marine organisms than DDT (Johnson, 1968) have been widely used in certain coral reef areas in recent years.

Few studies have been carried out on the effects (acute of chronic) of chlorinated hydrocarbons or other persistent pesticides on elements of the coral reef community. A reef coral, Acropora cervicornus, was found by McCloskey and Chesher (1971) to contain 3.12 ppb DDT, 260-320 ppt Dieldrin and 200-300 ppt DDT plus PCBs. The coral was able to concentrate rapidly experimentally introduced DDT, Dieldrin and Aroclor 1254. Johannes (1972, 1975) reported that barracuda obtained from reefs or the northern part of the Gulf of Mexico contained high levels of DDT and significant amounts of Dieldrin and Endrin. The coral-eating starfish Acanthaster planci collected from various localities contained from 0.04 to 3.89 ppm DDT and 0.01-1.04 ppm Dieldrin (McCloskey and Deubert, 1973).

Localized fish kills have occurred in the lagoon at Tahiti as a result of uncontrolled spraying of insecticides, especially Dieldrin (Randall, 1972). Indeed the introduction of pesticides into lagoons in large amounts could pose a health hazard. In 1970 fifteen to twenty tons of fish suddenly died in Truk lagoon and six people who ate some of them were hospitalized. The flesh of the fish contained the highest concentration of Endrin ever recorded in fishes to that date (Bourns, 1970). The potential hazard of lagoon contamination by spraying is exacerbated in some areas by the deliberate use of insecticides to kill fish. Hambeuchen (in Randall, 1972) has described how the inhabitants of Rarotonga in the Cook Islands use Lindane and Dieldrin to kill fishes in pools and lagoons.

Chronic effects elicited in members of the coral reef community by chemical pollutants have not been studied. It is possible that some species may be especially susceptible to these pollutants while others are particularly resistant. Selective elimination of some species could result in marked alterations in the reef community, particularly reef communities of the Indo-West Pacific region which are regarded as biologically accommodated. The selective elimination of specialized predators, for example, could profoundly affect community structure. The possible involvement of persistent pesticides in triggering recent crown-of-thorns starfish, Acanthaster planci, population explosions have been discussed by Pearson and Endean (1969), Fisher (1969) and Randall (1972).

Some of the detergents now being released in increasing quantities into waters bathing coral reefs may have adverse effects on corals or other elements of the reef community. Barnes (1973) has reported that a mild detergent (Palmolive) at concentrations as low as 0.05% was capable of killing healthy specimens of the coral Montastrea cavernosa in Jamaica.

It is apparent from this brief survey of chemical pollution in coralliferous areas that additional data are required on the extent to which coral reef communities are already contaminated with heavy metals, chlorinated hydrocarbons and other organic chemicals and of the long-term chronic effects of these pollutants on key elements in these communities. Obviously, steps should be taken to reduce the amounts of toxic compounds discharged into streams from industrial plants and in the run-off from agricultural lands in coralliferous areas. The effluents from mining ventures in these areas should be regularly monitored to detect the release of heavy metals or toxic compounds used in the treatment of ores. Detergents and cleaning compounds used domestically in these areas should be biodegradable. Obviously, the use of persistent pesticides such as Lindane and Dieldrin to kill fishes in lagoons should be officially discouraged.

4.4 Sewage Pollution

Increasing human populations and a tendency for concentration of these populations in villages and towns have, in recent years, led to problems connected with the disposal of increasing amounts of sewage. Indeed, coral reef communities in many parts of the Indo-West Pacific region are now being exposed to substantial amounts of sewage. In most cases, the long-term effects of such exposure can only be guessed at but the potential dangers involved

are well illustrated as a result of studies made at Kaneohe Bay, Hawaiian Islands (Banner and Bailey, 1970; Maragos, 1972: Smith et al., 1973; Banner, 1974; Johannes, 1975). Prior to 1950 Kaneohe Bay supported a flourishing coral reef community. After 1950 a heavy mortality of coral was observed and by 1970 corals had virtually disappeared from the southern part of the Bay which has an area of about 880 ha. The deaths of the corals were attributed, at least in part, to an increase in the amount of sewage entering the Bay. In 1970, it was estimated that the outfall from the two sewage systems discharging into the southern part of the Bay was about 3 million gallons per day. It was suggested that anaerobi conditions in the sediments resulting in hydrogen sulphide release may have been responsible (Maragos, 1972; Sorokin, 1973). However, increased freshwater runoff and increased siltatior stemming from urbanization of the Kaneohe Bay watershed may also have been involved.

Then again, phosphate levels near the major sewer outfall were observed to increase between 1966 and 1970 at an average annual rate of 0.75 µg atoms/litre (Caperon and Cattell, in Banner and Bailey, 1970). Eutrophication arising from increased levels of phosphate and other nutrients appears to have been responsible for changes in the plankton community and may also have caused changes among benthic organisms. In the summer of 1970 it was observed that corals in the central region of Kaneohe Bay were being blanketed by an algae, Dictyosphaeria cavernosa, which formed thick heavy sheets and it was noted that the accelerated growth of the algae had paralleled the increasing amounts of phosphate and nitrogen entering the bay in sewage (Banner and Bailey, 1970). The algae in some unknown way caused erosion of coral skeletons and disintegration of reef surfaces. Johannes (1975) noted that populations of reef fish were markedly reduced in affected areas.

It is considered that an apparent increase in algal growth on reefs in the vicinity of Waikiki Beach, Hawaii, may have been caused by eutrophication stemming from an increase in the volume of sewage to which the reefs are exposed (Johannes, 1975). No doubt coral reefs in other regions are currently being adversely affected by sewage pollution. Barnes (1973) has commented on the threat posed by sewage pollution to the Jamaican coral reefs as a result of the rapid development of the tourist industry in that country.

In some cases shore profiles, currents and winds may be such that sewage can be safely discharged into the ocean, but in most cases the sewage effluent will require extensive treatment in order to reduce any possibility of eutrophication occurring in shallow coastal regions. At the same time the question of the optimal siting of the openings of discharge pipes carrying industrial and domestic effluents is raised. To a large extent, local conditions will dictate the siting and detailed studies of these conditions may be required.

4.5 Thermal Pollution

As shown by Mayer (1918, 1918a), Mayor (1924) and Edmondson (1928), maximum ambient temperatures normally encountered by corals are only a few degrees below temperatures that are lethal for corals. Even at sub-lethal temperatures corals are adversely affected. Hence, thermal enrichment of the ambient sea water as a result of the release of large volumes of heated effluents from power stations and industrial plants poses a serious threat to shallow-water corals particularly if the heated effluent is discharged into shallow bays or partially land-locked regions with restricted water circulations. Johannes (1972, 1975) has drawn attention to the potential danger from heated effluents for tropical marine organisms generally. So far, few instances of mortality of marine organisms stemming from this cause have been recorded in the literature. A mass mortality of plants and animals extending 1.5 km from the outfall was caused by heated effluent from a power plant at Turkey point in Biscayne Bay, Florida (Roessler and Zieman, 1969). Corals were particularly susceptible, being killed at greater distances from the outfall than other species (Anonymous, 1970).

In the Indo-West Pacific region, destruction of corals in a 4 320 m^2 area of the reef margin at Guam by heated effluent from a power plant has been reported by Jones and Randall (1973). Damage to corals over a much greater area was observed and many species of fishes, echinoderms and crustaceans as well as benthic algae disappeared from affected areas.

In Hawaii, the reef at Kahe Point, Oahu, was surveyed before and after an increase in thermal discharge that accompanied expansion of the Kahe Power Plant (Jokiel and Coles, 1974). The power plant used 14 m^3 per sec of sea water for cooling purposes and the temperature of the sea water on discharge was approximately 5° to 6°C above intake temperature. Damage to corals from the heated effluent was most severe in late summer coinciding with annual ambient temperature maxima. Prolonged exposure to temperatures of 30° to 31°C caused corals to become pale (loss of zooxanthellar pigment) initially. Subsequently, the corals usually died. Most of the common species of coral encountered at Kahe Point were affected but Leptastrea purpurea showed some tolerance of the elevated temperatures involved, normal specimens of this species being occasionally found in areas from which all other corals had been eliminated by thermal stress. An increase in the quantity of heated effluent being discharged as a result of expansion of the power plant in 1972 led to an increase in the area of dead and damaged corals from 0.38 to 0.71 ha.

Because of the potentially adverse effects of heated effluents on elements of the coral reef community, careful attention should be given to the design of future power plants that are to operate in coralliferous areas with a view to reducing effluent temperatures. Also the siting of the opening of pipes discharging heated effluents should be such as to minimize damage to coral reef communities in the area.

4.6 Effluents from Desalination Plants

Johannes (1972, 1975) has discussed the threat to coral reef communities posed by effluents from desalination plants. Such effluents are characterized by elevated levels of salinity as well as temperature and heavy metals such as copper, zinc and nickel. Many species of corals are adversely affected by salinities only slightly above those normally encountered (Edmondson, 1928) and this factor alone warrants consideration when selecting sites for discharge of effluents from desalination plants. However, as pointed out by Johannes (1975, p. 32) "The effects of desalination effluents are greatly complicated by interactions between different stress factors. For example, zinc and copper can act synergistically on organisms, as can copper and elevated temperature".

Few studies have been made to determine the effects of effluents from desalination plants which are proliferating in coralliferous areas. Corals and other invertebrates have been killed to a distance of 200 m from the point of discharge of a power desalination plant near St. Thomas, Virgin Islands (Van Hepoel and Grigg, 1970). At Key West, Florida, desalination effluent appears to have caused marked changes in the population densities of many species in the discharge area (Clarke et al., 1970, 1970a; Chesher, 1975).

In view of the foregoing it would seem wise to attempt to reduce the toxicity of effluents from desalination plants operating in coralliferous areas. Again, careful attention should be given to the siting of discharge pipes in order to minimize damage to coral reef communities.

4.7 Oil Pollution

Because corals have been observed to flourish in some areas subject to chronic oil pollution (Spooner, 1970; Shinn, 1972) and because of a lack of reports in the literature of damage to coral reef communities stemming from oil spills (see Johannes, 1972) it has been generally assumed that corals are resistant to oil pollution. This belief was heightened as a result of experiments involving the floating of oil over submerged corals. In experiments carried out by Grant (1970) a layer of Moonie crude oil was floated on the surface of sea water in which specimens of Favia speciosa were immersed. The corals showed no visible

signs of injury over a six-day observation period. Five different types of oil were floated over groups of the corals Porites compressa, Montipora verrucosa and Fungia scutaria for 2.5 hours in unpublished experiments carried out by Johannes, Coles and Maragos (see Johannes et al., 1972). Again no visible signs of damage were observed during 25 days of subsequent observation.

Field studies appeared to support these laboratory studies. In experiments on Wistari Reef, Capricorn Group, Australia (Royal Commission, 1974, page 481) Grant sprayed oil on water flowing over corals during a falling tide for 1 hour and 5½ hours respectively. Corals with tips protruding secreted strands of mucus but otherwise no effects of the oil on the corals were observed. Haysom (Royal Commission, 1974, page 492) placed oil on the surface of tide pools on the edge of a reef flat. Submerged corals were undamaged. This result was in accord with the observations of Rützler and Sterrer (1970) who found that, although the inshore littoral fauna suffered heavily as a result of an oil spill in Panama, submerged corals offshore showed no signs of damage.

On the other hand, Lewis (1971) found that corals exposed in sealed containers to crude oil or an oil spill detergent were obviously affected adversely, displaying ruptured tissues and abnormal behaviour. His experiments were designed particularly to prevent the escape of volatile components of the oil. It is known that the most volatile components of crude oil are generally the most toxic (Blomer, 1971) and the first to evaporate (Royal Commission, 1974) so Lewis' results may not be indicative of what would occur during an actual oil spill.

Possibly of more significance for coral reef communities in the Indo-West Pacific area growing on reef flats which are frequently exposed to the atmosphere at low water spring tides are the experiments of Johannes et al. (1972) involving 22 species of corals. These authors found that floating oil can kill coral tissue if it adheres to corals exposed to air. Under these circumstances oil adhered strongly to branching corals such as species of Acropora and Pocillopora and was retained for weeks. On the other hand, oil did not adhere strongly to corals such as Fungia and Symphyllia which possessed large fleshy polyps and abundant mucus, and was soon removed when the corals were submerged.

Reimer (1975) exposed corals directly to undiluted crude oil for short periods before returning them to sea water. He observed a massive extrusion of symbiotic zooxanthellae followed by tissue death in some instances as well as an alteration in feeding behaviour. Growth rate was subsequently slowed. Experiments carried out by Birkeland et al. (1976) in Panama revealed that, although specimens of the coral Porites furcata were apparently unaffected the day after exposure to Bunker C oil for 2.5 hours, mean growth increments were significantly smaller than those of the controls during the following 61 days. However, an individual variation among colonies in susceptibility to oil pollution at low levels could be inferred from the results obtained. Fairy Bunker C oil was found to have a more damaging effect than volatile marine diesel oil on Porites furcata, Pocillopora damicornis, Pavona gigantea and Psammocora stellata. On the other hand, Bunker C oil seemed to promote the growth of algae.

Loya (1975) studied community structure and species diversity of hermatypic corals on two reef flats in the Gulf of Eilat, Red Sea, during 1969-73. One of the reef flats was chronically polluted by oil and minerals, the other was free from oil pollution and served as a control. In 1970 approximately 90% mortality of corals occurred in both reefs as a result of an extremely low tide. In 1973 there were few signs of recolonization in the chronically polluted reef but extensive recolonization and regeneration had occurred on the control reef. It was suggested that chronic oil spills prevent normal settlement and/or development of coral larvae. Birkeland et al. (1976) state that the effect of oil pollution on recruitment is of greater importance than the immediate mortality caused.

In view of these results it would seem wise to impose stringent controls designed to prevent oil leakage at oil transfer and oil storage facilities in coralliferous areas. Regulations should also be gazetted that would ensure that adequate precautions are taken to prevent release of oil from drilling rigs operating in these areas. In areas chronically polluted with oil where intermittent accidental discharge of oil from tanker loading facilities or shore-based industry is likely to continue, consideration might be given to the containment of oil by using floating barriers or booms. In any case the floating barriers should be available at strategically situated localities for use in the containment of oil spills. As suggested by Johannes (1975) consideration might be given to equipping and training mobile teams who can move quickly to deal with an oil spill anywhere in their area of operations. They could be trained in the use of oil absorbents or dispersants as well as in the containment of oil spills.

Many biologists would agree with Johannes (1975) that dispersants used in the past to control oil spills are sometimes more toxic than the oil on which they are used. Information is required about the effects of dispersants on the biota of coral reefs. As matters stand, it would appear preferable not to break up oil slicks over submerged coral reefs with dispersants. However, if winds, currents and tides are such that oil will be driven onto corals that are partially exposed to the atmosphere at low tide, then efforts should probably be made to break up the oil slick with absorbents or dispersants.

4.8 Blasting and Nuclear Weapons Testing in Coralliferous Areas

Explosives are often used to kill coral reef fishes in the West Pacific region (Konquillo, 1950; Fuchs, 1968; Chesher, 1969, 1969a; Owen, 1969; Ramas, 1969; Owens, 1971; Jones et al., 1972; Lulofs, 1973; R. Powell, unpublished). Sometimes the capture of fishes by this method is highly organized. Ramas (1969), for example, has described how blast fishermen in the Philippines surround sizeable coral formations with underwater lights to attract fishes. They also lure fishes into the selected areas by using baits consisting of pieces of fish and molluscan flesh. Periodic checks on fish numbers in each area are made and when numbers are deemed adequate, dynamite placed strategically throughout the area is exploded. Scuba divers are used to collect the fishes killed or stunned by the explosion but frequently only the larger fishes are retrieved. No information is available on the extent to which coral reefs have been damaged by commercial fishing involving explosives but at certain localities the damage inflicted may already have been extensive.

On Australia's Great Barrier Reef so-called "bangsticks" or "power-heads" - spears with .303 bullets or 12 gauge shotgun cartridges cradled at their tips in such a way that the charge is fired on impact - have been used extensively to kill reef sharks and large fishes such as groper (Promicrops lanceolatus).

Explosives are sometimes used to blast channels through reefs or to remove coral pinnacles that constitute navigational hazards. Thus, Johannes (1975) mentioned how surplus U.S. navy bombs were used to clear a channel through the reef at Kayangel Atoll, Palau, in 1973, and Endean (1976) reported on the use of blasting associated with dredging in the excavation of a harbour and swing basin at Heron Island in 1967. Coral damage was extensive at both localities. During World War II reefs around many islands in the West Pacific region were blasted with high explosives. According to Emery et al. (1954) such military bombardment may have caused the apparent "decadence" of reefs in the Marshall Islands noted by Stearns (1945).

Although, as pointed out by Johannes (1975), the extent of the destruction of habitat by explosives in coral reef communities has never been adequately evaluated, it would appear that extensive damage to habitat and reduction in numbers of site-attached fish could be caused by the repeated use of explosives. Hence, it would seem wise to enact legislation designed to prevent the use of explosives in the capture of reef fish. Likewise, the use of explosives to facilitate navigation in coralliferous areas should be restricted.

The types of anatomical damage apparent in fish killed by explosives has been summarized by Ronquillo (1950) and it should be possible to detect fish that have been captured in this way. Lulofs (1973) has commented on the possibility of reducing the extent of fishing by blasting in Malaysia by introducing legislation which, as well as prohibiting the sale of blasted fish, cancels the licences of those dealing in blasted fish. Perhaps attention should be given to the imposition of stringent controls on the sale of explosives.

In Queensland, Australia, legislation is about to be enacted which will ban the use of power-heads on spears by persons wearing scuba gear. Also, the use of power heads in association with spear guns will be banned. In effect, the use of power-heads will be lawful only if they are used on hand-held spears by persons not equipped with scuba gear.

Although the mechanical damage inflicted on coral reef communities as a result of blast when nuclear weapons are exploded in coralliferous areas is obviously extensive (Hines, 1962; Stoddart, 1968; Johannes, 1972), it is probable that, as pointed out by Johannes (1975) the associated radioactive contamination of food chains has a much greater significance for survival. According to Johannes (1975), a single nuclear blast may render fish and shellfish unsaleable for thousands of square kilometres. Unfortunately, little information is available on the ecological effects of radioactive contamination of the environment of coral reef communities but in view of the continued use of coral islands for the testing of nuclear weapons this aspect obviously requires urgent attention.

4.9 Collection of Elements of Reef Biota

The human activity that has probably had the most devastating and widespread effect on coral reef communities is the selective removal of elements of the fauna. Some species, particularly fishes, molluscs, crabs, turtles and worms, have been collected for food for centuries by the indigenous peoples inhabiting islands in coralliferous seas. Other species, especially molluscs, that produce materials that could be used as receptacles or as ornaments have also been collected by these peoples. It would appear that, in the main, removal of these coral reef species from any particular areas was on a restricted scale and well within the replacement capability of the coral reef community. However, in recent years the situation has changed. Commercial fisheries have been established in coralliferous areas. Most of the earlier fisheries involved the hand collecting by divers of elements of the fauna. The trepang or bêche-de-mer fishery involved the collection of various species of holothurians which, after treatment, provided stock for soups, stews and curries that were much favoured by some Asian peoples. The pearl shell and pearling industry involved initially the hand collection of species of Pinctada, some of which were found on coral reefs. The trochus shell, Trochus niloticus, was much sought after on coral reefs in the Indo-West Pacific before the large-scale introduction of plastic buttons caused a collapse of the market for trochus during the 1950s. Giant clams, particularly Tridacna maxima and T. derasa have for long been collected from reefs. Some Taiwanese clam fishermen still make journeys from Taiwan to reefs of the Great Barrier Reef and to reefs in the Coral Sea in order to collect giant clams. What effects, if any, the large-scale removal from reefs of holothurians, pearl shell, trochus and giant clams, all of which are microphagous, has had on the coral reef community is not known but warrants study.

In more recent times species which occupy key positions in food webs have been collected intensively. Thus, the introduction of self-contained underwater breathing apparatus, spear guns (some with explosive heads) and the advent of high-powered outboard motors for small craft have led to a spectacular increase in the numbers and variety of coral reef fishes captured for food in some areas. For example on some accessible reefs of the Great Barrier Reef, there is a dearth of sizeable fishes, particularly territorial fishes. Those fishes that are apparent are timid and flee readily from divers. According to Randall (1969) this behaviour pattern indicates that the fishes have been subject to spear fishing. In some cases, it is known that the reefs had been visited by so-called "spearoes" who move systematically over the reefs spearing as they move. Fish caught are filleted and the fillets are sold through commercial outlets as mixed fillets of reef fish. Sharks attracted by the spearing of fish are quickly despatched by the use of "power-heads" - spears carrying explosive devices.

One of the largest fishes found on reefs of the Great Barrier Reef is the groper, Promicrops lanceolatus. In 1974, 14 reefs in the central region of the Great Barrier Reef were searched for specimens of P. lanceolatus. A total of only 5 specimens, the largest estimated to weigh about 150 kg, were observed (Endean, 1976). The normal population density of P. lanceolatus on reefs is not known but on protected reefs, or reefs that are relatively inaccessible because of their distance from coastal towns, groper are commonly encountered.

Possibly, spearing parties have been responsible for the absence of large predatory fishes from reefs in the Western Indian Ocean visited by Bolunin and Frazier in 1973. Sharks (Carcharhinidae) and serranids (Serranidae) were frequently absent from the reefs yet in historic times these reefs were known to possess vast numbers of such fishes.

The implications for the coral reef community of the selective removal of large predatory fishes, particularly those occupying key positions in food webs can only be guessed at. The groper, Promicrops lanceolatus, will prey on juvenile specimens of the coral-eating crown-of-thorns starfish, Acanthaster planci (Endean and Stablum, 1975) and removal of groper by humans from certain reefs may have been a factor in triggering population explosions of the starfish.

When cleaner fish (Labroides sp.) are removed from reefs, dramatic changes in the distribution of other fishes occur (Limbaugh, 1961; Slobodkin and Fishelson, 1974). In recent years a flourishing trade in aquarium fishes from coral reefs has developed and in some areas reefs are rapidly being depleted of aquarium fishes. Cleaner fishes which remove parasites from other coral reef fishes are among the aquarium fishes eagerly sought after by enthusiasts.

Since World War II great interest has been shown in the collection of the shells of molluscs by dealers throughout the world. Because of the great variety of form and colour exhibited, shells from coral reef molluscs generally have been eagerly sought after by collectors and those of many species now command high prices. However, those of large coral reef gastropods such as balers (Melo species), giant helmets (Cassis cornuta), and giant tritons (Charonia tritonis) have been the prime target of collectors. Unfortunately, quantitative data on the extent to which these species have been collected throughout their range are not available. In Barrier Reef waters there has been an obvious reduction in the numbers of giant helmets. During the 1950s, specimens of Cassis cornuta were commonly encountered in sandy areas on reefs. The large burps that they made in the sand were obvious even to inexperienced collectors. During the 1960s, an apparent decline occurred in numbers of C. cornuta observed and in the 1970s this species appears to be a rarity in most sectors of the Great Barrier Reef. Likewise there appears to have been an obvious reduction in the number of Charonia tritonis seen on at least some reefs of the Great Barrier Reef since the 1950s. Endean (1973, 1976) has provided information which suggests that thousands of specimens of C. tritonis were collected during the 1950s by the crews of trochus luggers operating in Great Barrier Reef waters.

Again it is not known precisely what effects selective removal of large predatory gastropods such as balers, giant helmets and giant tritons would have on the structure of coral reef communities. However, the results could be far reaching. The giant helmets and giant tritons are specialist carnivores, the giant helmets preying on echinoids and the giant tritons preying on starfish and holothurians. It is known that the giant triton will prey on juvenile and adult specimens of the crown-of-thorns starfish, Acanthaster planci, and it has been proposed (Endean, 1969; Endean and Stablum, 1975) that removal of giant tritons from certain reefs by humans could have been a major factor in triggering population explosions of A. planci.

Likewise, Mann (1973) has proposed that population explosions of sea urchins which have occurred off the North American coast in recent years have been triggered by collection of their predators (sea otters and lobsters) by humans. It would seem wise to restrict or regulate in some way the activities of collectors of elements of the coral reef biota. In cases where the over-collecting of key species is involved, it will be necessary to prohibit the collecting and/or sale of these species. Thus, in Fiji and in Queensland, Australia, the collecting of giant tritons, Charonia tritonis, from coral reefs is completely banned. The collection of giant clams (Tridacna sp.) and the giant helmet, Cassis cornuta, is also banned in Queensland. In other cases it may be necessary to licence collectors so that their activities can be controlled. For example, in Queensland the collection of coral from reefs of the Great Barrier Reef is prohibited but a restricted number of licences are issued permitting the licensee to collect coral in specified areas.

Another approach is to prohibit the use of a particular technique in the collection of reef organisms. In Queensland legislation has just been introduced which will prohibit the spearing of fish by anyone wearing scuba gear. Also the use of power-heads in association with spear guns will be banned under this new legislation.

In order for any legislation of the type mentioned above to be effective it must be enforced. Desirably, public cooperation should also be sought by explaining the need for the legislation and giving the matter widespread publicity. Enforcement will involve the use of fisheries officers or rangers with adequate powers to search boats and interrogate visitors to reefs. Where foreign nationals are involved in poaching from reefs it may be necessary to use a coast-guard service or naval patrol vessels.

4.10 Population explosions of Acanthaster planci

Acanthaster planci is a large multi-armed starfish found on coral reefs in the Indo-West Pacific region (Endean, 1973). Hard corals comprise its principal prey. It digests their flesh but leaves their calcareous skeletons in situ (Mortensen, 1931; Gordon, 1964). Normal population densities of A. planci on Indo-West Pacific reefs are of the order of 6 specimens per km^2 of reef (Endean, 1974). Each specimen eats about 10 m^2 (flat projection) of coral per year. Thus, when present at normal population densities, A. planci causes negligible damage to the hard coral cover of reefs (Endean and Stablum, 1975).

During the last decade aggregations of A. planci containing hundreds of individuals have been reported from reefs in many parts of the Indo-West Pacific region (Endean and Chesher, 1973). On many reefs catastrophic destruction of the hard coral cover stemming from the feeding activities of the starfish has been reported (Pearson and Endean, 1969; Endean and Stablum, 1973; Nishihira and Yamazato, 1974). In some cases the bulk of the hard coral cover of entire reefs has been destroyed. There then occurs a switch from a coral-dominated to an algae-dominated community. This switch is associated with an obvious reduction in species diversity and the reef assumes a drab appearance. When present in large herds which migrate over a reef, adult A. planci can kill the bulk of the hard coral cover of a reef at a surprisingly rapid rate, massive as well as branching corals being affected.

Available data indicate that most reefs in the middle third of the Great Barrier Reef between lat. 15°S and lat. 20°S have been infested with A. planci during the last decade and many reefs in the southernmost third are now under attack by large numbers of A. planci. A massive destruction of coral has occurred on many of the infested reefs. The time required for the destruction of the hard coral cover of reefs averaging about 10 km^2 in flat projection that are heavily infested with A. planci is approximately 2.5 years (Endean and Stablum, 1975).

The causes of the A. planci infestations are not known. Some workers believe that the A. planci infestations are normal phenomena (Weber and Woodhead, 1970; Vine, 1970; Walsh et al., 1971; Dana et al., 1972; Frankel, 1975), others that they are unique phenomena, probably man induced (Endean, 1969; Chesher, 1969, 1969a; Randall, 1972; Endean and Stablum, 1975). It is the writer's opinion that the infestations have been triggered by the extensive collection by humans of molluscan and piscine predators of juvenile and small adult A. planci on certain accessible reefs. Such a release of predator pressure would allow populations of A. planci on these reefs to increase dramatically. Subsequently, other reefs would have become infested as a result of adult starfish migrating from reefs after devastating the bulk of the hard coral cover or as a result of invasion by current-borne larvae originating at the reefs first infested.

The damage already inflicted on reefs in some areas such as the Great Barrier Reef area has been so severe that it is the writer's opinion that, irrespective of the origin of the infestations, attempts should be made to control them. Manual collection of A. planci as has been carried out successfully at Okinawa, Fiji, Western Samoa, Tahiti, etc., or injection of specimens with formalin or ammonia as has been used successfully by Acanthaster control teams in Hawaii and the U.S. Central Pacific Trust Territory could be employed in control attempts.

There is an urgent need for international action to assess the magnitude of the A. planci problem throughout the Indo-West Pacific region and to coordinate large-scale control measures if these are indeed warranted.

4.11 Alien Species

It is possible that the introduction of a marine species to a coralliferous region from which the species has been previously excluded may have profound effects on the coral reef community. Certainly, the devastating ecological disturbances caused by importing alien terrestrial species to Australia are well known. Introductions of alien species into coral reef communities have been noted by Doty (1961, 1973) and Gilbert (1962) but others may have occurred and gone unnoticed to-date. It has been shown that the starfish Acanthaster planci will eat Caribbean corals and there has been speculation about the fate of Caribbean corals if the Pacific and Atlantic Oceans were linked with a sea-level canal across Panama (Thomas, 1970; Porter, 1972).

4.12 Tourism

The phenomenal increase in tourist establishments in coralliferous seas that has occurred in recent years is apparent to anyone who has travelled through these areas. The construction of new tourist resorts and the expansion of existing ones will obviously continue and these will bring with them problems relating to pollution in various forms. They will provide access to coral reefs for increasing numbers of tourists. The damage tourists themselves inflict on reefs by walking across reef flats, smashing corals, collecting molluscs and fish, overturning coral boulders, etc., can only be guessed at but where narrow fringing reefs are involved the damage may be substantial.

The control of pollution in all its forms in coralliferous areas will require the expenditure of considerable sums of money. Among those who will benefit most from the control of pollution are tourists and it would seem reasonable to recoup from tourist establishments some of the money expended on pollution control. If adequate tourist facilities were provided in coralliferous areas, it would seem inevitable that these areas which constitute a significant part of the world's few remaining wilderness areas will figure prominently among the world's principal tourist attractions. In time they could become major earners of foreign exchange. With respect to the development of tourism in coralliferous areas special attention should be given to making the development of tourism compatible with the conservation of the biota of coral reefs. The sites of new tourist

resorts should be carefully chosen so that the resorts themselves do not contribute substantially to pollution of coral reefs. Assessments will be required of the optimal sizes island-based tourist establishments should be allowed to attain and of the number of such establishments that should be permitted in a particular area. Visits to certain islands during the nesting seasons of birds and turtles should be prohibited.

5. DETECTION OF POLLUTION AND THE NEED FOR MARINE NATIONAL PARKS AND RESEARCH LABORATORIES IN CORALLIFEROUS AREAS

5.1 Detection of Pollution

With respect to the detection of pollution in coral reef ecosystems, the inadequacy of water column studies has been emphasized by Johannes (1975). He states (page 46) that "the continuous removal and replacement of water and its contents due to tidal flushing, and the high reproductive rates of planktonic organisms, makes water quality an inadequate indicator of pollution in shallow coastal waters". It is necessary to examine the coral reef community itself. In effect, regular surveys should be made of coral reef communities, particularly in the vicinity of ports and centres of human population in order to detect any significant changes in community structure that might stem from pollution in some form. It will of course be necessary to establish baseline data for coral reef communities in different geographical areas. Particular attention should be given to the detection of alien species before these become established over large areas. Another approach would be to use specific organisms as indicators of pollution. The use of benthic micro-organisms, foraminiferans and corals for bioassay work has been discussed by Johannes (1975).

5.2 Marine National Parks

It would seem wise to create marine national parks embracing groups of coral reefs in different geographical areas. Collecting of any element of the biota of these reefs should be completely banned. The reefs would then provide control situations where relationships among species undisturbed by humans could be studied. In this way, baseline data for coral reef communities in particular geographical areas could be obtained. When new marine national parks are being created, consideration should be given to the inclusion of a variety of reef types.

5.3 Research Stations

Wherever possible, research stations should be established in association with marine national parks in coralliferous areas. The fauna and flora of coral reefs are imperfectly known and a great deal of basic taxonomic research will be required to remedy this unfortunate state of affairs.

6. DESTRUCTION AND RECOVERY OF CORAL REEF COMMUNITIES

Theoretical aspects relating to the recovery of coral reefs devastated by catastrophic events have been discussed by Endean (1971, 1976). Recovery depends basically on the continued growth and reproduction of surviving coral colonies and the recolonization of devastated areas by coral planulae settling from the plankton. Complete recovery will involve the return of those species typically associated with corals and forming part of the coral reef community in the particular geographical region concerned and the re-establishment of the complex relationships normally existing among these species. A distinct progression of species with pioneer species being supplanted by later colonists could be expected.

To a large extent the rate at which recovery occurs is related to the extent of the damage inflicted on the hard coral cover by the catastrophic event. If few coral colonies have survived and if recolonizing planulae have to be carried over long distances then

recolonization may be long delayed. On the other hand, if destruction of coral colonies is localized or patchy and numerous colonies remain undamaged then recolonization could be relatively rapid. Recovery from small-scale localized destruction caused by natural events usually requires less than ten years providing that major sectors of the community remain virtually intact and the area involved is not marginal for coral growth or subjected to pollution. Periods of time ranging from 10 to 20 years are required for full recovery of affected reef areas following heavy destruction caused by natural events (Endean, 1976). If destruction caused by the natural event has been especially severe, several decades might be required for complete recovery. Indeed, Stoddart (1974) has suggested that, in the case of damage caused by tropical storms, there is a threshold of damage beyond which the effects of the damage may be prolonged.

As noted by Endean (1976) there are indications that when human activities are responsible for coral destruction, lack of recovery may prove to be common. In some cases, the activities responsible have rendered the area involved unsuitable for coral growth. Destruction of the coral reefs in the lagoon at Palmyra Island and their subsequent replacement by algal communities (Dawson, 1959) as a result of the erection of causeways which interfered with water circulation in the lagoon provides a classic example of the way humans can destroy coral reefs.

Recovery of reefs after devastation by Acanthaster planci has been studied and it may be instructive to examine the sequence of events that has occurred on these reefs. In the case of reefs of the Great Barrier Reef it was found that within 2-3 weeks the exposed skeletons of corals killed by the starfish began to acquire an algal coating that subsequently thickened and darkened (Endean and Stablum, 1973a). During this period there was an obvious breakdown of typical coral reef community structure, coral-associated animals being particularly affected by the change from a coral-dominated to an algae-dominated community.

Within a few months after a reef had been devastated by A. planci an obvious increase in the alcyonarian cover, particularly in lagoons and back reef areas, occurred. Frequently these soft corals grew over the skeletons of corals killed by the starfish. In some regions stalked algae (e.g. Turbinaria sp.) proliferated and covered coral skeletons. In other cases the skeletons of branching corals fragmented and formed piles of rubble. The rubble accumulated in lagoons and back reef areas, especially around the bases of coral pinnacles.

Within 3-4 years after devastation of a reef by A. planci, the first coral recolonizers were noted. Well known opportunistic species such as Pocillopora damicornis, Seriatopora hystrix, Stylophora pistillata and Acropora hyacinthus were among the first corals to settle. Endean and Stablum (1973a) noted an apparent relationship between the rate of recovery of an area of reef and the extent of coral destruction in the area caused by the starfish initially, the greater the initial destruction the slower the recovery.

Figures for the coral cover of numerous reefs devasted by A. planci several years after the devastation had occurred have been presented by Endean and Stablum (1973, 1973a), Endean (1974) and Pearson (1974). In a few regions, usually near patches of corals that had survived the A. planci attacks, coral regrowth had been impressive, particularly where fast-growing tabular colonies of Acropora hyachinthus were well represented among the recolonizers. However, on many reefs recolonization had been surprisingly slow and in many situations, particularly in back reef areas, was negligible 6-10 years after destruction of corals by A. planci had occurred. It has been estimated (Endean, 1973, 1976) that a period in excess of 20 years and possibly periods ranging from 20 to 40 years would be required for complete recovery (including restoration of typical species diversity) of reefs of the Great Barrier Reef devastated by A. planci. However, the factors that have triggered the A. planci infestations may still be operative and the possibility must be entertained that affected reefs will be reinvaded by A. planci during the course of recolonization by hard corals. Should this happen, then affected reefs might be impoverished indefinitely.

It may also be instructive to examine the ecological and economic consequences of the destruction of coral reefs by A. planci. The long-term ecological consequences of the destruction of the bulk of the hard coral cover of reefs in the central region of the Great Barrier Reef that has already occurred can only be guessed at. The reefs of the Great Barrier Reef can be regarded as constituting an ecosystem and major disturbances in one part of the system inevitably affect other parts. However, several years may elapse before such effects manifest themselves.

Naturally, tourists, particularly underwater enthusiasts and reef fossickers, are appalled by the appearance of reefs devastated by the crown-of-thorns starfish. However, most tourists to the Great Barrier Reef area visit only reef areas in the immediate vicinity of tourist resorts. To-date, only one tourist resort, Green Island, situated on the Great Barrier Reef proper, has been affected by an infestation of crown-of-thorns starfish. During the starfish infestation the management of the resort took measures to control the infestations, 27 000 starfish being collected from one small area of the reef flat visited by glass-bottomed boats (Barnes, 1966). When such control measures failed, the management appealed to the Queensland government for assistance. Subsequent to the Green Island infestation, the effects of the starfish depredations have not been highlighted because of the possibility of an adverse effect on the tourist trade.

The crown-of-thorns starfish kills only the veneer of living corals of reefs and there is no likelihood that the limestone cores of reefs will be exposed and subsequently eroded away as a result of the destruction of living corals. However, destruction of the hard corals and relocation of their skeletons as debris could well affect drainage patterns in shallow water on reef flats and alterations to drainage patterns could affect the stability of coral cays. It may be no more than a coincidence that Green Island, where the reef was devastated by A. planci during the 1960s, is now being severely eroded. However, the possibility that drainage patterns on the reef flat have been altered as a result of the A. planci infestations warrants investigation.

Many workers who have studied the A. planci infestations have commented on the effect of the destruction of the hard coral cover of a reef on the resident fish fauna of the reef. There is general agreement that the usual assemblage of coral associated fish disappears after the bulk of the hard coral of a reef has been killed. It might be expected that the disappearance of prime food fish such as coral trout (Plectropoma maculatum) from devastated reefs would be reflected in commercial fish catches landed on the coast of tropical Queensland. Data on weights of different species of commercial fish received each financial year (1st July to 30 June) at Fish Board depots at different ports along the Queensland coast for the financial years 1963-1975 are available from the Annual Reports of the Queensland Fish Boards. Information on the number of Barrier Reef fishing boats registered at these ports for the calendar year 1964-1973 inclusive has been made available by the Fisheries Section of the Queensland Department of Aboriginal and Islanders Advancement and Fisheries. The data on weights of coral trout received at different Queensland ports and data on fishing boats registered at these ports are presented in Figure 1. It can be seen that, in the main, there has been a steady increase in the number of fishing boats registered at each port during the period 1964-1973. In most cases the original number has more than doubled. However, the weights of coral trout received at each port, with the exception of Mackay, during the period 1963-1975 were much the same at the end of the period as at the beginning despite the apparent increase in fishing effort as indicated by the increase in numbers of boats registered. On the other hand, catches of coral trout received at the Mackay Fish Board have shown a phenomenal rise during the 1970s. The reasons for this rise are being evaluated. However, preliminary enquiries suggest that reefs off Mackay which until 1973 were virtually free of starfish damage have been worked by some of the boats registered at other Queensland ports because reefs off the home ports of these boats were devastated by A. planci during the mid and late 1960s and have since carried few commercial fish.

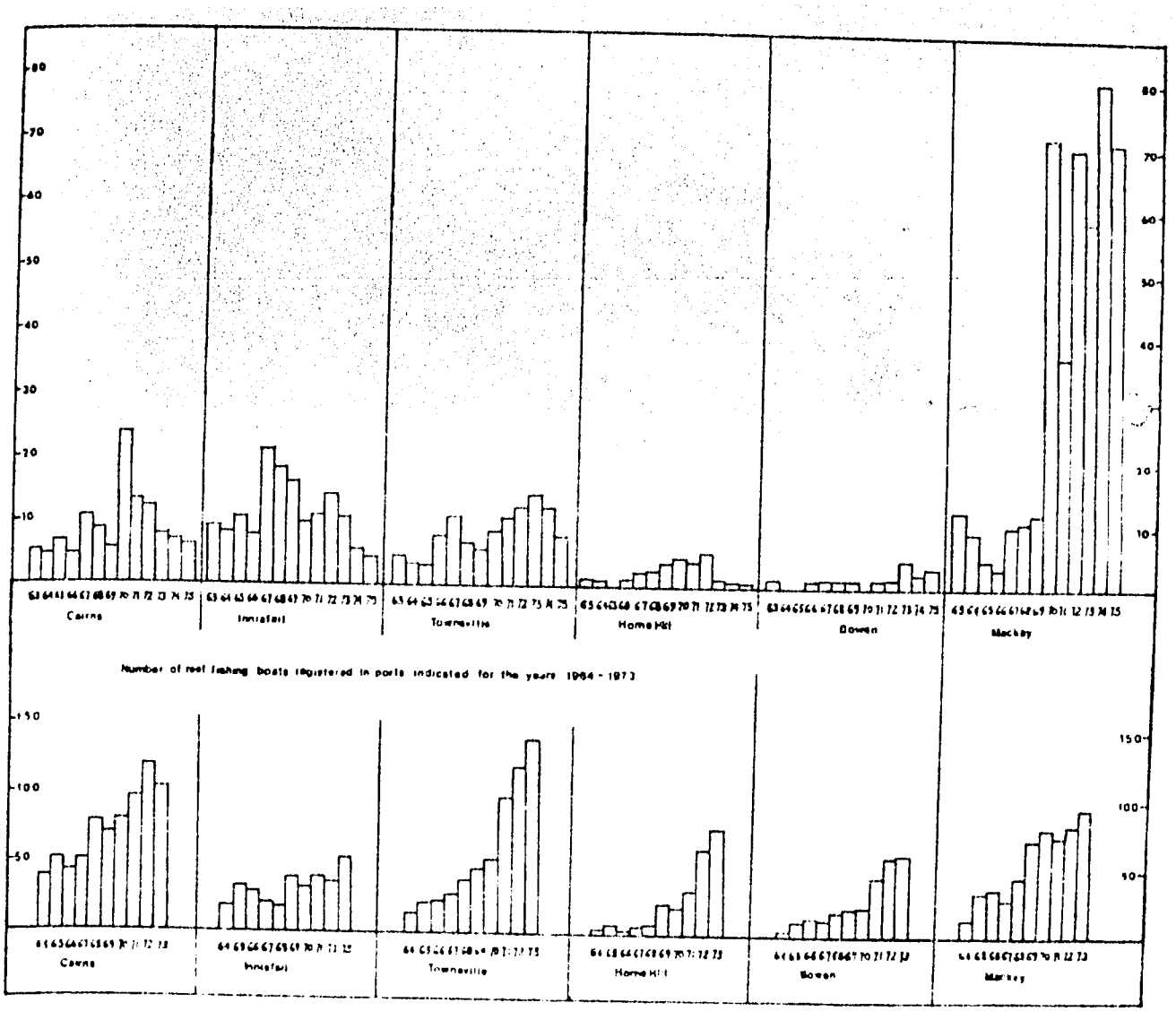

Figure 1. Graph showing weight (in thousands of kilograms) of coral trout (Plectropoma maculatum) received by Fish Boards at various Queensland localities for the financial years 1963-1975 inclusive and graph showing number of reef fishing boats registered in ports indicated for the calendar years 1964-1973 inclusive

7. CONCLUSIONS

If all forms of human activity that cause significant damage to natural ecosystems be regarded as pollution, then coral reef ecosystems throughout the world are being subjected to various types of pollution. These types include unplanned agriculture and deforestation near shorelines that lead to increased freshwater run-off and sediment deposition in coralliferous areas; mining activities that cause direct damage to the biota of reefs; dredging and filling activities that damage the biota directly or indirectly; the release into waters bathing coral reefs of toxic substances such as industrial wastes containing heavy metals; the indiscriminate use in coralliferous areas of man-made organic compounds such as persistent pesticides and detergents; the discharge of oil, the discharge of heated and/or highly saline effluents and the discharge of sewage into these areas; the blasting of coral reefs with conventional explosives; the testing of nuclear weapons in coralliferous areas; the introduction of alien species to these areas; the excessive collecting by humans of particular elements of the coral reef biota and the presence on reefs of large numbers of people (tourism) some of whom cause mechanical damage to elements of the biota. Instances

of the adverse effects on reef communities produced by each type of pollution are avail bl but the precise extent to which reef communities in any geographical area have already bee affected by any form of pollution is unknown. However, because of marked increases in hu populations and in industrial activity now occurring in most coralliferous areas, it can expected that most forms of pollution in these areas are increasing rapidly. In the not distant future the effects of this increased pollution could well be devastating.

It is known that catastrophic destruction of the hard coral cover of hundreds of reef throughout the Indo-West Pacific region as a result of population explosions of the coral eating starfish Acanthaster planci has occurred during the past twenty-five years and part cularly during the last decade. There are cogent reasons for believing that the A. planci population explosions are man-induced and stem from the excessive collecting by humans of natural predators of A. planci. If this is so, then overcollecting of elements of the biota by humans may be the most significant form of pollution currently occurring on coral reefs. Be this as it may, there is an obvious need for reliable information on the pres condition of coral reef communities in each of the major geographical regions where coral reefs occur and on the relative importance of each major form of pollution in each area. Analysis of this information should provide an indication of the extent to which reef communities have already been affected by pollution. However, before a realistic assessm can be made of the periods of time that will elapse before uncontrolled pollution reaches levels that will probably be critical for the viability of coral reef communities in parti areas, information must also be obtained on the expected rate of increase of each major f of pollution, the extent to which the various forms of pollution can act synergistically damage major elements of the reef biota and the extent to which pollution generally affe the ability of these elements to cope with natural stresses.

The long-term ecological and economic consequences of the destruction by pollution of major elements of the coral reef community, such as the hard coral cover, can only be gue at but examination of the effects of massive destruction of the hard coral cover of numer reefs in the central region of the Great Barrier Reef caused by Acanthaster planci infesta tions provide some indications of the short-term consequences to be expected. Initially, there is a switch on a devastated reef from a coral-dominated community to an algae-domi community, the switch being associated with marked changes in species composition. There are strong indications that, as a result of these changes, commercial fishing based on co reef fishes has already been adversely affected. Despite the drab appearances of devast reefs there are no obvious signs that tourism activity in the area has been adversely aff However, most tourist resorts there are located on or near the Queensland mainland and re (particularly fringing reefs around near-shore rocky islands) that have not been infested with Acanthaster planci remain available for inspection by tourists. It is possible that interference with drainage patterns in shallow water areas of reefs as a result of extens destruction of hard corals will affect the stability of some coral cays, such as Green Island cay (itself a tourist resort) but the results of studies on this aspect are not ye available. In countries where coralliferous areas are not as extensive as the Great Barr Reef area but where coral reef tourism and commercial fishing based on coral reef species figure more prominently in the national economy than they do in Australia, the consequence of massive destruction of the hard coral cover of reefs by pollution could well be far mo serious. Consideration of the long-term ecological consequences of massive destruction o hard coral cover of reefs by pollution raises questions about the length of the time requi for coral reef communities to recover from destruction caused by catastrophic events.

Studies of recovery of coral reef communities devastated by natural catastrophic even indicate that recovery from relatively small-scale patchy destruction requires less than ten years. Periods of time ranging from ten to twenty years are required for full recover of areas that have been subjected to heavy destruction over large areas. If destruction has been especially severe and involves all major areas of a reef, then decades may be required for full recovery. It is assumed that recovery in each case in uneventful and not punctuated by additional episodes of destruction caused by natural agencies or by pollution. There are indications that when human activities (pollution) are responsible

for destruction of coral reef communities recovery could well be prolonged because the areas are rendered unsuitable for coral growth. Also, destruction of biologically accommodated coral reef communities by some forms of pollution may be more severe and widespread than destruction caused by natural agencies, because the communities are not buffered against perturbations induced by novel factors whereas they have evolved mechanisms that buffer them against perturbations caused by natural agencies to which they have been exposed throughout their evolutionary histories.

The means of detecting, monitoring and countering each of the various forms of pollution affecting coral reef communities are available but the active support and cooperation of governments in all coralliferous areas will be required if pollution is to be effectively controlled in these areas. There is an urgent need for baseline data for the normal structures of reef communities on unpolluted reefs in different geographical areas to be obtained. This need underlines the desirability of creating adequate marine parks where the fauna is totally protected in each of the major coralliferous areas. Desirably too, these marine parks should be associated with research stations manned by coral reef biologists. Changes in the structures of coral reef communities stemming from pollution could then be detected by regular monitoring of reefs in each area, particularly those nearest centres of human population. If changes resulting from pollution are detected, appropriate counter-measures to control the particular form or forms of pollution involved could then be recommended to the relevant government or governments. Although pollution in most tropical marine environments does not appear, as yet, to have reached a critical stage, the A. planci population explosions that have occurred in recent years in many coralliferous areas may indicate that this critical stage is rapidly approaching. Now is the time for action and an excellent opportunity for concerted international action for the conservation of coral reef communities presents itself.

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