Status of Eutrophication in the Great Barrier Reef Lagoon

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Historical data on the levels of nutrients and phytoplankton in the GBR lagoon are reviewed. The results indicate that background levels of P-PO_4 and phytoplankton have increased significantly over the past 50-60 years and that the levels appear be at or above the eutrophication threshold level for coral reef waters. Other data indicate that river discharge probably has a major impact on the nutrient status of the GBR lagoon, but other factors such the nitrogen-fixing blue-green alga, *Trichodesmium*, could also be important. *Trichodesmium* has the ability to introduce large amounts of new nitrogen and it appears that the increased phosphorus levels could be driving its growth. To-date little effort has been made to assess the impact of eutrophication on the coral reef communities. Because the background nutrient levels are relatively high both run-off and sewage discharges could have serious impacts on nearby coral reef communities. Tertiary treatment (i.e. nutrient removal) of sewage should be required for all discharges in the vicinity of coral reefs and special precautions need to be exercised when designing run-off drainage systems.

Introduction

This paper is concerned with the 'inner lagoon' of the Great Barrier Reef (GBR). The inner lagoon is defined for the purposes of this paper as that expanse of water bounded on one side by mainland Australia and on the other by the mid-shelf coral reefs of the GBR. Within the inner lagoon itself there are many coral reefs fringing both the coastline and islands as well as numerous patch reefs and some coral cays. Detailed circulation patterns of waters within the GBR lagoon are not available but the available information demonstrates that the GBR restricts the exchange of lagoon waters with the Coral Sea (Wolanski, 1981) and hence the lagoon can be considered as a partially enclosed sea.

A significant proportion of the lagoon's coastline is now developed. Industrial, urban and agricultural development has increased rapidly over the past century. This development is continuing and this, in conjunction with the growth in tourist developments, pose particular environmental problems for the lagoon and its many coral reefs. Large non-point sources of nutrients discharge into the lagoon via river discharge (e.g. see Cosser, 1988 for review). Also point source discharges of nutrient laden treated and untreated sewage effluent occur along the coast and from island resorts within the lagoon itself. Detailed studies on the impact of such discharges have not been carried out but Bell et al. (1989) have reviewed the possible impacts. The region off Townsville is one of the most studied regions of the GBR yet the only "seasonal" phytoplankton analysis which has been completed in this region is that described by Revelante and Gilmartin (1982). Revelante and Gilmartin expressed their surprise that the only other "seasonal" phytoplankton study completed in the GBR lagoon is that carried out in 1928-29 by Marshall in the inner lagoon at Low Isles. In this paper the results from these two studies are compared.

In the present study the term eutrophication refers to a situation where an increase in nutrient levels has occurred and has resulted in "nuisance" algal growth. Such "nuisance" algal growth can lead to a complete change in the original community structure of an ecosystem and in the case of coral reefs can lead to the replacement of corals with benthic algae and a variety of filter feeders.

Impact of Nutrients on Coral Reefs

The impact of nutrients on coral reefs may be direct or indirect. Direct toxic effects will occur if the concentrations are high enough, however these effects will not be discussed in this paper. In this paper it is the indirect effects of relatively low levels of nutrients that are of interest. It is noted that coral reef communities are extremely efficient in recycling nutrients and hence it is generally accepted that they have the ability to thrive in nutrient-poor conditions. Salin (1983) notes they are like oases in the desert. It is very likely that the addition of even small amounts of nutrients will lead to eutrophication which will cause significant changes in the coral reef community structure by promoting the growth of phytoplankton and benthic algae. The phytoplankton

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compete with the symbiotic zooxanthellae for light and thus interfere with coral growth. Possibly a more important problem is that an increase in phytoplankton growth adds significantly to the sedimentation load and in particular to the organic fraction of that load. The benthic algae affect the coral by interfering with the complex life processes which normally occur at the coral surface. The benthic algae together with the increased numbers of filter feeders (promoted by the increased sedimentation load) directly compete with the corals for space. The effect of benthic growth appears to be most severe after other disturbances such as large run-off events or physical damage e.g. due to storms or crown-of-thorns attack. In such instances corals find it hard to reestablish. Now the levels of nutrients to bring about "nuisance" algal growth or eutrophication in coral reef communities appears to be quite small. Two regions which have well documented studies on the effects eutrophication are Kaneohe Bay, Hawaii (Smith et al., 1981; Laws and Redalje, 1979) and Barbados (Tomascik and Sander, 1985). Sewage effluent was discharged into Kaneohe Bay for many years. The coral community which existed in the south east (S.E.) section of the bay was once purported to be one of the finest in the world but this coral community was eventually destroyed and replaced by benthic algae and filter feeders.

Following diversion of the sewage effluent in 1977-78 very good recovery of the coral community occurred but there are still problems today with the benthic alga *Dictyosphaeria cavernosa.* In the Barbados study the degree of eutrophication was far less severe in that mass mortalities of corals were not recorded however significant reduction in coral growth rates (Tomascik and Sander, 1985) and in the settlement of coral spats (Tomascik, pers. comm.) were observed along the eutrophication gradient.

Threshold limits for Eutrophication of Coral Reefs

For the Kaneohe Bay studies chlorophyll *a* levels were highly correlated with the degree of eutrophication (Laws and Redalje, 1979). The results from Smith et al. (1981) for the least polluted section before diversion (yet still considered eutrophic by Laws and Redalje) show mean chlorophyll *a* levels of 0.68 mg/m^3 and mean nutrient levels of 0.23 µM P-PO_4 and 1.1 µM TIN (total inorganic nitrogen). As noted above, following the diversion of sewage effluent from Kaneohe Bay, considerable improvement in the coral community structure occurred. The mean chlorophyll *a* level recorded in the least polluted region was now 0.55 mg/m^3 with corresponding levels for P-PO_4 of 0.11 µM and for TIN of 0.78 µM.

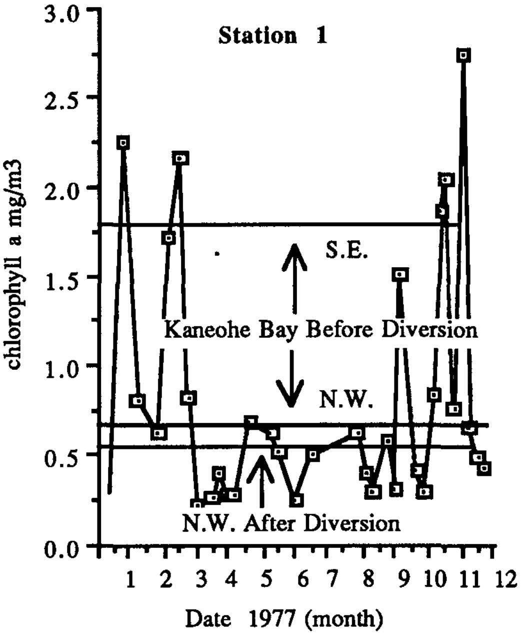

Figure 1. Comparison of chlorophyll *a* in near-shore station 1 during 1976-77 with values in Kaneohe Bay before and after diversion.

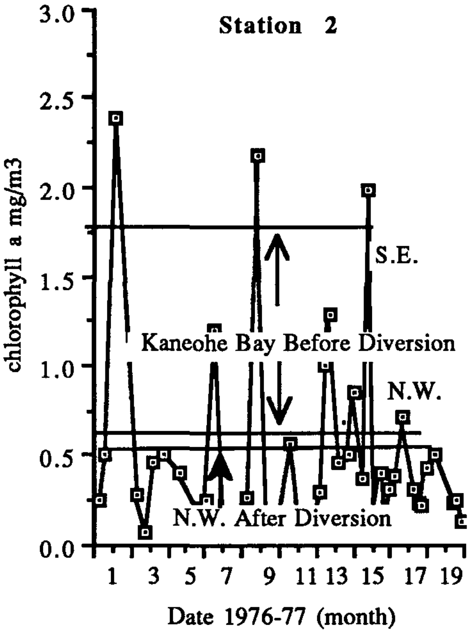

Figure 2. Comparison of chlorophyll *a* in mid-lagoon region 1976-77 with values in Kaneohe Bay before and after diversion.

Of all the water quality parameters measured in the Barbados study, chlorophyll *a* and suspended particulate matter showed the highest negative correlation with coral growth rate. The data for the three least polluted stations show that measurable changes for decreased coral growth rate occur for mean chlorophyll *a* levels of 0.4-0.6 mg/m^3. The corresponding mean nutrient levels were: total inorganic nitrogen (TIN) levels of around 1 µM and P-PO_4 levels of 0.06-0.08 µM.

The results from both sets of studies demonstrate that chlorophyll *a* is a good, if not the best, indicator of eutrophication and that the critical or threshold level for eutrophication in coral reef regions of similar physical (e.g. temperature, flushing time and turbulence) conditions to those in Kaneohe Bay or along the fringing reefs of Barbados is at or below 0.5 mg /m^3. It is important to note that this threshold level for eutrophication relates to calmer embayments or lagoonal type situations where the algae and organic detritus are able to settle onto the coral reefs. Higher values of suspended organic particulate matter could possibly be tolerated in regions with better flushing and higher turbulence.

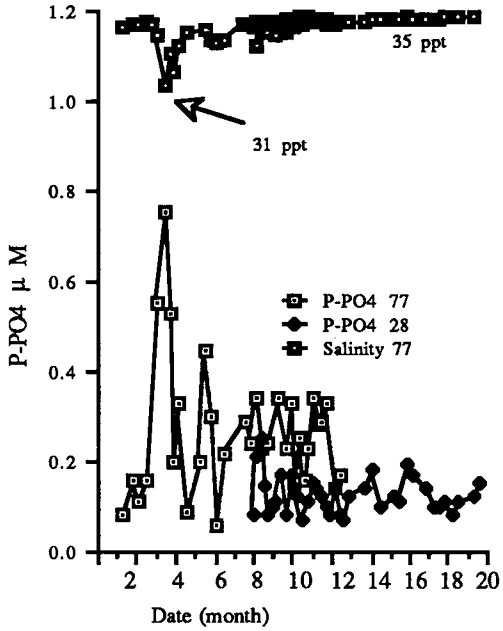

Figure 3. Comparison of phosphate levels at Low Isles (1928-29) with those at mid lagoon station 2 1976-77.

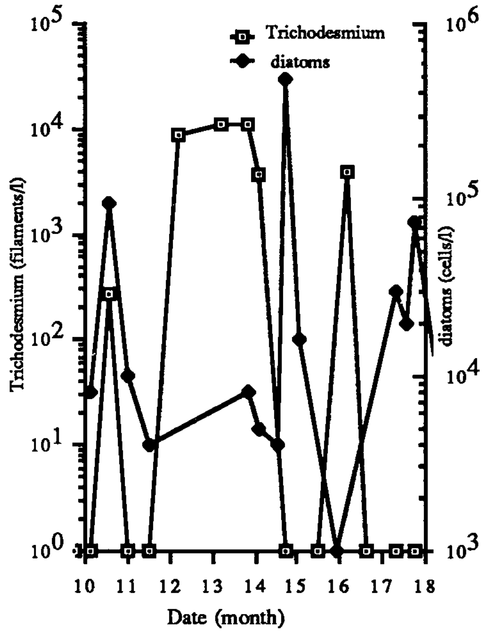

Figure 4. Example of diatom succession following *Trichodesmium* bloom at mid lagoon station 2 1976-77.

The threshold levels of nutrients are less well defined than is the level of chlorophyll *a* but the above results suggest eutrophication threshold levels of 0.1-0.2 µM for P-PO_4 and of around 1 µM for TIN. It is noted that in both studies a stronger correlation was found between P-PO_4 and the effects of eutrophication than was found for TIN. Bell et al.(1989) suggest that the stronger P-PO_4 relationship could be due to the fact that many algae and bacteria associated with coral reefs are nitrogen fixers and hence the growth rates and yield of such communities could be independent of added inorganic nitrogen levels. Also it is noted that the rate of nitrogen fixation of some cyanobacteria is proportional to P-PO_4 levels up to about 1 µM (Stewart and Alexander, 1971). Nitrogen fixers can also have high requirements for some trace compounds. For example the growth of nitrogen fixers may become limited by the availability of trace elements such as Fe and Mo, and even by vitamins. Dissolved organics could also be important as they may increase the availability of the trace elements for example through chelation (Howarth and Marino 1988). Thus sewage discharges and terrestrial run-off would not only provide the macro nutrients N and P but also could provide necessary trace components and through their organic content improve the availability of such components.

The low chlorophyll *a* threshold level and nutrient threshold levels reflect the high sensitivity of the coral reef communities to suspended organic particulate matter and to the competition with the attached algae. The importance of the organic content of the particulate matter cannot be over emphasised (e.g. see Tomascik and Sander, 1985). It is the high organic content that leads to competition by the filter feeders and to troublesome anaerobic conditions (e.g. production of extremely toxic H_2S) within the sediments and possibly on the surface of the corals. The state of eutrophication in the GBR lagoon will now be reviewed in the light of the proposed threshold levels for chlorophyll *a* and nutrients.

Eutrophication in the GBR lagoon

Bell et al. (1989) in their review note that the mean levels of nutrients within the GBR lagoon and nearby reefs are relatively high (e.g. Lizard Island 0.22 µM-0.26 µM P-PO_4; 1.0 µM TIN) in comparison with those in waters outside the GBR. The relatively high levels of nutrients near to the reef matrix reflect the high efficiency of nutrient recycling and also demonstrate the nitrogen fixing capabilities of the the reef ecosystem. The high nutrient levels at Lizard Island could result from upwelling and terrestrial inputs as this island is relatively close to both the barrier reef and to the mainland. In the inner regions of the lagoon terrestrial run-off is believed to be an important source of nutrients and in the case of TIN the nitrogen fixing alga *Trichodesmium* appears to play an important role (Revelante and Gilmartin, 1982).

Figures 1 and 2 summarise the the seasonal chlorophyll *a* data of Revelante and Gilmartin (1982) for the near shore Station 1 and the mid-lagoon Station 2 off Townsville. These figures compare the GBR lagoon results with the mean chlorophyll *a* levels for Kaneohe Bay before and after the sewage effluent diversion. Based on the discussion above and using a threshold value for chlorophyll *a* of 0.5 mg/m^3 it would seem that the inner GBR lagoon was eutrophic in 1976-78. The values for P-PO_4 in Figure 3 for the mid lagoon station tend to confirm this. Revelante and Gilmartin came to this conclusion for the inner stations but the present analysis, in conjunction with recent satellite imagery data (Gabric et al. 1990), suggests the problem may not be restricted to the inner near-shore stations but extends well into and along the lagoon for very considerable distances (100-1000 km). As noted by Revelante and Gilmartin a major contributor to the phytoplankton standing crop is the nitrogen fixing cyanobacteria (blue-green algae) *Trichodesmium spp.* (sometimes referred to as *Oscillatoria spp.*). Other studies have demonstrated that *Trichodesmium* has the ability to fix large amounts of nitrogen particularly in tropical waters (see review by Creagh, 1985). Some of the studies indicate that phosphorus deficiency may limit the growth of *Trichodesmium*. Thus an inorganic nitrogen source should not be necessary for *Trichodesmium* to grow, even at bloom proportions. All that should be required for *Trichodesmium* to bloom is the occurrence of a suitable physical environment and for sufficient chemicals besides TIN such as phosphorus and micro-nutrients.

Figures 3 and 5 compare Revelante and Gilmartin's phytoplankton and phosphate data with those collected from Low Isles (Marshall, 1933 and Orr, 1933). The correspondence of the highest P-PO4 value with the lowest salinity value for the 1976-77 data (Figure 3) does indicate that the river discharge is a principal source of P-PO_4. The data in Figure 3 suggest that P-PO_4 levels in the inner lagoon may have more than doubled since around 1930. Of course the reliability of Orr's analytical techniques would need to be assessed and a "seasonal" study would have to be repeated at Low Isles to confirm this. The results of Stewart and Alexander (1971) suggest that this order of increase is probably more than sufficient to have significantly increased the nitrogen-fixation rate of the cyanobacteria. Indeed the data in Figure 5 show that over ten years ago the levels of *Trichodesmium* in this river-affected area were orders of magnitude greater than they were at Low Isles in 1928. Also it appears that on decay (see Figure 6) the *Trichodesmium* releases ammonia (and possibly phosphate, not shown) which is then readily available for other non-nitrogen fixing algae such as diatoms. Indeed the data in Figure 4 show a quick succession of diatoms following the *Trichodesmium* bloom of Dec-Jan 1976-77. Such nutrient enrichment of waters and plankton succession following *Trichodesmium* blooms has been noted previously by Devassy et al. (1979). The data also show (not presented here) that the levels of diatoms in the river affected areas are also much higher than they were in 1928.

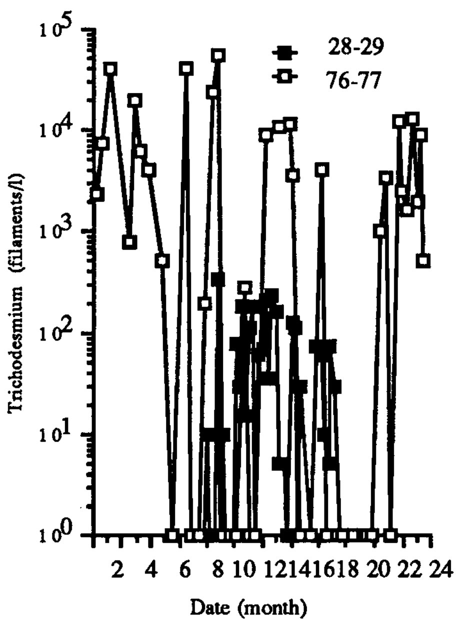

Figure 5. Comparison of temporal variation of *Trichodesmium* concentrations at Low Isles 1928-29 with those at Stn 2 Central GBR.

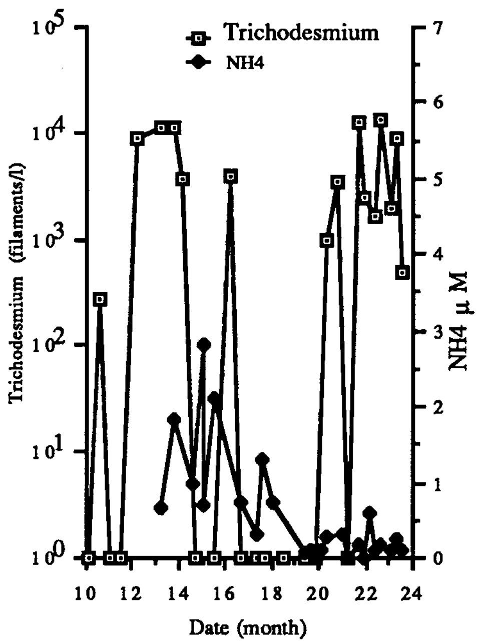

Figure 6. Example of N-NH_4 enrichment of waters by *Trichodesmium* 1976-77.

The increased levels of P-PO_4 in the lagoon are attributed mainly to the increased agricultural activities and in particular, to the increased use of synthetic fertilizers (e.g see Cosser, 1988). Cosser (1988) suggests the load of phosphorus may have doubled since such development. When one considers that Australian soils are typically low in soluble P then it is possible that the increase in some regions has been considerably more. For some agricultural regions wind-borne transport and atmospheric drop-out could also be important as well as run-off. Other chemical factors as well as phosphorus, such as trace components and organic matter, are probably also important in the promotion of the proliferation of *Trichodesmium*. In urban areas and on island resorts sewage and run-off could also be highly significant sources of P-PO_4 and other necessary constituents, especially on the local scale. The impact of these discharges is magnified by the fact that the background levels of the nutrients are already high. As a general rule it is suggested that sewage be treated to a tertiary level (i.e. removal of nutrients) before discharge to waters containing coral reefs. Local run-off to these waters also needs to be controlled (Bell et al., 1989).

It is noted that in the phosphorus-rich, but combined-nitrogen-poor, outer lagoon regions the availability of micro-nutrients such as Mo and Fe could limit nitrogen-fixing phytoplankton growth. As noted above the availability of such trace elements can be enhanced not only by increased concentrations but also by the presence of dissolved organic carbon because of its chelation properties. Organic carbon may also be important due to its vitamin content. In these outer regions, where the influence of the rivers is far less than for the near-shore regions, the impacts of local run-off and sewage discharges may be particularly severe. For these reasons it is suggested that the outer regions could be particularly prone to eutrophication and hence there may need to be very tight controls on the discharge of sewage and run-off in these areas.

Conclusions and Recommendations

The above data suggest that levels of P-PO_4 and chlorophyll *a* in the inner GBR lagoon were at or over the threshold for eutrophication in 1976-78 and that river run-off is a significant source of the phosphorus. The results also indicate that the nitrogen fixing algae *Trichodesmium* is responsible for much of the eutrophication and that its growth is driven by the increased levels of P-PO_4 and possibly by the increased availability of trace components. These findings need to be verified now by instigating a large scale "seasonal" monitoring programme. If these findings are verified then there are very serious management implications. Overall there is good evidence that the discharge of untreated sewage and even secondary treated sewage in the vicinity of coral reefs will lead to their demise, particularly in regions of poor flushing. Thus there is a good case for the enforcement of tertiary (i.e nutrient removal) treatment standards for the GBR lagoon as a whole. Run-off from developed areas can contribute large loads of nutrients and other contaminants and thus lead to the demise of the fringing reefs unless special precautions are taken.

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