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CORALS IN MARINE POLLUTION MONITORING

Beverly P. L. Goh and L. M. Chou

INTRODUCTION

Pollution can be described as anthropogenic inputs into the marine environment resulting in harm to marine life, danger to human health, hindrances to marine activities and a reduction in the quality and usefulness of sea water (GESAMP, 1969). Marine pollution by man has come about as a result of the rapid economic development and industrialization of countries, and the general attitude that the oceans are everyone's dumping grounds. Since the 1970s, the subject of marine pollution has been an issue of great international concern, stemming from the growing awareness of the vast amounts of man-made pollutants that find their way into the world's oceans and the effects these pollutants might have on marine life and man.

Although natural sources of pollutants exist, as in natural underwater gas and oil eruptions, and algal blooms, their effects are not as significant as those of man-made toxic substances that are introduced into the sea daily. Anthropogenic pollutive substances regularly dumped into the sea include radionuclides or nuclear waste substances, organochlorine compounds (e.g. pesticides and PCB's), heavy metals, oil, petroleum products and detergents (Patin, 1982).

As a result of the increasing concern for the well-being of the world's oceans and natural resources within them, much research has been generated to studying the problem of marine pollution. Research on marine pollution can generally be divided into three sections, namely, the mechanisms of pollution, the effects of pollutants on marine resources and preventive measures of pollution (Patin, 1982). The biological monitoring of marine pollution mainly involves the first two categories, where the accumulation, transformation and migration of pollutants within the biota, and the biological effects of pollutants on marine organisms are studied.

Several types of marine organisms have been used in pollution studies, namely, algae, molluscs (e.g. oysters, clams, mussels and gastropods), sea urchins, crustaceans (e.g. mysids, copepods, shrimps, crabs) polychaetes, fish and coelenterates. These studies include laboratory and field tests on the effects of pollutants on the survival of the test organisms, as well as using test animals as indicators of pollution, either in the measurement of pollutant content in their tissues or in population studies.

Scleractinian corals are builders of the highly productive and diverse coral reefs that can be found mainly between latitudes 30° north and south of the equator. These ecosystems serve not only as spawning, nursery and living grounds for a great variety of

Beverly P. L. Goh, Chou Loke Ming- Department of Zoology, National University of Singapore, 10 Kent Ridge Crescent, Singapore 0511, Republic of Singapore.

fish and other economically important organisms, but are also important in protecting coastlines from storm damage and erosion from the sea. In addition, coral reefs also harbour many natural chemical substances of biomedical importance to man. Research into the effects of pollutants on corals has increased because of the realization of the importance of coral reefs to man and the vulnerability of this ecosystem to anthropogenic disturbances (Johannes, 1975).

Perhaps the earliest experimental studies on the tolerance of corals to external factors were laboratory investigations into temperature tolerance (Mayor, 1914, 1918; Edmondson, 1928) and sedimentation (Marshall & Orr, 1931). Since then, research into the responses of corals to a wide variety of physical and chemical pollutants have been gaining ground. Experiments have been carried out both in the laboratory, correlated with field observations and results analysed in relation to environmental quality.

Pollution studies that have been carried out so far using corals include the following:

CORAL COMMUNITY / POPULATION STUDIES

In this approach, whole coral reef ecosystems are monitored using ecological methods. Ecological parameters like coral cover, diversity, evenness, colony number and size, and spatial distribution are investigated (Brown & Howard, 1985a). Regular quantitative and qualitative methods of surveillance of reef communities have been carried out using plotless, quadrat and transect methods to study the changes in reef community structures over a period of time, and correlated to see if these changes could be attributed to pollution or anthropogenic influences. Examples of such studies include the effects of recreational activities (Tilmant & Schmahl, 1983); dredging, (Dodge & Vaisnys, 1977; Bak, 1978; Dahl & Lamberts, 1978; Sheppard, 1980); oil and mineral pollution (Fishelson, 1973; Loya, 1975, 1976; Hudson *et al.*, 1982); thermal pollution (Jokiel & Coles, 1974); sewage pollution (Walker & Ormond, 1982; Pastorak & Bilyard, 1985); chemicals (Jaap & Wheaton, 1975); heavy metals (Brown & Holley, 1982; Brown & Howard, 1985b); and eutrophication (Tomascik & Sander, 1987a) on coral reef populations.

It must be noted that coral reef environments are extremely variable and changes observed do not necessarily reflect any anthropogenic impacts. Indeed, some of the studies mentioned above have even documented no apparent serious effects on reef community structure following anthropogenic disturbances (e.g. Sheppard, 1980; Brown & Holley, 1982). Factors like dispersal rate of pollutants in the affected area, duration and extent of pollution, types of corals present, their growth forms and tolerance levels have been put forward as possible reasons affecting how reef ecosystems react to disturbances. In order for coral community studies to be more effective in interpreting pollution, it has been suggested that surveys be carried out regularly, and on a long term basis (Brown & Howard, 1985a).

Another aspect of reef community research in pollution monitoring is the study of the recovery of reefs after a disturbance. This may be applied to estimating the degree of disturbance on a reef from its recovery rate, as well as to predicting the length of time it would take a perturbed reef to return to a stable or near stable equilibrium. Pearson (1981) outlines several factors affecting the recovery rate in coral reefs, namely, the extent of damage and location; the availability of coral larvae; time required for "conditioning" the substratum before corals can settle; the availability and diversity of substrata for colonization; presence of grazers; and competition with other organisms that are able to colonize the same space. Early examples of this approach to studying reef recovery from human disturbances are Loya's (1975, 1976) and Rinkevich & Loya's (1977) work on Red Sea corals. These three studies have combined both field observations and laboratory experiments. More recently, Coles (1984) observing the colonization and growth of corals on new and denuded substrata near a power station, predicted rapid recovery of the denuded reef. Maragos *et al.* (1985) investigated the recovery of reef corals in Kaneohe Bay, Hawaii six years after sewage discharges were terminated and concluded that sedimentation, dredging, urbanization and sewage were major factors causing the decline of coral communities within the Bay.

CORAL COLONY STUDIES

Apart from population studies, research on individual coral colonies has also been done. These studies are often carried out in more controlled laboratory conditions owing to the fact that individual colonies of many coral species are more easily transported and maintained in the laboratory. As far as possible, experiments are also run in the field to increase the accuracy and relevance of the interpretation of laboratory-based data.

Coral colony studies are important in that they monitor the effect of pollutants on the individual coral organism, from which predictions can be made as to how the entire coral reef population will react. The various responses that have been observed in corals exposed to physical and chemical disturbances include: metabolic; reproductive; zooxanthellae, behavioural; growth/calcification; histopathological; and biochemical indices. In addition, analysis of tissue and coral skeletons have also enabled scientists to determine levels of pollutants retained by corals.

Metabolism

Metabolic processes that have been monitored in corals include primary productivity, photosynthesis and respiration. The main objective of this method is to detect immediate effects of various pollutants impinging upon coral heads. Experimentations into this method of study have included measurements of respiration and photosynthesis in corals exposed to various concentrations of drilling mud (Szmant-Froelich *et al.*, 1983); suspended peat (Dallmeyer *et al.*, 1982); thermal stress (Coles & Jokiel, 1977) and heavy metals (Howard *et al.*, 1983); and the monitoring of photosynthesis in *Diploria strigosa* under stress from crude oil and dispersants (Cook & Knap, 1983).

Other methods of assessing metabolism include the measurement of calcification rate, protein concentration and free amino acids in *Acropora cervicornis* under the effect of kaolin (Kendall *et al.*, 1985). Also, work involving estimating the carbon and energy budgets in corals (Davies, 1984; Edmunds & Davies, 1986) has since been applied to pollution studies using corals (Edmunds & Davies, 1989).

Reproductive Biology

Corals exhibit a wide range of reproductive strategies. They may reproduce asexually, by fragmentation, polyp bail-out or the production of planula larvae. Sexually, they may spawn egg and sperm, with fertilization occurring externally, or brood planula larvae after internal fertilization has taken place. The reproductive stages of the coral are also potentially useful in pollution monitoring.

The stages in the life history of corals that have been used in pollution studies are the gamete and larval stages. The juvenile stages are especially sensitive to changes in the conditions of the surroundings and are therefore valuable in pollution monitoring, where the aim is to find out the highest level of pollution that organisms can still survive reasonably well in. Methods that researchers have used to study various pollution effects on the reproductive biology of corals include monitoring fertilization success in corals (Rinkevich & Loya, 1977, 1979; Kojis & Quinn, 1981; Glynn *et al.*, 1983; Tomascik & Sander, 1987b; Heyward, 1988); the viability and development of coral larvae (Loya & Rinkevich, 1979; Esquivel, 1983; Richmond, 1985; Goh, in press), and the settlement ability of planula (Rinkevich & Loya, 1979; Hodgson, 1990; Goh, in press). In view of the sensitivity of planulae to external disturbances, Stebbing & Brown (1984) pointed out that they would prove valuable in future pollution research on reef corals.

Zooxanthellae

Zooxanthellae is a common name for the symbiotic algae that lives within the tissues of coelenterates. Reef building corals harbour these algal symbionts within the endodermal layer. Studies have shown that this algae photosynthesizes, providing nutrients to its coral host (Goreau & Goreau, 1960; Muscatine & Cernichiari, 1969; Lewis & Smith, 1971; Trench, 1971, 1981), and more importantly, aids the coral in calcification and reef extension (Goreau, 1959; Goreau & Goreau, 1959; Pearse & Muscatine, 1971; Vandermeulen & Muscatine, 1974; Kevin & Hudson, 1979).

A unique phenomenon of this coral-host-algal-symbiont relationship is that under stressful conditions (e.g. a rise in temperature, increase in toxic substances, sedimentation, etc.), the zooxanthellae are released from their host coral tissue. If the stress is prolonged and more zooxanthellae are lost from the coral tissue, the corals will be discoloured or said to be "bleached". Several authors have suggested the use of the loss of zooxanthellae as an indicator of pollution (e.g. Jokiel & Coles, 1974; Jaap & Wheaton, 1975; Neff & Anderson, 1981).

Brown (1988) listed three useful quantitative measurements derived from this phenomenon of zooxanthellae expulsion namely, mitotic index, zooxanthellae numbers and chlorophyll analysis. Under stress, the rate of mitotic activity of zooxanthellae within the tissue of the host coral has been known to increase, together with the rate of expulsion of zooxanthellae. Of the three quantitative measurements mentioned, the monitoring of zooxanthellae numbers is the most commonly used index in the study of marine pollution. Anthropogenic disturbances affecting corals that have been studied using this method include thermal pollution (Coles, 1975; Jokiel & Coles, 1974, 1977; Neudecker, 1983), dredging (Bak, 1978; Marszalek, 1981), herbicide formulations (Glynn *et al.*, 1983), drilling muds (Thompson *et al.*, 1980), kaolin (Dollar & Grigg, 1981) peat (Dallmeyer *et al.*, 1982), quinaldine (Japp & Wheaton, 1975) oil (Peters *et al.*, 1981) and heavy metals (Howard *et al.*, 1983; Harland & Brown, 1989).

Behaviour

Corals also exhibit behavioural responses to pollution stress. Brown & Howard (1985a) outlined three behavioural features of corals under stress, namely, feeding and mesenterial filament extrusion; mucus production; and sediment shedding. Under normal circumstances, corals have been known to release mesenterial filaments in response to feeding stimuli (Duerden, 1902; Carpenter, 1910; Vaughan, 1912; Matthai, 1918; Yonge, 1930) and aggression (Lang, 1971; Bak *et al.*, 1982). This response has also been observed in corals exposed to pollutive materials, for example, crude oil and oil dispersants (Lewis, 1971; Wyers *et al.*, 1986); oil droplets and sediment (Bak &

Elgershuizen, 1976); and drilling muds (Thompson *et al.*, 1980). In addition to mesenterial filament extrusion, coral behavioural researchers have also observed coenosarc distension (Thompson *et al.*, 1980; Dallmeyer *et al.*, 1982) and polyp retraction (Jaap & Wheaton, 1975; Thompson *et al.*, 1980; Neff & Anderson, 1981; Knap *et al.*, 1983) in corals exposed to pollution. However, mesenterial filament extrusion, coenosarc distension and polyp retraction are only unique to certain species of corals, and the extents of these behavioural traits are highly variable, even within the same species of corals. As such, the use of these traits in pollution studies is limited.

Excess mucus production in corals resulting from human disturbances has been reported by several authors (Jaap & Wheaton, 1975; Mitchell & Chet, 1975; Bak & Elgershuizen, 1976; Thompson *et al.*, 1980; Marszalek, 1981; Neff & Anderson, 1981; Dallmeyer *et al.*, 1982; Neudecker, 1983). This response is brought about by the increase of the number and size of mucous secretory cells within the coral tissue (Peters *et al.*, 1981). It is believed that the mucus is produced in order to bind with or absorb pollutants to protect the coral tissue underneath. The use of mucus production to assess the effects of anthropogenic disturbance on corals has potential only if there is a standard method of quantifying the amount of mucus produced in corals under study (Brown & Howard, 1985a).

Corals have the ability to clear particles or sediment that fall on the surface of their bodies by the combined working of their tentacles, ciliary currents and mucus secretions. Different species of corals have varying rates and efficiencies in their sediment shedding abilities, depending on their growth forms. The sediment shedding behaviour of corals has also been used in pollution studies dealing with particulate pollutants, for example, drilling mud (Thompson & Bright, 1980; Dodge & Szmant-Froelich, 1984); oiled sediments (Bak & Elgershuizen, 1976); calcareous sediments (Rogers, 1983) and metal-laden sediments (Brown & Holley, unpublished). Brown & Howard (1985a) stated that the sediment shedding efficiencies of corals may be valuable in pollution bioassays but cautioned that other factors like feeding stages, species of corals and water movements must also be taken into account when employing this behavioural response in corals for study.

Growth / Calcification

The study of growth has been one of the most popular methods of assessing stress on corals. Research into the growth rates of the skeletons of corals has employed the following methodologies, namely, x-raydiography, reference marking using alizarin red S staining or using a fixed base line, measurement of increase in skeletal weight, and the rate of ^{45}Ca deposition in coral skeletons (Brown & Howard, 1985a). Growth measurements using x-raydiography has been employed mainly on massive coral species where growth bands or rings are put down regularly within the skeleton. Examples of research on anthropogenic disturbances using this method include the study of drilling muds on *Montipora annularis* (Hudson & Robbin, 1980); dredging on *Diploria strigosa* and *D. labyrinthiformis* (Dodge & Vaisnys, 1977); bombing activities (Dodge, 1983); drilling activities (Hudson, 1981; Hudson *et al.*, 1982); and eutrophication (Tomascik & Sander, 1985). In most cases, the calcification rate is predicted to decrease in corals under stress. However, in some of the studies mentioned, stressed corals showed no apparent change in growth rate (Hudson *et al.*, 1982; Dodge, 1983). In addition to skeletal bands, the presence of high-density or "stress" bands have also been observed in certain corals using the x-raydiography method attributable to declining environmental conditions (Hudson *et al.*, 1976; Hudson, 1977, 1981). However, care should be taken in analysing "stress" bands as banding patterns can sometimes be complex (Brown *et al.*, 1986).

In branching coral species, the alizarin dye staining or base line method is commonly used to measure skeletal growth. Growth rate experiments involving the dye staining or baseline marking of branching corals include investigations into the effects of thermal stress (Neudecker, 1983); drilling mud (Dodge, 1983); and sedimentation (Rogers, 1979). The method of using skeletal weight measurements of corals to monitor growth include studies by Jokiel & Coles (1977) on temperature stress; Bak (1978) on sediments from dredging activities; and Szmant-Froelich *et al.* (1983) on drilling muds, whilst Neff & Anderson (1981) and Birkeland *et al.* (1976) studied the effects of oil and crude oil on the rate of ^{45}Ca incorporation into coral skeleton.

A recent addition to the methodology of coral growth measurement is the use of ultraviolet radiation to expose fluorescent bands in massive coral skeletons (Brown, 1988). The fluorescent bands are believed to be the result of terrestrial fulvic acid incorporated into coral skeletons (Boto & Isdale, 1985). Brown (1988) stated that this method has much potential in the evaluation of environmental impacts e.g. terrestrial run-off and may prove to be more accurate than x-radiography, but cautions that much more research has to be done before it may be applied to pollution studies.

Histopathology

Histopathology in corals is the histological study of coral tissue to investigate causes of disease or physical abnormalities. This method of study has mainly been confined to determining bacterial infections and diseases in corals (e.g. black band disease reviewed by Antonius, 1983). However, studies have also reported tissue regression in corals in response to environmental disturbances like continuous sedimentation and excessive temperature stress (Antonius, 1983); and oil or oil dispersants (Lewis, 1971; Johannes *et al.*, 1972; Reimer, 1975). Peters *et al.* (1981) studied the effects of chronic oil exposure to corals and reported cellular degeneration and atrophy of coral tissue directly related to the oil. Elgershuizen & de Kruijf (1976) documented entire coral mortalities with exposure to crude oil, an extremely toxic pollutant if discharged in great concentrations. Howard *et al.* (1983) investigated the effect of copper to corals and reported extensive disruption of columnar ectodermal tissues in experimental corals. Brown & Howard (1985a), however, cautioned about the pitfalls in histopathological examination, such work being time consuming and thus generally lacking in replicates.

Biochemical Indices

Brown & Howard (1985a) described biochemical indices as potentially sensitive indicators of stress in corals. Preliminary experiments into the study of lipid-protein ratios in ahermatypic (containing no zooxanthellae) corals carried out by Szmant-Froelich & Pilson (1980) interpreted these ratios as a reflection of the nutritional status of the coral. Dodge & Szmant-Froelich (1984) subsequently carried out the same analysis on *Montastrea annularis* and recorded significant changes in the lipid content of corals exposed to drilling muds. Also, Cook & Knap (1983) studying the effects of crude oil and chemical dispersants on corals documented a reduced synthesis of major storage lipids in the affected corals. Other biochemical indices tested in other marine invertebrates (e.g. mussels and hydroids) mentioned in Brown & Howard's (1985a) review paper include measurements of protein content; total ninhydrin-positive substances; taurine/glycine ratios; and cytochemical latency of lysosomal hydrolases. These indices are potentially useful in future pollution stress studies using corals as indicators, especially since they are much more sensitive as compared to the other physiological studies already mentioned.

Tissue / Skeleton Analyses

Persistent pollutants that do not degrade over a prolonged period of time (e.g. heavy metals, phosphorus and radioisotopes) have been observed to be retained in the tissue and skeleton of corals. The growth rings within the skeletons of massive corals are believed to be able to retain historical records of pollution, for example, radionuclides (Noshkin *et al.*, 1975); phosphorus (Dodge *et al.*, 1984); lead (Dodge & Gilbert, 1984; Shen & Boyle, 1987); cadmium and other trace metals (Howard & Brown, 1984; Shen *et al.*, 1987; Shen & Boyle, 1988). Metals, in particular have been analysed from corals, for example, Brown & Howard (1985b) recorded zinc and copper from dredging activities in the tissue and skeleton of corals at Ko Phuket, Thailand; and Harland & Brown (1989) analysed iron levels in coral tissue in the same location. This approach in pollution monitoring is valuable as realistic environmental levels of pollutants can be traced in corals living in the vicinity.

In conclusion, the use of scleractinian corals in pollution studies has increased steadily, due to the realization of the importance of coral reefs to man and the vulnerability of these ecosystems to pollutive industries. Methods of monitoring pollution include field studies on coral reef populations as well as field and laboratory-based experiments on individual coral heads. An important consideration in pollution studies is that both laboratory and field experimental results be extrapolatable to predict changes in the quality of the environment, especially changes brought about by anthropogenic sources. Equally important is the need for experimental results to be applicable to the proper management of the marine environment, for example, in setting down acceptable limits for the discharge of effluents into the environment. Much potential still remains to be tapped in expanding existing methods of monitoring pollution using corals (Stebbing & Brown, 1984; Salvat, 1987). Sensitive tests that allow scientists to detect environmental deterioration before effects are felt in the entire community will no doubt pave the way for more realistic standards in pollution control to be set.

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