

REVIEW PAPER

EUTROPHICATION AND CORAL REEFS—SOME EXAMPLES IN THE GREAT BARRIER REEF LAGOON

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Abstract—Eutrophication or “nuisance” algal growth causes negative impacts on coral reefs via a number of routes and can eventually lead to the replacement of the coral community with various flora and fauna (e.g. attached algae, seagrasses and detrital/filter feeders). Chlorophyll *a* appears to be the best water quality indicator of eutrophication and a eutrophication threshold value at or below an annual mean of 0.5 mg m^{-3} is suggested. The concentrations of nutrients N and P associated with the onset eutrophication in coral reef communities are less well defined (annual mean DIN $\sim 1 \mu\text{M}$; P- $\text{PO}_4 \sim 0.1\text{--}0.2 \mu\text{M}$) but are in accord with eutrophication threshold levels for sensitive freshwater ecosystems. The proliferation of nitrogen fixing algae in pristine coral reef regions highlights the importance of phosphorus and trace components such as Mo and Fe and even soluble organic matter to the overall primary production. The concentration of nutrients and levels of chlorophyll *a* in some regions of the Great Barrier Reef (GBR) lagoon are comparable to those that would be classed as eutrophic in other coral reef regions of the world. The available evidence points to riverine run-off as the cause of elevated P- PO_4 levels in the inner lagoon. Historical evidence indicates that the levels of P- PO_4 and phytoplankton growth, and particularly that of *Trichodesmium* spp, are relatively high in the river affected areas and that the levels may have significantly increased in the inner lagoon over the past 50–60 years. The nitrogen-fixing ability of *Trichodesmium* suggests that increased levels of P alone may be driving increased levels of primary productivity in the lagoon. It is hypothesized that the riverine-promoted eutrophication is a significant factor in the demise of fringing reefs in the inner GBR lagoon. The recorded levels of nano plankton growth in some river-affected regions of the GBR lagoon are sufficient to promote the survival of *Acanthaster planci* (crown of thorns starfish) larvae and as such eutrophication could well be a principal causative factor of the crown of thorns outbreaks. Elevated levels of nutrients and algal growth occur in some outer regions of the GBR but these appear to be due to natural phenomena. The high background concentrations of nutrients and phytoplankton in both the inner and outer GBR, whether they are natural or not, demands that special precautions be exercised in the control of sewage effluents and run-off in the vicinity of coral reefs.

Key words—eutrophication, coral reef, nitrogen fixation, nutrients, *Trichodesmium*, *Acanthaster planci*

INTRODUCTION

The term eutrophication has become quite subjective in meaning. As noted by Griffith (in Reynolds, 1978, p. 226) “no two limnologists agree on what eutrophic means”. In this paper the term eutrophication refers to a situation where an increase in nutrient levels has occurred through anthropogenic activities which has resulted in “nuisance” algal growth. “Nuisance” categories defined by Paerl (1988) include: (1) perceptible water quality deterioration, including trophic changes; (2) chronic or intermittent health hazards, including toxicity; and (3) loss of aesthetic and hence recreational values. In their pristine condition coral reef ecosystems are highly productive but the reef’s waters are usually characterized by low standing crops of phytoplankton. “Nuisance” algal growth in the water surrounding a coral reef can, through various routes, lead to the replacement of corals with benthic plants and filter/detrital feeders. It appears,

as is discussed below, that the levels of nutrients associated with such “nuisance” algal growth or eutrophication in coral reef communities are quite low, but are in accord with eutrophication threshold levels for sensitive freshwater ecosystems. The limited amount of monitoring that has been completed in the Great Barrier Reef (GBR) lagoon has revealed that the background levels for some regions are at or above these threshold values.

The GBR extends for about 2000 km along the north east coastline of Australia (see Fig. 1). The lagoon, due to the barrier effect of the outer reefs and the inherent longshore currents, should be considered as a partially enclosed sea and as such has the potential to accumulate nutrients discharged from the ever increasing anthropogenic activities such as agricultural, urban and industrial development along the coast of Queensland (Bell, 1991). On the large scale, riverine inputs from agricultural areas would discharge large amounts of nutrients to the GBR lagoon

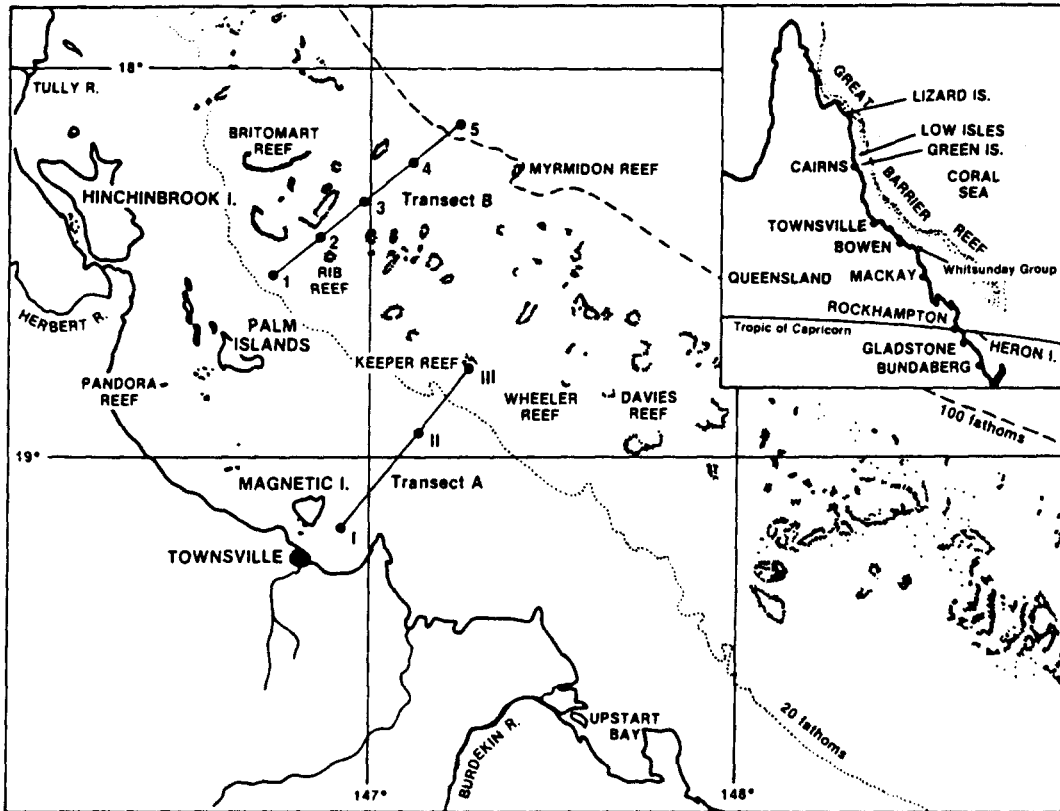


Fig. 1. Location and extent of Great Barrier Reef and sampling stations used by Revelante and Gilmartin (1982), Ikeda *et al.* (1980) and Furnas and Mitchell (1984a,b).

(Cosser, 1987; Walker and O'Donnell, 1981). There is some evidence that these riverine inputs are responsible for elevated "background" levels of nutrients in the inner lagoon (e.g. see Revelante and Gilmartin, 1982). The problem of high background levels is exacerbated locally in some regions by small-scale run-off from developed areas and point source discharges (e.g. sewage effluent). The high background levels pose particular problems for achieving the necessary dilution of sewage effluent in coral reef regions (Bell and Greenfield, 1987; Bell *et al.*, 1989).

There is some evidence that the reefs in the inner to mid GBR lagoon are deteriorating due to anthropogenic influences including eutrophication (see discussion below). Many of the fringing reefs are now dominated by large stands of macro and filamentous algae which is consistent with the region being eutrophic. Other anthropogenic factors, as are discussed below, such as overfishing and increased sedimentation could also encourage such conditions. Many fringing reefs around the world in addition to those described in the much cited studies in Kaneohe Bay (e.g. see Banner, 1974; Smith *et al.*, 1981) and Barbados (Tomascik and Sander, 1985, 1987) appear to be facing similar problems. The recent (in the last 20 years) degradation of reefs along the north coast of Jamaica are attributed to such a combination of anthropogenic influences (Lapointe, 1989). Johannes (1970) notes that many coral reefs fringing the

islands of Hawaii have suffered considerably due to the introduction of European style agriculture. The principal impacts noted are those due to increased sedimentation and freshwater run-off. Doty (cited by Endean, 1976, p. 232) notes that the nutrients from sewage discharges may have led to the increased algal growth and the demise of the reefs in the vicinity of Waikiki beach. Recent observations show that many of the fringing reefs of the islands of Hawaii are now dominated by algal growth. Particularly heavy growth occurs along the coast of Maui. Much of this algal growth can be attributed to the impacts of nutrients contained in run-off and groundwaters from both agricultural areas and the expanding tourist resort regions.

No systematic study on the extent of eutrophication in the GBR lagoon has been carried out although there are some historical data available on nutrient levels and algal growth. This paper summarizes these data and compares the levels recorded with those found for other coral reef regions. This paper also summarizes the available information which points to the relatively recent demise of coral reefs in the inner GBR lagoon.

EUTROPHICATION AND CORAL REEFS

Coral reef ecosystems appear to be able to out-compete other ecosystems when the surrounding

water environment is poor in nutrients, having been described as oases in the oceanic desert (Salin, 1983; Sorokin, 1973, p. 17; Odum and Odum, 1955). Their ability to do this is not fully understood but it is known that nitrogen-fixing organisms are often prolific in coral reef environs and that various symbiotic relationships occur within the biological community structure which result in very efficient recycling of nutrients. This recycling of nutrients provides longer residence times for the nutrients, or in other words, a storage capacity or capacitance for nutrients. This inbuilt capacitance means that the coral reef ecosystems are able to flourish with only periodic inputs of nutrients, e.g. from upwellings or river run-off. Some coral regions do have what appear to be naturally elevated nutrient levels due to upwellings, terrestrial run-off and groundwater (Crossland and Barnes, 1983; Revelante and Gilmartin, 1982). It is noted though that high levels of dissolved nitrogen (N) and/or phosphorus (P) do not always correspond to high standing crops of algae because other chemical, physical or biological factors may limit the algal population and it is the impact of the elevated algal populations on the coral community growth which appears to be of importance, not simply the elevated levels of the nutrients. It has been demonstrated that the discharge of sewage effluent and run-off from developed areas can cause adverse impacts on coral reefs. Near to discharge points toxic effects can be experienced but the impact due to eutrophication, i.e. the increased nutrient levels and the associated increase in both phytoplankton and attached algal populations, can be quite widespread (e.g. see Banner, 1974; Smith *et al.*, 1981; Laws and Redalje, 1979; Tomascik and Sander, 1985).

Impacts of eutrophication on coral reef ecosystems

Eutrophication or "nuisance" phytoplankton and attached algal growth causes negative impacts on coral reef ecosystems via a number of complex and sometimes interacting mechanisms. These impacts can lead to a reduction in diversity of coral species and eventually to the replacement of the coral community with various flora and fauna (e.g. attached algae, sea grasses and detrital/filter feeders). The principal mechanisms by which eutrophication impacts on coral reefs will now be briefly discussed.

Reduced light penetration and smothering. Obvious negative impacts on corals that result from increased phytoplankton concentrations are the inhibition of light penetration to the symbiotic zooxanthellae and the smothering effects caused by an increased organic sediment load. Baas-Becking (as reported by Endean, 1976, p. 223) has described coral deaths following their smothering with the planktonic blue-green alga *Trichodesmium*. Such an increased organic sediment load could lead to increased production of toxic hydrogen sulphide and will encourage the growth of filter and detrital feeders which will compete with the coral for space. Increased organic sediment load

discharged directly with sewage effluent would have a similar effect.

Competition for space, sediment traps and disease. Increased attached algae will also compete with the corals for space and will act as traps for sediment build-up (Brown and Howard, 1985, p. 19). Kaplan (1982, p. 116) notes the direct attack on coral polyps by blue-green *Oscillatoria*. Also algal infections by blue-green algae (*Oscillatoria submembranacea*, *Phormidium*) are believed to cause the black band disease (Brown and Howard, 1985, p. 48; Lapointe, 1989). Boring-type algae may also be promoted which could lead to direct destruction of the coral matrix. The fact that, given the chance, algae can out-compete with corals for space is not a new revelation. Indeed Wood-Jones (1912) notes algal growth as the cause of the failure of corals to recolonize after some 30 years following a discharge of foul water from a supposed volcanic vent in a lagoon of the Cocos-Keeling atoll.

Reduced coral growth rates and reduced laval settlement/survival. Evidence is emerging that eutrophication not only affects coral growth rates but also affects their recruitment and reestablishment abilities. In studies done in Barbados (Tomascik and Sander, 1985, 1987; Tomascik, 1992) the coral species *Montastrea annularis* was found to exhibit much slower growth rates in the more eutrophic regions. Also benthic algae was more prolific, the diversity of corals was lower and a significant reduction in the settlement/survival of coral spats (on artificial substrates) occurred in the more eutrophic regions. In the study, Tomascik and Sander (1987) took into account the distributions of herbivorous fish and conclude for their study area that the high abundance of benthic macrophytes and filamentous algae at the three southern more eutrophic reefs is indeed due to the increased nutrient levels and not to the exclusion of grazers. Also monitoring of permanent sites at Hayman Island in the GBR lagoon has revealed that recruitment of corals is markedly suppressed in the vicinity of the sewage outlet (van Woesik *et al.*, 1992). The actual mechanism or mechanisms associated with the eutrophication which lead to the reduction in settlement/survival of spats is not clear. Some workers have inferred that filamentous algae will inhibit coral laval settlement but others have noted that some biological preconditioning of the substrate is necessary by some corals (see review by Fadlallah, 1983) and that some species exhibit preferential settlement on algal coated substrates (Harriott, 1983). However subsequent survival of the settled spats does appear to be inversely related to the density of algal cover. Harriott (1983) suggests that once settled, spat survival may require slow growth or cropping of the algal layer to prevent competitive dominance by algae. Excess cropping may however lead to the destruction of the settled spats.

Other factors such as overfishing, sedimentation, freshwater input and physical destruction can act

synergistically with eutrophication in leading to the demise of coral reefs.

Overfishing. The effects of increased algal growth due to eutrophication could be magnified in regions where overfishing occurs. It is noted that overfishing alone could well cause benthic algal populations to out-compete with corals, even in pristine waters. For the GBR it has been found that algal biomass will become more profuse on coral reef sub-strata if the grazing fish are removed (Wilkinson and Sammarco, 1983). This fact complicates the use of attached algal growth as an indicator of eutrophication and it is suggested that phytoplankton levels or concentration of chlorophyll *a* in the water column would be a better indicator of eutrophication.

Sedimentation. Another complicating factor is that sedimentation can reduce coral laval settlement as well as provide a more suitable substrate for macro algae than for coral. Hodgson (1990) found that sedimentation, at a level that only partially covers a substrate and that is not directly harmful to adult colonies, could significantly reduce laval settlement. Also terrestrial-derived sediments could provide a significant source of nutrients for benthic plant growth (e.g. sea grasses, micro and macro algae). For example soluble P tends to sorb to suspended particulate matter and on settlement could well become available to benthic plants. Thus sediment load from run-off could not only smother and kill coral communities but also prevent the reestablishment of corals and greatly enhance the growth of benthic plants.

Freshwater inputs, and physical impacts. Of extreme importance to the ultimate effects of freshwater discharges (and associated sediments) and of physical impacts on coral reefs is the above finding that the settlement/survival of spats of some corals is significantly reduced in eutrophic regions. This means that the effects of eutrophication on coral reefs may not be obvious until after some other impact on the coral reef. For example the reef may be partially killed by a fresh water run-off event or physically destroyed by the forces of a cyclone or crown of thorns attack or simply damaged by other coral predators. If the region is eutrophic, fast growing algae may be able to take advantage of the situation to firmly establish their territory and in doing so, prevent the reestablishment of the corals. It is to such a combination of events that the destruction of many of the reefs in Kaneohe Bay are attributed (Smith *et al.*, 1981). The coral community in the south east (S.E.) section of Kaneohe Bay, known originally as the "coral gardens" and purported to have been once one of the finest in the world, was eventually destroyed by a combination of dredging activities, run-off and the discharge of sewage effluent (Banner, 1974; Smith *et al.*, 1981). The diverse coral community was replaced by algae and various filter and detrital feeders (e.g. sea cucumbers, oysters, clams). Most of the bay was inundated

to some extent by the alga *Dictyosphaeria cavernosa*. On redirection of the sewage effluent, very good coral recovery occurred. However it is noted that there is still today, some fourteen years after the sewage redirection, a problem with attached algal growth in some sections of Kaneohe Bay. Also some regions of coral, which were destroyed by more recent run-off events, have not reestablished (personal observations, June, 1990). This lack of reestablishment of the corals could well be due to eutrophication. The main input of nutrients to the bay now is run-off from the ever increasing coastal development areas.

Importance of hydrodynamic regime

The hydrodynamic regime is important in determining the magnitude and extent of the impact of eutrophication on coral reef communities. For example, Pastorok and Bilyard (1985) note that large outfalls in well flushed open-coastal regions have minimal, at least in the short term, impact on coral reefs. However these same discharges could prove devastating to near-by or even far-distant bays where calmer conditions exist. The longer residence times and the calmer conditions of such bays are conducive to both the growth of algae and settling of detritus. Endean (1976, p. 229) reports that the building of causeways reduced the renewal of waters around Palmyra Atoll in the Line Islands and this resulted in the replacement of corals with algal communities dominated by *Lyngbya* (Dawson, 1959 cited). It is stressed that even small discharges if not effectively flushed can cause serious problems, e.g. Johannes (1972) has reported that seepage from a single public rest room in Honaunau Bay has brought about the degradation of a nearby coral community. Benthic (attached) algae populations were found to be larger than normal in this area, with much of the coral dead and encrusted.

Importance of N-fixation, P and trace components

Attached or benthic microorganisms which have the ability to fix large quantities of atmospheric nitrogen have been shown to be prolific in unpolluted coral reef regions around the world (e.g. see Johannes *et al.*, 1972; Hatcher and Hatcher, 1981; Wilkinson *et al.*, 1984; Wilkinson and Sammarco, 1983). Also the planktonic cyanobacterium (or blue-green alga) *Trichodesmium* spp, which has been found to exhibit high nitrogen fixation rates in the tropical Caribbean (Carpenter and Price, 1977), often dominates the micro (> 20 μm) phytoplankton in the GBR lagoon (Revelante and Gilmartin, 1982). Carpenter and Price (1977) and Carpenter and McCarthy (1975) conclude that nitrogen fixation is the main source of N for *Trichodesmium thiebautii*, the most abundant of the three *Trichodesmium* species identified in their studies. Thus the usual assumption taken for oceanic waters that availability of inorganic nitrogen limits the rate and yield of primary production is probably

not directly applicable to coral reef regions such as the GBR lagoon.

Carpenter and Price (1977) found that the high *Trichodesmium* levels correlated with elevated P-PO₄ levels and hypothesized that the relatively large populations (in comparison with those in the Sargasso Sea) are due to the higher levels of P-PO₄. Their data show that the high cellular nitrogen fixation rates also correlate with the high P-PO₄ region. This finding is in agreement with the work of Mague *et al.* (1974) which showed that increased phosphate levels stimulated acetylene reduction (a measure of nitrogenase activity and hence nitrogen fixation) in samples containing *Richelia intracellularis/Rhizosolenia* spp. Stewart and Alexander (1971) found in laboratory studies on freshwater cyanobacteria that the acetylene reduction rate is directly proportional to the P-PO₄ concentration up to about 0.6 μM. As is discussed below, in the river affected regions of the GBR lagoon, the annual mean (average of results collected weekly to bi-weekly throughout year) P-PO₄ levels are around 0.2–0.3 μM and may have more than doubled over the past 50–60 years (Bell, 1991). If the above findings are applicable to the nitrogen fixing alga of the GBR then such an increase in P-PO₄ levels could well have resulted in a significant increase in the fixation of "new" nitrogen. The nitrogenase complex requires some 30 atoms of Fe for every two atoms of Mo and hence Fe could well limit nitrogen fixation in oceanic waters (Howarth *et al.*, 1988). High Mo levels have been associated with cyanobacteria blooms and in particular with a *Trichodesmium* bloom (Howarth *et al.*, 1988). Phosphorus, Mo and Fe are probably more available to the benthic nitrogen fixing organisms than to the planktonic organisms in the oxic water column because reducing conditions and high dissolved organic carbon (which could act as a chelation agent) are more likely to occur at the bottom (Entch *et al.*, 1983; Howarth *et al.*, 1988). This could well explain the proliferation of benthic nitrogen-fixing algae in coral reef regions, including the Great Barrier Reef.

THRESHOLD LIMITS FOR EUTROPHICATION ON CORAL REEFS

Of all the water quality parameters measured in the Barbados study, the particulate matter concentrations and chlorophyll *a* showed the highest negative correlation with coral growth rate (Tomascik and Sander, 1985). The results of Tomascik and Sander (1985) suggest that mild amounts of eutrophication may have a positive effect on coral growth but beyond the threshold limit adverse impacts occur. A comparison of the 1981–1982 results from the least polluted stations indicates that measurable changes for decreased coral growth rate occur for annual mean suspended particulate matter concentrations (SPM) greater than 4–5 mg/l with a corresponding annual mean chlorophyll *a* level above 0.4 mg/m³.

The corresponding annual mean nutrient levels were: dissolved (total i.e. NH₃-N + NO₃-N + NO₂-N) inorganic nitrogen (DIN) concentration of around 1 μM and P-PO₄ levels of 0.06–0.08 μM. Historical data presented by Tomascik and Sander (1985) for Barbados indicated that the onset of eutrophication may be characterized by even lower levels of the above water quality parameters. For the Kaneohe Bay studies, chlorophyll *a* levels were also highly correlated with the degree of eutrophication (Smith *et al.*, 1981; Laws and Redalje, 1979). The results of Smith *et al.* (1981) for the least polluted section of Kaneohe Bay before diversion, yet still considered eutrophic by Laws and Redalje, show an annual mean chlorophyll *a* level of 0.68 mg/m³ and annual mean nutrient levels of 0.23 μM P-PO₄ and 1.1 μM DIN. Laws and Redalje (1979) report annual mean values for the same region of 0.61 mg/m³ chlorophyll *a*, 0.20 μM P-PO₄ and 1.97 μM DIN. As noted above, after diversion of the sewage considerable improvement in the coral community structure occurred, the annual mean chlorophyll *a* level in the least polluted region was now 0.55 mg/m³ with corresponding levels for P-PO₄ of 0.11 μM and for DIN of 0.78 μM (Smith *et al.*, 1981).

The results from both these sets of studies suggest that chlorophyll *a* is a good, if not the best, indicator of eutrophication and that the critical or eutrophication threshold level in coral reef regions of similar physical (e.g. temperature, depth, flushing time and turbulence) conditions to those in Kaneohe Bay or the fringing reefs of Barbados is around an annual mean value of 0.4–0.6 mg/m³. The levels of chlorophyll *a* corresponding to the onset of eutrophication for these two different coral reef communities are relatively low yet remarkably similar and suggest a chlorophyll *a* threshold value at or below an annual mean of 0.5 mg/m³. This chlorophyll *a* threshold level for eutrophication relates to calmer embayments or lagoonal type situations where the phytoplankton and the resultant detritus is able to settle onto the coral reefs. Higher values of suspended particulate organic matter could probably be tolerated in regions with better flushing and higher turbulence, as would be the case, for example, in outer shelf-break regions. The corresponding eutrophication threshold levels of nutrients are less well defined but the results for Kaneohe Bay and Barbados suggest levels of 0.1–0.2 μM for P-PO₄ and around 1 μM for DIN (Connell and Hawker 1987; Bell *et al.*, 1987; Bell, 1991).

It is recognized that the N and P threshold levels quoted here could be only indicators of the degree of anthropogenic impacts and may for example only reflect the concentrations of available nutrients in the sediments or of other limiting components for algal growth, e.g. other nutrients, such as Mo, Fe, Se, Cu and vitamins (Ishimaru *et al.*, 1989), or even dissolved organic matter that may be required for chelation of existing trace metals. Also many tropical marine

algae have high phosphatase activity (Lapointe, 1989) which may allow them to utilize the organically bound P not recorded by the usual P-PO₄ analysis. Many studies in the past have recorded levels of soluble reactive phosphorus (P-PO₄) only and hence the true status of the nutrient enrichment levels may have been obscured. However the suggested N and P threshold levels do compare to those found for "nuisance" algal growth in other aquatic systems. For example, for DIN, MacIsaac and Dugale (see Bougis, 1976, p. 39) found a half saturation constant of 0.98 μM for eutrophic waters and Nakamura *et al.* (1989) found for *Chattonella antiqua* a half saturation constant for DIN of 1 μM . Also Revelante and Gilmartin (1982) note that NO₃ values above 1 μM are usually considered non-limiting to a phytoplankton crop. The suggested eutrophication threshold level for P is also in general agreement with values found to limit growth of phytoplankton in other aquatic systems. Collingwood (1978) notes that it is generally accepted that mean levels of P-PO₄ in excess of 0.3 μM will cause eutrophication problems in static freshwater systems but that different species of algae do require different levels for comparable growth and to reach maximum density. Brydges (1978) gives data on the effect of fertilization of Middle Lake Ontario. Raising the level from 0.08 to 0.27 μM caused a large increase in the phytoplankton biomass which suggests that a value somewhat less than 0.3 μM is the threshold level for that system. Bougis (1976, Chap. 4) notes for marine algae that the concentration of phosphorus in the environment below which the growth rate decreases is in the range of 0.22–0.55 μM . Thomas and Dodson (1968) found that the final cell concentration of *Chaetoceros gracilis*, an oceanic diatom isolated from tropical oceanic waters, was directly proportional to P-PO₄ concentration up to 0.8 μM and that the rate of growth drops off rapidly below about 0.22 μM . Nakamura *et al.* (1989) found the half-saturation constant for *Chattonella antiqua* to be 0.11 μM P-PO₄.

It is recognized that the above analysis for determining threshold levels is based on correlations of the mean values of the temporally variable water quality parameters and thus does not prove any direct cause and effect relationship. However the fact that both sets of data from two different coral reef environments, one in the Pacific Ocean and one in the Caribbean, give similar values for the eutrophication threshold levels of chlorophyll *a* and nutrients suggests that similar eutrophication threshold levels will be applicable for coral reefs in the inner GBR lagoon which are near to the mainland and/or mainland islands. When one considers the corresponding nutrient levels in secondary treated sewage and even run-off and groundwater can be orders of magnitude greater than the suggested threshold levels the actual value chosen for the threshold value is really not so critical when deter-

mining management policies for the control of such discharges.

STATUS OF EUTROPHICATION IN THE GBR LAGOON

It is noted that no systematic study on the extent of eutrophication in the GBR lagoon has been carried out although there are some historical data available on nutrient levels and primary productivity. Revelante and Gilmartin (1982) expressed their surprise that no seasonal productivity data set had been collected since the 1928–1929 British Museum expedition. Little has changed since the study of Revelante and Gilmartin (details of data given in Ikeda *et al.*, 1980) as no comprehensive (i.e. weekly to bi-weekly sampling of nutrients, chlorophyll *a* and phytoplankton enumeration) annual survey has been completed for the inner to mid-lagoon since their work. Walker and O'Donnell (1981) did collect a fairly comprehensive data set near to Station 1 (see Fig. 1) during the same period as Revelante and Gilmartin (1982) and Ikeda *et al.* (1980) but it would appear that they missed some critical data. Some data have been collected for the outer regions of the lagoon, but as is discussed below, these data are biased towards the summer upwelling periods. Other less complete data sets have been published but these are of little value for establishing the annual or seasonal mean values that are required for comparison with the suggested eutrophication threshold levels.

As is discussed below the available data show that on the large scale, the background levels of nutrients and phytoplankton are relatively high, particularly in the river impacted regions. Also there is some evidence that localized run-off and point source discharges result in localized or small-scale eutrophication. Many of the coral reef communities in these regions are characterized by large stands of macro and filamentous algae. Other reefs, once renowned for their prolific coral growth, have either been destroyed or are now dominated by seagrasses and/or soft corals. These observations although not conclusive proof of eutrophication are consistent with the region being eutrophic.

Large-scale impacts and effects

Inner lagoon off Townsville. Information on annual mean background levels of chlorophyll *a* and nutrients in the GBR lagoon is quite limited. The most comprehensive study since the Great Barrier Reef expedition of 1928–1929 is that of Revelante and Gilmartin (1982) for the region off Townsville (see Fig. 1). Figures 2 and 3 compare the results obtained by Revelante and Gilmartin (1982) for chlorophyll *a* and P-PO₄ (in surface waters) with the suggested threshold levels. These results indicate that the inner to mid lagoon off Townsville could be classed as eutrophic (Bell, 1991). If the suggested threshold criteria are valid for the GBR lagoon then this means

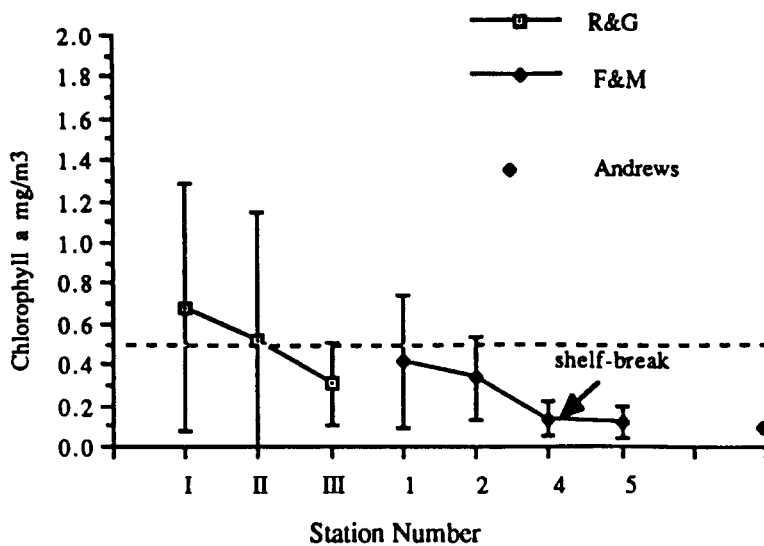


Fig. 2. Cross-shelf variation of chlorophyll *a* as recorded by Revelante and Gilmartin (1982), Ikeda *et al.* (1980) (R & G); Furnas and Mitchell (1984) (F & M); and Andrews (1983)—see Fig. 1 for station location.

that coral reefs in this region could now be experiencing stress through the effects of eutrophication. The revelation that the inner region of the GBR lagoon off Townsville is eutrophic is not new, Revelante and Gilmartin (1982) came essentially to the same conclusion using the productivity classification method of Koblenz-Mishke and Vedernikow, however their conclusion has been largely ignored by the scientific community and regulatory bodies. Satellite imagery data has shown that the phytoplankton growth can be quite extensive and indicate that, based on

the suggested threshold level, that eutrophication may extend well beyond the immediate vicinity of the river discharges (Gabric *et al.*, 1990; Bell and Gabric, 1990). Now it is important to note that, in the vicinity of reefs fringing the mainland and the islands in this region, mean concentrations of nutrients and chlorophyll *a* would probably be significantly higher than the values given in Figs 2 and 3 due to the effects of local discharges and hence the need for strict control of all discharges into this region is indicated.

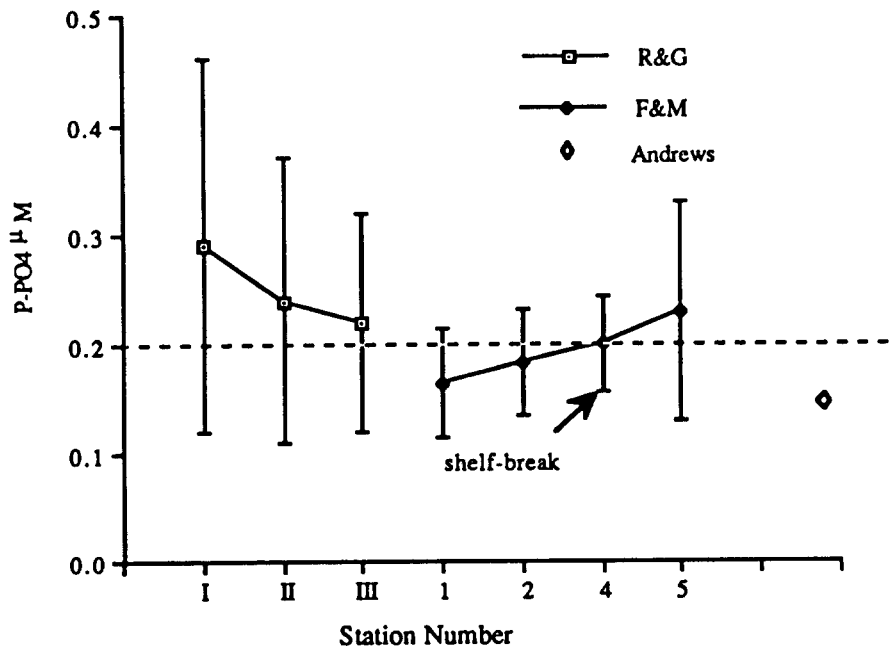


Fig. 3. Cross-shelf variation of P-PO₄ as recorded by Revelante and Gilmartin (1982), Ikeda *et al.* (1980) (R & G); Furnas and Mitchell (1984) (F & M); and Andrews (1983)—see Fig. 1 for station location.

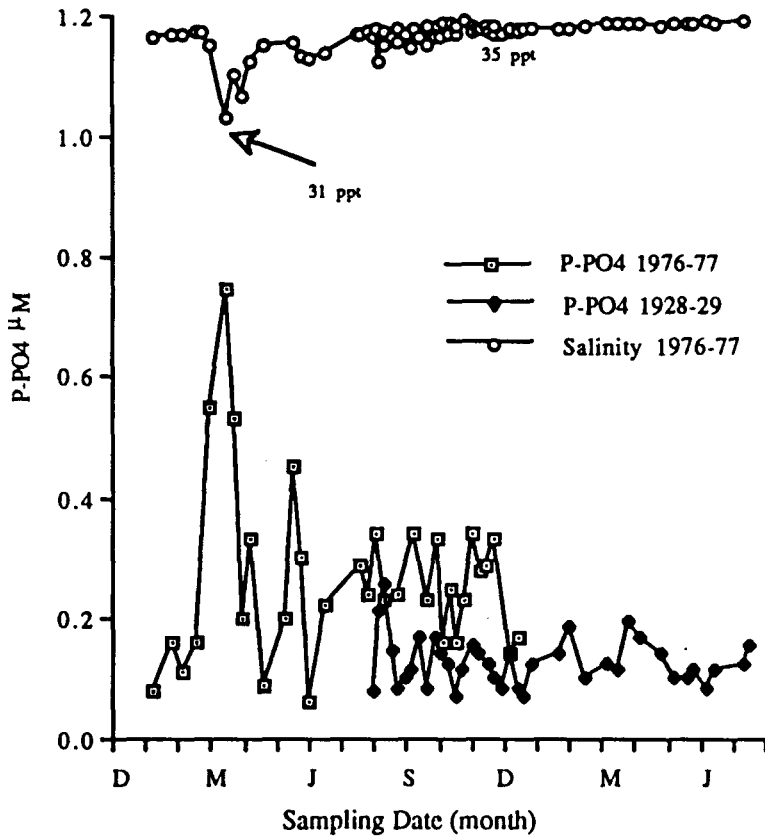


Fig. 4. Comparison of seasonal variation of P-PO₄ and mid-lagoon Station II, 1976-1977 (Revelante and Gilmartin, 1982; Ikeda *et al.*, 1980) with that recorded 3 miles east of Low Isles, 1928-1929 (Orr, 1933).

Revelante and Gilmartin (1982) concluded that riverine discharge is the principal source of the elevated nutrient levels for the near shore region. The

results in Fig 4 and 5 do indeed demonstrate a close correspondence between P-PO₄, silicate and lowered salinity. Walker and O'Donnel's (1981) data also

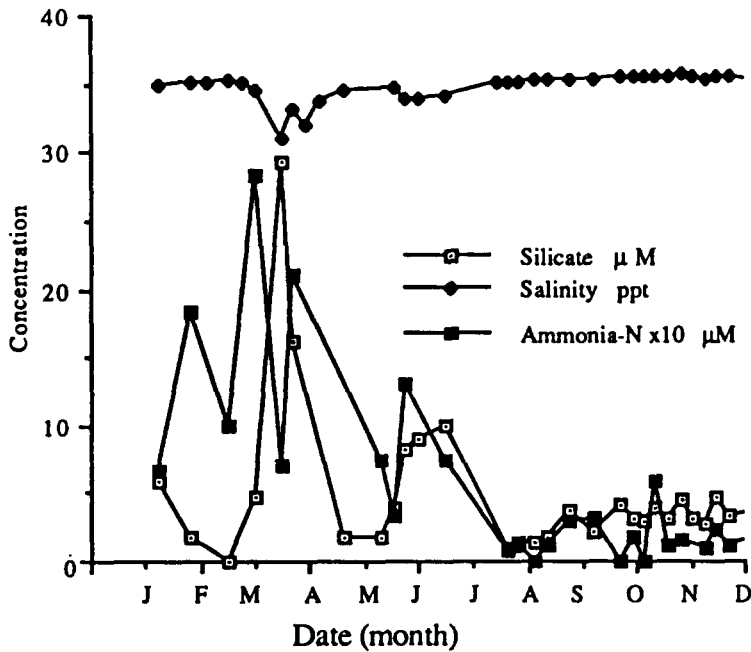


Fig. 5. Seasonal variation of NH₃-N, salinity and silicate at mid-lagoon Station II (see Fig. 1) during 1977 (Revelante and Gilmartin, 1982; Ikeda *et al.*, 1980).

show a close correspondence between high silicate and low salinity but the correspondence between P-PO₄ and salinity is not so clear. However it is noted that the maximum P-PO₄ did correspond to the low salinity period and it would appear that their sampling schedule missed the salinity minimum and corresponding P-PO₄ maximum on 21/3/1977 as recorded by Ikeda *et al.* (1980). Neither data set shows any clear correlation between dissolved inorganic nitrogen (DIN) and salinity. In fact the data of Ikeda *et al.* (1980) show that the DIN (see values for ammonium-N in Fig. 5) actually peaked prior to the minimum salinity value indicating other factors are involved. Bell and Gabric (1990) note that the observed ammonium-N peak follows a relatively high chlorophyll *a* peak and hence could be produced by a decaying antecedent algal bloom. Also Ullman and Sandstrom (1987) have demonstrated that wind-driven resuspension is an important factor contributing to the DIN flux in the GBR lagoon.

There is some limited evidence (also see Fig. 4) which suggests that the levels of P-PO₄ may have more than doubled in the inner lagoon since 1928 (Bell, 1991), which is consistent with the increased loads of phosphorus suggested by Cosser (1987, 1988). However before any definitive conclusion on the increased levels of P-PO₄ can be made the reliability of analytical techniques used in the 1928–1929 study needs to be assessed and a "seasonal" study would have to be repeated at Low

Isles to confirm whether or not the levels of P-PO₄ have actually increased in that region. The data of Revelante and Gilmartin (1982) also show the concentration of micro-phytoplankton (i.e. phytoplankton > 20 μm, principally *Trichodesmium* and diatoms) in the lagoon in the river-impacted regions is some 1–2 orders of magnitude greater than that recorded by Marshall (1933) at Low Isles in 1928–1929 (see Fig. 6). Now the methods used by Revelante and Gilmartin (1982) in enumerating the phytoplankton differ from those used by Marshall (1933) and hence an exact comparison of the results may not be valid, but the results do indicate that the levels of micro-phytoplankton are significantly higher in the river-affected region off Townsville than was the case in the lagoon near Low Isles in 1928–1929. From the discussion above on nitrogen fixation, the high level of *Trichodesmium* growth in the river-affected region off Townsville could well be driven by the elevated P-PO₄ levels of the region. Of course other factors such as increased loads of organics and trace components such as Fe, Mo and vitamins could be as or even more important than the increase in P-PO₄ but there are no data available on these.

Outer lagoon off Townsville. Some data for the outer regions of the GBR lagoon are also available (see Table 1 and Figs 2 and 3) but no complete weekly or fortnightly annual data set has been collected. The results in Table 1 are temporal means of particular sampling periods and not annual means and

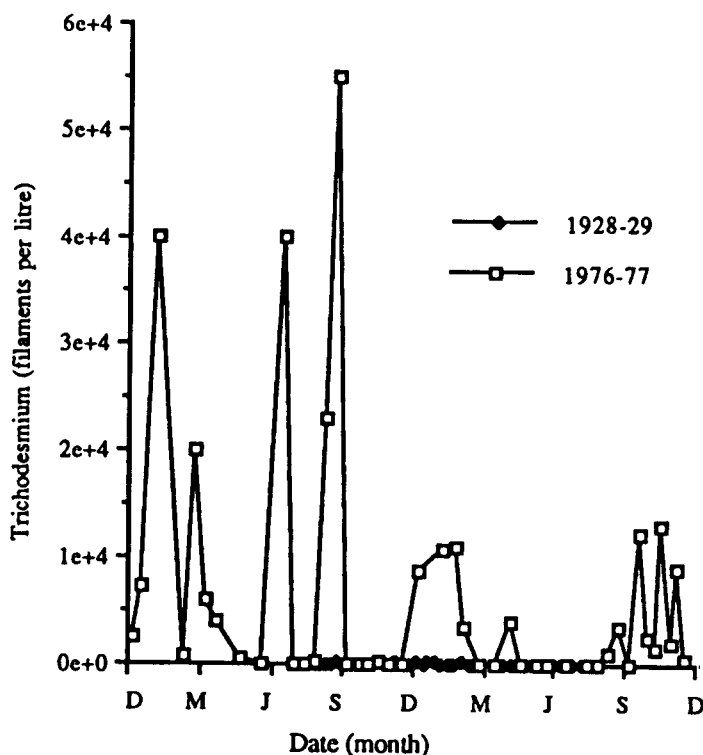


Fig. 6. Comparison of seasonal variation of *Trichodesmium* at mid-lagoon Station II off Townsville, 1976–1977 (Revelante and Gilmartin, 1982; Ikeda *et al.*, 1980) with that recorded in mid-lagoon 3 miles east of Low Isles, 1928–1929 (Orr, 1933).

Table 1. Mean nutrient and chlorophyll *a* in outer GBR lagoon

Region	P-PO ₄ (μM)	DIN (μM)	Chl. <i>a</i> (mg/m ³)
<i>Lizard Island</i> ¹			
Across reef	0.22	0.99	
Offshore	0.26	1.02	
<i>Central GBR</i> ²			
Lagoon	0.13 (0.07)*		0.39 (0.24)
Shelf-break	0.32 (0.22)		0.32 (0.46)
Coral sea (surface)	0.13 (0.10)		0.13 (0.10)
Reef zone			0.56
<i>Davies Reef</i>			
Inside reef ³	0.105	0.39†	
Outside reef	0.105	0.05†	
Inside reef ⁴			
II (summer)			0.72 (0.01)
I (winter)			0.42 (0.06)
Outside reef ⁴			
II (summer)			0.36 (0.03)
I (winter)			0.27 (0.05)
<i>Palm Passage</i> ⁵ (surface waters)			
Station 1	0.16 (0.05)	0.30 (0.2)	0.42 (0.33)
Station 2	0.18 (0.05)	0.22 (0.2)	0.33 (0.20)
Station 4	0.20 (0.04)	0.23 (0.2)	0.14 (0.08)
Station 5	0.24 (0.10)	0.23 (0.2)	0.10 (0.06)

*(SD).

†(NO₃ + NO₂).(1) Crossland and Barnes (1983); (2) Andrews (1983); (3) Entch *et al.* (1983);(4) Furnas *et al.* (1990); (5) Furnas and Mitchell (1984a,b).

therefore cannot be directly compared with the suggested threshold values. In particular the results of Andrews (1983) and Furnas and Mitchell (1984a,b) are probably biased towards the high side because these data were mostly collected during the upwelling periods. However the data do illustrate that some regions of the outer lagoon are characterized by naturally high levels of nutrients and phytoplankton productivity for considerable portions of the year. The high levels of nutrients are attributed to phenomena such as upwellings (Andrews, 1983; Furnas and Mitchell, 1986, 1987) and in addition, in the case of DIN, to nitrogen-fixing algae and bacteria which inhabit the sub-strata of coral reefs (e.g. see Entch *et al.*, 1983; Hatcher and Hatcher, 1981; Wilkinson *et al.*, 1984; Wilkinson and Sammarco, 1983). The results show relatively high chlorophyll *a* levels in the mid-shelf region, and particularly in the lagoons of the mid-shelf reefs (see results for Davies Reef in Table 1). This region is apparently characterized by naturally high concentrations P-PO₄. The results in Fig. 3 show that P-PO₄ enrichment of the waters occurs towards the outer shelf, which is consistent with the source of P-PO₄ being due to upwelling. At these levels of P the growth of N-fixing algae may only be limited, if at all, by the availability of micro nutrients such as Fe and Mo and possibly vitamins (e.g. B₁₂). Also the availability of such trace components may be only limited by the concentration of soluble organic matter. Thus in these naturally enriched outer regions not only is the addition of N and P important but most probably so is the addition of trace components (e.g. organic matter, Fe, Mo and vitamins). Hence special precautions may be required in controlling the

discharge of run-off and sewage effluent in the outer regions of the lagoon.

Low Isles. Since the 1928–1929 British expedition to Low Isles, the corals have been subjected to the destructive forces of cyclones and to attacks by the crown of thorns starfish. A large portion of the reported flourishing hard coral cover in the shallower waters has been replaced by sea grasses, algae and soft corals. These observations, although they are not conclusive evidence, are consistent with the region being eutrophic. The principal cause of the eutrophication is surmised to be due to river discharges transporting nutrients from agricultural areas. The fact that the Low Isles region is impacted by river run-off has been recognized by various workers. Fairbridge and Teichert (1948, as cited by Johannes, 1972) note that many of the corals in the vicinity of Low Isles had apparently been killed by sedimentation which they attribute to "colossal soil erosion due to unplanned agriculture". Brown and Howard (1985) note that Yonge came essentially to the same conclusion on revisiting Low Isles, 50 years after the 1928 British expedition. The data summarized in Fig. 7, which were collected over the period 1977–1982 (CSIRO, 1989), certainly show significant freshwater influence at Low Isles. The correspondence of low salinities with high silicate levels is an indicator that the freshwater is river derived (Bell and Gabric, 1990) and not simply precipitation. Nitrate levels were also recorded (mean $0.33 \pm 0.52 \mu\text{M}$), but not P-PO₄ as reported incorrectly by Rasmussen and Cuff (1990), and these are of similar magnitude to the values measured by Revelante and Gilmartin (1982) for the river-affected inner lagoon off Townsville. Some more recent results obtained by Rasmussen and

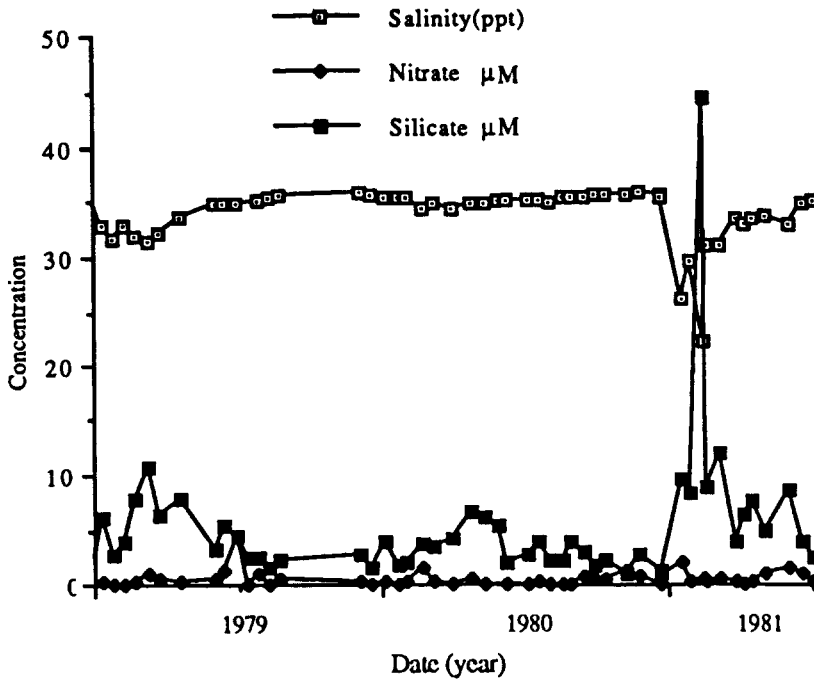


Fig. 7. Seasonal variation of nitrate, silicate and salinity off Low Isles (CSIRO, 1989).

show that, following heavy rainfall, the levels of $P-PO_4$ are often relatively high near to Low Isles. A more useful assessment of the changed status of eutrophication would be obtained if the Low Isles study could be repeated. Until this is done definitive conclusions on the status of eutrophication in the region are not possible.

Lizard Island. The results in Table 1 for Lizard Island, which were collected during September 1977, indicate relatively high background levels for nutrients both offshore and across the reefs. The high $P-PO_4$ levels at Lizard Island probably result from a combination of terrestrial run-off and upwelling due to its closeness to both the mainland and the outer barrier reef. The results in Fig. 8 show a

close correspondence between low salinity and high silicate, which again indicates that the reduced salinity is due to the river discharge not simply to precipitation (Bell and Gabric, 1990). The fact that this region is probably already enriched by both river discharge and upwellings suggests that it may be particularly susceptible to impacts from local run-off, groundwater and sewage discharges.

Importance of *Trichodesmium*. As noted above the data of Revelante and Gilmartin (1982) show the concentration of *Trichodesmium*, in a river-impacted region of the GBR lagoon, is some 1–2 orders of magnitude greater than that recorded by Marshall (1933) at Low Isles in 1928–1929 (see Fig 6). If it is shown that the levels at Low Isles today are

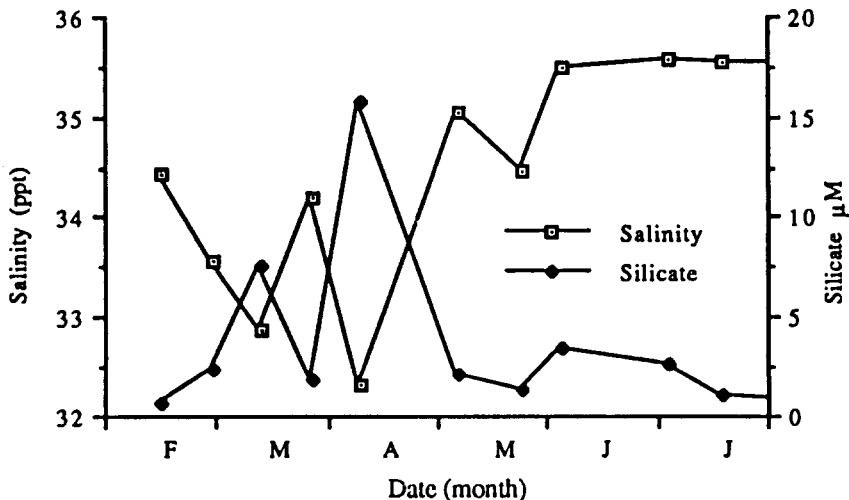


Fig. 8. Seasonal variation of salinity and silicate at Lizard Island, 1979 (CSIRO, 1989).

much higher than they were in 1928–1929 then this would be good evidence that eutrophication is indeed a problem in the GBR lagoon. The importance of *Trichodesmium* spp lies in its apparent ability to utilize atmospheric N_2 as its sole source of nitrogen under aerobic conditions (e.g. see review by Creagh, 1985) and thus provide “new” nitrogen to the system. Another important point in regard to *Trichodesmium* is that it should be able to utilize organic forms of phosphorus due to its high alkaline phosphatase activity (Fogg, 1982, p. 505). Hence *Trichodesmium* should be able to out-compete with many other algae in waters with low values of combined nitrogen and even inorganic phosphate, provided of course, that the supply of other essential nutrients is adequate and the physical and chemical factors are conducive to nitrogen fixation. It appears that on decay the *Trichodesmium* releases “new” nitrogen (and probably phosphate) which is then readily available for other non-nitrogen-fixing algae such as diatoms (see data of Ikeda *et al.*, 1980; Bell, 1991). Indeed the data of Revelante and Gilmartin (1982) show a quick succession of diatoms following the *Trichodesmium* bloom of Dec.–Jan. 1976–1977 (see Bell, 1991). A more detailed analysis of this succession phenomenon (see Revelante *et al.*, 1982) shows that the bloom also produced a marked rise in the records of dinoflagellates. Such nutrient enrichment of waters and plankton succession following *Trichodesmium* blooms have been noted previously by Devassy *et al.* (1979) who found a rapid diatom succession after the *Trichodesmium* followed by cladocerans, then dinoflagellates and green algae, copepods and finally carnivores.

Crown of thorns. Endean and co-workers found in many cases, particularly in back reef areas, recolonization was negligible 6–10 years after the corals had been destroyed by *A. planci*. Endean (1976, p. 245) notes the extensive cover of alcyonarians (soft corals) on some reefs, and mats of filamentous and stalked algae on others, must hamper recolonization by the hard corals. These observations are consistent with the premise that eutrophication hinders and may even prevent the reestablishment and regrowth of corals after their destruction by *A. planci*. Eutrophication and *A. planci* may be related even more closely than has been suggested above. Indeed there is some evidence that the outbreaks of *A. planci* could well be due to eutrophication. Birkeland (1982) notes the correspondence between the occurrence of run-off, phytoplankton blooms and outbreaks of *A. planci* in Guam. He proposes the hypothesis that the coincidence of phytoplankton blooms, brought about by run-off events, and the spawning of *A. planci* would increase the survival of the phytoplankton-grazing *A. planci* larvae. The hypothesis is based to a large extent on the work of Lucas (1974, cited by Birkeland, 1982). Lucas (1982) notes that nanoplankton (i.e. phytoplankton $< 20 \mu m$) is a suitable food source for the *A. planci* larvae provided the concentration of the

phytoplankton is greater than a critical level. Lucas notes that this critical level is characterized within the ranges 5×10^2 to 1×10^3 cell ml^{-1} , 0.4 – 1 mg m^{-3} chlorophyll *a* and 130 – 300 nl l^{-1} volume of nutritious particles. It is considered significant that the suggested chlorophyll *a* threshold level for eutrophication, 0.5 mg m^{-3} , is in this critical range.

Lucas (1982), in reviewing the data set used by Revelante and Gilmartin (1982), notes for the outer regions that during December–February, the breeding season for *A. planci*, the concentrations of phytoplankton are low or marginal for the nutritional requirements of *A. planci* larvae and hence food could well be a major environmental influence on survival and development of *A. planci* in these waters. Further analysis of the same data set shows the mean annual nano plankton count for the inner, mid and outer lagoon regions are greater than the critical level which suggests that conditions do occur quite frequently when there is sufficient food to promote the growth of the larvae. Hence survival and development of *A. planci* could well be promoted if the occurrence of high nano plankton levels coincided with the breeding season. Thus the general hypothesis that the occurrence of *A. planci* outbreaks in the GBR lagoon have been promoted to some extent by eutrophication appears more than feasible and should be followed up by more intensive research. It is hypothesized that eutrophication of the inner to mid GBR lagoon has provided a link between the normal inshore habitat of the *A. planci* and the naturally nutrient enriched, highly productive outer reef waters.

Small-scale impacts and effects

There is some evidence that small-scale discharges of run-off, groundwater and sewage are also contributing to eutrophication in the GBR lagoon and in doing so are impacting upon coral reef ecosystems. In the GBR region there are some legislative controls on the discharge of sewage but essentially none on the discharge of run-off. In general the current practice in the GBR region is to treat sewage to secondary level and to discharge the treated sewage to marine waters. Discharges are often located near to fringing reefs and in several cases near to recreational waters. Over the years there have been exceptions to the general rule of secondary treatment. Hamilton Island has until recently, discharged primary treated sewage to the marine waters in close proximity to fringing coral reefs. The main discharge from Green Island, while it is chlorinated, receives little or no treatment beyond primary settling. Septic tanks are used in several areas and some effluents from sewage treatment plants are discharged to the groundwater system (e.g. as is done on the coral cay, Heron Island). The effects of these discharges have not been assessed in detail but some pilot programmes have recently been initiated (see van Woesik *et al.*, 1990; Steven *et al.*, 1990). Evidence is emerging which is consistent with several of the

fringing reefs being adversely affected by this localized or small scale eutrophication.

Green Island. The discharge from Green Island, although chlorinated, has at times, a quality worse than raw sewage in that it is partially fermented in the overloaded septic system prior to discharge. This often results in relatively high concentrations of potentially toxic sulphides. Dye tracer studies have shown that both the north-western and northern sides of the cay are impacted by the discharge (Kurchler, 1978; van Woesik, 1989). It is in these very same areas that there has been a marked expansion in the extent of seagrass beds (Kurchler, 1978) and the demise of coral communities. The region nearby the jetty was known as the "coral gardens" and an underwater observatory was located to view these corals (Gillett and McNeill, 1959). These corals have met with a similar fate as their namesake in Kaneohe Bay. The area directly impacted by the sewage is also used for recreational purposes and although the effluent is chlorinated, could pose a health hazard to bathers.

Whitsunday Group—Hamilton and Hayman Islands. Dye tracer studies carried out on Hamilton Island in November 1984 by the Water Quality Council of Queensland (Water Quality Council, 1985a,b) showed that effluent of the primary treated sewage was transported north of the discharge point on both ebb and flood tides. It was postulated that the resultant elevated nutrients had facilitated the profuse algal growth to the north of the outfall. Run-off from the resort area, which is relatively turbid and rich in soluble-P ($\sim 6 \mu\text{M}$) (Bell *et al.*, 1987), flows directly into Catseye Bay, the fringing reef of which is now overgrown by algae.

Dye tracer studies of the discharge from Hayman Island showed that some of the effluent was discharging through a hole directly onto the reef flat and the rest was discharging through a broken pipe at the reef edge. On the flood tide much of the fringing reef was bathed in diluted effluent and much of this was transported towards the main water sports recreational area (Bell, 1989). Rubble and the few remaining corals in the vicinity of the discharge were noted to be covered with filamentous algae. Monitoring of permanent sites in the region has shown that recruitment of corals is markedly suppressed in the vicinity of the sewage outlet (van Woesik *et al.*, 1992).

Townsville and Magnetic Island. Some of the most diverse fringing coral reefs in the world are struggling for survival in Cleveland Bay along the shoreline of Magnetic Island. The results of Revelante and Gilmartin (1982) demonstrate that the waters of Cleveland Bay were eutrophic in the late 1970s. In addition to the large scale impact of river discharge on the bay there are a number of local or small scale impacts. The harbour channel is dredged regularly and the spoil is dumped into Cleveland Bay. The discharge of partially treated sewage from the

city of Townsville flows to Cleveland Bay. The plant has been undergoing an up-grade for some time now and when completed will discharge around 35,000 m³/d. Much of the sludge from this sewage plant is also discharged to the bay. It is noted that it is normal for such sludge to contain not only high levels of nutrients but also heavy metals and toxic organics. Also there is some evidence of seepage of sewage, from the septic tanks and/or from the irrigation of treated sewage, into creeks which discharge to the coral reef area of Nelly Bay, Magnetic Island.

Nelly Bay was once renowned for its coral reef platform of *Acropora*, *Turbinaria* and *Montipora*, much of which emerged at low tide and was ironically also known to many as the "coral gardens" (e.g. see Johannes, 1972, p. 366; Collins, 1978; Endean, 1976, p. 227). "As recently as the latter half of the 1960s the island still possessed coral gardens that were equal, and in fact often superior, to anything... on the Great Barrier Reef... the diversity and form and delicate colouring of the corals painted an exquisite picture of unequalled beauty" (T. Brown as quoted by *Townsville Daily Bulletin*, 8/3/1972). The demise of the reefs at Nelly Bay and the nearby Geoffrey, Arthur and Florence Bays on Magnetic Island have been attributed to increased sedimentation which results from the dumping of spoil from harbour dredging and also to effects of cyclone "Althea" (Collins, 1978; Endean, 1976, p. 227). However there is some evidence that eutrophication has played an important role in the demise of the reefs. Brown has noted that seaweed growth invaded the silt-saturated environment which effectively eliminated many of the remaining corals (paraphrased by *Townsville Daily Bulletin*, 8/3/1972). Endean reports (1976, p. 229) that algae invaded many areas after destruction of part of the coral cover and this precipitated further destruction by trapping sediment. Collins (1978) notes that following the effects of "Althea" and further heavy rainfall between 8 and 12 January 1972 the majority of *Turbinaria* and *Montipora* colonies were alive but in contrast very few branches or stumps of *Acropora* could be found and the numerous dead branches were covered in a film of algae. Less than 5% of the *Acropora* was alive on the reef to a depth of 2 m by the end of February 1972. *Acropora* was observed to regenerate from fragments in the deeper waters ($> \text{LWD} + 2 \text{ m}$) but no recruitment of new colonies of *Acropora* resulting from the settlement of larvae was observed in the following 15 months. Collins (1978) notes that both increased sedimentation and algal growth make the conditions unsuitable for the settlement of larvae on inshore reefs and also eludes to the possibility that eutrophication may be causing an increase in the algal growth on reefs in the Townsville region. These observations are consistent with the hypothesis that lack of recovery of the "coral gardens" of Nelly Bay is not only due to the impacts of spoil dumping but also due to eutrophication.

While there is no quick and easy solution to controlling the large scale eutrophication of waters surrounding Magnetic Island, small scale or more localized eutrophication due to point source discharges such as sewage, can be more easily controlled e.g. by using more appropriate sewage treatment and disposal technology. The impact of localized run-off from developed areas is also manageable to some extent, particularly if taken into account at the design stage. The concept of leaving an undeveloped vegetated buffer zone between the development and the waters edge appears to have worked on parts of the island of Maui, Hawaii (personal observation, 1990). Another concept gaining acceptance is to develop with minimal disturbance to the local landscape. For example a resort at Maho Bay, St John, U.S. Virgin Islands, was built with little or no alteration to the natural contours of the land. All walkways are raised boardwalks and accommodation is in separate units, all raised above the ground so that minimal removal of the natural vegetation was required. In stark contrast to this minimal impact scenario is the maximum impact scenario occurring at Nelly Bay, Magnetic Island. For this development no buffer zone is allowed for. In fact the existing buffer zone of parkland, mangrove stands and public beach have been taken over by the developer. The development will not only destroy much of the existing buffering capacity of the foreshores which provides a biological filter for the septic seepage from the existing local population but will also increase run-off to the fringing reefs. A most beautiful headland dotted with large granite boulders and majestic pines was literally blasted apart and dumped into Nelly Bay in order to reclaim land and to construct a marina. The entrance to the marina requires the mining of the fringing coral reef. As part of this development it has been proposed to irrigate secondary treated sewage on parts of the remaining public grassed foreshores of Nelly Bay. The impact of wastewater discharges from this development could prove to be disastrous for the remains of the "coral gardens" in Nelly Bay and adjacent Geoffrey Bay.

CONCLUSIONS

Chlorophyll *a* appears to be the best water quality indicator of eutrophication in coral reef regions and a eutrophication threshold value (annual mean) at or below 0.5 mg m^{-3} is suggested. The concentrations of nutrients N and P associated with the onset eutrophication in coral reef communities are less well defined (annual mean DIN $\sim 1 \mu\text{M}$; P-PO₄ $\sim 0.1\text{--}0.2 \mu\text{M}$) but are in accord with eutrophication threshold levels for sensitive freshwater ecosystems. There is evidence that some near-shore regions of the GBR lagoon are already eutrophic and that this is caused principally by river run-off. Impacts of eutrophication on coral reefs namely,

increased dominance of macro algae and filamentous algae and expansion of seagrass beds into regions which in the past were renowned for their corals, has been recorded. *Trichodesmium* blooms may have been promoted by the increased nutrient levels, and particularly by P-PO₄ and these blooms could be an important source of new nitrogen to the system. The recorded levels of nano plankton growth in some river-affected regions of the GBR lagoon are sufficient to promote the survival *Acanthaster planci* (crown of thorns starfish) larvae and as such eutrophication could well be a principal causative factor of the crown of thorns outbreaks. Elevated levels of nutrients and algal growth occur in some outer regions of the GBR but these appear to be due to natural phenomena. The high background concentrations of nutrients and phytoplankton in both the inner and outer GBR, whether they are natural or not, demands that special precautions be exercised in the control of sewage effluents and run-off in the vicinity of coral reefs. Evidence suggests that wastewater discharges (sewage, run-off, groundwater seepage) will cause further impact on coral reef systems of the GBR unless the appropriate control measures are implemented. The components of most concern appear to be the nutrients (N, P and trace components such as Fe, Mo and organic matter) and, in addition with run-off, suspended solids and the freshwater carrier itself. Thus tertiary treatment of sewage (i.e. the removal of nutrients) is necessary for discharges in the vicinity of coral reefs if acceptable levels (after dilution) of nutrients are to be achieved. Efforts, preferably at the planning stage, need to be made to ensure that run-off is not discharged in the vicinity of fringing reefs.

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