Title: Studies of nutrient variability and the consequences for benthic communities on the Coral Coast fringing reefs, Fiji

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# Studies of nutrient variability and the consequences for benthic communities on the Coral Coast fringing reefs, Fiji

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# STUDIES OF NUTRIENT VARIABILITY AND THE CONSEQUENCES FOR BENTHIC COMMUNITIES ON THE CORAL COAST FRINGING REEFS, FIJI

A thesis submitted in fulfillment of the requirements for the award of the degree

DOCTOR OF PHILOSOPHY

from

UNIVERSITY OF WOLLONGONG

by


ULUKALESI BALE TAMATA

(BSC, MENVSTUDIES)

SCHOOL OF EARTH AND ENVIRONMENTAL SCIENCES


- 2007 -

## Thesis Certification

I, Ulukalesi Bale Tamata, declare that this thesis, submitted in fulfillment of the requirements for the award of Doctor of Philosophy, in the School of Earth and Environmental Sciences, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Ulukalesi Bale Tamata

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## LIST OF ACRONYMS

| | |
|---|---|
| AIMS | Australian Institute of Marine Science |
| ANOVA | Analysis of variance |
| ANZECC | Australian and New Zealand Environment and Conservation Council |
| CCC | Coral Cay Conservation |
| COTS | Crown-of-thorns starfish |
| CSM | coral surface microlayer |
| EEZ | Economic Exclusive Zones |
| EHMP | Ecosystem Health Monitoring Program |
| FVB | Fiji Visitors Bureau |
| FLMMA | Fiji Locally Managed Marine Areas Network |
| GAR | Great Astrolabe Reef  Lagoon of Kadavu, Fiji |
| GBR | Great Barrier Reef of Australia |
| GCRMN | Global Coral Reef Monitoring Network |
| GDP | Gross Domestic Product |
| GESAMP | Joint Group of Experts on the Scientific Aspects of Marine Environment Protection |
| IAS | Institute of Applied Sciences |
| ICLARM | International Center for Living and Aquatic Resources Management |
| ICM | Integrated Coastal Management |
| ICRI | International Coral Reef Initiative |
| IDA | Inside Demarcated Areas |
| IOC | International Oceanographic Commission |
| IOI | International Ocean Institute |
| IUCN | International Union for Conservation of Nature and Natural Resources |
| LNSW | Low nutrient seawater |
| MPA | Marine Protected Area |
| RDM | Relative Dominance Model |
| SEAKEYS | The Sustained Ecological Research Related to the Management of the Florida Keys Seascape |
| SIDS | Small Island Developing States |
| SOPAC | Pacific Islands Applied Geoscience Commission |
| SPREP | South Pacific Regional Environment Program |
| USP | University of the South Pacific |
| UNCED | United Nations Conference on Environment and Development |
| UNEP | United Nations Environment Program |
| WFD | Water Framework Directive |

## LIST OF NON-ENGLISH (FIJIAN) WORDS

| | |
|---|---|
| Cawaki | Sea urchin harvested by locals for subsistence or commercial use |
| Dabi | *Xylocarpus granatum*, a coastal plant with medicinal  uses |
| Dogo | *Bruguiera gymnorhiza*, a coastal mangal species |
| I Qoliqoli | Traditional fishing grounds for indigenous Fijians |
| Kuka | *Sesarma erythrodactyla*, red-clawed mangrove crab harvested for subsistence and commercial use by locals |
| Qari | *Scylla serata,* mud crab harvested for subsistence and commercial use by locals |
| Sinugaga | *Xecocaria agallocha,* a coastal mangal species |
| Tabu | MPA, ‘no-take’ zone |
| Tiri | *Rhizophora stylosa,* a mangrove species |
| Tiritabua | *Rhizophora mucronata,* a mangrove species |
| Tiriwai | *Rhizophora mangle,* a mangrove species |

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## Abstract

The Coral Coast region, in south-western Viti Levu, Fiji, is the 'hub' of tourism development in Fiji, and is one of the fastest developing areas in Fiji. Since the 1980s, development along the Coral Coast has occurred at a rate never previously seen in this area. Large resorts and smaller backpacker facilities emerged from the once coconut-tree lined coastal stretch, from Serua, to Natadola. Village populations have also increased. Anecdotal information and the few, sporadic studies conducted in this area have indicated that the water quality and the biological communities on the fringing reefs have deteriorated dramatically since the 1980s. Live corals which used to feature prominently on the fringing reefs (hence the name 'Coral Coast), have been replaced by weedy macroalgae, the most common of which is the brown algae *Sargassum.* The Coral Coast fringing reefs were apparently undergoing phase shifts (like other reefs around the world), and anthropogenic factors have been blamed. The need for scientific information on the effects of anthropogenic activities on the Coral Coast water quality and fringing reef communities prompted this study.

The study had several objectives. Two major components addressed the need to establish baseline scientific information on the variability of dissolved nutrients in the water column, and the status of biological communities on the reef flats of the fringing reefs, for control sites (away from human impacts), and impacted sites (close to villages and resorts).  Nutrients from anthropogenic sources on land have been identified as one the major bottom-up controlling factors for phase shifts on coral reefs. Control, village and resort sites were monitored for nutrient concentrations from 2003 – 2006, and sampling times covered seasonal as well as weather effects, particularly the effects of storm-associated rainfall. Benthic surveys were also carried out in control and impacted sites several times over the period 2004 – 2006. To complement the results from the longer term monitoring of water quality and reef benthic communities, a number of short-term, targeted experiments were conducted in the laboratory and in the field, to examine nutrient uptake by algae, herbivory impacts and nutrient sources.

A combination of the Line Transect and Quadrat Point Intercept methods were used for the assessment of the abundances and distribution of the main species on the fringing reefs, especially *Sargassum* sp. Nutrient enrichment experiments were conducted in the laboratory and also in the field to assess uptake of nutrients by *Sargassum* sp. Herbivore-exclusion caging experiments were conducted in the field to assess influence of herbivory in a ‘tabu’ or marine protected area (MPA) as well, as in non-‘tabu’ or open-fishing sites. Samples of *Sargassum* sp. and a few other dominant macroalgae species from the study sites were analysed for tissue nitrogen and phosphorus contents and for $\delta^{15}N$ content, to aid nutrient source identification.

Nutrient concentrations were highly variable, showed little association with season, but were strongly linked to rainfall. The results indicated the clear influence of pulse (storm runoff related) events on the nutrient concentrations in the water column. Control sites generally recorded lower nutrient concentrations than impacted sites, confirming the anthropogenic effects on water column nutrients. The biological communities on the fringing reefs reflected the status of nutrients in the water column, i.e., reefs close to human impacts recorded higher abundances of macroalgae, especially *Sargassum* sp., and lower abundances of live corals. The nutrient enrichment experiments showed the ability of *Sargassum* sp. to take up nutrients very quickly from the water column, but the rhizoids showed greater responses than the leafy shoots used in the experiments. The ‘low growth’ season for *Sargassum* sp. during the Cool season (May to October) may be the explanation for the differential responses between the rhizoids, and the leafy parts of the *Sargassum* plants used in the experiment. Caging experiments showed the significance of herbivory in the control of *Sargassum* sp., and the ‘tabu’ sites appeared to show a greater intensity of herbivory (lower suvivorship for uncaged shoots). Both tissue nutrient and $\delta^{15}N$ contents in macroalgae samples matched the findings from the water column nutrient studies, i.e., the human-impacted sites exhibited nutrient enrichment in the water column and in the macroalgae on the reef flats. *Sargassum* samples from impacted sites had higher tissue % N and higher $\delta^{15}N$ contents compared to the control sites confirming that human activities were enriching the coastal waters with nutrients.

On the basis of the results from this research, recommendations are proposed for better management of nutrient sources on land for the protection of the water quality, and therefore promote healthier coral reef systems. The significance of protecting herbivorous species is also important, and the setting aside of ‘tabu’ sites is encouraged. Areas of further research are also identified, for better understanding of the interrelationships among all the factors involved in the phase shift occurring on the fringing reefs along the Coral Coast of south-western Viti Levu, Fiji.

**Acknowledgement**

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# CHAPTER 1 – GENERAL INTRODUCTION AND BACKGROUND.

## GENERAL INTRODUCTION

There is widespread concern about the way we humans, in our quest for a 'better life', are bringing about changes to our environment, changes which may or may not be good for the natural ecosystems being affected. In the catchments, we have cleared forests and replaced them with food crops to feed our increasing populations; we have also cleared forests and natural vegetation to make way for roads and cities to accommodate our changing needs and lifestyles. The coastal areas are particularly vulnerable to human-induced modifications because of the varied and often conflicting interests and opportunities pertaining to these areas.

While in some cases these changes have not had drastic effects, in others, the changes have caused irreversible alterations. One of the main reasons for such gloomy scenario is our lack of understanding of what is happening in this situation. We do not have adequate information at our disposal to enable us to mitigate against the effects of our own actions, yet we continue on our destined course of actions to achieve our goals, hoping that in time we will have acquired the necessary information to mitigate the adverse effects of our actions. This is especially true for the less developed countries where scientific and technical expertise are generally lacking, the funds to support scientific research are not easily accessible and therefore, there is a general lack of reliable, baseline scientific information about the environment and the natural resources therein. The Republic of the Fiji Islands, and most other island nations of the South Pacific fall into this category. These countries are classified as 'Small Island Developing States' (SIDS) under the United Nations system of socio-economic groupings for countries. It is encouraging, however, to see an increasing number of national and regional initiatives aimed at addressing the need for scientific, baseline information about our natural resources.

This thesis presents the findings of my research conducted for the degree of Doctor of Philosophy (PhD) in Environmental Science at the University of Wollongong, New South Wales, Australia. The field work for the research was conducted in my home country, Fiji, while the literature research, data analyses and formal writing of the thesis was conducted at the University of the Wollongong, Australia

This study was conducted in an area of rapid development known as the Coral Coast, located in south-western Viti Levu in the Fiji Islands (see Figure 3.1). The Coral Coast is probably the part of Fiji that has undergone the greatest change in the last thirty years, yet hardly any information existed about the water quality, the nutrient status of the coastal waters or the benthic characteristics of the inshore fringing reefs of this area, except for a few isolated studies (Morton and Raj 1980; Ryland 1981; Raj *et al*., 1981; Mosley and Aalbersberg, 2003). However, since about 2001, there has been renewed interest in the marine ecosystems along the Coral Coast, as people became more informed about the threats of human-induced changes on the natural ecosystems, in the light of rapid development of the Tourism sector in Fiji. The Coral Cay Conservation (CCC) group with their team of scientists conducted coral reef surveys on most of the reefs on a one-off basis, and the locally-based group FLMMA (Fiji Locally-Managed Marine Areas) operating out of the University of the South Pacific (USP) also conducted biological surveys, utilizing trained village personnel. My research had already commenced by the time these initiatives got under way, so while the biological information from their work complemented mine, my other main research focus, which was nutrient status of the waters in relation to development activities, should provide the information necessary to understand at least, in part, the changes that are being observed in the reefs.

From the few and sporadic studies, and general observations made when traveling along the Coral Coast, it is clear that conditions have deteriorated over the years, especially where land-based sources of pollution are close by. The water quality has worsened due to increased sediment loading and sewage pollution appeared to have increased. Human populations in the coastal communities and villages have also increased. The recent boom in the number of small, commercial operations such as restaurants and shopping centers, resorts, hotels and motels along the coast have contributed to the current status of the Coral Coast reefs. The fringing reefs have shown signs of being affected, with macroalgae especially *Sargassum* sp. becoming more prominent, and live corals becoming scarce. The selection of the study area is based on the fact that the Coral Coast with beautiful, white sandy beaches, blue waters and the sunny weather, is one of the fastest developing regions in Fiji today, and the boom is attributed to growth in the tourism industry.

## 1.2 RATIONALE FOR RESEARCH

The subject of the research is probably one of the most important challenges that we face today: how can we reconcile our need to develop and utilize the coastal areas for economic reasons on the one hand, and the impacts of such activities on the environment, particularly the water quality and the coral reefs on the other?

International concern for coral reefs is manifested in many ways: 1997 was declared as the "International Year of the Reef" to spearhead public awareness about the threat to coral reefs, under the International Coral Reef Initiative (ICRI). The United Nations then declared 1998 as the "International Year of the Oceans". Global monitoring efforts were enhanced, and included Reef Check 97, and ReefBase. ReefBase, initiated in 1993, is a database produced by the International Center for Living and Aquatic Resources Management (ICLARM), to provide information on ecological and socioeconomic data on coral reef sites around the world. In 1995, the International Coral Reef Initiative (ICRI) was launched in the Philippines, and ICRI has now been endorsed by most coral reef countries of the world. ICRI was the international response to the UNCED Rio Earth Summit in 1992, and the concerns of Small Island Developing States. In October 1997, the World Bank and the ICLARM sponsored a conference dedicated to coral reefs: "Coral Reefs: Challenges and Opportunities for Sustainable Management" (The World Bank, 1998). A number of volunteer programs assist in the drive to build up data on the status of coral reefs, and these include Reef Watch, Reef Keeper, REEF, Frontier, Coral Cay Conservation and Reef Check (Bryant *et al*.,1998).

There is consensus that the coral reefs of the world are being devastated by human impacts. The first global survey of human impact on coral reefs through the initiative called Reef Check 97, surveyed 250 coral reefs in 30 countries around the world. The results were alarming: hardly any pristine reefs, there was evidence of pollution and human impacts in most reefs, the depletion of high-valued target species in Southeast Asia, and a growing incidence of disease among both hard and soft corals (The World Bank, 1998).

The role of science in understanding the complex interaction between the coral reefs and anthropogenic stresses cannot be over emphasized. To address this need, a number of global, regional and local initiatives have been developed.

The Global Coral Reef Monitoring Network (GCRMN) is a joint program of the International Oceanographic Commission (IOC), the World Conservation Union (IUCN) and the United Nations Environment Program (UNEP), coordinated by the Australian Institute for Marine Sciences (AIMS), and ICLARM. The GCRMN collaborates with governments and local communities in efforts to regularly assess the coral reefs and data gathered is fed into ReefBase (Bryant *et al*., 1998).

At the International Coral Reef Initiative (ICRI) Regional Symposium on Coral Reefs held in Noumea, New Caledonia during May 2000, one of the points highlighted was the lack of monitoring capacity and support for assessment of the coral reefs in the countries of the southwest Pacific, including Fiji. This prompted the formation of the Global Coral Reef Monitoring Network (GCRMN) Node by seven Pacific Island countries namely Fiji, Nauru, New Caledonia, Samoa, Solomon Islands, Tuvalu and Vanuatu. The node for these countries is the International Ocean Institute (IOI) of the University of the South Pacific. The need for a coral reef monitoring network for the southwest Pacific showed prominently when large-scale coral bleaching affected many reefs in the region in early 2000. The absence of information about the status of the reefs before this bleaching event made it impossible to assess the extent of the impact of the bleaching (South & Skelton, 2000).

Various studies have been completed especially to address the problem of pollution of the marine ecosystems due to land-based sources. However, these studies have been concentrated in the developed countries where the technical expertise, the financial resources and the policy frameworks are in place and available for such research to be carried out. The problem takes on new dimension in developing, small island nations like Fiji because the economy of the countries and the livelihood of the ordinary people depend to a much greater extent on the marine resources. The economy is very much dependent on tourism which is concentrated along the beautiful coastlines of these islands, yet there is limited capacity all around to monitor the impacts of these developments on the marine environment and ecosystems. This is one of the main reasons for choosing Fiji as the research site for this research.

Much is being debated about the impacts of nutrient enrichment on coral reefs. There are differing views about threshold levels for nutrients, or whether threshold levels should be even considered as such. The complexity of interactions among the physical, chemical and biological attributes of an inshore fringing reef must be appreciated and taken into account in any discussion of nutrient effects on the biological communities on the reefs. There is also debate about the relative effects of nutrient enrichment on the one hand, and herbivory on the other, on the seemingly successful displacement of corals and coralline algae by the fleshy, macroalgae on coral reefs worldwide. The Coral Coast in Fiji is no exception to this trend, but hardly any scientific investigation has been conducted to investigate just how significant these two factors are in controlling the changing character of the fringing reefs. My research has tried to look at both of these, i.e., to assess the 'bottom-up' influence by way of nutrient level analysis for the ambient water, and also the 'top-down' control by conducting controlled herbivory experiments using cages.

One common fallacy among people of the Pacific, including Fiji, is that marine habitats and resources are almost unlimited and that if one is degraded or depleted, there will always be another to replace it. Slowly, people are waking up to the fact this is not the case and that drastic measures need to be taken now if the generation of tomorrow are to share this heritage also. For Pacific Islanders, coral reefs are intricately linked to their traditional roles, as well as provide for their subsistence, and protection against forces of nature in the form of storms and tidal waves. Managers of coral reef resources have to balance conservation and ecological concerns on the one hand and the social/cultural pressures on the other. This requires participatory and integrative approach to coral reef management. The Pacific Regional ICRI Symposium in Noumea, New Caledonia, agreed on three principal sets of recommendations one of which was to improve scientific understanding of coral reef ecosystems with effective translation and transfer of information (Crosby *et al*., 2002).

## 1.3 OBJECTIVES OF MY RESEARCH

My research has attempted to address the problem statement below:

**THE AESTHETIC VALUE, WATER QUALITY AND FRINGING REEFS' COMMUNITIES ALONG THE CORAL COAST, IN SOUTH-WESTERN VITI LEVU, FIJI ISLANDS, ARE AT RISK OF FURTHER DEGRADATION AS A CONSEQUENCE OF INCREASED TOURISM DEVELOPMENT ACTIVITIES, AND COASTAL VILLAGE POPULATIONS. NUTRIENT ENRICHMENT FROM THESE LAND-BASED SOURCES NEEDS TO BE MONITORED AND MANAGED, FOR THE PROTECTION OF THE COASTAL WATERS AND THE FRINGING REEFS IN THE AREA. UNREGULATED FISHING AND OVER-FISHING OF HERBIVOROUS SPECIES MAY EXACERBATE THE PROBLEM BY ENHANCING THE GROWTH CAPABILITIES OF ALGAE OVER THOSE OF CORALS, IN IMPACTED FRINGING REEFS.**

The research had five general objectives in light of the problems outlined above. These research objectives were:

a) through long-term monitoring of the water quality including nutrients, establish baseline information on the physical and chemical characteristics of the in-shore coastal waters, and main creeks discharging into the coastal waters of the Coral Coast Region of South-western Viti Levu, Fiji Islands;
b) through long-term monitoring of the fringing reef communities along the Coral Coast, determine the general physical and biological characteristics of the fringing reefs, in particular the distribution and abundance of the macroalgae *Sargassum* sp., and possibly the controlling factors;
c) conduct an assessment of the possible sources of nutrient pollution at the study sites;
d) conduct controlled experiments in the field and in the laboratory, to investigate nutrient uptake by *Sargassum* sp., effects of herbivory using caging experiments, variation in tissue nutrients and $\delta^{15}N$ concentrations in macroalgae from the study sites; and,

e) from the results and findings of the research, put forward recommendations for improved usage of the coastal resources, better management of nutrient sources affecting this highly-valued asset of Fiji known as the *Coral Coast*, and suggest areas for further research.

## 1.4 RESEARCH STRUCTURE

The thesis has seven chapters:

Chapter One presents a general introduction and background to the research. The chapter has four subsections, each with a brief overview of the research. In this chapter, the rationale for the research is presented, as well as the background as to why the research was important for the study area selected. The problem statement which forms the basis of the research, and the five research objectives are also presented in Chapter 1.

Chapter Two presents the review of the literature relevant to the research. The review starts with general aspects such as the significance of coral reefs and why they needed special attention for conservation purposes. The literature on anthropogenic effects on coral reefs is quite phenomenal, and some of this is reviewed. The current research on causes of coral reef degradation including methodologies is also reviewed. Particular emphasis is paid to the effects of nutrient enrichment and herbivory on the benthic communities of coral reefs because these are the factors investigated in the research. Finally, the data available from the recent studies from my study sites along the Coral Coast of south-western Viti Levu are reviewed.

Chapter Three presents an overview of my study sites. Not only are the physical boundaries of the localities discussed, the socio-economic factors which characterise each locality within my study area are also discussed in order to understand the local setting, the national economy and how tourism is one of the main drivers of the economy, and how these are impacting on the marine environment, specifically the in-shore coastal waters and the fringing reefs.

Chapter Four discusses the field and laboratory work conducted to investigate the status of water nutrient levels along the Coral Coast. Nutrients from land-based sources have been identified as some of, if not the major contributing factors to coral reef degradation. By comparing nutrient levels in creeks in my study sites, to those of coastal waters, the relative contributions from these different sources to the nutrient pool in coastal waters could be assessed. The influence of weather is also investigated by comparing date from 'dry' sampling events to those from 'wet' sampling events.

In Chapter Five, the results of surveys of the benthic communities on the in-shore fringing reefs along the Coral Coast of south-western Viti Levu, Fiji are presented. This has been an interesting research in that during the period of the monitoring, changes were also occurring along the shore and inland. Land was being cleared and more buildings were being constructed. In fact one of the sites I had designated as a 'control' site progressively became an impacted one as more 'bures' or thatched houses were built to accommodate the growing demand for backpacker-type operations. This site provided a clear case of 'before vs after' impact situation. The changes on land were certainly reflected in the benthic communites on the fringing reefs nearby.

Chapter Six describes the experiments conducted in the field and in the laboratory to investigate the research questions further. Caging experiments were conducted in the field to investigate effects of herbivory on the macroalgae *Sargassum* sp. In the laboratory, nutrient enrichment and their effects on growth of *Sargassum* sp. was investigated. Through collaboration with colleagues from the University of Queensland, some macroalgae samples were prepared at the USP and taken to UQ for sewage-tracing tests using isotopic methods. The results from that one-off test is also discussed in this chapter. Some macroalgae sample from my study sites were also sent to the Government Laboratory at Koronivia Research Station for nutrient content analysis. The findings from that analysis will also be discussed.

Chapter Seven discusses the main conclusions drawn from the field monitoring of nutrients and benthic communities, the results of the field and laboratory experiments, and examines whether there are clear patterns of relationships among these.

# CHAPTER 2 – GENERAL LITERATURE REVIEW

## 2.1 INTRODUCTION

This chapter reviews the literature on coral reefs and the way in which these valuable ecosystems are being affected by anthropogenic factors. The significance of coral reefs is reviewed, especially the complexity of interrelationships that control the responses of coral reef organisms, species and communities as a whole. There is still much that is not understood about these webs of interactions. Despite this, the effects of human activities on these ecosystems continue to grow day by day because there is an imbalance, human activities continue to increase while the understanding of coral reefs, and therefore mitigative responses are lagging behind. This chapter reviews two models or paradigms that have been proposed to explain the 'phase shift' from coral dominance to algal dominance, as reported from the numerous observational studies on coral reefs. Methods used to study the mechanisms of nutrient effects on algae are reviewed. Finally, the actions taken by large groups of developed countries to try and mitigate against the impacts from human actions are discussed as examples of what can be done. The socioeconomic value of coral reefs for smaller, developing countries is highlighted because to them, coral reefs are much more than biological ecosystems, rather coral reefs form the basis of their economies and their livelihood.

## 2.2 SIGNIFICANCE OF CORAL REEFS

Coral reefs are among the most highly diverse ecosystems of the world (Dubinsky, 1990; Birkeland, 1997). It has been stated that coral reefs have the greatest biological diversity per hectare, at the phyla and classes levels of classification, of any ecosystem in the oceans (Paulay, 1997; Birkeland, 1997). It is also suggested that for some of the large regions including Southeast Asia, the Mediterranean, and some other temperate regions, the standing stock of coral reef fishes are about 30 – 40 times greater than standing stocks on demersal fishing grounds (Russ, 1984a). Coral reef ecosystems have evolved over both geological time and geographic space to present the unique, boundless diversity and complex interrelationships that characterise coral reefs and which modern researchers are still trying to unravel (Dubinsky, 1990).

The value of coral reefs is enormous and varied, e.g., for Florida's economy, $1.6 billion from reef tourism (Birkeland, 1997). Seaweeds from coral reefs provide food for people dependent on coral reefs for their subsistence. Other resources are harvested for medicinal use, or sold for agar and carrageenan. In the Philippines in 1989, a total of 65,600 metric tons of algae of the genus *Eucheuma* was sold (South, 1993). Reefs protect coastlines against strong wave action. On Guam, the storm damage to coastal communities was much less where there were reefs, compared to unprotected coastlines, at the villages of Inarajan and Merizo, where fringing reefs are narrow (Birkeland, 1997).

It is of interest to note that there are two different views or explanations for the high diversity associated with coral reef communities (Grigg and Dollar, 1990). Endean (1976) and others have described coral reefs as being fragile ecosystems that have evolved under relatively stable physico-chemical conditions, into highly specialized but predictable communities (Johannes, 1975; Loya, 1976). Endean (1976) also suggested that the coral reefs were being protected against large scale disturbances, by the natural buffering systems of the tropical waters. However, because of the delicate linkage between coral reefs and the environment they occur in, any human-induced impacts would have disastrous effects on the reefs (Johannes, 1975). This view of coral reef diversity even suggested that it is very unlikely that a coral reef will recover to its previous status following disturbance or destruction due to human activities (Endean, 1976; Pearson, 1981).

The second school of thought described coral reef communities as being a "temporal mosaic" in space (Grassle, 1973). According to this theory, coral reef communities are not stable, but are in various stages of succession or recovery from a variety of stresses and disturbances that affect coral reefs daily (Grigg and Maragos, 1974; Connell, 1978). This second theory had been supported by other studies (Grigg and Maragos, 1974; Connell, 1978). Connell's work (1978) with the Australian Great Barrier Reef led to the formulation of his hypothesis, known as the "Intermediate Disturbance Hypothesis". This hypothesis postulates that the high species diversity in coral reefs is a resultant of intermediate or mid-level disturbances from a whole range of stress factors (Connell, 1978; Grigg and Dollar, 1990). In my view, the challenge is to protect coral reefs from the ever increasing threats of anthropogenic stress, while understanding that natural stresses or disturbances are beyond our control.

In spite of being highly diverse, coral reefs thrive in oligotrophic or low nutrient seawater of the tropics (Dubinsky, 1990; Miller, 1998). The unique symbiotic association between the coral polyp (animal) and the zooxanthellae (algae – plant) holds the answer to this apparent paradox (Goreau 1959; Goreau and Goreau 1959; Dubinsky, 1990; Muller-Parker and D'Elia, 1997). Coral reefs are also unique in that, despite the high biological diversity, the net organic production from coral reef systems is low (Hatcher, 1997; Muller-Parker and D'Elia, 1997). Coral reefs are highly complex but somewhat complete in the sense that the production-decomposition processes are intricately woven into the various levels of organisation of the reef, from species level up to the community and ecosystem level (Grigg and Dollar, 1990; Dubinsky, 1990). Therefore any disruption to the '*status quo*' is expected to have far reaching effects for the reef as a system. This has been proven in the case of increased nutrients, increased sediment loading, and increased temperature (Crossland and Barnes, 1983; Smith, 1988; Crossland *et al.*, 1991; Hatcher, 1997). Because coral reefs have low net biological production, they tend to have little or no influence on the other marine ecosystems close to them (Birkeland, 1997).

A good understanding of coral reef systems is important and essential for their conservation and proper management (Birkeland, 1997). Coral reefs exist within specific environmental limits (Hubbard, 1997). They are affected by the water temperature, salinity, light availability, and nutrient levels in the surrounding water. The optimum temperature range for best coral growth is 26 – 28 $^{o}$C, but they survive in the range 18 - 36 $^{o}$C (Jokiel and Coles, 1977; Logan and Tomascik, 1991; Hubbard, 1997). For this reason, coral reefs are found only between 30$^{o}$ north and 30$^{o}$ south of the equator (Miller, 1998). For most coral reefs, the impact of climate change and especially global warming can be devastating because they are already existing near their upper, thermal limit (Hubbard, 1997). Coral bleaching events have been attributed to unusually high seawater temperatures (Glynn, 1984). The high temperatures above the tolerance range for corals destabilise the coral-algae symbiotic association causing the expulsion of the zooxanthellae from the corals, thereby resulting in bleaching of the coral (Muller-Parker and D'Elia, 1997).

Salinities in the range 3.3 – 3.6% which is normal for seawater, also suit the growth of corals (Achituv and Dubinsky, 1990; Hubbard, 1997) . Low salinities arising from freshwater input like rivers and creeks, reduce coral growth, thus we find the presence of reef passages and passes in reefs close to freshwater discharges into coastal waters (Coles and Jokiel, 1992; Hubbard, 1997).

Coral reefs thrive in low nutrient, well illuminated and warm waters (Dubinsky, 1990; Birkeland, 1997). The success of coral reef systems in 'nutrient-poor' waters is attributed to the corals having two modes of feeding, an autotrophic and an heterotrophic mode (Muller-Parker and D'Elia, 1997). In the autotrophic feeding method, the symbiotic zooxanthellae embedded in the gastrodermis layer carry out photosynthesis using sunlight and nutrients in the water column. Light thus controls the distribution of corals and also their form or morphology (Muller-Parker and D'Elia, 1997). At greater depths where there is less light, the corals adapt by a change in shape from the mound shape typical of shallow waters to the flat, and plate-like forms exposing a larger surface area to trap light (Hubbard, 1997). The heterotrophic mode of feeding involves capture of zooplankton by the coral polyps (Muller-Parker and D'Elia, 1997).

## 2.3 CURRENT STATUS OF CORAL REEFS

In the "Status of Coral Reefs of the World: 1998" report, Wilkinson concluded that: a) the coral reefs around the world were being degraded at an increasing rate due to direct human activities, and that: b) people everywhere were becoming increasingly aware of this fact and actions were being taken at all levels (global, regional, national and local) to try and conserve the reefs (Wilkinson, 2000).

Coral reefs are highly complex and highly variable by region, and also from reef to reef (Dubinsky, 1990). However, they face similar threats or stresses. These stresses may be categorised into ‘natural stresses’ or ‘anthropogenic stresses’ (Grigg and Dollar, 1990).

The natural stresses vary from low disturbance with insignificant effects, to catastrophic events such as the major El Nino events (Glynn, 1984), the population explosion of the crown-of-thorns starfish *Acanthaster planci* (Dana *et al*., 1972; Endean, 1976) or the severe storms (Stoddart, 1963; Maragos *et al.*, 1973). For a proper assessment of the effects of such stress events on a coral reef ecosystem, one needs to consider the magnitude and frequency of the stress event on the one hand, and the natural recovery rates of reefs on the other (Grigg and Dollar, 1990). Examples of anthropogenic stresses are discussed in Section 2.4.

## 2.4 ANTHROPOGENIC EFFECTS ON CORAL REEFS

### 2.4.1 Overview of global anthropogenic effects on coral reefs

Anthropogenic impacts are becoming more threatening to coral reefs around the world (Hutchings, 2001). Such impacts include overfishing, destructive fishing, run-off, sediments from catchments, and recently, rising sea temperatures (Hutchings, 2001). One of the locations where such impacts have been monitored is the in-shore reefs of the Great Barrier Reef where evidence of these impacts (Bell 1991; Kinsey 1991) has been gathered over about 30 years.

According to GESAMP (2001), the deterioration of water quality in coastal waters is an increasing global problem. There are many reasons for this, but in most, if not all of them, humans have been responsible. Increasing urbanization, increasing development of the coastal areas as well as development of the catchment areas are some of the main causes of deteriorating water quality and threats to marine ecosystems including the coral reefs (GESAMP, 2001). The use of nitrogen fertilizer has increased globally more than sixfold since 1960 (Matson *et al*., 1997). Land clearing continues at a rate of 1% of the Earth’s surface per year (GESAMP, 2001). The coastal waters are becoming more eutrophic and marine ecosystems including coral reefs are being affected by increased nutrient loading, sediments and other pollutants from land based sources (Bryant *et al*., 1998). Terrestrial run-off must therefore be monitored and managed if coral reefs are to be sustained in good ‘health’, for the over 100 nations that have been blessed with coral reefs (Bryant et al., 1998).

The effects of land-based pollution sources and terrestrial runoff on the marine environment are complex (Fabricius, 2005; Littler *et al*., 2006). For coral reefs, the effects of runoff may be categorized into three broad categories:

(1) effects on growth and survival of hard corals;
(2) effects on coral reproduction and recruitment; and
(3) indirect effects via other organisms that associate with corals, for example, macroalgae and bioeroders (Fabricius, 2005).

Likewise, current research in this area can also be broadly categorized into four broad categories as proposed by Fabricius (2005). This is just one method of reviewing this cause-effect phenomenon, i.e., by splitting up the ‘causes of effects’ into broad categories of:

(1) increased dissolved inorganic nutrients;
(2) enrichment due to particulate organic matter;
(3) reduction of light due to increased turbidity; and
(4) increased sedimentation (Fabricius, 2005).

Eutrophication manifests itself in the same manner in temperate and tropical ecosystems, i.e., increased productivity, alteration of species composition and development of algal blooms have been attributed to nutrient enrichment from sewage (Brennan *et al.*, 1998). In other studies in coastal lagoons, eutrophication was marked by increased turbidity, nutrients (dissolved inorganic phosphate) and algal blooms which followed a regular seasonal pattern (particularly in temperate areas). Studies have found that many of these effects can be highly correlated with water temperature (Boynton *et al*., 1996).

According to GESAMP (2001), inorganic nutrients and particulate material are the most significant pollutants at national and regional levels. Previously, nutrients were believed to be essential for the life of coral reefs. However, it is now well recognized that excessive levels of nutrients are in fact detrimental to the survival of coral reefs (Kinsey and Davies, 1979), and sediments and associated nutrients are considered the most significant threats to reefs (Johannes 1975; Hatcher, *et al*., 1989; Birkeland 1997). This threat continues to increase with increasing human population, agricultural activities and urbanization/industrialization taking up more land. In Queensland, Australia, since western agriculture began, the amounts of sediment, nitrogen and phosphorus entering the marine environment off the Queensland coast has increased by as much as four times (Brodie, 1995).

In other studies of major coral reef areas around the world, it has been established that in the last thirty years, with increasing human population, increasing agricultural activity and increasing development of the coastal areas, the quality of the coastal waters have progressively deteriorated and the marine ecosystems including the coral reefs exposed to impacts of land-based human activities are becoming degraded at an alarming rate (Hodgson, 1999). These include the Great Barrier Reef of Australia (Zann, 1995; Bell, 1991, 1992; Furnas *et al.*, 1995; Brodie 2000; Devlin *et al.*, 2000; Brodie & Furnas, 2001); Indonesia (Edinger *et al*., 1998); the Florida Keys in the United States of America mainland (Lapointe and Clark, 1992; Grigg, 1995; Stoicher and Peterson, 1997); Hawaii (Smith *et al.*, 1981); Western Indian Ocean (Naim, 1993), and the South West Pacific including Fiji (Zann, 1994). In Fiji, limited studies have also revealed eutrophication of coral reef areas (Lovell and Tamata, 1996; Hoffmann, 2002; Mosley and Aalbersberg, 2003).

In the USA, concern for the Florida coral reefs prompted the setting up of a program called SEAKEYS. The program involved monitoring of nutrients (ammonium, nitrate, orthophosphate, total N and total P) in the water column and in sediments, along a gradient from nearshore to offshore (Szmant and Forrester, 1996). The study found higher levels of nutrients and chlorophyll-a nearshore, but these quickly decreased to oligraphic levels not far offshore (Szmant and Forrester, 1996). This situation is not unusual, because there is a whole host of factors in play in any one case, phytoplankton and other algae that quickly take up available nutrients in the water (as was concluded from this study by Szmant and Forrester), as well as the physical hydrological factors of dilution and dispersion. Hawker and Connell (1989)

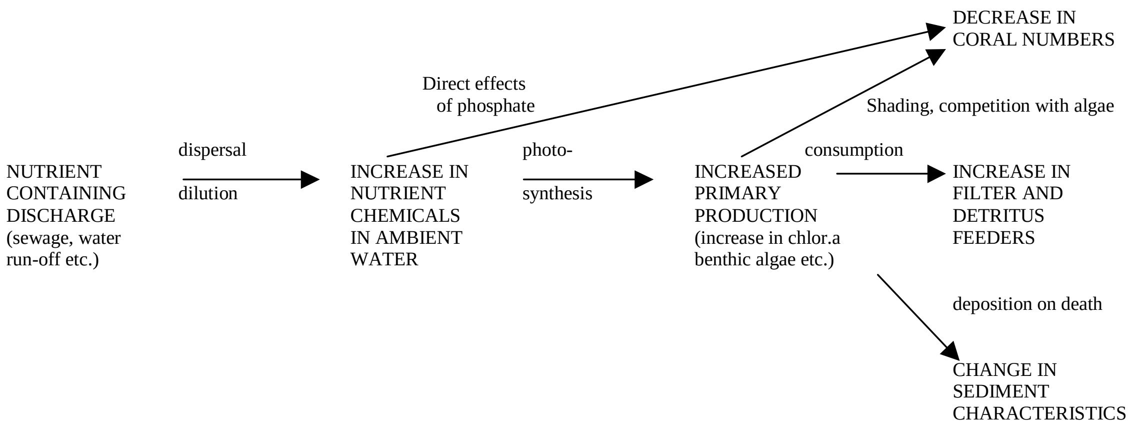



Figure 2.1 Simplified pathway for nutrient effects on water quality and coral reef communities (from Hawker and Connell, 1989).

presented a simplified diagrammatic representation of what happens to nutrients discharged into coral reefs areas (see Figure 2.1).

In Indonesia, increased nutrients and sedimentation were found to cause a variety of effects including reduced coral cover and diversity, the massive corals having low skeletal density, and an increase in bioerosion activity (Tomascik *et al*., 1997; Edinger *et al*., 1998; Edinger *et al*., 2000 and Holmes *et al*., 2000). For the reefs of Indonesia and the Philippines, only about 5 % is considered to be in excellent condition, and about 60-70% have been seriously degraded, on the basis of percent living coral cover as the index of reef health (Yap and Gomez, 1985).

In the Great Barrier Reef of Australia, studies found that increased nutrients caused increased macroalgal cover and reduced coral cover (Fabricius and De'ath, 2004). Similar results had been reported from the earlier, well known case, in Kaneohe Bay, Hawaii (Smith *et al.*, 1981). In this famous 'live field experiment' in Kaneohe Bay, Hawaii, discharge of sewage into the Kaneohe Bay caused a phase shift, and coral cover was reduced while macroalgal cover was increased. As is well known today, this situation was reversed following the diversion of sewage discharge from the Bay (Smith *et al*., 1981; Hunter and Evans, 1995). In Barbados, studies showed positive correlation between nutrient concentration and photosynthetic (chlorophyll) pigments, (Marubini, 1996; Tomascik and Sander 1985). In Brazil, Costa Jr *et al*., (2000) found an increase in macroalgae abundance following incidences of eutrophication.

Nutrient concentrations in pristine coral reef waters are generally low (oligotrophic conditions), but anthropogenic factors have caused elevation in some areas. Table 2.1 lists some of the values of nutrient concentrations from selected coral sites.

Table 2.1 Nutrient concentrations (uM) at some reef sites (cited in Szmant, 1997).

| **Sites** | **$NO_3 + NO_2$** | **$NH_4$** | **$PO_4$** |
|---|---|---|---|
| Kaneohe Bay pre-sewage diversion<br>Smith et al., 1981 | 0.33 to 0.91 | 0.57 to 2.28 | 0.28 to 0.88 |
| Kaneohe Bay post-sewage diversion<br>Smith et al., 1981 | 0.27 to 0.66 | 0.38 to 0.57 | 0.09 to 0.18 |
| GBR, One Tree Reef; Hatcher and Hatcher 1981 | | | |
| offshore | 0.31 | Nd | |
| reef slope | 0.31 | 0.76 | |
| lagoon | 0.95 | 2.86 | |
| reef crest | 1.54 | 5.52 | |
| GBR, mid-lagoon Station 11, Furnas et al. 1995 | 0.05 | 0.46 | 0.08 |
| Houtman Abrolhos Islands, Australia, Easter Group;<br>Crossland et al. 1984 | | | |
| front reef flat | 1.02 | 0.21 | 0.22 |
| back reef flat | 0.96 | 0.28 | 0.24 |
| lagoon | 0.93 | 0.32 | 0.29 |
| Brazil, developed; Costa et al. 2000 | | | |
| Wet | 8.03 | 4.81 | 1.42 |
| Dry | 5.75 | 10.69 | 0.35 |
| Brazil, less developed; Costa et al. 2000 | | | |
| Wet | 1.68 | 3.59 | 0.18 |
| Dry | 0.41 | 0.86 | 0.13 |

The effects of development on the water column nutrients is evident in the results between developed and less developed parts of Brazil (Costa Jr *et al*., 2000).

### 2.4.2 Effects of sewage pollution

Sewage pollution is an increasing problem in tropical marine environments (Pastorok and Bilyard, 1985). In fact, sewage pollution and related nutrient enrichment have long been recognized as critical issues for coral reef health in the tropics (Doty, 1969; Banner 1974; Pastorok and Bilyard, 1985). Sewage pollution is compounded when there is large discharge of effluent and the receiving water is poorly flushed. Conversely, impact of sewage pollution may be little or non-existent when effluent volume is small into well-flushed lagoons and bays (Pastorok and Bilyard, 1985).

Sewage effluent affects coral reefs through the effects of its three components: a) nutrients, b) sediment and particulate matter, and c) through toxic substances (Pastorok and Bilyard, 1985). Sediment and particulate matter in sewage affects coral reefs in a number of ways: sediment in the water column reduces light which affects coral photosynthetic mode of nutrition; large amounts of sediment may kill corals by smothering; smaller amounts may favour some species over others, or may induce changes in the growth forms of some coral species (Pastorok and Bilyard, 1985).

Effects of toxic substances in sewage have not been as widely researched as those of nutrients. This is a risky situation because very little is known in detail about the chemicals contained in sewage, (especially as the toxic components vary with sewage source); their reactions under conditions of relatively high temperatures (as is common in tropical waters); their combined effects under these conditions and the possibility of additive and synergistic effects (Johannes, 1975; Pastorok and Bilyard, 1985).

There appears to be high incidence of coral disease and mortality where reefs are close to heavily populated areas, and it has been suggested that faecal bacteria in sewage are causing these problems for the corals (Lipp *et al*., 2002; Schrope, 2002). This was reported from the Florida Keys in the USA. The studies, although preliminary, found that the coral surface microlayers (CSM) or the mucus layer covering the heads of the corals were contaminated with bacteria and viruses normally found in human faeces, and were causing diseases and even death of the corals (Lipp *et al*., 2002). This discovery indicated that the CSM may be better indicators of human faecal contamination than the water column where bacteria die-off occurs more rapidly (Lipp *et al.*, 2002). Schrope (2002) also reported more disturbing findings where chemicals and prescription drugs were affecting freshwater ecosystems and organisms. The study involving the water fleas *Daphnia* sp., found that cholesterol-lowering and antidepressant drugs caused deformities and death to the *Daphnia* population (Schrope, 2002). Although these examples were from fresh water ecosystems, they are noteworthy for any aquatic ecosystems including the marine environment.

Stimson *et al*. (2001) reported interesting results from studies of sewage inputs in Kaneohe Bay, Hawaii. During the 1960s when sewage was discharged into the Kaneohe Bay, the macroalga *Dictyosphaeria cavernosa* invaded and displaced corals on the reef slopes and outer reef slopes. Following sewage diversion in 1977-78, there was significant reduction in the abundance of *D. cavernosa* in some parts of the Bay (southern) which was the site of most historical discharge, but less so in some other parts (Stimson *et al*., 2001). The results highlighted the complex interrelationships among nutrients, the macroalgae and other equally important factors such as herbivory (Stimson *et al*., 2001). The role of herbivory in these studies is discussed below.

On Reunion Island in the Indian Ocean, nutrients from untreated sewage and coastal urbanization caused reduction in coral cover and coral species diversity for affected reefs. Bioerosion rates were also higher in nutrient-affected reefs than in unaffected ones further away from the nutrient sources. Studies here also found that before the 1970s, there was generally higher coral cover, higher coral diversity and lower macroalgal cover (Cuet *et al*., 1988; Montaggioni et al., 1993; Naim, 1993; Chazottes *et al*., 2002).

In Florida, the coral reefs off the southeast coast have had unprecedented occurrence of macroalgal blooms and invasions (Lapointe *et al*., 2005). Studies found that land-based sewage N (nitrogen) was the major source of N for the harmful algal blooms. Samples of macroalgae were collected from sites ranging in depth from shallow, subtidal reefs to deeper reefs at the shelf break, and also at increasing distances from sewage discharge points (via ocean outfalls). Tissue from the macroalgal samples was subjected to stable nitrogen isotope ($\delta^{15}N$) analysis and values of $\delta^{15}N$ were significantly higher on shallow reefs and decreasing with increasing depth (Lapointe *et al*., 2005). Use of stable nitrogen isotope analysis is discussed further in Section 2.7.

Wetlands and marshes have significant roles in filtering and soaking up pollutants, and thereby protecting the water quality from effects of sewage pollution. Mallin *et al.* (2007) conducted surveys of the water quality and sediment, to monitor the effects of a raw sewage spill in Wilmington, on the southeast coast of North Carolina, USA in July 2005, and found that while nutrients in the water column declined rapidly, the sediment retained relatively high concentrations of faecal coliform bacteria for several weeks after the spill. The spill had caused a high faecal coliform bacteria (up to 270,000 CFU/100 ml), several algal blooms and death of fish and other aquatic life. The study reinforced the need to include sediment monitoring in addition to water quality monitoring for sewage pollution, and more importantly, the need to conserve wetlands along the coasts because of their pollutant filtration capability.

### 2.4.3 Effects of catchment activities on coastal environments

The importance of controlling and managing human activities in catchment areas for the protection of water quality in coastal areas and the inshore reefs is well known; however such controls have been rather difficult to implement (Wooldridge *et al.*, 2006). The connection between the two has been clearly shown in a number of studies. In the case of the Great Barrier Reef (GBR), there is clear gradient from north to south along the length of the GBR, corresponding to extent of human impact in the catchment areas on land, and this was reflected in the gradient of nutrient enrichment, as estimated by chlorophyll a concentrations, and was generally higher towards the central and southern parts of the GBR, and lower towards the north (Wooldridge *et al*., 2006). In the northern parts of the GBR, catchments are relatively undisturbed in contrast to the more human-impacted central and southern parts of the GBR catchment. Wooldridge *et al*. (2006) also found that flood plumes originating from human-impacted central and southern catchments of the GBR, carried higher dissolved inorganic nitrogen (DIN) compared to the relatively undisturbed northern catchments. The study in Australia utilised modelled historical flood plume data and other archived data to quantify the extent of the summer run-off-seawater mixing zone, and from developed spatial relations, Wooldridge et al. (2006) concluded that for the heavily-impacted catchments, there was a need to a reduce the 'end-of-river' DIN by 50 – 80 % in order to attain pre-European conditions.

Investigations of nutrient enrichment in groundwater, in order to assess its significance to coral reef degradation has been conducted on Ishigaki Island, Japan, using two catchments of different levels of human impact (Umezawa *et al*., 2002). The study compared concentrations of dissolved inorganic nitrogen (DIN) in groundwater near coastal areas, for two catchments (namely the Shiraho and Kabira catchments). Up in the catchments, DIN was estimated from the various land uses. Interestingly, the two values of DIN (one for the catchment and one for the coastal area) for each catchment agreed to within a factor or two, even though different methods were used to estimate DIN (Umezawa *et al*., 2002). More interesting and important, however, was the fact that the more human-impacted Shiraho catchment and coastal groundwater recorded about 5-fold more nitrogen than the less impacted Kabira catchment (Umezawa *et al*., 2002). The study did not indicate whether this pattern of variation was reflected in the biological communities on the Shiraho and Kabira reefs. However, the results showed strong correlation between levels of human impact and concentrations of DIN. The study also showed that activities in the catchment affected levels of nutrients (nitrogen) in the coastal areas (Umezawa *et al*., 2002).

## 2.5 PHASE SHIFT

When a reef is described as being degraded, it usually means that the corals have been replaced by algae, in other words, there has been a 'phase shift' from coral dominance to algal dominance (Done, 1992; McCook, 1999). In these situations, the coral reefs undergo changes from coral dominance to algal dominance, often as a result of anthropogenic factors or in association with natural stresses, and the two states of the reef have been described by some researchers as 'alternate stable states' of the reef (Hatcher, 1984; Done 1992; Hughes 1994).

This phase shift has usually been linked to anthropogenic impacts, through various pathways. For example:

- nutrient enrichment of the water column;
- increased sedimentation, and effects of nutrients associated with sediment;
- sewage effluent, and more recently,
- overfishing of herbivorous fish and other grazers (Hawker and Connell, 1989; Hutchins, 2001; GESAMP 2001).

The causes of reef degradation are varied and complex. Nevertheless, the many examples mentioned above clearly show how anthropogenic factors have significantly contributed to reef degradation and 'phase shifts' on coral reefs in many countries (Miller, 1998; McCook,1999). McCook (1999) described five sets of factors which directly and indirectly influenced the distribution and abundance of algae and other marine benthic species on coral reefs. In brief, these five factors are:

- resource availability (e.g., light, nutrients, suitable substrate);
- survivorship factors (fecundity, dispersal, settlement and recruitment);
- stress factors (exposure, cyclones, sediment deposition);
- species interaction (e.g., especially herbivory); and
- the interactions among these.

GESAMP (2001) had singled out inorganic nutrients (nitrate, ammonium, phosphate) and particulate material as being the most significant pollutants at national and regional levels. Most of the studies on phase shifts have focussed on the effects of nutrients (nitrogen and phosphorus), and herbivory.

The results from the many observational studies mentioned in Section 2.4 suggest that algae actually outcompete the corals under eutrophic conditions. Sheppard (1988, as reported in Miller, 1998) in his surveys of coral reef communities in the Red Sea and Arabian Gulf also found changes in reef communities along gradients of temperature, salinity and sedimentation. Sheppard (1988) reported a shift from coral dominance (*Acropora* and *Porites*), to algal dominance (*Sargassum*), along the gradient from less stressful (normal temperature and salinity and less sedimentation) to more stressful conditions (high temperature and salinity and more sedimentation). Sheppard (1988, as reported in Miller, 1998) called this shift in species dominance 'algal replacement'. The actual mechanism of this 'algal replacement' cannot be ascertained from observational studies alone (Miller 1998).

A simplistic model proposed to explain the mechanism behind 'phase shifts' focussed solely on nutients as the prerequisite for the change. This was known as the "Direct Effects of Nutients on Algae" model (McCook, 1999).

### 2.5.1 The 'Direct Effects of Nutrients on Algae' Model

McCook (1999) discussed the relative importance of two factors influencing nutrient impact on reef systems: nutrients as contributing factors to algal dominance in contrast with herbivory as a controlling factor. One of the earlier conceptual models proposed to explain the causes of phase shifts was the simple **'direct effects of nutrients on algae'** paradigm (see Figure 2.2).

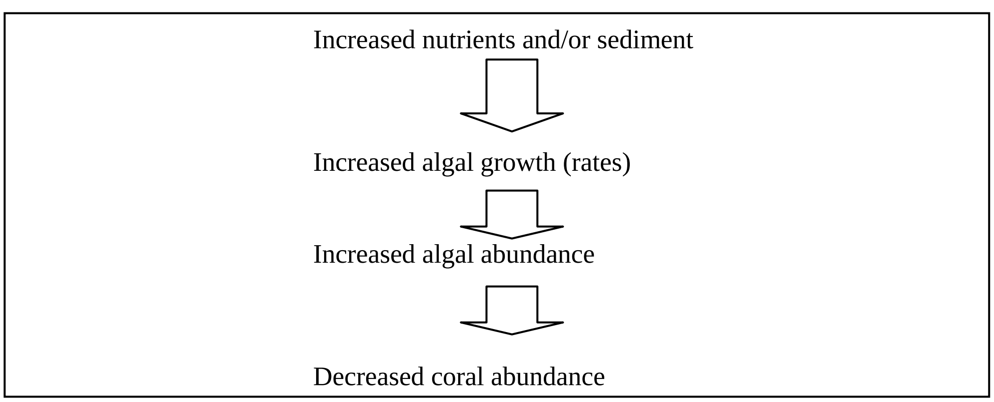



Figure 2.2 The 'Direct Effects of Nutrients on Algae' Model (from McCook, 1999).

As has been found, nutrient enrichment from anthropogenic sources causes excessive growth of "weedy" nuisance algae on reefs in affected areas (Goreau and Thacker, 1994; Lapointe, 1997), and the mechanism of how this cause-effect phenomenon occurs has been the subject of numerous investigations (e.g., Scaffelke and Klumpp, 1997a, b; 1998a, b; Delgado and Lapointe, 1994). Some researchers have held the view that the problem starts once a certain "threshold" concentration of nutrient is exceeded, and it is argued that the nutrient levels must be maintained at or well below this threshold level to prevent overgrowth of coral reefs by macroalgae (Bell, 1992). The suggested threshold concentrations are 0.1 *u*M for $P\text{-}PO_4$, and 1 *u*M for $N\text{-}NO_3$ (Bell, 1992). Lapointe (1997) had suggested that algal blooms on reefs of Jamaica and southeast Florida were associated with nutrient concentrations exceeding this threshold level.

For some time, the simple idea of "threshold" nutrient concentration effect was generally accepted (Lapointe 1997) - the 'Direct Effects of Nutrients on Algae' model (McCook, 1999). Several studies investigated this direct effect relationship by manipulative experimentation in the field and also in the laboratory (e.g., Schaffelke and Klumpp 1998a, b). It was found that the "direct effects" model was incorrect, and that while nutrients did enhance algal production to a certain degree, the effect was certainly not one of a direct proportionality (Bell, 1992). Studies from the Great Barrier Reef found that growth of macroalgae *Sargassum baccularia* was indeed enhanced by increased nutrient concentrations, but only within the range of concentrations relevant to fringing reefs. At higher concentrations, growth was no longer enhanced (Schaffelke and Klumpp, 1997a, 1998 a, b). The studies concluded that it was not the nutrient levels in the water column that were critical for algal growth, rather nutrient supply and nutrient uptake (of which concentration is only one aspect).

The concept of 'threshold' nutrient concentration was disputed by other researchers including Hughes *et al*. (1999), who concluded that concentration of dissolved inorganic nutrients in the water was not a reliable indicator of reef status. This was supported by McCook (1999). Instead, it was noted that the spatial and temporal patterns of algal abundance in Jamaica and other places were correlated better with levels of herbivory, rather than nutrient variation. Numerous investigations looked into the mechanism of nutrient uptake from the water column by algae, in order to understand the phase shift that was occurring in most coral reefs around the world. This concern led to the dedication of a special issue of *Coral Reefs* to the subject of “Coral Reef Algal Community Dynamics” in an effort to draw attention to this crisis (Szmant, 2001).

Another point of argument against using water column nutrient levels as indicators of eutrophication, and the notion that reefs only thrive in tropical waters with very low nutrient levels, is the fact that in-shore fringing reefs like some of the Great Barrier Reef areas are often exposed to highly turbid and nutrient-enriched waters (Goreau and Thacker, 1994). Studies also found that generally, the more eutrophic an area becomes, the less reliable is the use of nutrient concentrations in the water column as an indicator of nutrient input, as most nutrients are quickly taken up by algae (Goreau and Thacker, 1994).

### 2.5.2 Shortfalls in the ‘direct effects’ model

The ‘direct effects’ model is not supported by most studies (McCook, 1999) as other factors have been found to influence the phase shift from coral to algal dominance, one of the most important ones being reduced herbivory as a result of overfishing or disease (Carpenter, 1986; Lewis, 1986). A review of the role of nutrients on coral reefs (McCook, 1999), concluded that while nutrient overloads may contribute to reef degradation, they are unlikely to lead to phase shifts unless herbivory is unusually low. McCook (1999) suggested that protection of herbivorous fishes is critical in addition to reduction of nutrient loading, in order to prevent phase shifts on coral reefs. Recently, research on this subject has been broadening its scope and more and more, herbivory is included in with nutrient-based studies for coral reefs (Thacker *et al.*, 2001; Stimson *et al.*,2001; Williams and Polunin, 2001).

Following concern that anthropogenic factors were causing a ‘phase shift’ on the inshore reefs of the Great Barrier Reef, several studies examined in detail how nutrients affected the reproductive output, or fecundity of the invading macroalgal species under conditions of nutrient enrichment (Diaz-Pulido and McCook, 2005). Working with the brown macroalga *Sargassum siliquosum,* one of the more common invading macroalgae on the inshore reefs of the Great Barrier Reef, studies found that there was no simple relationship between nutrient enrichment and the reproductive capacity of the *S. siliquosum.* The study found that increased nutrients correlated positively with increased tissue nitrogen levels, but this was not so for phosphorus levels. It has been argued that if nutrient enrichment led to increased growth and abundance, then one would expect the reproduction of the macroalgae to be enhanced by nutrient enrichment (Diaz-Pulido and McCook, 2005). This was not the case. In fact, under conditions of nutrient enrichment, there was reduction in the biomass and density of the reproductive material. There was no proportional allocation of biomass to reproductive and vegetative structures (Diaz-Pulido and McCook, 2005). Obviously the interaction between nutrients and algae reproduction is much more complex than a simple numeric relationship.

A number of studies have investigated coral/algal interactions to test the common belief that algae were more competitive and were superior over coral in eutrophic waters (McCook, 2001; McCook *et al*., 2001). Interestingly, these studies found that algae were not the superior competitor, and in one study, the coral *Porites* was competitively superior over the algal filamentous turfs (McCook, 2001). It appeared that algal overgrowth occurred after the corals have been damaged or killed by some external disturbances (McCook *et al.,* 2001).

The importance of herbivore control on algae was clearly evident from observational studies (McCook, 1999; Thacker *et al.,*2001). Different algal groups were favoured by different conditions. The simplistic 'Direct Effects of Nutrients on Algae' model was not appropriate, as it ignored the role of herbivory, and also the direct effects of nutrients on corals. Littler and Littler (1984) had proposed a more comprehensive model which incorporated the relative effects of both nutrients and grazing - the 'Relative Dominance Paradigm'.

### 2.5.3 The 'Relative Dominance Paradigm'

This model examines how the dominant benthic functional groups on coral reefs namely, microalgal turfs and frondose macroalgae on the one hand, and the reef-building corals and calcareous coralline algae on the other, are influenced by the two principal controlling factors of nutrients and herbivory (Littler *et al.,* 2006).

Studies by Littler *et al.,* (2006) which included manipulative experiments, descriptive surveys of existing reef communities and field bioassays, revealed just how complex the interactions were between the two controlling factors (nutrients and herbivory) and the resultant benthic species or communities. These controlling factors influenced, either directly or indirectly, by either stimulating or limiting, the growth of a particular functional group (Littler *et al*., 2006). The studies found that increased nutrients stimulated harmful fleshy algae, thereby altering the abundance patterns for other groups, while at the same time, increased nutrients were found to inhibit the growth of reef-building corals (Littler *et al*., 2006). The 'relative dominance model' shows how corals are favoured when nutrients are low and herbivory is high, and at the other extreme, macroalgae like *Sargassum* are favoured by high nutrients and low herbivory.

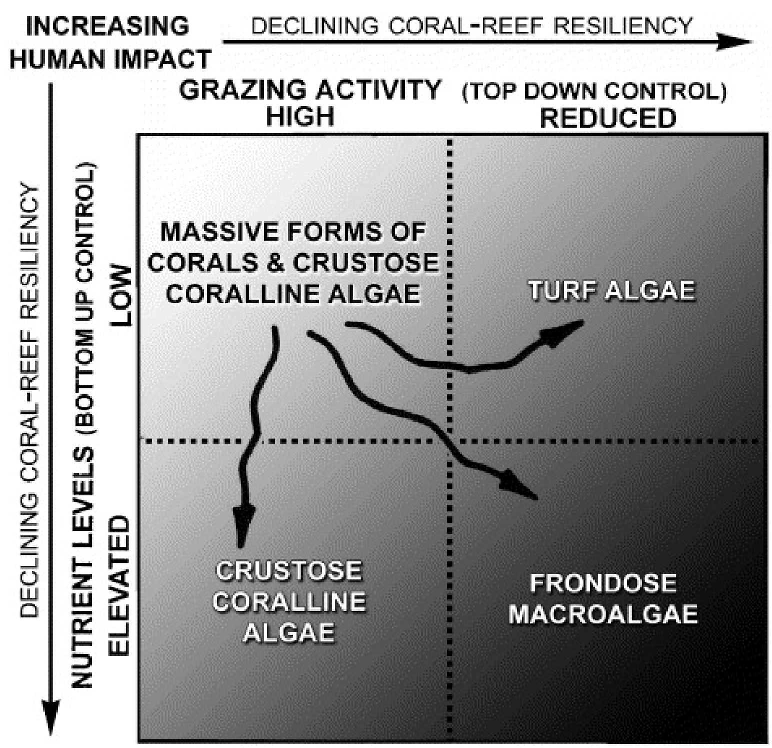



Figure 2.3 The Relative Dominance Model (RDM, from Littler *et al*., 2006).

In their studies, Littler *et al*. (2006) found that herbivory had direct effects by reducing the fleshy-algal biomass, and thereby indirectly favour the grazer-resistant coralline algae. The conclusions therefore are that, in order to control or reverse the phase shift on coral reefs, a wholistic approach is necessary whereby nutrient input must be reduced and herbivory be enhanced or supported (Littler *et al*., 2006). Man had directly and indirectly caused just the opposite of what this approach entails; through increased development of the coastal areas, nutrient loading of coastal waters had increased and continues to do so. At the same time, through overfishing and destruction of fishery breeding areas like mangrove ecosystems, herbivory is being reduced. It is little wonder, therefore, that coral reefs are being degraded at alarming rates throughout the world. The studies on the actual mechanism of nutrient effects on macroalgae or corals have revealed a lot of variation.

## 2.6 MECHANISMS OF NUTRIENT EFFECTS ON CORAL REEF COMMUNITIES

The mechanism of nutrient effects on corals or other biological species on coral reefs, is being researched extensively (e.g., Lapointe *et al*., 2004), and results have been varied. In several studies, nutrient enrichment has been found to enhance activities of microborer species. In a study conducted on Glovers Reef, Belize, Carreiro-Silva *et al.*, (2005) found that the dominant microborer species identified was the green alga *Phaeophila* sp. The study also found that the exclusion of herbivores resulted in an increase in bioerosion rates by the microborers (Carreiro-Silva *et al.,* 2005). So while nutrient enrichment may not directly enhance the more common, larger macroalgae such as *Sargassum* sp. (Diaz-Pulido and McCook, 2005), its enhancement of other similarly destructive species such as microborer *Phaeophila* sp. is in fact contributing to the overall degradation of the coral reef carbonate structure (Carreiro-Silva *et al.,* 2005).

One of the more comprehensive large scale investigations into effects of nutrients on corals was conducted on One Tree reef, GBR, Australia – the ENCORE experiments.

### 2.6.1 ENCORE

The simple ‘Direct Effects of Nutrients on Algae’ model is based on the central paradigm for coral reefs that their primary producers (principally algae) are limited by nutrient supply – namely nitrogen and phosphorus, and therefore any increases in nutrient supply to reefs increases the growth, and therefore standing crop of algae (McCook, 1999). However, the effects of elevated nutrients on corals were less well known. This paradigm was tested in the ENCORE (“The effects of nutrient enrichment on coral reefs”) project, a multi-million dollar and multi-stakeholder research project undertaken on One Tree Island at the Great Barrier Reef (Koop, *et al.,* 2001). The project investigated responses of coral reef organisms and processes, to controlled additions of DIN and/or phosphorus (P) on One Tree Island – an off-shore reef at the southern end of the GBR, Australia (Koop, *et al.,* 2001). The experiments tested effects of nutrients on coral reef organisms *in situ.*

The study produced some unexpected results of nutrient enrichment of these coral reef communities. Phytoplankton primary production did not increase significantly following nutrient enrichment thus may not be useful indicator of enrichment, and the macroalgae showed variable responses to the increased nutrients (Koop, *et al.,* 2001). The study also found that for reef-building corals, coral mortality increased for some species during the high-loading phase. Soft corals were generally not affected by nutrient enrichment. While there were variable effects of nutrient enrichment on coral growth, reproductive capability was clearly affected adversely (Koop, *et al.,* 2001).

The ENCORE study concluded that nutrient enrichment caused significant effects at the **organism level** for the corals through increased mortality and reduced reproduction, but it did not cause coral reefs to convert from coral communities to seaweed-dominated reefs as has been recorded elsewhere (Koop, *et al.,* 2001). Contrary to common belief, primary production was not significantly increased as a result of nutrient enrichment. Even epilithic algal communities (EAC), normally of highest productivity, did not respond to nutrient enrichment (Koop, *et al.,* 2001). It was thus concluded that EAC was not nutrient limited. The research found that the impact on coral reproduction was of great significance - growth and mortality of corals were affected. Production of viable gametes and successful fertilization were reduced (Koop *et al.*, 2001). These findings suggested that the impact of nutrients on coral reproduction may be the cause of depleting/disappearing coral reefs in coastal waters near development sites.

### 2.6.2 Effects of nutrients on corals

Coral growth rates, or more specifically individual coral extension rates, are not good/reliable indicators of reef “health” in an eutrophied coastal environment (Edinger *et al*., 2000) There is still an uncertainty about the metabolic response of the corals to increased nutrient levels. For example, under high nutrient influx, individual corals may grow heterotrophically by feeding on dissolved and particulate organic matter (Edinger *et al*., 2000), or the increased dissolved inorganic nutrients will boost zooxanthellae production and subsequently photosynthetic activity in the coral which would grow by autotrophic pathways (Edinger *et al*., 2000). A study was conducted in thirteen reefs from three regions of Indonesia, where a number of parameters were measured and compared between the nearshore reefs and offshore reefs (Edinger *et al.,* 2000). Observations showed that there was no major difference between the affected reefs and the offshore reefs when comparing individual coral extension rates (vertical extension). The study also showed what would be expected, i.e., total coral cover and coral species diversity were lower for the nearshore reefs (Edinger *et al*., 2000). Conversely, cover of fleshy algae and invertebrates was higher for neashore reefs. The study also found bioerosion intensity to be higher for nearshore reefs (Edinger *et al*., 2000). Carbonate budgets for reefs were negative for nearshore reefs, from a combination of low live coral cover, higher algal and non-calcified invertebrate cover and bioerosion. (Edinger *et al*., 2000). This observational study identified outcomes that were occurring in other reefs.

Cox and Ward (2002) in their studies with two Hawaiian scleractinian corals (*Montipora capitata* and *Pocillopora damicornis*), found that exposure to elevated ammonium concentrations disrupted the reproductive capacity of the corals. The study also showed the complexities in the responses of corals to nutrient enrichment, i.e., it appeared that the responses are related to whether the eggs of the corals contain zooxanthellae or not, and those corals whose eggs contain zooxanthellae may not be as adversely affected as those that do not (e.g., *Acropora* sp.). Atkinson *et al*. (1995) even found that corals were not inhibited by some level of nitrate elevation up to 5 *u*M nitrogen, in an aquarium experiment in Waikiki, Hawaii, and they reiterated the fact that growth responses of corals under nutrient enrichment conditions are complex processes, and that statements that corals only thrive in oligotrophic waters was an over-simplification of the interactions between nutrients and corals. Kleypas (1996) through reef coring and studies of NOAA/AVHRR imagery concluded that reef development was affected by suspended sediment concentrations (SCC), and the higher the SCC, the poorer the development of coral reefs.

Nutrient enrichment have also been associated with an increase in coral diseases. Bruno *et al*. (2003) reported that increasing nutrient concentrations up to 5x during field experiments, caused significant increases in aspergillosis of the common gorgonian sea fan coral *Gorgonia ventalina*, and the yellow band disease of the reef-building corals *Montastraea* sp., on a Carribean fore-reef, in Mexico.

### 2.6.3 Nutrients in seawater

Before reviewing the effects of nutrients on macroalgae, the nature and behaviour of nutrients the marine environment are discussed.

Nutrients that may cause problems for marine ecosystems include nitrate ($NO_3^-$), nitrite ($NO_2^-$), ammonium ($NH_4^+$), phosphate ($PO_4^{3-}$) and silica ($H_4SiO_4$), but in pristine coral reef areas, these occur in relatively low concentrations (*u* mol/L or *u*M concentration range) and are classified as non-conservative substances, because their distribution and concentrations are influenced by biological and chemical processes in the marine environment (Libes, 1992). The nutrients from land sources reach the coastal areas and the marine environment via the rivers and creeks, run-off and through the process of leaching (GESAMP, 1990; Sparks, 2003). Nitrate is more mobile than phosphate (Li *et al.*, 1997), and it is often leached out or transported more easily than phosphate (Li *et al.*, 1997; Shuman, 2001), especially during heavy rainfall and storm events (Schaffelke, 1999). While nitrate is positively associated with rainfall, Jarvie *et al.,* (2006) found in their studies that phosphate behaviour with rainfall can reveal the source of phosphate. When phosphate concentration is reduced during higher flow (for example during flood events), it often pointed to point sources of phosphate such as sewage (dilution effect), rather than diffuse sources such as agricultural sources.

Ammonia and phosphate are two of the most common weak bases and acids in seawater, the others being carbonate, silicate and borate (cited in Libes, 1992). In as far as concentrations are concerned, studies have found that for aerobic seawater, ammonia concentrations averaged <0.5 *u*M in the three types of seawater reviewed, i.e. 'Warm Surface', 'Deep Atlantic' and 'Deep Pacific'. For phosphate concentrations, the concentrations averaged <0.2 *u*M for 'Warm Surface Water'; 1.7 *u*M for 'Deep Atlantic' and 2.5 *u*M for 'Deep Pacific Water' (cited in Libes, 1992).

The transformations of nutrients and the elements nitrogen, phosphorus, carbon and sulfur, in seawater, occur by way of biogeochemical cycles, and the biogeochemical cycles are driven by the two processes of photosynthesis and respiration, and related redox processes (Libes, 1992). Broadly speaking, these redox processes are driven by the presence of oxygen (and its reduction), and organic matter (and its oxidation); oxygen and organic matter are the most abundant of the oceanic oxidising and reducing agents (Libes, 1992).

The role of nutrients in plant photosynthesis can be looked at in the case of the simplest and also the most abundant of marine producers, the phytoplankton (Libes, 1992). Apart from carbon dioxide ($CO_2$) and water ($H_2O$), phytoplankton also assimilate dissolved inorganic nitrogen (DIN) and phosphorus (DIP) from the surrounding water (Libes, 1992; Lobban and Harrison, 1997). Analysis of phytoplankton tissue showed that on average, the elements carbon, nitrogen and phosphorus exist in the atomic ratio 106C : 16N : 1P, sometimes called the Redfield – Richards Ratio (Redfield *et al.,* 1963; Libes, 1992). From this, it is inferred that one molecule of phytoplanktonic organic matter can be represented by the empirical formula $C_{106}(H_2O)_{106}(NH_3)_{16}PO_4$ and the process of photosynthesis is approximated to:

$$106\ CO_2 + 122\ H_2O + 16\ HNO_3 + H_3PO_4 \longrightarrow (CH_2O)_{106}(NH_3)_{16}H_3PO_4 + 138\ O_2$$

(cited in Libes, 1992).

The assimilation or uptake of nutrients occurs by active transport of the chemical species across the cell membrane, and this process requires energy. Nitrogen may be assimilated as nitrate ($NO_3^-$), or nitrite ($NO_2^-$) or ammonium ($NH_4^+$), while phosphorus is assimilated as phosphate ($PO_4^{3-}$ ). Nitrogen has been found to be the most important element limiting seaweed growth, which depends to a large extent on nitrate and ammonium ions (Lobban and Harrison, 1997). The uptake of ammonium ions exceeded that of nitrate ions for seaweeds (Lobban and Harrison, 1997). Ammonium would tend to be present under anaerobic conditions, for example, in hypolimnetic waters of eutrophic lakes (Wetzel 1975), but otherwise in relatively low concentrations in natural seawater (Libes, 1992). Ammonia is oxidised to nitrites by *Nitrosomonas* bacteria, and from nitrites to nitrates by *Nitrobacter* bacteria. The overall nitrification reaction:

$$NH_4^+ + 2O_2 \longrightarrow NO_3^- + H_2O + 2H^+$$

is a spontaneous redox reaction (Libes, 1992), and the intermediate products (hydroxylamine and nitrite) are usually present in very low concentrations in natural seawater (Lobban and Harrison, 1997).

### 2.6.4 Nutrient studies with *Sargassum* sp.

*Sargassum* has been described as an invasive species because of its extensive occurrence in many eutrophied marine environments (e.g., Lapointe, 1995; McCook, 1997; McCook, 1999). The Sargasso Sea of the western North Atlantic Ocean was given that name by the early explorers, because of the flourishing *Sargassum natans* which they found in the area (Lapointe, 1995). In a study to compare biological productivity in neritic (inshore) *Sargassum natans* with oceanic *S. natans* in the. Sargasso Sea, Lapointe (1995) found that the water column nutrient concentrations may not always correlate positively with the distribution of *Sargassum natans*; the neritic waters were definitely nutrient enriched, and this was reflected in the higher levels of tissue N and P (Lapointe, 1995). The average N : P ratios in tissues of *Sargassum natans* from enriched neritic waters was 10.2 in comparison with 18.1 for oceanic *S. natans* (Lapointe, 1995). However, while the Sargasso Sea flourished with *S. natans*, the nutrient concentrations were typically low (Lapointe, 1995). The explanation for the presence of *S.natans* in oligotrophic, oceanic waters of the Sargasso Sea was the influential, storm-driven westerly winds that affected the area from time to time (Lapointe, 1995).

Similar observations were made by Lovell and Tamata (1996) in a study conducted in Fiji where, the few studies conducted to date have also revealed eutrophication of coral reef areas (Lovell and Tamata, 1996; Mosley and Aalbersberg, 2003). Of particular interest was the proliferation of the reefs at Levuka, with *Sargassum* sp. The affected reefs were downdrift of the wastewater outfall from the tuna cannery at Levuka, a small town (the former capital of Fiji) on the island of Ovalau in the middle of the Fiji Group of Islands. In contrast, the reefs updrift of the outfall were not affected, and live corals thrived there as before (Lovell and Tamata, 1996). This study showed the significance of winds and surface currents in the dispersal and distribution of *Sargassum* sp.

The increasing prominence of macroalgae is not well understood at present, especially the mechanisms of their dispersal, recruitment, and vegetative growth (McCook, 1999). Nevertheless, it is interesting to note that studies on *Sargassum* showed that, unless there is an established adult population of this species, recruitment and dispersal to new areas is very difficult and therefore unlikely. In other words, invasion by *Sargassum* can only occur if there is an established, adult community in the area (McCook, 1997; McCook, 1999). There are exceptions to this, as in the case of some temperate species of *Sargassum*, and explanations for this invasive capability lies in the reproductive alternatives for the species. An example of such a species is *S. natans* which propagated by vegetative fragmentation, and had successfully invaded the Sargasso Sea (Lapointe, 1995).

Other studies have also shown how nutrient enrichment boosted the growth rates of *Sargassum baccularia* (Schaffelke and Klumpp, 1998a). In controlled experiments, the growth rates of *Sargassum baccularia* was measured under varying nutrient concentrations, in continuous flow culture set-up, at the Australian Institute of Marine Science (AIMS). The study found that within the range 3 *u*M ammonium plus 0.3 *u*M phosphate to 5*u*M ammonium plus 0.5 *u*M phosphate, the growth of *Sargassum baccularia* was almost doubled. Outside of this range, the growth was reduced. Schaffelke and Klumpp (1998a) found that both N and P stimulated growth of *Sargassum baccularia.* From another perspective (top-down control), McCook (1996) found that herbivory had greater influence on the distribution and abundance of *Sargassum baccularia* on the central GBR, compared to any other factor. The abundance and distribution of *Sargassum* spp. on the GBR has been attributed mainly to the influence of herbivory (McCook 1996; Schaffelke and Klumpp 1997b)

### 2.6.5 Bottm-up and top-down controls in coral reef communities

Studies have tested the RDM by manipulative experiments in which one or both of the controlling factors (nutrients or herbivory), is controlled, and the resulting benthic communities assessed (Littler *et* al., 2006). Littler *et al*. (2006) conducted a series of manipulative experiments, combined with assessments of existing communities plus assays, at two sites on Carrie Bow Cay (CBC) in Belize, Mexico and found interesting results that revealed how complex the interactions were, among nutrients and herbivory, and their effects on the main groups of species on coral reefs. Littler *et al*. (2006) found that reduced nutrients alone did not preclude fleshy algae, even under conditions of low herbivory, and high herbivory alone did not inhibit fleshy algae, even when nutrients were high. However, the combined conditions of reduced nutrients and intense or high herbivory eliminated all forms of fleshy algae. Other studies have found results along the same lines (Lapointe, 1997; Thacker, *et al*., 2001; Smith *et al*., 2001). The problem of phase shift is exacerbated in situations where nutrient enrichment is increasing, while at the same time, there is overfishing and overexploitation of grazers such as herbivorous fishes and sea urchins (Pedersen *et al*., 2005).

## 2.7 Methods for assessing nutrient limitation effects on macroalgae

### 2.7.1 Water column nutrients

Generally speaking, all macroalgae groups on coral reefs are nutrient limited in their productivity (Lapointe, 1997). This is proven by increases in their productivity following increases in nutrient availability, e.g., algal turfs (Hatcher and Larkum, 1983), frondose macroalgae (Lapointe, 1987), and coralline algae (Littler, 1973). Valiela *et al.* (1997) found that increases in nitrogen supply in the water column may generally increase the rate of N uptake by macroalgae, resulting in increased N tissue content. They also found that nitrogen supply appears to have greater control over net primary production by macroalgae in coastal systems. Phosphate, on the other hand, may actually limit macroalgae production in tropical, carbonate-rich waters, because P is strongly adsorbed onto the carbonate-rich substrate/sediment in tropical coral reef areas, thus keeping them away from the water column and from macroalgae (Lapointe *et al*., 1992).

Fong *et al*., (2003) described three approaches to working out the status of nutrient limitation for macroalgae in marine environments. The first two approaches are indirect methods: the use of water column nutrient concentrations, and the use of nutrient content in the tissues of macroalgae. The third approach is the direct measurement of nutrient limitation effects via experimental manipulation (Fong *et al*., 2003). In the nutrient enrichment experiments, the measurement of growth response variables such as photosynthesis rates, growth, and changes in tissue and water column nutrient concentrations are correlated with whichever nutrient was added or not added to the experimental water medium, i.e., if addition of N led to increases in growth or tissue N content, then N was limiting to that macroalgae (Fong *et al*., 2003).

Clearly, the use of water column nutrient concentrations as a guide to nutrient limitation for macroalgae has shortcomings (Fong *et al*., 2003). The water column N : P ratios are compared with nutrient requirements of algae, based on the N : P ratio in the atomic and molecular composition of a particular algal species. For example, for marine phytoplankton, the optimum N : P ratio (known as the Redfield ratio) is 16 : 1 (Redfield *et al*., 1963). Water column N : P ratios greater than 16 : 1 have been interpreted as being indicative of phosphorus-limited situations, while ratios less than 16 : 1 indicated a nitrogen-limitation situation. However, this is not always true as different algal species and indeed different functional forms of an algae often required N or P in varying quantities, as was found by Fong *et al* (1994). The water column nutrient concentrations are not truly representative of the ambient conditions, because they provide only a snapshot in time of the situation (Fong *et al*., 2003). For tropical areas (for example, Fiji) where nutrients are often delivered in pulses to the marine environment (McCook, 1999), water column nutrient concentrations should be viewed with caution, and long term monitoring of water column nutrients may provide a better assessment of their status.

Fong *et al.*, (2003) found that the initial tissue nutrient status of macroalgae affected their responses to nutrient enrichment. The study found that macroalgae with enriched tissues (collected from sites close to sewage sources) did not respond as strongly as those algae with depleted tissue nutrients (collected from sites further away from sewage sources).

There is still much to be understood about nutrient limitation in macroalgae, for example, which species of N is taken up by which macroalgae species. There is a great deal of variation in this matter; some algae preferentially take up $NH_4^+$ while others take up $NO_3^-$, and others still take up either species equally well (e.g., Lotze and Schramm, 2000; Naldi and Wheeler, 2002). There is an advantage in taking up ammonium compared to nitrate. Before the absorbed $NO_3^-$ can be assimilated into tissues of macroalgae or plants in general, it must first be reduced into $NH_4^+$ by the nitrate reductase (Hurd *et* al., 1995). This step is not necessary when $NH_4^+$ is taken up by plants, and therefore, energy is saved for other metabolic processes. Cohen and Fong (2004) found in their studies with *Enteromorpha intestinalis* (L.) Link that there was preference for ammonium ($NH_4^+$) over nitrate ($NO_3^-$) in the nutrient uptake experiments. The response of plants to nutrient enrichment is always variable and complex (Fong *et al*., 2004; Cohen and Fong, 2004).

Lapointe, (1997) found that the water column nutrient concentrations and ratios matched the nutrient ratios in the tissues of representative macroalgae from these reefs. For the Jamaican reefs, the high DIN : SRP ratio in the water column (range from 33.0 to 103), matched the high N : P ratios in the macroalae tissues, indicating phosphate limitation in the carbonate-rich reefs. Of interest is the fact that *Sargassum* was one of the expanding macroalgal groups on the carbonate-rich Jamaican reefs (Lapointe, 1997). In contrast, the Florida reefs which have been described as being siliciclastic, recorded lower DIN : SRP ratios (range from 3.1 to 14.3), and was characterized more by the bloom-forming chlorophyte *Codium isthmocladum*.

Fong *et al*., (2004) found in their experiments with the macroalgae *Enteromorpha intestinalis*, that when nitrogen and phosphorus were supplied in pulses (up to the highest treatment of 1000 uM $NO_3$ + 100 uM $PO_4$), the algae reduced inorganic N in the experimental jars to very low concentrations (<3.5 uM). The increased N was either transferred to growth, or stored in the tissues. The interesting finding was that in the highest treatment (1000 uM $NO_3$ + 100 uM $PO_4$), the mean tissue N was double the initial values, but growth was less than for the lower nutrient treatments. This result showed that uptake of nutrients during very high nutrient pulses does not always equate to growth. In fact this may explain the unusual finding by Schaffelke and Klumpp (1998a) that high concentrations above 5 uM ammonium plus 0.5 uM phosphate did not cause a corresponding increase in growth rate, even though they were working with a different species (*Sargassum baccularia*). In other words, the responses of macroalgae to nutrient pulses are complex and highly variable according to species.

### 2.7.2 Tissue nutrients

The concentrations of nutrients in tissues of marine macroalgae provide a more accurate indication of the ambient nutrient levels, compared to water column nutrient concentrations (Edwards *et al*., 2006). This stems from the fact that macroalgae tend to ‘grab’ nutrients from the water column and even store them for periods of low nutrient concentration, as is often the predominant set of conditions in oligotrophic waters of tropical coral reef areas (Fong *et al*., 2004; Raikar and Wafar, 2006; Edwards *et al*., 2006).

Tissue nutrient concentrations and N : P ratios provide a better measure of nutrient limitation for macroalgae, particularly for tropical areas where nutrient pulses are the usual pathway for nutrient enrichment of coastal waters (McCook, 1999). While an instant measure of water column nutrient concentration can easily miss the effects of rain-induced flushing within a few days from sampling, the macroalgae on the other hand would have responded to the enrichment by a greater uptake and possibly storage of the nutrients. Tissue nutrient concentrations and N : P ratios often reflected the history of nutrient enrichment in an area (Fong *et al*., 2001). However, because different algae have different capabilities of uptake and storage, for the different nutrient forms (ammonium as opposed to nitrate, for example), the tissue N : P ratios may not always accurately portray the nutrient limitation conditions in the ambient environment.

From an extensive study of tropical and temperate waters and macrophytes, Lapointe (1992) found that the tissue N : P ratios in the macroalgae tissues matched the average ambient N : P ratios. The tropical waters N : P ratios had a mean of 36 as compared to N : P ratios of temperate waters with a mean of 3 (Lapointe, 1992). The mean N : P ratio of macroalgae from carbonate-rich tropical waters was 43.3, and for macroalgae from temperate waters was 14.9. The results from the study suggested that the tropical macrophytes tended to be phosphorus-limited while the temperate macrophytes tended to be nitrogen-limited (Lapointe, 1992).

Of the nutrients in the marine environment, nitrogen is the primary nutrient limiting growth of seaweeds (Lobban and Harrison, 1997). It follows then that variation in seaweed growth should be linked to variations in nitrogen supply (Lobban and Harrison, 1997). However, nitrogen exists in various forms in the water column, and different macroalgal species may vary in their preference for which form of nitrogen they take up from the surrounding water.

### 2.7.3 Use of stable isotopes

The ratio $^{15}N/^{14}N$ usually quoted as $\delta^{15}N$ (Heikoop *et al.*, 2000) provides a measure of anthropogenic influence or effects. The higher $\delta^{15}N$ is, the greater the presence of nitrogen derived from anthropogenic sources such as sewage. This tracer methodology has been used to map the effects of sewage and eutrophication (Costanzo *et* al., 2001). The method has also been proven in studies with seagrass (Yamamuro *et al*., 2003), coral tissue ( Heikoop *et al*., 2000) and benthic algae (Umezawa *et al*., 2002). To a less extent, $^{13}C/^{12}C$ expressed as $\delta^{13}C$ has also been used to assess sewage effects on certain species, for example, in reef corals (Heikoop *et al*., 2000). The higher (or less negative) the value of $\delta^{13}C$, the less the effects of sewage. Costanzo et al. (2005) emphasized the importance of distinguishing between the different sources of DIN in the environment, before the sources can be controlled.

In Moreton Bay, on the east coast of Australia, sewage tracing using stable nitrogen isotopes ($\delta^{15}$ N) has been used since 1997. The technique was developed in response to public demand for a better monitoring technique that could distinguish between the different sources of nitrogen causing problems in Moreton Bay (Dennison and Abal, 1999; Udy and Dennison, 1997a, b). The technique is based on the two naturally occurring atomic forms of nitrogen $^{14}N$ and $^{15}N$, and how their ratios in the test biological species compare with an accepted standard, (atmospheric $N_2$). The ratio of $^{15}N$ to $^{14}N$ in the dried plant species is compared to the worldwide standard and the resultant parameter $\delta^{15}N$ gives the relative amount of $^{15}N$ in the plant species, according to the formula below:

$$\delta^{15}N(^{0}/_{00}) = (R_{sample}/R_{standard} - 1) \times 10^{3}$$

where R is defined as the atomic $^{15}N/^{14}N$ ratio (Costanzo *et al*., 2005).

Sewage and other wastewater effluents are usually enriched with $^{15}N$ and therefore have a higher $\delta^{15}N$ because bacterial and other biochemical transformations of the nitrogen in waste prefer to use up the lighter and therefore the more easily metabolized $^{14}N$, leaving the residual dissolved inorganic nitrogen (DIN) in wastewater with a higher $\delta^{15}N$ (Heikoop et al., 2000; Costanzo et al., 2001). Aquatic plants, reef corals and other organisms that take up nutrients from the water column enriched with $^{15}N$ from anthropogenic sources also show high $\delta^{15}N$ signals, and this is the basis of using this technique to assess extent of human impacts on the aquatic environments.

In the Moreton Bay sewage monitoring program, the red algae *Catenella nipae* was used as the test species (EHMP, 2004; Costanzo et al., 2005). This red algae is collected from the eastern side of Moreton Bay, a relatively clean site where there is no sewage signal and the $^{15}N$ levels are low, about 2 ppt. The *Catenella nipae* are deployed all around Moreton Bay for 4 days and then collected and analysed. The $\delta^{15}N$ concentrations usually range from 2 ppt at the clean sites, to about 6 – 7 ppt near the western side of the bay where there is a concentration of population and sewage plants, and up to a maximum of about 9 – 10 ppt adjacent to tertiary sewage discharges (EHMP, 2004; pers. comm., Moore, UQ Centre for Water Studies, 2005).

The techniques of tracing sewage pollution using stable isotopic methods is becoming more popular (Heikoop *et al*., 2000; Yamamuro *et al*., 2003). The advantage of this technique is that it incorporates time factor and provides a more accurate assessment of nutrient enrichment in comparison to instantaneous measurements. Sewage often has a higher proportion of $^{15}N$ and consequently a higher $\delta^{15}N$ indicated a greater level of sewage pollution (Yamamuro *et al*., 2003).

## 2.8 EFFECTS OF HERBIVORY ON MACROALGAE

Stimson *et al*. (2001) concluded from herbivory exclusion tests and species distribution tests that herbivory was just as important as nutrient effects in determining communities on coral reefs. Another interesting conclusion which should be part of future herbivory investigations is the effects of herbivory preference on the macroalgae. In the Kaneohe Bay study (Stimson *et al.*, 2001), part of the possible explanation for continued prevalence of *D. cavernosa* was the preference for other introduced species over *D. cavernosa* by the grazing herbivores (Stimson *et al*., 2001).

Boyer *et al*. (2004) reiterated the importance of sustaining herbivore populations as a mechanism to compensate for the effects of nutrient enrichment in coral reef, seagrass and mangrove habitats. In a study conducted near Honduran Island in an area protected from fishing, Boyer *et al*., (2004) found that nutrient enrichment resulted in significant increases in grazing rates at the three habitats studied. The study methodology involved exposing nutrient (nitrogen and phosphate) enriched *A. spicifera* to herbivores at the three habitats. Controls used non-nutrient enriched *A. spicifera*. For the coral reef habitat, herbivore consumption of enriched *A. spicifera* increased by 20% (Boyer *et al*, (2004). This is an interesting phenomenon because it implies that somehow the herbivores are able to 'sense' and locate a nutrient-enriched food source for their consumption. This scenario therefore strongly advocates for the setting up of 'no take' fishing areas where nutrient enrichment is prevalent, for example in the inshore reefs.

Studies conducted on reefs at Dravuni Island (Fiji), Uepi Island (Solomon Islands) and on Vava'u and Ha'apai (Tonga) again showed the significant role of herbivores in controlling algal assemblages on coral reefs (Gobler *et al.*, 2006). At Dravuni in Fiji, herbivore exclusion (by caging) and nutrient enrichment resulted in significant increases in brown macroalgae abundance, at the expense of the red macroalgae (Gobler *et al.*, 2006).

Armitage and Fourqurean (2006) investigated the role of herbivore preference involving different seagrass species, namely *Halodule wrightii* and *Thalassia testudinum.* The results showed the importance of herbivore preference in the coexistence of several species of the same trophic level. In caging experiments, the more herbivor-resisent *T. testudinum* was not affected by herbivory, whereas *H. wrightii* was significantly reduced in uncaged plots compared to caged plots (Armitage and Fourqurean, 2006).

Littler *et al*., (1986), in a study conducted at Carrie Bow Cay in Belize showed how edible macroalgae species escaped being consumed by herbivorous fishes, through their close association with herbivore-resistant species. In this study, the herbivore-resistant brown alga *Stypopodium zonale*, through its association with some relatively edible macroalgal species including *Laurencia poitei*, *Amphiroa tribulus* and *Digenia simplex*, provided the edible species a degree of protection. This sort of association contributes to high species diversity within habitats

## 2.9 MITIGATIVE MEASURES AND MANAGEMENT OPTIONS

Risk (1999) raised some very interesting, and 'truthful' points in his analysis of how the scientific community has reacted to the crisis facing the coral reefs of the world. He criticized the response as being slow in comparison to other two large scale (international) environmental crises: the eutrophication of the Great Lakes, and the problem of acid rain in the Northern Hemisphere (Risk 1999). The lessons learned from these two crises are very appropriate for addressing the crisis facing coral reefs:

- avoidance of arguments over methods;
- genuinely multidisciplinary teams (biologists, chemists, geologists, hydrogeologists working as a team); and
- the involvement of experienced and competent managers to lead the teams.

In the coral reef crisis, often it is only biologists that are actively involved and therefore, the management of the crisis does not take on a wholistic approach and therefore fails (Risk 1999). It took some years before affected countries acted to put in place national policies and standards to guide the authorities in management of the crisis (Risk, 1999). Indonesia was the first country to do this, and for some time was the only country to have adopted a national policy framework and guidelines to mitigate the degradation of coral reefs (Risk, 1999).

The use of clearly identified and accepted national bioindicators for coral reef degradation was the most significant step towards addressing the coral reef crisis. Unfortunately this is not the case for most other less developed countries including those in the Pacific like Fiji (Zann, 1992; South & Skelton, 2000; Vuki *et al*., 2000). Much time, money and resources are still being spent on comparing different monitoring methods and gathering of scientific data. Meanwhile, conditions on the reefs continue to deteriorate (Risk, 1999).

In terms of biological methods, line transects, quadrats and visual fish counting were described as early as 1972 (Risk, 1972). Other researchers have gone on to prove that regardless of methods used, one basically got the same results (Done, 1977; Chiaponne and Sullivan, 1991). Risk and Risk (1997) proposed that for management purposes, a 20% precision in the results is sufficient and anything beyond that was 'a waste of time and money'. Today, many countries have adopted more efficient methodologies such as the 'rapid reef assessment' programmes (Hill and Wilkinson, 2004). An example is the one developed in Florida (Miller and Swanson, 1999). However, a monitoring strategy that has been widely accepted and used internationally is the Reefcheck Method of biological survey (Hodgson, 1999). The Reefcheck method is suitable for most communities including those in developing countries with limited financial and technical expertise, because it uses volunteer labour and locally identified bioindicator species (Hodgson, 1999). While monitoring of coral reef is good, it should not be an end in itself. Monitoring should really serve the purpose of identification of stressors and this step should lead on to how these stressors can be mitigated (Risk 1999).

Arevalo *et al., (*2007) investigated how eutrophication affected species composition, as part of the Water Framework Directive in Europe. They found changes in species composition, often along a gradient of changing nutrient concentration and water quality (Arevalo, *et al*., 2007). The problem is worldwide and in Europe, the setting up of the Water Framework Directive (WFD, 2000/60/EC) is a combined response by the European countries to address the increasing problem of eutrophication. Although this study was conducted in a temperate environment (Tossa de Mar, a famous tourist destination in Spain), the findings are similar to those from tropical situations. Arevalo *et al.,* (2007) compared dominant benthic communities at sites near the sewage outfall and along transects moving away from the outfall. The study found, (as would be expected), macroalgal dominated communities (*Ulva*-dominated) nearest to the sewage outfall, changing to *Corallina*-dominated communities further away from the outfall, and changing further to *Cystoseira*-dominated communities in reference sites (Arevalo *et al.*, (2007). However, the fact that *Cystoseira*-dominated communities were also found at polluted sites showed that there was no simple, clear-cut relationship between nutrients and marine species. Arevalo *et al.,* (2007) explained that certain species belonging to a particular functional grouping can behave quite differently under different conditions of pollution. For this reason, Arevalo *et al.,* (2007) concluded that the use of indicator species rather than functional-form groups of algae provided a more accurate assessment of the status of water quality, at least in Tossa de Mar in Spain.

The setting up of the Water Framework Directive (WFD) by the European countries is a lesson for other regions and countries. The aim of WFD is to achieve good ecological status in all waterbodies by 2015 (Devlin *et al*., 2007). This involves re-setting thresholds so that the water quality targets move beyond the narrow, “nutrient concentration” or purely chemical assessment of a water body, to one that encompasses the ecological structure of the system. The ecological standards will be based on conditions one would expect in the absence of human impact (Devlin *et al.*, 2007). While this may appear an insurmountable task, it is certainly possible for developed countries in Europe because of technical expertise and financial resources available. The work in the Australian GBR by Wooldridge *et al.*, (2006) can be likened to the WFD in Europe, because the aim of the GBR study is to develop ‘end-of-catchment’ water quality targets that would eventually restore pre-European conditions in Australia’s GBR. For small island developing (SIDS) countries like Fiji, the time to act is now, while human impact is still at a ‘manageable’ level.

## 2.10 THE SITUATION OF THE SOUTH PACIFIC AND FIJI

In the status of coral reefs report on Fiji and the southwest Pacific region, South & Skelton, (2000) noted that while most reefs are in good condition, there are increasing pressures from anthropogenic impacts resulting in some reefs being severely degraded. Coral reefs are important to people in this region for provision of food resources, cash income from reef fisheries, for coastal protection, for sand and rock for building of roads and housing, and the healthy reefs to support tourism industry (South & Skelton, 2000).

In developing countries of the Pacific where sewage treatment and disposal are not always properly managed and monitored, the impacts of sewage on the quality of coastal waters and the marine ecosystems therein are already evident (IAS, 2004). However, little has been done to research and understand the mechanism of these impacts, and this state of affairs is due to a number of reasons including lack of funds, limited technical expertise and the lack of commitment at the national and policy level (South and Skelton, 2000).

The fringing reefs of the Coral Coast in southern Viti Levu already show signs of being impacted by anthropogenic factors (Mosley and Aalbersberg, 2003). The fringing reefs here are exposed to a number of threats:

- sewage from the resorts, hotels, motels and coastal villages;
- increasing village population means an increased fishing pressure including gleaning on the reefs;
- the difficult economic climate that is currently affecting many rural communities in Fiji means that the number of people turning to the sea and the reefs for their source of livelihood is also on the increase (Vuki *et al*., 2000).

Currently, there is no scientific information on the variability in status of the water quality and the fringing reef communities of the Coral Coast as no long term monitoring has ever been undertaken (Mosley and Aalbersberg, 2003). Some work on nutrient assessment in the coastal waters has begun as part of a new initiative, the Integrated Coastal Management (ICM) involving several stakeholders from government level down to the village administration level (IAS Annual Report, 2005). A number of non-government agencies including the USP are also part of the ICM initiative. The vision of ICM is to identify appropriate management strategies to address the problem of degrading coastal water quality and reefs (IAS Annual Report, 2005). For this vision to become reality, scientific information on the status of the coastal resources, and factors influencing this status must be available.

Recently, the support for marine protected areas has spiraled because of the awareness of the value of MPAs in restoring coral reef ecosystems. This initiative in

Fiji is part of the activities of the Fiji Locally Managed Marine Areas (FLMMA). Setting up MPA or 'tabu' sites is also seen as one of the possible management strategies to address the increasing algal dominance of coral reefs because herbivore populations would be protected.

Coral reefs have significant social and economic value for small island developing states (SIDS) such as Fiji (Vuki *et al*., 2000). Likewise, for the rural and coastal communities in other tropical countries, coral reefs have very significant social and economic value. In some cases, the whole economy may be dependent on coral reefs. In Palau, for example, scuba diving and other related activities bring in about $13 million per year for the population of 14,000 (Birkeland 1997). The story is the same for other atoll island nations in the Pacific. In Fiji, tourism has become the number one foreign exchange earner, beating sugar and other traditional export industries (Fiji Bureau of Statistics, 2004).

Coral reefs have always provided a link to the past for the traditional, indigenous communities of the Pacific including Fiji. In Fiji, for example, the role of catching fish for the chiefs is a traditional one and only members of that clan traditionally known as the *Gonedau* have the privilege of fishing from designated *kanakana* or fishing ground for the chief. However, the members of the village communities are allowed access and use of the *I Qoliqoli* as well, and such activities are always enjoyed by all (Veitayaki, 1995).

In Fiji, the Great Astrolabe Reef Lagoon (GAR) in the Kadavu Group of Islands to the south of the Fiji group, is probably the most frequently surveyed reef site, as a result of the location of a marine science field station on one of the islands within the Lagoon. Two separate studies at the GAR found average nitrite concentrations were 0.07 and 0.02 *u*mol/L respectively; average nitrate concentrations were 0.74 and 0.30 *u*mol/L; average ammonium concentrations were 0.12 and 0.27 *u*mol/L and average phosphate concentrations were 0.07 and 0.18 *u*mol/L (Morrison *et al*., 1992; Charpy *et al*., 1996). The reefs at the GAR are relatively in a better condition than most other reefs around Fiji, but it was noted that those reef sites close to land and human settlement were less ‘healthy’ than the other reefs near passages and far from human impacts (Morrison *et al.*, 1992).

## 2.11 GENERAL SUMMARY

The review of the literature on the research topic has revealed a number of important general points:

- coral reefs are being threatened by anthropogenic factors at a scale never experienced before;
- the scientific community, especially in developed countries has responded to the threats by concerted research efforts into anthropogenic effects on coral reefs;
- there is still much to be understood about the complex interactions among nutrients and biological systems in coral reef areas; and
- control and management of anthropogenic sources of pollution, especially nutrients, may be lagging behind as human activities continue to effect changes and alterations on the environment, including the marine environment.

The research reported in this thesis is an attempt to assess how anthropogenic factors are affecting the water quality and the coral reefs along the Coral Coast of Fiji.

# CHAPTER 3 – STUDY AREA

## 3.1 THE FIJI ISLANDS

### 3.1.1 Physical setting

The Fiji Islands consist of about 330 islands and 500 islets and cays spread across thousands of kilometers of ocean in the South Pacific (Figure 3.1). The islands form an archipelago on an ocean platform known as the Fiji Plateau. The islands are spread out between the latitudes $15^o$ – $22^o$S and longitudes $177^o$E and $179^o$W. The $180^o$ meridian passes through the island of Taveuni in the north east of the Fiji Group. The total land area is about 18,333 $km^2$ (Fiji Islands Bureau of Statistics, 2006). Fiji has a large Exclusive Economic Zone (EEZ) of 1.3 million square kilometers (South and Veitayaki, 1998). Viti Levu is the largest island with a land area of 10,429 sq. km. The main study area is along the Coral Coast, on the South-west coast of Viti Levu. The capital city of Suva and the only international airport at Nadi are on the island of Viti Levu. Figure 3.1 shows the location of Fiji in the South Pacific, the location of the Coral Coast on Viti Levu, and the detailed map of the section of the Coral Coast where the study sites are located. The location of the water sampling sites are shown on Maps A1 to A7, appended to the thesis.

The Fiji Plateau on which the group sits is surrounded by deep waters, up to 2000 – 3000 m in the deepest parts, for example, between the islands of the Lau Group to the east. Around Viti Levu and Vanua Levu it is generally shallower. The surface currents flow in a south-westerly direction through the group and are influenced strongly by the South East Trade Winds, setting up the westerly-flowing longshore currents along the southern shoreline of Viti Levu (Ryland, 1981).

### 3.1.2 Climate

The Fiji Islands enjoy a moderate tropical climate with temperatures falling within the range 22 – 28 $^oC$, with the occasional high of up to 32 $^oC$ in the hot and wet season, and the occasional low down to 18 $^oC$ at night in the cool and dry season (Gale, 1991). In the interior of Viti Levu, temperatures are generally lower than on the coast, and in the cool season, air temperatures can drop to below 16 $^oC$ at night.

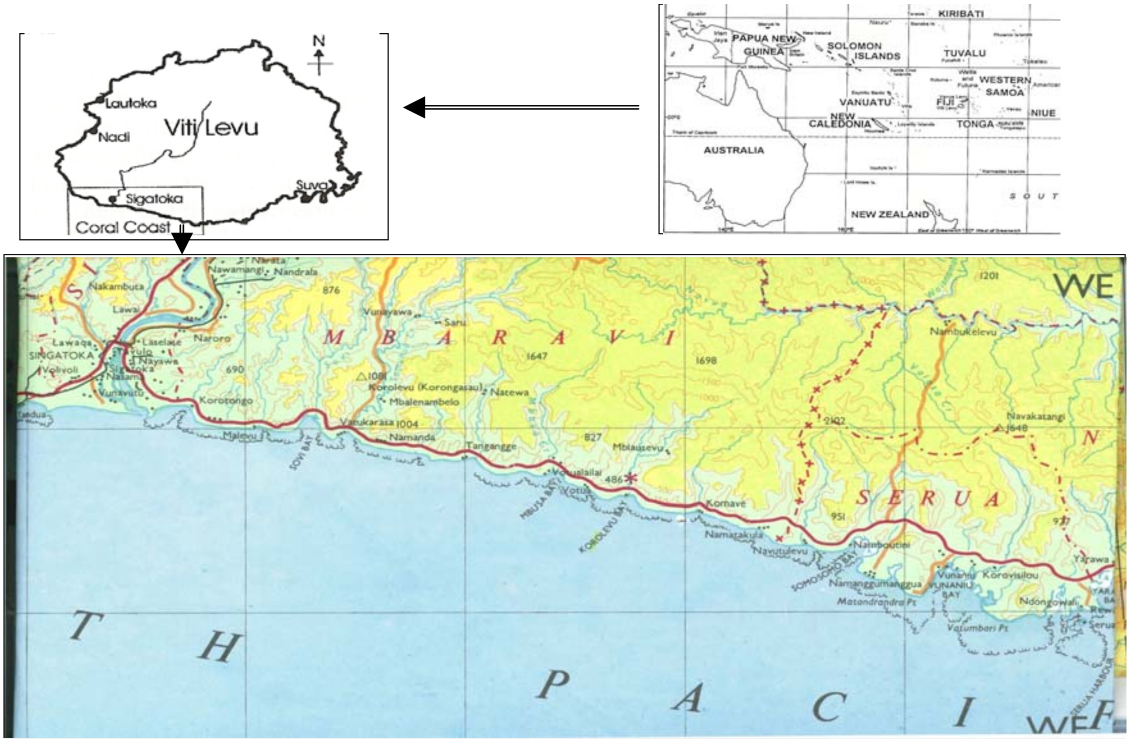



Figure 3.1 Locality Map for the Coral Coast Region, South-west Viti Levu, FIJI.

There are two main seasons – the hot and wet season from November to April, and the cool and dry season from May to October each year. Tropical cyclones are always a threat during the hot and wet season. The rainfall is orographic and is highly variable. It is controlled by the South Pacific Convergence Zone, the major rainfall producing system for the region (Ryland, 1981). The predominant winds affecting the Fiji Group are the easterlies and the South East Trade winds, which are often light to moderate. The high mountain ranges dissecting the two large islands, along with the influence of the South East Trade winds produce a clearly wet, windward side on the southeastern parts of the main islands, and a drier, leeward side on the north and northwestern parts of the main islands. The best coral reefs in the Fiji Islands are found in the drier, leeward sides of the main islands, especially in the west and north-west of Viti Levu, and linking up with the highly-valued Great Sea Reef to the north of Vanua Levu (Vuki *et al.*, 2000). Fiji has one of the largest coral reef systems in the South West Pacific, and Fiji's largest fringing reefs are along the Coral Coast (Zann, 1994).

### 3.1.3 Social and economic features

*Population*

The population of Fiji was estimated at 832,446 in December 2003 of which 49% are urban dwellers living in the towns and the two cities of Suva and Lautoka (Fiji Bureau of Statistics, 2004). The population growth is estimated at 1.41 %. Population increase is a global phenomenon and Fiji is not without her share of environmental problems arising out of increased human population. Since these population concentration centres are on or close to the coastlines, there is an increased level of stress on the marine environment and the ecosystems therein including the coral reefs. In Fiji, 82% of the population live within 10 km of the coast (Fong, MA thesis, 2006). There has been an observed deterioration in water quality over the years in coastal waters around the major urban centres of Suva and Lautoka on Viti Levu; and Labasa on Vanua Levu (Naidu *et al*., 1991; Tamata *et al*., 1993; Vuki *et al*., 2000) .

Unemployment is on the increase due to limited opportunities. There is much potential in the largely, under-developed agriculture sector. In 1999, unemployment was around 7.6 % and in 2000, this had increased to 12.1 % (Ministry of Labour, Fiji Government, 1999 - 2000). The increasing unemployment has forced many people to turn to the sea and inshore reefs to meet their subsistence as well as monetary needs. This is becoming increasingly common for people living in ‘squatter’ settlements on the outskirts of the main urban centers such as Suva and Lautoka. The health issues arising out of these peri-urban settlements is a major concern for the authorities (Vuki *et al*., 2000).

*Economy*

Historically, the economy of Fiji has always been based on the primary industries of agriculture, forestry and fisheries. The Asian Development Bank (2001) highlighted the fact that Fiji’s economy is very much dependent on her natural resources and the environment. For over 100 years, sugar had been the mainstay of Fiji’s economy, contributing around 14% of the total foreign exchange and providing employment for about 25% of the labour force in 2000 (Fiji Bureau of Statistics, 2001). There was always a risk associated with limited export commodities. Fiji's export base has been described as 'narrow' (Siwatibau, 1993), but in comparison to other South Pacific countries, Fiji's economy is more developed and diversified (Gillett and Lightfoot, 2002:4). Fiji's Gross Domestic Product (GDP) was FJD 4,168 per head of population in 2002, with annual growth rate of 6.2 % (Fiji Bureau of Statistics, 2002a). The high rate of unemployment is a real concern for Fiji. There are a lot of tertiary-qualified young people but the employment opportunities are very limited. The last five years have seen an increasing growth in the manufacturing and service sectors of Fiji's economy and Tourism has replaced sugar as the largest gross foreign exchange earner. In 2004, Tourism contributed about 60% of GDP (Fiji Bureau of Statistics, 2005). The boom in tourism comes at a cost to the environment as seen in some parts of Fiji (Zann and Lovell, 1992).

In the rural communities, subsistence fishing and farming are still the main activities supporting the livelihood of the people (Vuki *et al.*, 2000). This will continue to place pressure on the marine resources, especially the inshore waters and reefs. However, a positive initiative currently being undertaken by a number of non-government organizations (NGOs) including the University of the South Pacific, is the training and empowerment of local communities in the rural villages to conserve and protect their marine resources. This initiative uses a number of tools including the setting up of 'no take' or *tabu* areas within their traditional fishing grounds. The umbrella organization coordinating this marine conservation initiative is known as the 'Fiji Locally-Managed Marine Areas' organization (FLMMA), and there have been several success stories and useful lessons from the various FLMMA project sites (Tawake and Aalbersberg, 2001).

### 3.1.4 Tourism

In 2003, the Tourism sector recorded 430,800 visitors, and in 2004 for the first time in Fiji's history, more than 500,000 visitors arrived in Fiji. The total number of visitors to Fiji was 502, 765 in 2004 and this again increased to a record level of 531,914 in 2005 (Fiji Bureau of Statistics, 2006). New resorts are being built while others are expanding, for example, the Naviti Resort on the Coral Coast of Viti Levu. Overall, the Room Occupancy Rates showed an increase from 61.3 % in 2004 to 64.4

% in 2005. Comparing the ‘Room Occupancy by Area’ for the first and second quarters of 2006 shows that the Coral Coast has one of the highest occupancy rates (see Figure 3.2).

Please see print copy for Figure 3.2

Figure 3.2  Hotel room occupancy by area for first 2 quarters of 2006.
(Source: Fiji Bureau of Statistics, 2006)

The contribution of tourism to the economy cannot be overemphasized. In the second quarter of 2006, there was an increase of 2.6 % in paid employment in the hotel sector, in comparison with the same period in 2005. Income from the sale of food, liquor and other miscellaneous expenditures also showed an increase of 0.9% compared to 2005 takings. The total earnings from Tourism was F$ 717.6 million in 2004 increasing to F$729.1 million in 2005 (Fiji Bureau of Statistics, 2006).

The largest resorts and hotels are located on the drier western side of Viti levu and also in the Mamanuca and Yasawa Group of Islands off the west of Viti Levu, and along the Coral Coast of south-western Viti levu.

The growth in tourism activity has, along with other anthropogenic factors, placed increased pressure on the marine environment, particularly the coral reefs. This situation is exacerbated by the fact that there are no clear standards or guidelines on wastewater treatment for resorts. At the same time, enforcement of other government legislation such as the Public Health Act of 1978 (Fiji Government, 1978), which can address pollution by resorts and other coastal development, is hardly occurring.

### 3.1.5 Marine resource use and management

At the National Policy level, there is support for protection of marine resources. The Department of Fisheries is tasked to "promote marine biodiversity through better conservation and management of resources" according to the Ministry of Fisheries and Forests Strategic Development Plan 2005 – 2007 (2003:3). The large size of the marine area in Fiji's EEZ and lack of technical expertise and financial resources to enable comprehensive studies in the marine sector has meant that there is insufficient scientific information and data on the use of marine resources and the environmental impacts of fishing (Watling and Chape, 1992; Gillet, 1997). However, data from the Department of Fisheries Annual Reports show a steady decline in the inshore fisheries catch, and this may well be the result of overfishing within the inshore waters. This is an important factor when considering the changes that are happening on the reefs. Overfishing reduces the effective top-down control of macroalgae and may therefore lead to their expansion on the reefs. People are turning to fishing as a main or secondary source of income because of the high return relative to effort, and there is increasing need for money these days to meet individual, communal and cultural and religious needs. The fishing pressure would not be as great, if it was solely for subsistence purposes (South *et al.*, 1994.).

### 3.1.6 Fisheries resources

The decline in fishery resources is not only a local observation but is reflected in the national fisheries statististics (see Table 3.1).

Table 3.1 Changes in average catch for IDA (inside demarcated areas) license holders (1976 – 2003).

Please see print copy for Table 3.1

(Source: Fong, MA Thesis, 2006)

### 3.1.7 Coral reefs of Fiji

There are about 1000 reefs in Fiji, consisting of well developed barrier and fringing reefs, atolls and cays (IUCN, 1988). The fringing reefs surround almost all of the high islands and these have been degraded to varying degrees depending on the proximity to urban centres or high population densities (Zann, 1992).

The reefs are geologically young, generally younger than 10,000 years and have formed over previous reef formations. They are of varied geomorphological features reflecting their Pleistocene and Holocene histories. There are examples of raised or uplifted reef forms and there are the submerged reef forms. The Coral Coast reefs are described as windward, mid and outer shelf fringing reefs (Vuki *et al*., 2000).

The main types of reefs in Fiji are the fringing reefs which can be found around most of the high islands, barrier reefs on the edge of island shelves, and patch reefs which are the smallest in size measuring not more than 50 m long. The most prominent reefs are the fringing reefs along the Coral Coast which stretches for about 100 km along the south-western coast of Viti Levu, and the 370 km long barrier reef chain of the Mamanucas/Yasawas/Great Sea Reef System to the north-west of the Fiji Group (Vuki *et al*., 2000).

In terms of marine species diversity, Fiji has strong affinity with the South East Asian-Great Barrier Reef Region, the center of Indo-Pacific marine species diversity, and is thus blessed with relatively high diversity. However, because of its geographical isolation, Fiji's species diversity is still significantly lower than those of Southeast Asian reefs (Veron, 1995). There have been no long-term ecological studies on the reefs in Fiji because of minimal technical expertise and little financial support for such studies. Most studies have concentrated on conducting inventories of the different marine species, for example, Paulay (1990) identified and described 100 species of stony corals from the Great Astrolabe Reef, Kadavu; Zann, (1992) described 198 species from the Mamanucas and the Southern Viti Levu; Muzik and Wainwright (1977) identified and listed 5 species of gorgonian coral or sea fans; Muirhead and Ryland, (1981) identified and listed 15 species of zoanthids from Viti Levu.

South & Skelton, (2000) reporting on the status of coral reefs in Fiji, highlighted the following points which are of relevance to this research:

- reefs around urban centers are significantly degraded through eutrophication, pollution, crown-of-thorns starfish (COTS), coastal development and siltation;
- most commercial species are depleted and some species are locally extinct;
- destructive fishing, mining, forestry, agriculture, and poor tourism developments are impacting reefs in some areas;
- periodic severe cyclones cause extensive reef damage in localized areas;
- a lack of coordinated monitoring prevents adequate assessment being made on the status of the reefs;
- a lack of Marine Protected Areas is hindering conservation efforts; and,
- reef degradation is exacerbated by coastal development, mangrove destruction and other anthropogenic impacts.

### 3.1.8 Traditional system of marine resource management

The role of traditional, marine resource management practices in sustaining coral reef health has not been fully investigated, and therefore not well understood or acknowledged by the scientific community. Hoffmann (2002) in his study compared the status of the coral reefs in two islands in the Cook Islands (Aitutaki and Rarotonga) and two in the Fiji Group (Ovalau and Vatulele). These islands differed in many respects: their levels of economic development, population pressure, land-use pratices and marine management regimes. Hoffmann concluded that coral reef degradation is not a simple, ecological phenomenon but is intricately tied in with the way the local people valued their reefs. He also proposed that external economic factors played a very significant part in the health of coral reefs. As the local communities 'sold' off access to the reefs to dive operators and hotels, there is a winding down of their bonding or relationship with the reefs and this significantly contributed to the degradation of the coral reefs. Hoffmann (2002) found that where customary marine tenure was the only resource management system in place, then the health of the coral reefs was relatively better than for those islands which had both customary marine tenure and 'open access' areas.

## 3.2 THE CORAL COAST OF VITI LEVU

### 3.2.1 Physical Setting

The stretch of coastline known as the Coral Coast commences from the eastern end at Serua, at the site of the Namaqumaqua Village and the Coral Village Beach Resort, all the way to Natadola Beach to the west of the Fijian Resort, west of Sigatoka Town. The appended locality maps (A1 to A8) show the Coral Coast with its series of fringing reef platforms, clearly incised by the channels created by fresh water discharged from the rivers and streams on land. The Coral Coast is one of the fastest developing regions in Fiji, in terms of tourism development. The environmental costs of this rapid development are quite obvious to the casual observer, but there has been no real, long term scientific monitoring of the coral reefs to establish the extent of the changes. This research is an attempt to address this information gap.

### 3.2.2 Coastal changes over time

The coastline along the Coral Coast of Viti Levu and the Nadi coastline have changed dramatically in the last twenty years as the demands for increased housing for an expanding population, as well as the demand for more tourism facilities increased. A review of aerial photographs from 1967 onwards shows a number of distinct changes: increased village sizes and house numbers; construction, diversion and expansion of the Queens Highway; construction and expansion of resorts (Warwick and Naviti resorts); reduced coastal vegetation and in more recent cases, complete removal of the coastal fringe, whether it be mangrove zone or other coastal flora (Fiji Lands Department, Map Section, 2006). The coastal flora that have been progressively removed due to development included members of the Rhizophoraceae Family, *Rhizophora mangle* (local name 'Tiriwai'), *Rhizophora stylosa* (local name 'Tiri), *Rhizophora mucronata* (local name 'Tiritabua'), *Bruguiera gymnorhiza* (local name 'Dogo') and other species including *Excocaria agallocha* (local name 'Sinugaga') and *Xylocarpus granatum* (local name 'Dabi'). The coastal flora of Fiji has always been highly valued by the indigenous people because of the medicinal and cultural uses they provided (Smith, 1988).

In a study conducted by a team of scientists and social scientists from the University of the South Pacific in 2001, of changes in the coastline area, and the biological and hydrological characteristics of the Yanuca channel leading to the famous Fijian Hotel, it was found that the removal of the mangroves and the coastal forests played a major role in causing increased sedimentation, increased coastal erosion particularly during tropical cyclones and tidal waves. One notable example of such ill-planned development was the reclamation of the extensive mangrove areas in the current site of the "Ka Levu Center" between Cuvu and Rukurukulevu villages. This site previously had lush mangrove communities with rich, characteristic fauna including mud crabs 'qari' (*Scylla serata*), red-clawed mangrove crab 'kuka' (*Sesarma erythrodactyla*) and other subsistence and commercial species of great importance to the local communities (Terry and Thaman, 2001). Unfortunately, this example is just one of many for the coastal areas of Fiji.

Coastal erosion has become increasingly important recently, particularly near cleared areas. The western boundary of Tagaqe village along the Coral Coast is a classic example of coastal erosion, and for many years, it had been an issue of contention between Tagaqe villagers and the Hideaway Resort management. The seawall constructed by the Hideaway Resort less than 100 m to the west of Tagaqe village has been blamed for the erosion of the coastline at Tagaqe.

The factors contributing to coastal erosion are complex and varied. In response to concerns raised by the villagers of Tagaqe through the Fiji Mineral Resources Department, a study was conducted by a team from the South Pacific Applied Geoscience Commission (SOPAC) to collect and review baseline data on the coastlines along the Coral Coast, in view of the foreseen increased tourism development in that area (SOPAC MR 222 in Pitman *et al*., 2000). For that study, the area from Bucona Point (177$^{o}$ 38’34.3”) to the west across to the Nayawayawa Point (177$^{o}$ 40’17.14”) on the east was selected by the team from SOPAC. This area is within the current research area. The study included bathymetric and hydrogeological investigations.

### 3.2.3 Hydrogeological features of the Tagaqe-Hideaway coastline

The study found the presence of a large, underwater plateau or ridge in between the Tagaqe Passage just east of Tagaqe village, and the Ono Passage west of the Hideaway Resort. This ridge has a gradual slope dropping from 40 m to deeper than 840 m and is larger than any other ridge in the area and is close to the reef (Pitman *et al*., 2000). This underwater plateau has enormous influence on the currents and the hydrodynamic character of the area, as it is very large and shallow. This ridge is presumed to be an extension of the ridge system on land, and was most probably formed from a large volcanic flow out to sea. The ridge actually extends for some way beyond the fringing reef system. The presence of this large and broad plateau is believed to be a major factor in determining wave action and currents in the area. In my view, this plateau acts to increase wave action and wave height on approaching the shore, and with the vertical seawall erected on the eastern boundary of the Hideaway Resort, the eroding effects of the waves on the adjacent shoreline has been increased. The vertical seawall had since been modified into a zigzag and slanting one. This submarine plateau may also restrict inshore circulation and actually push nutrients back onto land in a westerly flowing direction.

In the SOPAC study, currents were measured in the Tagaqe-Hideaway area by deploying an Aanderaa current meter for a month from 19 November, 2000. This showed that the main direction of flow was in the westerly direction. The currents in the Ono Passage just off the Hideaway Resort moved mainly to the south (away from land) to south-west direction, but measurements at the reef showed a north to north-westerly direction (or towards the shore). This pattern of current flow would result in a continuous transfer of material including nutrients from sources such as the Hideaway Resort, towards the shore, west of the Hideaway Resort.

The influence of tides is also important in the direction of the current as was found at the Tagaqe Passage; during high and incoming tides, the flow was northerly or towards land, and at low tide and outgoing tide, the flow was in a southerly direction or away from the shore. However, within the Tagaqe Passage,the current during the SOPAC study was not flowing away in any particular direction, but was moving in a circular pattern with very slow speeds, mostly below 10 cm/sec. This situation at Tagaqe Passage meant that materials will not be moved away from the in shore waters quickly. This raises questions about pollutants from land-based sources like Tagaqe village pig-pens, the nutrients from forestry plantations inland of Tagaqe village and impacts from Valase Backpacker Operation and Nagasau Development to the east, being moved aroung the Tagaqe area and probably back on the reef flats. In fact, this phenomenon may be part of the explanation for the very degraded reef flat in front of Tagaqe village as was found during my surveys in 2003. The reef near Tagaqe village and part of the Hideaway Resort was set aside as a ‘no take’ zone in 2003, and it will be interesting to see if there is any improvement in the health of this reef following the declaration (and enforcement) of this reef as a ‘no take’ of *tabu* area.

### 3.2.4 Village expansions and increasing populations

The populations in the coastal villages have increased quite rapidly since the 1980s, and Table 3.2 (for all villages on or near the coast, within the Nadroga Province), and Figure 3.3 (for villages within the study area) show the increases clearly.

Table 3.2 Village populations and number of households for the villages along the Coral Coast, 1946 – 1996.

Please see print copy for Table 3.2

(Sources: Fiji Bureau of Statistics – Population Census Data; 1996 Data from 1994-1995 Provincial Profile Project Notes)

Village names are:

| | | |
|---|---|---|
| NMT – Namatakula | VOT – Votua | VCL – Vucilevu |
| VOTLL – Votualailai | NVL – Navola | TGQ - Tagaqe |
| KMV – Komave | NMD – Namada | BSV – Biausevu |
| VTKR- Vatukarasa | KRL – Korolevu | MLV – Malevu |
| KRTG – Korotogo | Cuvu – Cuvu | |

* means other residents apart from indigenous Fijians.

Out of these, only the villages on the coast were surveyed in the research (see Fig.3.3)

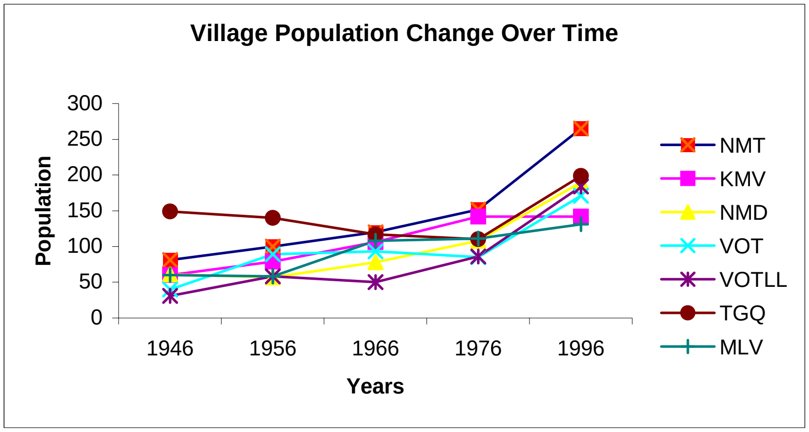



Figure 3.3 Changes in coastal village populations along Coral Coast, 1946 - 1996

As can be seen in Table 3.2 and Figure 3.3, there has been steady increase in both the number of households as well as the population. It is likely that the establishment of resorts and their expansion from the 1980s to the present have actually attracted more people to these coastal villages, because of job opportunities at the hotels. The expansion of populations on the coastline will no doubt affect the marine environment and resources.

With the increase in population in these coastal villages, there would have been increased fishing and gleaning of the inshore reefs. The common observation by the local people that fish numbers were on the decline and seaweeds had become more common in the last twenty years (pers.comm. /Tevita Love of Qalito, December 2003) may have been a direct result of the increasing human population and the effects of their activities. However, in the absence of information on fishing habits of the people during those times, it is difficult to be certain about the situation. The development of tourist resorts in the area would certainly have added another dimension to the problem.

### 3.2.5 Land-based sources of pollution

As with most developing island nations of the South Pacific, the coastal areas of Fiji are the most populated, partly a result of historical pattern of habitation, and partly because of the commercial and agribased activities available for the people. For the Coral Coast, the major sources of land-based pollution are the villages and tourism operations, and sewage appears to be the main source of nutrients and pollution in this area (Mosley and Aalbersberg, 2003).

Sewage from the land sources enters the coastal waters via the slow process of groundwater seepage, but a more significant effect comes from wash-out during heavy rainfall, which can be common in the eastern section of the area. It is suspected that following heavy rain, sewage enters the marine environment via the creeks and rivers in the area (pers.observation, 2002).

Sewage from villages constitutes one of the main sources of nutrients in coastal waters. In 1996, a survey of the villages showed that the most common type of toilet in use was the water seal type. In fact almost 90% of the toilets were of this type (1994-1995 Provincial Profile Project). This sort of situation presented a high risk of groundwater contamination, and increased nutrient loading of creeks, rivers and coastal waters during periods of heavy rain. Over the years, with improved economic standing of most villagers, modern homes were built of concrete and flush toilets replaced the water seal types. However, the location of septic tanks in relation to the shoreline, and the location of pig-pens next to the creeks and rivers still pose a high threat of pollution for the coastal waters.

According to a survey of 18 resorts including those along the Coral Coast, the standard of wastewater treatment in Fiji's resorts is generally poor (IAS, 2004). Most resorts did not meet recommended international standards for effluents. It follows therefore that wastewaters from resorts comprise a significant point source of pollution in Fiji's coastal waters. Of interest also is the fact that only a third of the resorts reuse their greywater, despite the high usage of freshwater (>1000 L/room/day). Apart from 2 large 5 star resorts in my study area, all the other resorts

(5 in total) only use $1^{o}$ treatment of sewage, in combination with septic tanks or basic aeration in settling ponds. In primary treatment ($1^{o}$), the main process is one of separating the liquid from the solid components of sewage but the wastewater still contains high concentrations of faecal coliform, other bacteria and suspended organic waste solids which are high in nutrients. In one of the large resorts, this wastewater is pumped out to the sea along a pipe, while in others, the wastewater is discharged to soak pits and these are usually located near creeks or on the shore. The discharge of primarily-treated wastewater into the sea (a bay not more than 100 m from the shore) by one large resort has caused proliferation of the macroalgae *Sargassum prolifera*. in the bay. For those using soak pits, the location of soak pits in relation to the creeks and shorelines, and the fact that the soils are generally very porous (sandy soils) would mean that nutrients are not adequately filtered out before the seepage reaches the coastal waters. Currently, there are no legislative standards on how resorts are to treat their wastewater and this is a root cause of the problem. With the recently enacted Fiji Resource Management Act (2006), it is hoped that the situation will improve. It is encouraging to note that already, some resort managements have taken the initiative to improve their sewage treatment processes (IAS, 2004).

Besides the effects of poorly treated wastewater, the impact on reefs of large numbers of tourists visiting the reefs can be enormous, especially if resort management do not take this issue seriously. Damage from boat anchors, removal of live coral pieces for ‘souvenirs’, are just two examples (Levett and McNally, 2003).

What is happening in Fiji is typical of small island nations of the South Pacific (SPREP, 2003). The situation is expected to deteriorate unless the main stakeholders from the national government level, the tourist facilities management down to the local community or village members take stock of the situation and implement strategies to reduce pollution from land-based sources, as well as put in place some conservation options including setting aside “no-take” or “tabu” areas in their “I Qoliqoli” or fishing grounds.

### 3.2.6 Nutrient status of Coral Coast coastal waters

The status of nutrient levels in the coastal waters of the Coral Coast area was the subject of a one-off study by Mosley and Aalbersberg, (2003). The study found elevated concentrations of nitrate and phosphate near the resorts, but much higher levels in the Sigatoka River. For the coastal waters close to resorts, average nitrate ($NO_3^{2-}$) concentrations were 1.69 uM and average phosphate ($PO_4^{2-}$) values were 0.21 uM. For the river, the average nitrate levels were 10.8 uM and for phosphate, it was 1.30 uM. For healthy reefs, researchers have proposed threshold levels of 1 uM nitrate and 0.1 uM phosphate (Bell 1992; Lapointe, 1997), above which corals are adversely affected. As noted in Chapter 2, the use of threshold levels as criteria for classifying coastal waters has been the subject of debate for some time (Hughes *et al*., 1999).

### 3.2.7 Fringing Reefs along the Coral Coast – Earlier studies

It is of interest to note that in the late 19$^{th}$ century, scholars recognized the value of the reefs in Fiji, even for development of coral taxonomic studies (Gardiner 1898; Agassiz 1899; Dana 1846). One can only assume that the reefs at that time must have been very interesting with high coral species diversity, yet very accessible from the shore. The fringing reefs of the Coral Coast were among such reefs (Ryland, 1981). Despite this early interest, it was not until the 1980s that the first attempts at systematic surveying the reefs were conducted.

The first ecological description of the fringing reefs of the Coral Coast was in 1980 by Morton and Raj (1980), who had put together a Field Manual describing the foreshore and fringing reef communities on three reefs along the Coral Coast - Korolevu Reef, Namatakula Reef and Naevuevu Reef in Cuvu, Nadroga.

In the early 1980s, the reefs along the Coral Coast were mostly in pristine condition. Ryland (1981) highlighted the significance of the Coral Coast as a tourist centre in his presentation to the 4$^{th}$ International Coral Reef Symposium when he said, "With the attractive features of reef and beach, high insolation, and moderate rainfall, the Coral

Coast is developing as a premier tourist area". At that time, there were few hotels and those were of smaller sizes. The hotels were concentrated at Korolevu (Hyatt-Regency, now known as the Warwick Hotel); along the Malevu – Korotogo stretch, and new hotels had just opened near Namada village (Tambua Sands Resort) and near Tagaqe (Hideaway Resort).

The fringing reefs along the Coral Coast all have similar structure, and during the early 1980s, the reefs also had similar coral species diversity (Morton and Raj, 1980; Ryland, 1981; Raj *et al.*, 1981). Interestingly, all the available reports acknowledged the high coral species diversity of the fringing reefs, particularly at the outer reef slope, and even within the moats and micro-atolls zone, some some 100 m - 300 m or so from the beach, in waist –deep water. The management of Hyatt-Regency (now called the Warwick Resort) at the time approached the National Trust of Fiji in a move to try and set aside part of the reef in front of the hotel as a marine park (Raj *et al*., 1981). In March 1981, during a survey relating to this request, it was noted that the hotel had already constructed the artificial island off the western end of the resort, as well as two groynes to trap sand for the beach. More interesting though, is the artificially deepened swimming hole in front of the hotel. At the time, a boat channel had also been dug out in the coral platform, starting from the swimming hole towards the west. The explanation for the boat channel is that at low tide, the boats can be moved from the Korolevu Bay to the west of the resort, across the boat channel, around the artificial island and to the marina. During the survey by Raj *et al*. (1981), it was noted that the artificially deepened lagoon had a heavy sediment load, low visibility and was dominated by the macroalgae *Padina commersoni* and *Sargassum prolifera*. Also abundant was the apodan holothurian *Synapta maculata.* The situation at the resort highlights the fact that any artificial manipulation of the natural, physical environment, particularly the marine environment must be subjected to a holistic assessment, to take into account the water flow regime, the recovery and rehabilitation of the disturbed area and potential pollution problems arising out of the activity.

### 3.2.8 Structure of the fringing reefs along the Coral Coast

The formation of the fringing reefs along the southern coastline of Viti Levu is explained by the specific geology and physiography of the area. With moderately deep water not too far (<18 km) from land, the availability of fresh, pristine oceanic waters needed for good coral growth is ensured. At the same time, the 100 fathom (183 m) isobath is close to shore in southwestern Viti Levu supporting the development of the fringing reefs which is continuous from Serua to the east, up to west of Sigatoka in the west, except for the passes and passages created by the fresh water discharge from rivers and streams in the area (Ryland, 1981). The result is a series of reef platforms of between 1 to 5 km in length, and between 300 to 700 m in width ( Raj *et al.*,1981). Except for small variation, the basic structure of the fringing reefs varies little.

The whole reef is usually accesible and wadable at low tide. The reef can be divided into five or six zones, from the surge zone and outer reef slope at the seaward end to the shallow lagoon and coral limestone platform on the landward end of the reef.

The different zones of the fringing reef are characterised by specific physical and hydrological features which in turn determine the type of biological communities, especially the coral types and growth forms. Moving from seaward end towards land, the zones ang their characteristic species composition can be briefly described as follows:

- The surge zone and outer reef slope is characterised by very high species diversity and luxuriance of corals and a mosaic of encrusting algae, all of low growth forms as an adaptation to the strong wave action and surge that continually pounded this part of the reef. The coral species here include *Pocillopora* spp., *Favia* spp., *Montipora* spp., with low crusts of *Acropora* sp. A variety of soft corals is also present including *Lobophytum expansum* and *Sarcophyton* sp. (Raj *et al*., 1981). The pink encrusting and red algae dominated by *Lithophyllum moluccense* are also found in this zone.

- The reef summit just behind the surge zone is a fairly 'clean' zone because of the sweeping effects of the surge over the summit. This zone is characterised by a clear band of the brown macroalgae *Sargassum cristaefolium* and the stalked *Turbinaria ornata*. Other low growing algae include red, calcareous *Amphiroa* sp. (Raj *et al*., 1981), and the dense cover of *Diplosoma virens*.
- Behind the summit is a reef flat many scientists regard as the 'dead' part of the reef. It is considered dead because of absence of corals (due to exposure) except for some *Acropora* sp., *Pavona* sp. and *Porites* sp. in pools. The reef flat is, however, cemented by encrusting coralline algae of various species including *Lithophyllum* sp. and colonies of the ascidians *Diplosoma* sp. (Raj *et al*., 1981).
- Moats and micro-atolls - the next zone is perhaps the most interesting because of the high coral species diversity and yet their very close proximity to shore. This is a disadvantage as well as is being witnessed today for most of these reefs. This zone consists of interconnecting channels between and among fairly large and extensive coral formations. This area of luxuriant coral growth is in waist-deep water (at low tide), and coral species include *Porites lutea, Favia* sp., *Acropora* sp., *Pavona divaricata* and others (Morton and Raj, 1980; Raj *et al*., 1981; Ryland, 1981).
- The landward part of the reef is often a coral limestone platform, with coral sand cover in some places. This zone stretches from the beach to about 50 – 100 m offshore. Depending on the depth of the water at low tide, some small clumps of the corals *Porites lutea* and some *Acropora* sp. may be found in pools, however, the brown macroalgae *Padina* sp. and *Sargassum* sp. dominated this zone. In the crevices, the black brittlestars *Ophiocomina scolopendrina* are abundant (Morton and Raj, 1980; Ryland, 1981).

## 3.3 WATER SAMPLING AND BENTHIC SURVEY SITES

The whole of the study area is divided into 8 separate units defined by the reef channels/passages, solely for ease of data management. Due to logistical and other factors, these 8 Localities were not equally assessed: some were visited and assessed more than others, but inclusively, they represented a generalized spectrum of nutrient status in the coastal waters, as well as an opportunity to compare benthic communities on reef flats exposed to varying degrees of human impacts. Appendices A1 – A8 show the 8 Localities visited and assessed during the 3 year period of survey.

Within each unit/location, pollution sources were identified and study sites were placed at varying distances from these impact sources. At least 3 sites were selected within each location. The presence of significant nutrient sources like creeks and rivers in each unit were also noted and investigated wherever and whenever possible.
The strategy proposed by the Australian and New Zealand Environment and Conservation Council (ANZECC, 2000) was used as a guide to the methodology of study, i.e., most of the studies would be investigative (category E) since there was no scientific data for the sites. However from personal observations and the few studies conducted in the area (Mosley and Aalbersberg, 2003), category D was also appropriate, and distance from the impact source was the major determining independent variable on which to make comparisons among sites (ANZECC, 2000). Figure 3.4 shows the ANZECC guideline for types of impact studies.

Please see print copy for Figure 3.4

Figure 3.4 Flow chart depicting the broad categories of assessment designs (ANZECC, 2000)

## CHAPTER 4 - NUTRIENT AND WATER QUALITY VARIABILITY ALONG THE CORAL COAST OF SOUTHERN VITI LEVU, FIJI ISLANDS

This chapter presents the outcomes of a study of the variations in nutrient concentrations in the coastal waters around the Coral Coast area of Viti Levu, Fiji. Following an introduction and a brief literature review on the subject, there is a description of the sites and methods used, a summary of the results obtained and discussion of the implications of these results for reef ecology and health.

### 4.1 INTRODUCTION

Coral reefs around the world are being degraded at an increasing rate and nutrients in the water column are one of the factors being blamed for this phenomenon (GESAMP, 2001). Nutrients in the marine environment include nitrate ($NO_3^-$), nitrite ($NO_2^-$), ammonium ($NH_4^+$), phosphate ($PO_4^{3-}$) and silica ($H_4SiO_4$). While these occur in coral reef areas in relatively low concentrations under natural conditions, problems start when the nutrients are added to the marine environment in larger amounts, as a results of man's manipulation of the land through agriculture, use of fertilizer, removal of natural vegetation for construction of roads, buildings, resorts, and simply the increase in organic waste and wastewater production from increased human population (GESAMP, 1990). The nutrients from these land sources are transported to the marine environment through a number of means: surface flow in rivers and creeks, from run-off, through groundwater seepage and through the process of leaching (GESAMP, 1990; Sparks, 2003).

The leaching of nutrients and its consequences depend on a number of factors: amount of rainfall, soil type and the depth of the water table in any one location (Li *et al.*, 1997). Properties of the nutrient forms are also important, e.g., nitrate in soils is leached out at a faster rate compared to phosphate (Li *et al.*, 1997; Shuman, 2001). In a study to compare the leaching rates of nitrate, ammonium and phosphate (Li *et al.*, 1997), different composts (sugarcane, filter cake, biosolids and mixtures of wastes and biosolids) were applied to the same type of soil and leached with deionized water at the rate of 300 mL/day for 5 days. At the end of the experiment, the concentrations of nitrate, ammonium and phosphate in the leachate were 246, 29 and 7 mg/L respectively. The study also found that the amount of N and P leached accounted for 3.3 – 15.8 % of total N, and 0.2 – 2.8 % of total P. In other words, leaching of nitrate was occurring many times faster than phosphate and even ammonium (Li *et al.*, 1997).

From another perspective, Jarvie *et al.*, (2006) have shown that point sources of phosphorus via effluent, pose a more significant threat to river water quality and river eutrophication, compared to diffuse sources of phosphorus such as agricultural activities. The same study linked this phosphorus source with sewage effluent, and sewage sources of phosphorus were characterized by the presence of a relatively unreactive chemical tracer, boron (B) present in detergents which are part of sewage effluents. The risk is greatest under conditions of low flow (spring/summer in UK rivers), and this is also the period of greatest biological activity and algal proliferation (Jarvie *et al.,* 2006*).* The risk is less during increased flow, and this is further evidence of point sources of phosphorus being the dominant sources of phosphorus into rivers, and ultimately to coastal waters (Jarvie *et al.*, 2006*).*

In the marine environment, inorganic nutrients and particulate material are the most significant marine pollutants at the national and regional level (GESAMP, 2001). For coral reefs in particular, sediment and associated nutrients have been identified as the most significant threats (Birkeland, 1997; Hatcher *et al.*, 1989). Under pristine conditions, nutrients in seawater make up a relatively small proportion of chemical constituents of seawater (*u* mol/L or *u*M concentration range) and are classified as non-conservative substances, because their distribution and concentrations are influenced by biological and chemical processes in the marine environment (Libes, 1992). The other seawater components that fall into this category include particulate matter, colloids, organic matter and trace metals (Libes, 1992).

Ammonia naturally occurs in very low concentrations in most waters (< 0.5 uM, Libes, 1992), whereas phosphate varies for different regions and also with depth, for example, phosphate has been reported as being < 0.2 uM for ‘warm surface waters’, but generally increasing with depth up to 2 uM for deep Atlantic and deep Pacific (cited in Libes, 1992).

In seawater, the concentrations of nutrients are affected by biological, chemical and physical processes; this is why they are classified as non-conservative components (Libes, 1992). As with terrestrial life, the two basic processes of photosynthesis and respiration determine the uptake or release of nutrients in marine environments (Hatcher, 1997).

For some time, the notion of simple "threshold" nutrient concentrations, above which algal production would be boosted, was generally accepted (Bell, 1992; Lapointe, 1997). In fact, Lapointe (1997) had linked algal blooms on Jamaican reefs with nutrient concentrations exceeding these critical levels. However, the mere presence of nutrients in the water column does not necessarily mean that this will transfer to organic production and growth in the producer organisms, and the "threshold" concentration theory has been disputed by several researchers including Hughes *et al.*, (1999). This is why water column nutrient concentrations should never be taken as the sole indicators of primary productivity in aquatic systems. However, nutrient concentrations in the water column provide a reasonable estimate of potential, primary biological production, since these nutrients exist in very low concentrations in pristine conditions, they limit photosynthetic, biological productivity (Libes, 1992).

While nutrients were previously thought to be important for the life of coral reef communities, studies (e.g., Kinsey and Davies, 1979) have proved that high concentrations of nutrients caused problems for corals and created an imbalance in the often fragile web of life in coral reef systems (Birkeland, 1997). Many studies have confirmed the detrimental effects of nutrients on coral reefs. In the Australian Great Barrier Reef, increased nutrient concentrations were found to cause reduced coral cover, and increased macroalgal cover (Fabricius and De'ath, 2004). In Kaneohe Bay, Hawaii, the discharge of sewage and associated nutrients caused a decrease in coral cover and an increase in macroalgal cover (Smith *et al.*, 1981).

In Fiji, studies conducted at the Great Astrolabe Reef (GAR) by Morrison *et al.* (1992) and Charpy *et al.* (1996) found relatively low concentrations of the nutrients:

nitrite concentrations were 0.07 *u*mol/L and 0.02 *u*mol/L respectively, nitrate concentrations were 0.74 and 0.30 *u*mol/L respectively; ammonia were 0.12 and 0.27 *u*mol/L respectively and phosphate concentrations were 0.07 and 0.18 *u*mol/L respectively. These values represented more or less pristine conditions for Fiji, but at the time, there were observations of human impacts on the general water quality (Morrison *et al*., 1992)

The fringing reefs along the Coral Coast of southern Viti Levu, have been described by the local people as being degraded (community interviews by this author, Namada Village, 3 November, 2005). It is assumed that one of main factors causing such changes is nutrient enrichment of the coastal waters, due to an increase in anthropogenic activities on land and in the catchments of the area. While nutrient enrichment is assumed to be responsible for the degradation of the fringing reefs along Coral Coast, there has not been any major study, except for a small monitoring study undertaken by the University of the South Pacific Institute of Applied Sciences, in 2002 (Mosley and Aalbersberg, 2003). Mosley and Aalbersberg (2003) found nitrate concentrations in the range 0.10 – 7.01 *u*M with a mean of 1.69 *u*M, and phosphate concentrations in the range 0.07 – 1.51 *u*M with a mean of 0.21 *u*M. These mean values are above concentrations usually recommended for healthy reefs, 0.1 *u*M for phosphate and 1 *u*M for DIN (Bell, 1992). It is for this reason that this research has placed much emphasis on studying the variability in the concentrations of the nutrients (nitrate, phosphate and ammonia) in coastal waters of the Coral Coast. Initially, only nitrate and phosphate were analysed in the water samples because of lack of facilities but, starting in December 2004, with the availability of research assistance, ammonia was also analysed using a Flow Injection Autoanalyser (FIA).

This chapter will address the following research objectives:

- to gather as much information on nutrient concentrations as was practically possible during the study period, covering a wide range of sites along the Coral Coast, but with specific interest in eight localities;

- to compare the nutrient concentrations among sites that were isolated from human impacts (control) and those that were close to human impacts (impacted), and discuss the possible causes of the variation;
- to assess whether there was any particular pattern in the temporal variation in nutrient concentrations for sites close to human impact and those that were not;
- to compare the nutrient concentrations in the adjacent creeks and rivers, with those in inshore coastal waters, and those in waters off the fringing reefs, and to consider these in relation to reef health;.
- to examine how rainfall affected the general water quality and nutrient concentrations in the inshore coastal waters along the Coral Coast.

## 4.2 METHODS

This section presents a description of the study sites, the sampling strategy and techniques, and the analytical procedures used.

### 4.2.1 Study sites

Since one of the research objectives was to gather as much information as possible over as wide an area as was possible, the study area stretched from Namaqumaqua in the province of Serua to the east, and as far as Korotogo in the province of Nadroga to the west (Figure 3.1). This was important because of the lack of previous information on nutrients along the Coral Coast (Vuki *et al.,* 2000). For ease of discussion, the study area is divided up into 8 sections I have called Localities, separated by reef passages: Locality 1 (LOC 1) to Locality 8 (LOC 8). The reef passages are caused by freshwater discharged from rivers along the coast, and these play significant roles in the movement of material within the inshore waters along the Coral Coast. To some extent, the reef passages provide physical barriers to lateral transfer of material along the coast, and for this reason they are useful as boundaries for each Locality. Within each Locality are sampling sites, labeled by codes (see Table 4.1). Each Locality is numbered 1 – 8, and they are shown in the Appendices as A1 to A8, i.e. LOC 1 with coded sampling sites are shown in Apendix A1; LOC 2 in Appendix A2; LOC 3 in Appendix A3 and so on to LOC 8 (Appendix A8).

The selection of water sampling sites within each Locality was influenced by a number of factors:

- accessibility from the main road;
- distance from known nutrient sources; and,
- approval for access and work from local resource owners and resort operators.

The ‘control’ sites were selected based solely on distance from suspected nutrient sources, since there was no previous information on the nutrient status of the area (Vuki *et al.*, 2000). The objective was to sample three broad categories of sites:

- control or more appropriately pseudocontrol sites (C)
- village sites (V)
- resort sites (R)

Interestingly, the choice of ‘control’ sites turned out to be very limited; in fact, one site that was chosen as a control site initially, became another ‘impacted’ site as the ecotourism operation expanded with the construction of more thatched ‘bures’ or huts and houses (Valase) at the end of the first year of the study. For impacted areas, the water sampling sites were located in the middle of the impact zone, whether it was a village or a resort.

The influence of rivers and creeks could not be ignored and so these were also included in the study. While catchment activities may be reflected in the nutrient status of the creeks and rivers, the fringing reefs and waters off the coast may be influenced by land-based sources in the area, as well as other nutrient sources updrift of the area. In a smaller study, the nutrient concentrations in waters off the reefs were also assessed and compared with inshore waters and creek waters (see Section 4.3.4).

The water sampling sites are coded with letters representing the names of the area, whether they be villages, resorts or control sites, for example, NMQ is a sampling site at Namaqumaqua. The numbers identify the different sampling stations within each site, for example NMQ1 or NMQ2. Creek sites are designated the letter ‘C’ at the end of each code, for example 'NMC' instead of 'NMT1' or 'NMT2' for Namatakula creek near the village site. Table 4.1 shows a summary of the main water sampling sites visited and assessed. For each site, its category (whether control, village or resort) and its Locality number (LOC #) are included, for reference to the appropriate Locality Maps appended (A1 – A8), from page 275 to 277.

TABLE 4.1 SUMMARY OF WATER SAMPLING SITES AND FEATURES

| **Site Code** | **Category (C, V or R) – LOC #** | **Site Description (all water samples from Coastal, inshore waters)** | **River/creek within 50m** |
|---|---|---|---|
| NMQ1 | Control – LOC 1 | 5m east/updrift of NMQ village | None |
| NMQ2 | Control – LOC 1 | 5m west/downdrft of NMQ creek. | Yes, NMQ Creek |
| NMQ4 | Village – LOC 1 | Midway along NMQ village. | Yes, abt. 20m to east |
| CRS1 | Resort – LOC 1 | In front of resort. Steep rise to resort. | None |
| NMT4 | Village – LOC 2 | Midway along NMT village. | 50 m to the east and updrift of site |
| BCH1-3 | Resort – LOC 2 | About 50m out from HWM and resort. | Small creek, low flow. |
| NVL2 | Village – LOC 2 | Small village. About 50 m from HWM. | Small creek to east. |
| KMV1 | Village – LOC 3 | Large village. About 50 m from HWM. | Large creek/pig pens to west of village. |
| NAQ1 | Control – LOC 3 | >200 m frm KMV village and creek | Yes, KMV creek to east. |
| EWRC | Resort – LOC 3 | ~100 m east of WRC resort. | None |
| WRC1 | Resort – LOC 3 | ~10 m west and dwndrft of WRC resort | None |
| QLT1 | Resort – LOC 3 | ~20 m west of WRC resort. Wastewater pipeline pass ~ 70m from HWM | None |
| QLT2 | Resort – LOC 3 | ~30 m west of WRC resort, or 10m west (downdrft) from QLT1 | None |
| MKD1 | Small Dive center /village (Impacted) - LOC 4 | Next to Votua village. | Votua creek (from Votua Housing) to west (< 100 m) |
| MKD2 | Control – LOC 4. | > 2 km from MKD1, in middle of reef passage | > 5 km from Votua creek mouth |
| VOT1 | Village – LOC 4, | Inshore - large Votua village | ~ 20 m E of Votua Crk mouth |
| VOT2 | Village – LOC 4, | Inshore, large Votua village | ~50 m W of Votua Creek |
| VIL1 | Control – LOC 4 | Inshore, EE of Vils. restaurant | |
| CBN1 | Control – LOC 5 | No village or resort within 1 km. | Small (usually dry) creek to the east |
| VLS1 | Control – LOC 5 | No village or resort until 2005 | Small/dry creek |
| WVLS1/ TGQ1 | Control – LOC 5 | No village or resort within 100m. | TGQ creek to the west and dwndrft ~100m |
| TGQ3 | Village – LOC 5 | Large village, sample from ~ 10 m from HWM and village | TGQ creek is within 50 m |
| HDW1 | Resort – LOC 5 | Large resort. Good waste | Small creeks drain |

| | | | |
|---|---|---|---|
| | | management | resort |
| TBS1 | Resort – LOC 6 | Small resort. | Creeks on either side |
| ENMD1 | Resort/village – LOC 6 | ~midway between TBS resort and Namada village | Creek to the east |
| NMD1 -3 | Village – LOC 6 | Large village. Steep beach profile. Beach vegetation prominent | None. |
| VTK1 | Village – LOC 7 | Large Vatukarasa village | Large river and bay to the east & updrift |
| VTK2 | Control – LOC 7 | ~ > 5 km offshore from VTK1 | Offshore. None |
| BUL1 | Control – LOC 8 | No village or resort on coast. | Large Bulu River estuary within 100 m |
| BUL2 | Control – LOC 8 | No village or resort on coast | Large Bulu River estuary within 50 m |
| BUL3 | Control – LOC 8 | No village or resort but old picnic site | ~ small creek |
| MLV1 | Village – LOC 8 | Large village. Drier parts of Viti Levu | Dry creek at west end of village |
| TBK1 | Resort – LOC 8 | Small resort. Drier parts of Viti Levu | No large creek |
| OTR1 | Resort – LOC 8 | Large resort. Near swimming beach | None within 50 m |
| CRW1 | Resort – LOC 8 | Small resort. Small restaurants nearby | Small creeks drain area. |

### 4.2.2 Sampling methods

The dates for water quality measurement and sampling were chosen to include both the Hot/Wet and Cool/Dry Seasons, as well as the rainy and dry weather. In Fiji, the Hot/Wet Season is from November to April, and the Cool/Dry Season is from May to October each year. However, it is not unusual to find flood events during the Cool/Dry Season. One of the limitations faced during the research was the non-availability of rainfall data for the Coral Coast, as there were no weather stations within my area of study (pers. comm. this author/meteorology department, January, 2004). The best approximation of rainfall was to use the standard measure of 25mm/day as the guide. Dry weather was defined as those days with < 25 mm/day, and conversely, ‘wet’ days were defined as days on which > 25 mm/day fell in the area. Table 4.2 shows a summary of the sampling dates and related features. The results from the sampling events in Table 4.2 are either included in the ‘Spatial Variation’ section (section 4.3.1) or the ‘Temporal Variation’ section (section 4.3.2) or the ‘Inshore vs Off-reef’ section (section 4.3.3). The nitrate results represent both nitrate plus nitrite concentrations ($NO_2$ + $NO_3$), but since nitrate is the more dominant form of the two, the results are presented as $NO_3^-$ rather than ‘NOx’ in the analyses of data. Collection of water samples was always carried out during outgoing tide, from approximately 2 hours after high tide during slack water. This was done to ensure that the samples contained any pollution originating from land-based sources, without any diluting effects of clean, oceanic water.

At each site, three replicate samples of the coastal water, river or creek water were collected. Standard procedures were followed in the preparation of sampling equipment (Hansen and Koroleff, 1999). All bottles, syringes and filtration equipment were soaked for at least 24 hours in 10% hydrochloric acid solution, rinsed three times in deionised water before being used. Samples were collected from a depth of about 10 cm below surface, in 300 mL, large-mouthed polypropylene bottles. The bottles were rinsed three times with the water to be sampled and ensuring that each time, the rinse water was discarded downdrift (depending on the current at that point in time) from the site of collection. The sample was then collected for filtration. The sample was filtered immediately using the Whatman GF/C, 1.2 um pore size filter, into another acid-cleaned polypropylene bottle. The total volume filtered was 100 mL for each replicate sample. The filtered samples were then transported in coolers of ice to the laboratory (2 hrs away by road), and analysed the same evening for nitrate and phosphate. Analysis for ammonia in the water samples did not start until December 2004. When analyses could not be completed immediately, the samples were frozen for up to a week before analysis. Occasionally, samples were kept frozen for longer because the cadmium column of the Flow Injection Autoanalyser (FIA) had been damaged or broken and a replacement column had to be brought from Australia. Qu (2004) has shown that samples can be stored frozen for up to 12 weeks with no significant impact on the results. In the laboratory, the samples were brought to room temperature on the day of analysis prior to analysing them on the FIA (Grasshoff *et al*., 1999).

Faecal coliform measurements were done whenever possible, depending on personnel and logistical factors. Standard procedures were followed (APHA-AWWA-WEF, 1998).

TABLE 4. 2 SUMMARY OF WATER SAMPLING DATES/SITES/SEASONS AND PARAMETERS MEASURED

| DATE | SEASON | PREVAILING WEATHER | SITES VISITED | PARAMETERS MEASURED |
|---|---|---|---|---|
| 2 August 2003 | Cool and Dry | Dry | NAQ (C); VLS (C); EWRC(R); QLT (R); | PO4; NOx; NH3 |
| 22 January 2004 | Hot and Wet | Dry | VLS (C); NMD (V) | PO4; NOx |
| 23 January 2004 | Hot and Wet | Dry | NMD (V); TBS (R) | PO4; NOx |
| 10 February 2004 | Hot and Wet | Wet | NAQ (C); VLS (C); QLT (R); NMD (V) | PO4; NOx |
| 25 February 2004 | Hot and Wet | Very wet | NAQ (C); EWRC(R); NVL (V) | PO4; NOx |
| 25 March 2004 | Hot and Wet | Dry | NAQ (C); NVL (V); KMV (V); NMT (V); BCH (R); QLT (R); EWRC(R) | PO4; NOx; GWQ |
| 5 May 2004 | Cool and Dry | Dry | HDW (R) | PO4; NOx; GWQ |
| 13 May 2004 | Cool and Dry | Dry | NAQ (C); VLS (C); EWRC(R); QLT (R); BCH (R); NMT (V); NVL (V); KMV (V) | PO4; NOx; Some GWQ |
| 25 May 2004 | Cool and Dry | Dry | NAQ (C); BCH (R) | PO4; NOx |
| 4 and 8 June 2004 | Cool and Dry | Very wet | NAQ (C); VLS (C); WHDW (C); NVL (V); KMV (V); NMT (V) | PO4; NOx; GWQ |
| 2 August 2004 | Cool and Dry | Wet | BL2 (C); BL3 (C); NMD (V); TBK (R); OTR (R); CRW(R) | PO4; NOx; GWQ<br><br>FC |
| 4 August 2004 | Cool and Dry | Dry | CBN (C); TGQ (V); TBS (R); HDW (R); WRC (R) | PO4; NOx |
| 11 August 2004 | Cool and Dry | Dry | NAQ (C); VLS (C); NVL (V); KMV (V); NMQ (V); WRC (R); BCH (R); CRS (R) | PO4; NOx; GWQ<br><br>FC |
| 12 August 2004 | Cool and Dry | Dry | BL1 (C); BL2 (C); MLV (V); NMD (V); TBK (R); OTR (R); CRW(R) | PO4; NOx; GWQ<br><br>FC |
| 12 October 2004 | Cool and Dry | Dry | NMQ1 (C); NMQ2 (C); NAQ (C); NVL (V); KMV (V); NMQ (V); NMT (V); BCH (R); CRS (R) | PO4; NOx; GWQ<br><br>FC |
| 13 October 2004 | Cool and Dry | Dry | CBN (C); VLS (C); NMD (V); TGQ (V); WRC (R); QLT (R); TBS (R); HDW (R). | PO4; NOx; GWQ<br><br>FC |
| 14 October 2004 | Cool and Dry | Dry | BL1 (C); BL2 (C); MLV (V); TBK (R); OTR (R); CRW(R) | PO4; NOx; GWQ<br><br>FC |
| 22 December 2004 | Hot and Wet | Dry | TGQ – HDW inshore and offshore | PO4; NOx; NH3 |

| | | | | |
|---|---|---|---|---|
| 6 January 2005 | Hot and Wet | Dry | CBN (C); VLS (C); NMD (V); TGQ (V); NMT (V); TBS (R); HDW (R). | PO4; NOx; NH3<br>GWQ<br>FC |
| 7 January 2005 | Hot and Wet | Dry | NAQ (C) plus OFF-REEF sites | PO4; NOx; NH3<br>GWQ<br>FC |
| 4 February 2005 | Hot and Wet | Dry | VLS (C); NMD (V); QLT (R); TBS (R) | PO4; NOx; NH3 |
| 23 March 2005 | Hot and Wet | Very wet | VLS (C); WVLS (C); NMT (V); QLT (R); WRC (R); EWRC (R) | PO4; NOx; NH3 |
| 27 April 2005 | Hot and Wet | Very wet/flooding | CBN (C); VLS (C); ETGQ (C); QLT (R); HDW (R); BCH (R) | PO4; NOx; NH3<br>GWQ<br>FC |
| 16 May 2005 | Cool and Dry | Dry | VLS (C); WVLS (C); CBN (C); HDW (R); BCH (R); WRC (R); | PO4; NOx; NH3<br>GWQ<br>FC |

GWQ – General Water Quality : Salinity, temperature, dissolved oxygen.
FC – Faecal coliform

### 4.2.3 Chemical Analysis of Water Samples

The first batch of samples to be analysed were those collected in August 2003. At that time, the FIA had not been purchased, and so the samples were analysed for nitrate and phosphate using standard colorimetric methods detailed by Kirkwood (1994) and analyses performed on the Skalar San Plus autoanalyser, based at the Kinoya Government Wastewater Laboratory in Suva. Ammonia analysis was conducted at the University of the South Pacific, using the blue indophenol colour methods (Strickland and Parsons, 1968). For preparation of nutrient standards, low nutrient seawater ( LNSW) was used instead of artificial seawater because of the risk of contamination, especially in low nutrient level analysis. The LNSW has also been described as the best matrix for the preparation of standards (Hansen and Koroleff, 1999). The LNSW was collected in clean 20 litre polyethylene jerry cans from oceanic waters near Kadavu Island to the south of Viti Levu, well away from land and nutrient sources. The seawater was filtered straight away through a 10 *u*m pore size filter to remove particulate matter, and then stored in the dark for two weeks before use (Hansen and Koroleff, 1999).

A new FIA was purchased and set up in September 2003 at the Chemistry Department of the University of the South Pacific in Suva, Fiji. All of the water samples collected after January 2004 were analysed using the FIA.

The FIA provided a number of advantages for this research, the most important being the capability of analyzing many samples for more than one analyte (depending on the number of channels) at any one time. The number of samples that can be analysed in an hour were 70 for phosphate alone; 48 for nitrate alone and 45 for ammonia alone. However, with two channels, it was found that the FIA was able to analyse about 60 samples in an hour, once calibration procedures were completed satisfactorily, using the freshly prepared standards. The other main advantage was the capability of analyzing more than one analyte at any one time. In fact, the System Unit of the FIA may have up to 8 channels (therefore 8 different analytes) which are able to run simultaneously (QuikChem® FIA+ Automated Ion Analyzer User Manual, Hach Company 2003). The FIA used in this study had two channels: one for phosphate analysis while the second channel was interchangeable between nitrate and ammonia analyses.

The computer software package used for the FIA system is the Omnion FIA, developed by Lachat Instruments (QuikChem® FIA+ Automated Ion Analyzer User Manual, Hach Company 2003).

#### 4.2.3.1 Phosphorus Analysis by FIA Colorimetry

A standard FIA method for phosphorus analysis was used (QuikChem Method 10-115-01-1-B, William Prokopy, Lachat Instruments, Milwaukee, USA, 2000). The method is based on the reaction between the orthophosphate ion ($PO_4^{-3}$) in the sample with ammonium molybdate and antimony potassium tartrate under acidic conditions to form a complex which is subsequently reduced with ascorbic acid to form a blue complex. This complex absorbs light at 880 nm and the absorbance is proportional to the concentration of the orthophosphate in the sample. The method detection limit is 0.7 *u*g P/L or 0.02 *u*mol P/L .

One of the common problems with this method is contamination of the glassware, especially with low level phosphorus determinations. To reduce and eliminate this source of interference, all of the glassware including the glass calibration vials or tubes are soaked in 10% hydrochloric acid solution for at least 24 hours and rinsed several times with deionised water. Any contamination of the glassware or deionised water, or any of the reagents by the smallest quantity of phosphate produced negative peaks, and this problem was encountered initially. Each of these potential sources of contamination had to be investigated and the cause of the negative peaks identified by elimination. Glassware had to be re-rinsed; reagents tested separately and if found to be the problem, a new, fresh reagent was prepared; and, the deionised water also checked. On occasion, the source of deionised water had to be changed because of phosphate contamination.

From my personal experience, this contamination problem can be eliminated by ensuring that the ‘carrier’ line or tube for the phosphate line is kept separate from the other carrier lines, i.e., the line for nitrate, and in its own beaker of ‘carrier’ solution namely deionised water and not placed with other ‘carrier’ tubes for nitrate or ammonia, whichever was being analysed at the same time as the phosphorus. Furthermore, the level of the ‘carrier’ solution in the beaker should not be allowed to decrease too much, as this concentrates any traces of phosphate in the deionised water, which then adheres onto the sides of the beaker. Thorough rinsing of all glassware, including beakers used to hold ‘carrier solution’, with deionised water, usually solved the problems of negative peaks.

#### 4.2.3.2 Nitrate analysis by FIA Colorimetry

For the analysis of nitrite/nitrate in the water samples, a standard FIA method was used (QuikChem Method 31-107-04-1-A, David Diamond, Lachat Instruments, Milwaukee, USA, 2001). The method is based on the reaction of the nitrite ($NO_2^-$) ion, so the nitrate ions in the water sample are first reduced to nitrite ions, by passing the sample through a copperized cadmium column. The resultant nitrite ion which consists of reduced nitrate and original nitrite ion in the water sample reacts with sulphanilamide under acidic conditions to form a diazonium ion, which produces a pink dye upon mixing with N- (1-naphthyl)ethylenediamine dihydrochloride . The pink dye absorbs at 520 nm. Standards are prepared using deionized water and the method works best in the range 1.25 to 5.0 *u*mol/L NOx-N. The method detection limit is 0.01 *u*mol/L NOx-N. The results, NOx-N, consist of both $NO_2^-$ and $NO_3^-$ concentrations. Given the naturally low concentrations of nitrites in natural seawater (Lobban and Harrison, 1997), the results (NOx) will be presented and discussed as nitrate, $NO_3^-$.

The quality of the data depends very much on the efficiency of the cadmium column (QuikChem Method 31-107-04-1-A, David Diamond, Lachat Instruments, Milwaukee, USA, 2001). One common cause of column breakdown is air or water entering the column because the analyst forgets to turn off the cadmium line during flushing of the system with deionised water.

#### 4.2.3.3 Ammonia Analysis by FIA Colorimetry

The water samples were not initially analysed for ammonia because of a number of reasons: technical support for the use of the FIA was not always available when required. Secondly because the FIA had only 2 channels, this meant that one nutrient (either nitrate or ammonia) had to be analysed separately. Nitrate and ammonia channels were interchangeable (QuikChem Method 31-107-06-1-B, Ninglan Liao, Lachat Instruments, USA, 2002). In December 2004, the ammonia analysis using the FIA was first conducted, and after that, ammonia was regularly analysed along with nitrate and phosphate. The method used was a standard FIA method, the QuikChem Method 31-107-06-1-B. The method is based on the Berthelot reaction, where ammonia reacts with hypochlorite to form monochloramine, under alkaline conditions. The monochloramine in the presence of phenol, nitroprusside and excess hypochlorite, gives indophenol blue. The indophenol blue, measured at 630 nm, is proportional to the original concentration of ammonia in the water sample (QuikChem Method 31-107-06-1-B, Ninglan Liao, Lachat Instruments, USA, 2002). The pH is critical and is maintained below 9.6 to avoid possible precipitation of calcium and magnesium as hydroxides and carbonates (in seawater samples), by addition of $Na_2EDTA$. Deionised water is used for preparation of all standards. The method detection limit is 0.7 ug N-$NH_3$/L (0.05 *u*mol $NH_3$-N/L)

#### 4.2.3.4 Some lessons learnt from the FIA ammonia methods

Based on this study, for the most accurate results, ammonia analysis must be conducted immediately after sampling. The risk of contamination is very high, and so it is very important that all reagent bottles and the beakers with 'carrier' deionised water are covered with parafilm. Another lesson learned was that the samples should not be left exposed to the air in the tubes arranged on the rack, awaiting analysis. Instead, the tube should only be filled with the sample just before the autosampler draws it in to enter the manifold. This minimises the chances of contamination.

#### 4.2.3.5 Quality control of nutrient data

To ensure quality control of the data, a number of standard procedures were implemented. At each sampling station, three replicates of water samples were collected and treated as described above. The average nutrient concentration was calculated from the three replicates, excluding any outliers from the calculation. At the start of each FIA run, standards of known concentrations were run to set up the calibration of the FIA. Also during the analysis, 'check' standards of known concentrations were included after each batch of ten samples, to ensure the accuracy of the data (QuikChem Methods, 2003). One useful feature of the FIA QuikChem Method and the Omnion FIA software program, was the opportunity to exclude any standard that distorted the calibration line, and to repeat runs (using the software program) for more accurate data. This corrective step was done after the samples had been analysed on the FIA (QuikChem® FIA+ Automated Ion Analyzer User Manual, Hach Company 2003). On a number of occasions, the seawater certified reference material MOOS-1 was included with the samples for analysis on the FIA, with good agreement with the certified values being obtained (National Research Council of Canada, 2003).

## 4.3 RESULTS AND DISCUSSION

Nutrients are non-conservative components of seawater (Libes, 1992) and their variability is influenced by biological, chemical and physical processes in the marine environment. However, the effects of human activities on land along the coastline of the Coral Coast appeared to be reflected in the biological communities on the fringing reefs in the area. As a first assessment of such effects, the nutrient concentrations in coastal waters close to human habitation, are compared with those from sites further away from human impacts.

The results are presented in accordance with the research objectives (see Section 4.1).

### 4.3.1 General overview of status of nutrient concentrations along the Coral Coast

One of the research objectives was to gather as much information on nutrient concentrations as was possible, and to compare these among the eight Localities. Due to the large amount of data collected, the nutrient concentrations are summarized by a) the range of nutrient concentration values, and; b) the average nutrient concentration for each site and date of sampling. The sites are grouped according to Locality and the full results for the eight Localities are appended (Appendix B1 – B8). For comparison and discussion purposes, the main features of the results for each Locality are tabulated in Table 4.3.

#### 4.3.1.1 Results and Discussion - Nutrient Overview

Table 4.3 summarises the main features of the nutrient data for each Locality, in order that broad comparisons can be made. Following the Table is a discussion of similarities and differences among the eight Localities.

Table 4.3 Comparison of general features of nutrient concentration patterns among the eight Localities studied along the Coral Coast.

| LOC# | **PO4 RANGE (averg.) uM** | **PO4 % > 0.1 uM** | **NH3 RANGE (averg.) uM** | **NH3 % > 1.0 uM** | **NO3 RANGE (averg.) uM** | **NO3 % > 1.0 uM** | **DIN RANGE (averg.) uM** | **DIN % > 1.0 uM** | **NO3:PO4 % > 16** | **DIN:PO4 % > 16** | **NH3/DIN RANGE (AVERG.)** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **LOC 1** | 0.06 – 1.31 | 89% | 0.28 – 3.53 | 25% | 0.08 – 15.72 | 28% | 1.96 – 20.36 | 100% | 11% | 25% | 0.05 – 0.39 |
| **LOC 2** | 0.01 – 2.48 | 95% | 0.52 – 7.71 | 25% | 0.03 – 5.39 | 19% | 0.61 – 7.83 | 75% | 5% | 5% | 0.73 – 0.98 |
| **LOC 3** | 0.02 – 6.75 | 85% | 0.27 – 13.36 | 70% | 0.02 – 19.15 | 27% | 0.18 – 14.61 | 73% | 22% | 9% | 0.42 – 0.99 |
| **LOC 4** | 0.04 – 0.98 | 92% | 1.12 – 5.04 | 100% | 0.13 – 7.64 | 25% | 2.36 – 10.45 | 100% | 25% | 63% | 0.17 – 0.94 (CRK) |
| **LOC 5** | 0.01 – 1.16 | 87% | 0.30 – 8.33 | 48% | 0.03 – 3.60 | 23% | 0.31 – 9.05 | 95% | 17% | 39% | 0.43 – 0.99 |
| **LOC 6** | 0.01 – 1.45 | 69% | 1.27 – 11.83 | 100% | 0.15 – 12.41 | 54% | 1.56 – 12.92 | 100% | 8% | 0% | 0.81 – 0.92 |
| **LOC 7** | 0.03 – 1.35 | 75% | 10.81 | 100% | 0.18 – 3.64 | 25% | 11.47 (one value) | 100% | 0% | 100% | 0.94 |
| **LOC 8** | 0.03 – 2.61 | 92% | 3.26 – 4.78 | 100% | 0.09 – 12.25 | 64% | 3.64 – 5.35 | 100% | 4% | 4% | 0.89 – 0.90 |

Overall, there appeared to be some clear similarities among the Localities, particularly in the status of nutrients against threshold levels that are often quoted as being required for good coral health (Bell, 1992). The prominence of ammonia as opposed to nitrate appeared to be common among most of the Localities.

For phosphate concentrations, the concentrations ranged from below the detection limit, (which is recorded as half of the detection limit for that particular nutrient in the analysis of the data patterns), up to more than 6 uM in one Locality (3). There appeared to be wide variation in the behavior of phosphate. For some Localities, the lowest phosphate concentrations were recorded on fine dry days (Locality 3) while for others, lowest phosphate concentrations were recorded on wet days (Locality 2). Wet days are those when there is 25 mm or more rainfall in the 24 hours prior to sampling. The critical observation was the very high percentage of phosphate concentrations exceeding the threshold level of 0.1 uM (Bell, 1992), recommended for the protection of coral reefs, in all of the Localities, from 69 % to 95 %. Such high phosphate concentrations indicated that the local coral reefs are already under threat.

In contrast to phosphate, ammonia concentrations appeared to be invariably high most of the time for all Localities. The minimum concentrations were well above the detection levels, and for five of the eight Localities, the percentage of ammonia concentrations above the coral reef health protection threshold level of 1 uM (Bell, 1992) ranged from 70 to 100 %. In fact, in four Localities, 100 % of the average ammonia concentrations exceeded the threshold of 1 uM. Again this observation indicated the high risk to which the coral reefs along the Coral Coast are exposed. The significance of ammonia in the DIN in all of the Localities is shown in the high proportions ($NH_3$/DIN) around 0.90 up to 0.99 (see last column in Table 4.3). The prevalence of ammonia may be indicative of a high degree of organic pollution and lower concentrations of dissolved oxygen (Hawker and Connell, 1992).

The behavior of nitrate appeared to be more consistent for all Localities. The highest nitrate concentrations were always associated with high rainfall, and exacerbated by the effects of creeks and rivers. Generally though, the nitrate concentrations were low and often well below the reef protection threshold level of 1 uM (Bell, 1992). The exceptions were days of heavy rainfall when nitrate concentrations peaked, in some cases up to ten times the threshold level, in what could be described as pulses.

Another similarity among the Localities was the high concentrations of DIN, and how most of the DIN values exceeded the reef protection threshold level of 1 uM (Bell, 1992). For five of the eight Localities, 100 % of the average DIN concentrations recorded more than 1 uM. The remaining three Localities recorded 73 %, 75 %, and 95% respectively of DIN values > 1 uM. Just as in the case of phosphate variability, the high DIN concentrations indicated that the coral reefs along the Coral Coast were already being exposed to high risk of degradation from nutrients.

In terms of primary biological productivity, both $NO_3$ : $PO_4$ and DIN : $PO_4$ ratios appeared to be indicating nitrogen limitation since the ratios were mostly below 16. A small percentage of $NO_3$ : $PO_4$ and DIN : $PO_4$ were above 15 as shown in Table 4.3. These were the events of high rainfall when the concentrations of nitrate and ammonia far exceeded those of phosphate, thus resulting in an increase of NOx : $PO_4$

and DIN : $PO_4$ ratios above 16, which could indicate a phosphate-limited environment for biological productivity.

The following sections examine in detail the variation in nutrient concentrations for the various sites within the Localities, according to the research objectives listed in Section 4.1.

### 4.3.2 Spatial Variation in Nutrient Concentration along the Coral Coast

To assess the impacts of humans on water quality and nutrient concentrations in the inshore waters along the Coral Coast, the control sites are compared with impacted sites, by dates. Due to logistical problems, it was not always possible to sample the same sites each time. Due to its geographical location in Fiji, the Coral Coast experiences a relatively dry climate. This is reflected in the volume of data collected during the study period, i.e., the amount of dry weather data far exceeded the wet weather data. This section discusses first the results for dry weather sampling events, followed by wet weather events. Comparisons are then made between the dry weather data and wet weather data. The results are either presented as graphs or in tables. For the graphs, the heights of the bars represent average nutrient concentrations for 3 independent replicate samples at each site. For some of the sampling events in which microbiological tests (faecal coliform) were completed, the results are also presented.

During the study period, parts of the Coral Coast were being developed quite rapidly and one of my control sites, Valase was influenced by this change. This change was not anticipated during the selection of control sites. However, Valase (VLS) was not abandoned as a control site but was continually monitored as a typical BACI (before/after control/impact) site. Table 4. 4 shows a timetable of the developmental changes that took place at Valase and the eastern shoreline at the Maui Resort development site, during the study period.

Table 4.4 Summary of Changes at Valase and adjoining Maui Bay Resort Development.

| Sites | Year 2004 | Year 2005 | Year 2006 |
|---|---|---|---|
| Valase – from 'control' to impacted (backpacker operation) | February: 1 thatched 'bure' or hut, unoccupied | Expansion of Backpacker Operation: at least two more huts built. Caretaker and owner residing on site | April: 4 new 'bures'; 1 swimming pool.<br>June: Wastewater treatment plant; drains to creek on west boundary |
| Maui Bay Resort Dev. (east of VLS) | Typical coastal vegetation – coconut trees; no buildings | Clearing of land on coast and inland | Construction of Road, wall and buildings within walls |

#### 4.3.2.1 Dry weather spatial variation in nutrient concentrations for sites along the Coral Coast, south-western Viti Levu, Fiji.

Figures 4.1 and 4.2, and Tables 4.5 – 4.11 show nutrient data for the different sites, during dry weather (< 25mm rain) sampling events.

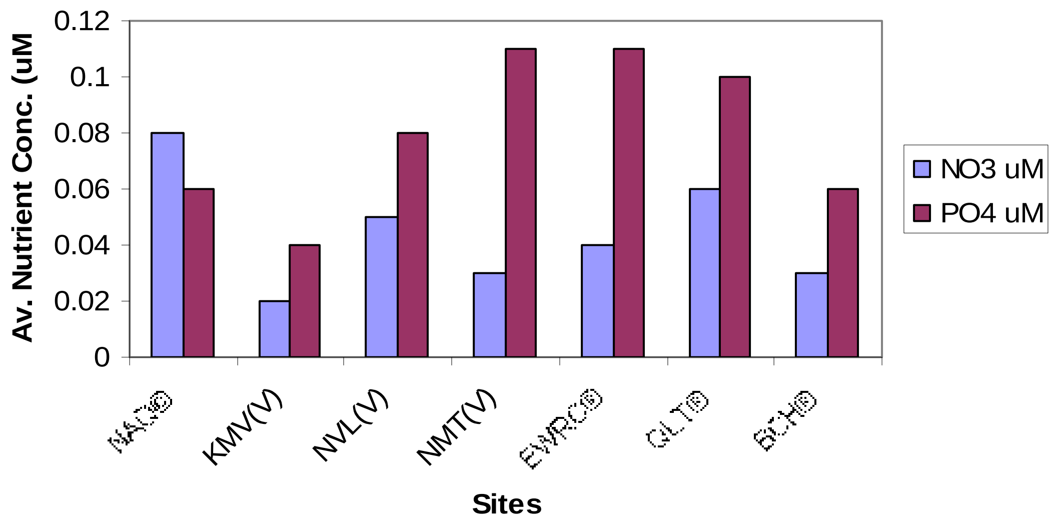



Fig. 4.1 Nutrient concentrations at control and impacted sites sampled on 25 March 2004, along the Coral Coast, Fiji.

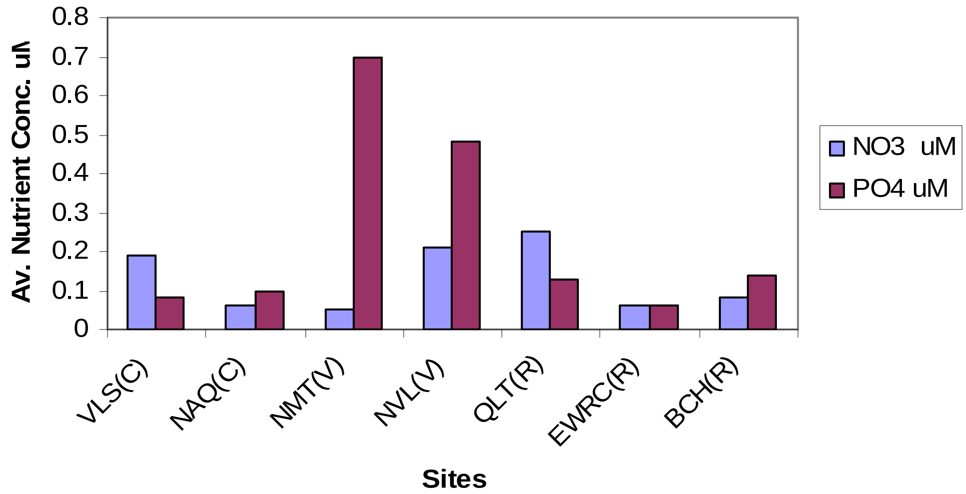



Figure 4.2 Nutrient concentrations at control (C) and impacted (V and R) sites sampled on 13 May 2004, Coral Coast, Fiji.

Table 4.5 Nutrient and faecal coliform concentrations for sites (including creeks) sampled on 11 August 2004.

| **Sites** | **NO3 Av. uM** | **PO4 Av. uM** | **$NO_3$: $PO_4$** | **Faecal coliform (c/100 ml)** | **Salinity (ppt)** | **Temperature (°C)** |
|---|---|---|---|---|---|---|
| VLS ( C) | 0.9 | 0.34 | 2.65 | 28 | 36.5 | 25.6 |
| NVL CRK | 1.62 | 0.49 | 3.31 | 6700 | 0.5 | 24.0 |
| NVL (V) | 0.37 | 0.78 | 0.47 | 360 | 29.6 | 26.7 |
| KMV CRK | 2.62 | 1.30 | 2.02 | No data | 2.5 | 24.2 |
| KMV (V) | 0.22 | 0.90 | 0.24 | 140 | 26.0 | 26.0 |
| NAQ (C) | 0.28 | 0.88 | 0.32 | 9 | 35.5 | 25.7 |
| NMQ CRK | 0.61 | 1.31 | 0.47 | 19000 | 1.2 | 25.7 |
| NMQ (V) | 0.97 | 0.15 | 6.47 | 210 | 35.9 | 27.7 |
| BCH (R) | 0.06 | 0.95 | 0.06 | 23 | 35.2 | 27.8 |
| WRC (R) | 0.17 | 1.34 | 0.13 | 55 | 36.5 | 26.3 |

Table 4.6 Nutrient and faecal coliform concentrations for sites (including creeks) sampled on 12 August 2004.

| **Sites** | **NO3 Av. uM** | **PO4 Av. uM** | **$NO_3$: $PO_4$** | **Faecal coliform (c/100 ml)** | **Salinity (ppt)** | **Temperature (°C)** | **Diss.$O_2$ (mg/L)** |
|---|---|---|---|---|---|---|---|
| BUL1 (C) | 0.43 | 1.22 | 0.35 | 1 | 36.2 | 25.7 | 7.8 |
| BUL2 (C) | 0.35 | 0.18 | 1.94 | <1 | 36.2 | 25.6 | 6.6 |
| TBK1 (R) | 0.86 | 0.41 | 2.10 | 6 | 35.4 | 25.7 | 7.0 |
| OTR1 (R) | 1.48 | 0.06 | 24.67 | No data | 33.2 | 26.3 | 6.9 |
| NMD2 (V) | 1.64 | 0.37 | 4.43 | 400 | 35.8 | 25.4 | 5.9 |
| MLV1 (V) | 1.72 | 0.71 | 2.42 | 40 | 32.9 | 26.3 | 6.8 |
| VTK1 (V) | 0.40 | 0.15 | 2.67 | <1 | 36.3 | 26.2 | 6.6 |
| CRW1 (R) | 0.39 | 0.44 | 0.89 | 2 | 33.2 | 26.3 | 6.9 |
| KUC1 (CRK) | 0.71 | 0.15 | 4.73 | 34 | 0.7 | 24.4 | 5.0 |

Table 4.7 Nutrient and faecal coliform concentrations for sites (including creeks) sampled on 12 October, 2004.

| **Site** | **PO4 Av. *u*M** | **NO3 Av. *u*M** | **$NO_3$: $PO_4$** | **Faecal coliform (c/100 mL)** | **Salinity (ppt)** | **Temp. (°C)** | **Diss. O2 (mg/L)** |
|---|---|---|---|---|---|---|---|
| NMQ1 (C) | 0.36 | 0.57 | 1.58 | 4 | 37.3 | 26.5 | 7.6 |
| NMQ2 (C) | 0.41 | 0.74 | 1.80 | 7 | 37.3 | 26.5 | 7.6 |
| CVC3 (CRK) | 0.18 | 0.57 | 3.17 | TNTC | 1.1 | 23.7 | 4.2 |
| NMQ4 (V) | 0.13 | 15.71 | 120.85 | 135 | 36.6 | 27.0 | 7.6 |
| CRS1 (R) | 0.08 | 0.32 | 4.00 | 79 | 36.2 | 27.1 | 7.5 |
| BCH1 (R) | 0.44 | 0.43 | 0.98 | 49 | 34.9 | 26.4 | 6.8 |
| NVC1 (CRK) | 0.61 | 10.29 | 16.87 | 133 | 2.3 | 23.4 | 7.1 |
| NVL2 (V) | 0.72 | 0.31 | 0.43 | 1380 | 32.9 | 26.7 | 7.5 |
| NMT4 (V) | 1.73 | 0.36 | 0.21 | 214 | 33.1 | 27.9 | 7.0 |
| KMC2 (CRK) | 0.17 | 19.04 | 112.00 | TNTC | 1.9 | 23.6 | 8.2 |
| KMV1 (V) | 0.08 | 19.15 | 239.38 | 34 | 36.5 | 26.3 | 7.7 |
| NAQ1 (C) | 0.04 | 18.76 | 469.00 | 8 | 35.6 | 25.3 | 8.0 |

Table 4.8 Nutrient and faecal coliform concentrations for sites (including creeks) sampled on 13 October, 2004.

| **Site** | **PO4 Av. *u*M** | **NO3 Av. *u*M** | **$NO_3$: $PO_4$** | **Faecal coliform (c/100 mL)** | **Salinity (ppt)** | **Temperature ($^oC$)** | **Diss. O2 (mg/L)** |
|---|---|---|---|---|---|---|---|
| CBN1 C) | 0.42 | 0.36 | 0.86 | 37 | 33.3 | 25.0 | 9.8 |
| VLS1 C) | 0.11 | 0.19 | 1.73 | 3 | 36.5 | 26.7 | 8.3 |
| TGQ1 V) | 2.70 | 0.18 | 0.07 | 36 | 32.2 | 26.8 | 8.3 |
| NMD2 (V) | 1.81 | 10.72 | 5.92 | <1 | 35.5 | 25.9 | 7.5 |
| HDW1 (R) | 3.58 | 2.75 | 0.77 | <1 | 36.2 | 26.5 | 7.3 |
| TBS1 (R) | 0.11 | 0.29 | 2.64 | ND | 34.9 | 26.4 | 7.9 |
| QLT1 R) | 0.09 | 0.15 | 1.67 | 21 | 36.6 | 26.7 | 8.4 |
| WRC1 (R) | 0.11 | 0.17 | 1.55 | 4 | 36.5 | 25.8 | 7.2 |
| VOC3 (CRK) | 0.24 | 0.17 | 0.71 | 76 | 1.3 | 24.5 | 7.9 |
| VOT2 (V) | 0.04 | 0.14 | 3.5 | 380 | 32.1 | 26.2 | 7.8 |
| NVT1 (R) | 0.10 | 0.19 | 1.90 | 40 | 33.8 | 26.8 | 7.5 |

Table 4.9 Nutrient and faecal coliform concentrations for sites (including creeks) sampled on 14 October, 2004.

| **Site** | **PO4 Av. *u*M** | **NO3 Av. *u*M** | **$NO_3$: $PO_4$** | **Faecal coliform (c/100 mL)** | **Salinity (ppt)** | **Temperature ($^oC$)** | **Diss. O2 (mg/L)** |
|---|---|---|---|---|---|---|---|
| BUL2 (C) | 0.05 | 0.19 | 3.80 | <1 | 36.6 | 26.4 | 8.4 |
| BUL3 (C) | 0.05 | 0.14 | 2.80 | <1 | 36.6 | 25.5 | 7.1 |
| TBK1 (R) | 0.03 | 0.14 | 4.67 | <1 | 36.4 | 25.4 | 7.2 |
| MLV1 (V) | 0.07 | 0.10 | 1.43 | 41 | 34.7 | 25.8 | 7.1 |
| VTK1 (V) | 0.03 | 0.18 | 6.00 | <1 | 36.8 | 25.6 | 7.2 |
| OTR/CRW (R) | 0.03 | 11.79 | 393 | <1 | 35.6 | 26.0 | 7.1 |
| KUC1 (CRK) | 0.03 | 12.64 | 421.33 | 260 | 0.8 | 23.7 | 6.3 |

Table 4.10 Nutrient and faecal coliform concentrations for sites (including creeks) sampled on 6 January, 2005.

| Site | PO4 Av. *u*M | NH3 Av. *u*M | NO3 Av. *u*M | DIN Av. *u*M | DIN:PO4 | Faecal coliform (c/100 mL) | Salinity (ppt) | Temp. ($^{o}$C) | DO (mg/L) |
|---|---|---|---|---|---|---|---|---|---|
| VLS1 (C) | 0.41 | 7.38 | 0.91 | 8.29 | 20.22 | ND | 36.5 | 30.1 | 7.8 |
| CBN1 (C) | 0.41 | 4.44 | 1.30 | 5.74 | 14.00 | 1000 | 31.2 | 29.7 | 6.6 |
| CBC2/U (CRK) | 0.69 | 2.55 | 0.42 | 2.97 | 4.30 | 1200 | 0.4 | 27.3 | 6.4 |
| CBC2/D (CRK) | 0.58 | 4.51 | 0.48 | 4.99 | 8.60 | 2500 | 0.4 | 27.1 | 6.3 |
| NMT4 (V) | 0.54 | 5.60 | 0.87 | 6.47 | 11.98 | TNTC | 35.4 | 29.4 | 8.2 |
| NMC2 (CRK) | 2.50 | 1.31 | 0.30 | 1.61 | 0.64 | 180 | 0.4 | 27.7 | 7.1 |
| NMC3 (CRK) | 4.14 | 3.17 | 0.59 | 3.76 | 0.91 | TNTC | 2.4 | 28.1 | 6.5 |
| NMD1 (R/V) | 1.23 | 11.83 | 1.08 | 12.91 | 10.50 | 2200 | 36.7 | 29.3 | 8.8 |
| NMD2 (V) | 1.06 | 6.14 | 1.16 | 7.30 | 6.89 | 2 | 36.8 | 29.1 | 8.0 |
| TGQ1 (V) | 1.14 | 4.10 | 0.55 | 4.65 | 4.08 | TNTC | 33.8 | 30.0 | 7.5 |
| TBS1 (R) | 1.18 | 6.66 | 1.27 | 7.93 | 6.72 | 1 | 36.1 | 30.4 | 7.8 |
| HDW1 (R) | 1.01 | 8.33 | 0.72 | 9.05 | 8.96 | 410 | 36.7 | 30.0 | 8.1 |
| VTK1 (V) | 0.50 | 10.81 | 0.66 | 11.47 | 22.94 | 18 | 37.2 | 30.8 | 6.5 |

Table 4.11 Nutrient and faecal coliform concentrations for sites (including creeks) sampled on 16 May, 2005.

| Site | PO4 Av. *u*M | NH3 Av. *u*M | NO3 Av. *u*M | DIN Av. *u*M | DIN: PO4 | Faecal coliform (c/100 mL) | Salinity (ppt) | Temp. ($^{o}$C) | DO (mg/L) |
|---|---|---|---|---|---|---|---|---|---|
| VLS1(C) | 0.10 | 1.27 | 0.07 | 1.34 | 13.4 | 700 | 34.4 | 29.1 | 8.2 |
| CBN1(C) | 0.18 | 1.33 | 0.23 | 1.56 | 8.67 | 467 | 34.4 | 28.1 | 6.5 |
| TGQ1 V) | 0.09 | 1.57 | 0.83 | 2.40 | 26.67 | 0 | 34.5 | 29.2 | 8.2 |
| HDW1 (R) | 0.13 | 1.59 | 0.56 | 2.15 | 16.54 | 357 | 34.6 | 28.3 | 6.8 |
| BCH1 R) | 0.36 | 1.52 | 1.72 | 3.24 | 9.00 | 523 | 34.1 | 27.4 | 6.3 |
| WRC1 (R) | 0.36 | 1.76 | 0.86 | 2.62 | 7.28 | 225 | 34.5 | 28.3 | 7.7 |
| VOC3 (CRK) | 0.98 | 1.11 | 5.57 | 6.68 | 6.82 | 6267 | 0.1 | 25.1 | 4.5 |

#### 4.3.2.2 Discussion of dry weather nutrient results

One of the more obvious features of the whole dataset was the variability that existed among the data. It is generally accepted that water column nutrient concentrations provide only a snapshot in time and space of the reality of the situation, and therefore may be highly variable even within a site (e.g., Fong *et al.*, 2003). However, water column nutrient concentrations provide a direct and often simple method of assessing human impacts on the adjacent land or coastline. A number of common patterns of nutrient variability were apparent and these are discussed in the following paragraphs.

**Phosphate concentration variability during dry weather events**

With phosphate concentrations, the results are compared with the threshold level of 0.1 *u*M P-PO4 suggested for healthy coral reefs (Bell, 1992). On some occasions, all of the phosphate concentrations were < 0.1 *u*M P-PO4 (Table 4.9). At other times, they all exceeded this threshold (Table 4.5; Table 4.6; Table 4.10 and Table 4.11). On most occasions however, there were results above and below the threshold (Fig. 4.1; Fig. 4.2 and Table 4.7). The 'Control' sites appeared to record lower phosphate concentrations than the impacted sites (e.g., Table 4.7; Table 4.8 and Table 4.10).

When comparing the phosphate variability among the three categories of sites (C, V and R), the control sites tended to be less polluted than the other two types of sites. On 12 October 2004, NAQ control site was the only site with < 0.1 uM *u*M P-PO4, while the rest of the sites recorded around 0.1 *u*M or more (see Table 4.7). On 13 October 2004, the two control sites Cabana (CBN) and Valase (VLS) recorded the lowest phosphate concentrations (about 0.1 *u*M) while the village and resorts recorded from about 0.5 uM to about 3.5 uM P-PO4 (see Table 4.8). On 11 August 2004, the Valase (VLS) control site recorded the second lowest phosphate result of 0.34 uM phosphate, but this was already above the threshold concentration for healthy coral reefs (see Table 4.5). Similarly on 6 January 2005, the two control sites (CBN and VLS) recorded the lowest phosphate concentrations (average of 0.41 uM), but these, together with the rest of the results for that day were above the guideline threshold (see Table 4.10).

Wherever the control sites recorded phosphate levels higher than the impacted sites, the causes can often be attributed to specific (e.g., updrift) sources; for example, on 11 August 2004 (Table 4.5), NAQ (control, 0.88 uM P-PO4) being affected by the Komave creek (1.30 uM P-PO4) and Komave village (0.90 uM P-PO4), to the east and updrift of NAQ (see Locality 3 Map, Appendix A3).

The creeks and rivers in the region were also found to be significant sources of phosphate and sewage to the coastal waters. On 11 August 2004, the Namaqumaqua creek (NMQ CRK) which is updrift of NMQ4 site (see Locality 1 Map, Appendix A1), recorded high faecal coliform counts, high phosphate and also elevated nitrate concentrations. It would appear that the Namaqumaqua Creek which drains part of the village as well as the small Coral Village Beach Resort, was the source of nutrients at NMQ4 site on this occasion (see Table 4.5). On 12 August 2004, the high phosphate concentration at Bulu (BUL1, 1.22 uM P-PO4), was probably derived from the Bulu River nearby, as BUL1 is <5 m from the estuary (see Locality 8 Map, Appendix A8). On 6 January 2005 (see Table 4.10), the Namatakula creek above the village (NMC2, 2.50 uM P-PO4), and the same creek below the village (NMC3, 4.14 uM P-PO4), would have been important sources of phosphate to the Namatakula coastal waters (NMT4, 0.54 uM P-PO4). NMT4 is west and downdrift from the creek mouth (see Locality 2 Map, Appendix A2). On 16 May 2005 (see Table 4.11), the Votua Creek (VOC3) recorded the highest phosphate level on that day (0.98 uM P-PO4).

The villages and the resorts appeared to be significant sources of phosphate as well to the coastal waters, even on dry days (e.g., see Tables 4.7, 4.8 and Table 4.10). This may be indicative of point sources of phosphate (such as sewage) rather than diffuse sources (agricultural) in the villages and resorts (Jarvie *et al.*, 2006). For protection of coral reefs, these point sources of phosphorus must be eliminated or managed properly. The highest phosphate concentration recorded for Namatakula Village (NMT4) site on 12 October 2004 (see Table 4.7), may be explained by the fact that on fine, dry days, the village women use the upper sections of the Namatakula Creek for washing, with the use of detergents that contain $PO_4$. The Namatakula Creek also drains the village homes. The Namatakula Creek mouth is updrift of the NMT4 sampling site. At Namada, the site located between the Tambua Sands resort and the Namada village (NMD1), recorded a high phosphate level (1.23 uM P-PO4), and this decreased to 1.06 uM P-PO4 at NMD2, < 100 m west and downdrift from NMD1 (see Table 4.10).

The size of the village or resort had an effect on the concentrations of nutrients in the coastal waters nearby. From the 13 October 2004 (Table 4.8) results, for example, TBS (Tambua Sands Resort with 0.11 uM P-PO4) is a smaller resort than HDW (Hideaway with 3.58 uM P-PO4).

High phosphate concentrations in inshore coastal waters, such as those recorded on 6 January 2005 (from 0.41 *u*M at the control site, to 1.23 *u*M at NMD1), are a real threat to coral reef health along the Coral Coast. It has been suggested that macroalgae do not outcompete healthy corals, rather the corals themselves are degraded by other stressors such as elevated concentrations of phosphate, exposure and low salinities, before macroalgae appear and grow on the already dead or dying coral heads (Diaz-Pulido and McCook, 2004). These results help explain the changing face of the Coral Coast, from being a coral dominated to an algal dominated fringing reef system (see Chapter 5).

**Nitrate concentration variability during dry weather events**

Most of the nitrate results were below the threshold (Bell, 1992) of 1 *u*M $N\text{-}NO_3$ (Fig. 4.1; Fig. 4.2). On some occasions, a few results would be above the threshold while the majority of the results fell below the threshold (Table 4.5; Table 4.6; Table 4.8; Table 4.9 and Table 4.10). On other occasions, there was clear gradient in nitrate concentration from low human impact (control) sites, to high human impact sites (Table 4.6 and Table 4.9). There appeared to be very high variability in the nitrate concentrations, and unlike phosphate variability, there seemed to be no clear difference between the control sites and the impacted sites. While the majority of nitrate results were low and below the threshold (< 1 uM N-NO3), the high nitrate concentrations were clearly associated with nutrient sources including the creeks and rivers, the villages and resorts, and even commercial operations such as restaurants. These are discussed in the following paragraphs.

The creeks were significant sources of nitrate and also faecal coliforms to the coastal waters (see Table 4.5, Table 4.7 and Table 4.11). On August 11 2004, the Navola creek (NVL CRK) recorded 1.62 uM N-NO3 while the receiving coastal waters at Navola village (NVL V) recorded 0.37 uM N-NO3 (see Table 4.5) Similarly on the same day, Komave creek recorded 2.62 uM nitrate while the receiving water at Komave village recorded 0.22 uM N-NO3. The results for the creeks were the highest for that day. Much higher nitrate concentrations were recorded in the Navola creek (10.29 uM) and the Komave creek (19.04 uM) on 12 October, 2004 (see Table 4.7). Incidently on 12 October 2004, the high nitrate concentrations at Naqau (NAQ (C)), and Komave Village (KMV (V)) may be sewage-related and originating from the Komave Creek (KMV CRK) that flows beside the village. All three sites are within the same area (see Locality 3 Map, Appendix A3). The KMV Village and KMV Creek are both updrift of the control site at NAQ.

On some occasions, the villages and resorts were clearly the sources of elevated nitrate concentrations in the coastal waters (see Tables 4.6; 4.7 (NMQ4); 4.8; and 4.10), and the nitrate concentrations measuring up to more than ten times the threshold, should be cause for concern. On one occasion, the sources of elevated nitrate in the coastal waters (11.79 uM N-NO3) at Korotogo (OTR/CRW) may have been the chain of commercial operations along the shore, as well as the Creek (KUC1) updrift of the site (see Table 4.9).

The very high nitrate concentration at Namada Village (10.72 uM NOx-N) on 13 October 2004, should be a cause for concern, because it shows that this site (as with other sites of similarly high nitrate concentrations), is vulnerable to algal infestation. From preliminary observations, it is possible that the high presence of herbivorous fishes (as a consequence of this site being set aside as a ‘no-take’ site or *tabu* site, see Section 6.3.1) is controlling macroalgae abundance and subsequently allowing the nitrate to remain in the water column. This issue should be investigated further.

**Ammonia concentration variation during dry weather events**

The significance of ammonia becomes very clear as seen in the January 2005 nutrient results (Table 4.10). While nitrate concentrations may be around 1 *u*M, the concentrations of ammonia for all sites sampled (including the one control site CBN) all exceeded 1 *u*M; in fact, the values ranged from about 4 *u*M to about 12 *u*M NH3-N. In this instance, it appears that the ammonia is sewage-related as very high faecal coliform counts were also recorded for most of these sites. Incidently, January is within the Hot and Wet Season for Fiji, and thunderstorms occur regularly. The January 2005 results confirmed that any nutrient assessment must always include ammonia analysis. On the two dates when ammonia was analysed for, all of the results were either around 1 uM or above (Table 4.10 and Table 4.11). Following on from this, all DIN concentrations were above the threshold of 1 *u*M (Bell, 1992). There appeared to be positive correlation between faecal coliform concentrations and ammonia levels (Table 4.10).

**$NO_3$:$PO_4$ and DIN:$PO_4$ variability during dry weather events**

Almost all $NO_3$ : $PO_4$ ratios were below 16, indicating a situation of nitrogen-limited biological productivity. However for creek sites and those sites affected by the creeks, where nitrate concentrations were much higher than in coastal waters, the $NO_3$ : $PO_4$ ratios were raised above 16, creating a situation where phosphorus would be limiting biological production. The inclusion of ammonia in the analyses made important changes in the discussion of biological productivity. The DIN (ammonia + nitrate + nitrite) values were relatively higher than the threshold of 1 *u*M (Bell, 1992), and the DIN : $PO_4$ ratios were also relatively higher than the $NO_3$ : $PO_4$ ratios obtained in the pre-2005 samples (see Tables 4.10 and 4.11). The DIN : $PO_4$ ratios were closer to the ideal (16 : 1, Lobban and Harrison, 1997), and even higher than 16 at some sites.

The results so far showed that the control sites are relatively less nutrient rich than sites close to villages and resorts. For long term management purposes, the aim should be to treat wastewater on land so that the discharged effluent is of the same water quality as that being recorded for control sites. This is the sort of strategy that is being explored and implemented by developed countries, for example the European Water Directive in Europe (Devlin *et al.*, 2007) and the Great Barrier Reef Initiative in Australia (Wooldridge *et al*., 2006).

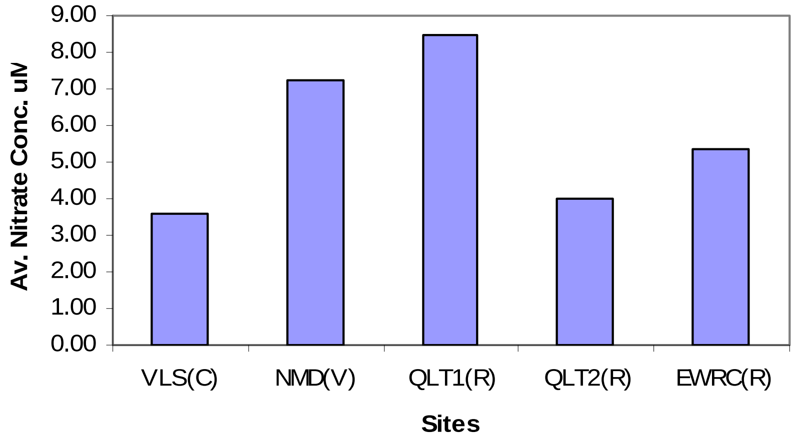
#### 4.3.2.3 Wet weather spatial variation in nutrient concentrations for Coral Coast sites, south-western Viti Levu, Fiji.

Figures 4.3, 4.4 and 4.5, and Tables 4.12 and 4.13 show nutrient variation among the different sites, during wet weather sampling events (10 Feb. 04, 25 Feb. 04, 4/8 June 04, 2 August 04 and 27 April 05). Wet weather events were when rainfall > 25 mm/day fell in the 24 hours prior to sampling.

#### 4.3.2.4 Discussion of wet weather nutrient results

While the results were also variable, there were clear differences between the wet weather data and the dry weather data discussed in Section 4.3.2.1. On one occasion, heavy rain affected the number of sites visited, and only three sites were sampled on 25 February 2004 (Fig. 4.4). The nutrient concentrations are compared with the threshold concentrations normally associated with good coral health, and discussed for each nutrient species.

Nitrate Concentrations on 10 February 2004




Phosphate Concentrations on 10 February 2004

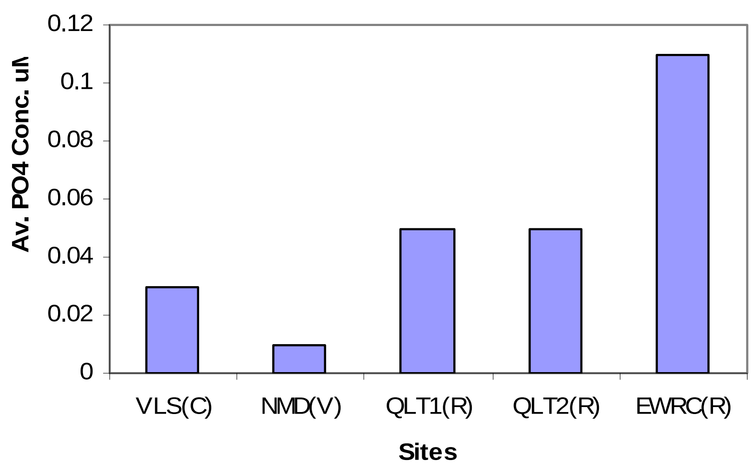
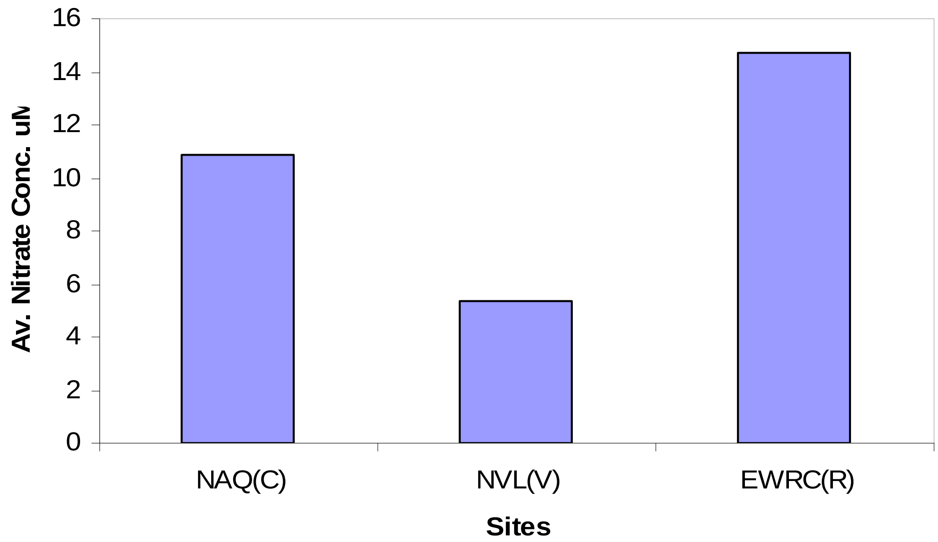



Figure 4.3 Concentrations of nitrate and phosphate for control (C), and impacted village (V) and resort sites (R), on 10 February, 2004.

Nitrate Concentrations at control and impacted sites on 25 February 2004




Phosphate concentrations at control and impacted sites on 25 February2004

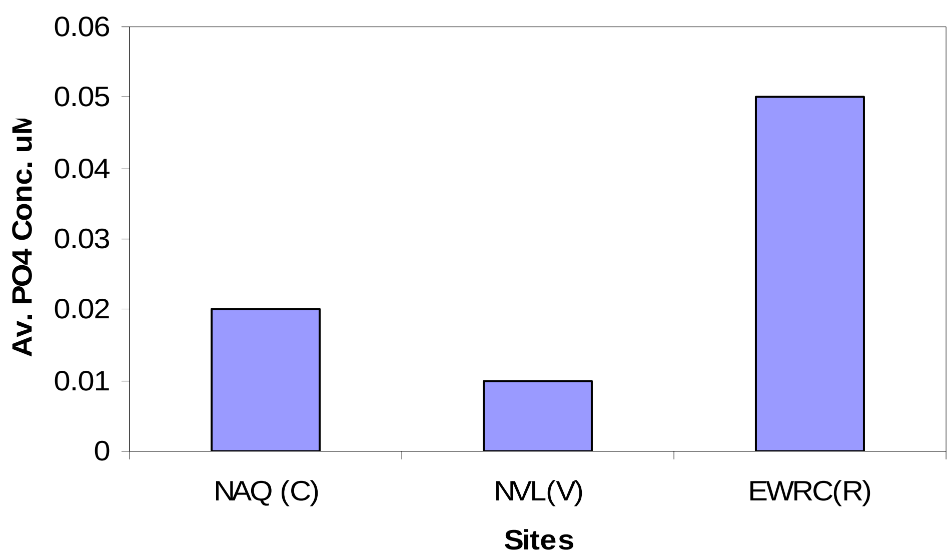



Figure 4.4 Concentrations of nitrate and phosphate for sites sampled on 25 February 2004.

Nutrient concentrations on 4 & 8 June 2004

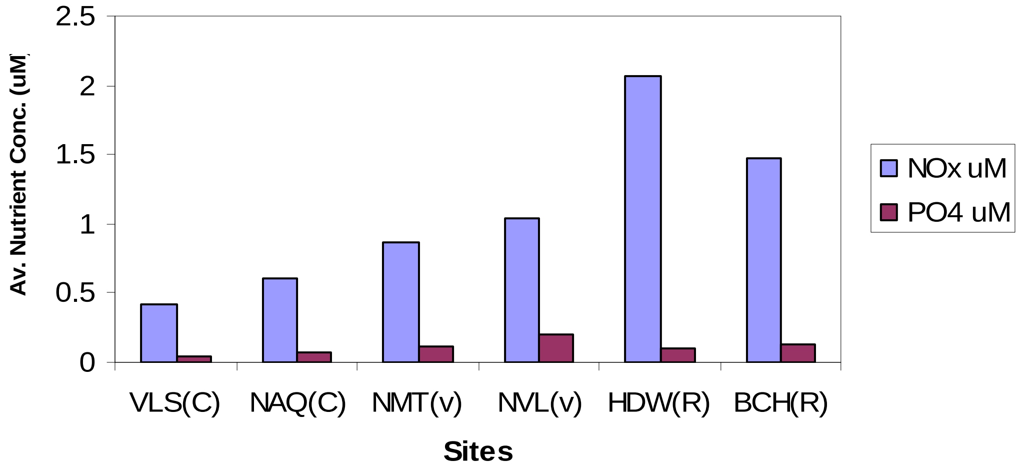



Figure 4.5 Concentrations of nutrients for control (C) and impacted sites (R) and (V) sampled on 4 & 8 June, 2004.

Table 4.12 Nutrient and faecal coliform concentrations, and water quality for sites sampled on 2 August, 2004.

| Site | PO4 Av. *u*M | NO3 Av. *u*M | NO3: PO4 | Faecal coliform (c/100 mL) | Salinity (ppt) | Temp. ($^{o}$C) | DO (mg/L) |
|---|---|---|---|---|---|---|---|
| BUL2 (C) | 2.72 | 10.70 | 3.93 | 710 | 35.1 | 26.2 | 5.5 |
| BUL3 (C) | 1.03 | 5.08 | 4.93 | 3000 | 16.5 | 24.4 | 6.8 |
| VTK1 (V) | 1.35 | 3.64 | 2.70 | 560 | 29.3 | 25.5 | 6.5 |
| NMD1 (V) | 1.39 | 12.41 | 8.93 | 5 | 33.7 | 26.3 | 6.6 |
| TBK1 (R) | 1.14 | 1.29 | 1.13 | 89 | 35.0 | 26.0 | 5.1 |
| KUC1 (CRK) | 1.84 | 17.18 | 9.33 | 14000 | 0.6 | 24.1 | 6.6 |
| OTR1 (R) | 1.28 | 2.16 | 1.69 | 80 | 35.4 | 26.0 | 5.2 |
| CRW1 (R) | 1.54 | 2.57 | 1.67 | 760 | 34.2 | 25.9 | 5.5 |

Table 4.13 Nutrient and faecal coliform concentrations, and water quality for sites (including creeks) sampled on 27 April 2005.

| **Site** | **PO4 Av. *u*M** | **NH3 Av. *u*M** | **NO3 Av. *u*M** | **DIN Av. *u*M** | **DIN:PO4** | **Faecal coliform (c/100 mL)** | **Salinity (ppt)** | **Temp. ($^oC$)** | **DO (mg/L)** |
|---|---|---|---|---|---|---|---|---|---|
| VLS1 (C) | 0.37 | 25.47 | 6.06 | 31.53 | 85.22 | 22 | 32.7 | 25.7 | 6.60 |
| WVLS (C) | 0.21 | 0.81 | 0.66 | 1.47 | 7.00 | 1010 | 34.1 | 26.2 | 6.77 |
| CBN1 (C) | 0.04 | 1.25 | 0.26 | 1.51 | 37.75 | 10 | 36.0 | 26.2 | 7.40 |
| CBC2 (CRK) | 1.19 | 2.90 | 6.86 | 9.76 | 8.20 | ND | 15.0 | 24.9 | 7.40 |
| VOC3 (CRK) | 0.97 | 2.81 | 22.93 | 25.74 | 26.54 | 2855 | 0.1 | 24.5 | 6.90 |
| BCH1 (R) | 0.31 | 0.52 | 1.66 | 2.18 | 7.03 | 3040 | 35.6 | 27.2 | 7.90 |
| HDW1 (R) | 0.20 | 2.52 | 2.74 | 5.26 | 26.3 | 3 | 35.7 | 25.5 | 6.31 |
| WRC (R) | 0.33 | 0.17 | 0.21 | 0.38 | 1.15 | 24 | 35.6 | 27.1 | 7.5 |

### Phosphate concentration variability on wet days

It was clear from the phosphate results that rainfall did cause an elevation of phosphate concentrations in most of the sites. Comparing the phosphate results with the threshold of 0.1 uM P-PO4 (Bell, 1992), most results exceeded the threshold (Fig. 4.5; Table 4.12 and Table 4.13). This has significant implications for the health of coral reefs along the Coral Coast. On a number of occasions, the control sites recorded lower phosphate concentrations than the impacted sites, for example, on June 4 and 8, 2004 (Fig. 4.5), Valase (VLS with 0.05 uM P-PO4) and Naqau (NAQ with 0.07 uM P-PO4) had the lowest phosphate concentrations, while the other village and resort sites exceeded 0.1 uM P-PO4. On 27 April 2005, the only site that recorded < 0.1 uM P-PO4 was a control site, Cabana (CBN). The rest of the sites had > 0.1 uM P-PO4 (Table 4.13). The 2 August 2004 results showed how rainfall can cause conditions extremely detrimental to the coral reefs along the Coral Coast. All of the phosphate results exceeded 1.0 *u*M P-PO4, ten times more than the acceptable concentration for good coral health (Table 4.12).

The creeks and rivers remained significant sources of phosphate to the coastal waters, just as in dry weather. On June 8 2004, the Namatakula creek (NMC1 and NMC2) sites both recorded 0.42 uM P-PO4, while the receiving water at Namatakula shore (NMT4) recorded 0.12 uM P-PO4 (see Fig. 4.5 and Appendix B2). Kula Ecopark creek (KUC1) also recorded the second highest phosphate result on 2 August 2004, while the highest P-PO4 results of 2.72 uM for BUL2 control site on the same day, was undoubtedly the effect of the Bulu river nearby (see Table 4.12). On the 27 April 2005 results, the creeks at Cabana (CBC2) and at Votua (VOC3), recorded the highest phosphate concentrations for that day (Table 4.13).

Phosphate is less mobile than nitrate and behaves in a less predictable way to rainfall. On 10 February and 25 February 2004, almost all sites recorded < 0.1 uM P-PO4 (see Figs. 4.3 and 4.4). In fact most of the concentrations were around 0.05 uM P-PO4. When phosphate concentrations are reduced with increased flow as in heavy rain situations, it may be indicative of point sources of phosphorus such as sewage, rather than diffuse sources such as agricultural sources (Jarvie *et al.*, 2006).The explanation for this unusual pattern of phosphate variation is that the phosphate is diluted by increased flow. Also, runoff from land in this area will carry the more mobile N species relative to less mobile (dissolved) $PO_4$.

**Nitrate concentration variability on wet days**

For the coastal waters, the highest nitrate concentrations were recorded during the wet weather sampling events (14.75 uM for EWRC and 10.89 uM for NAQ on 25 February 2004, Fig. 4.4; 8.50 uM for QLT on 10 February 2004, Fig. 4.3). In fact on 25 February 2004, all nitrate results ranged from 5 uM to > 14 uM $NO_3$ (Fig. 4.4). The flushing effects of rain were also evident in the elevated nitrate concentrations ranging from 1.29 uM $NO_3$-N (TBK Resort) to a high 12.41 uM $NO_3$-N (NMD Village) on 2 August, 2004 (Table 4.12).

While there was general variability, there appeared to clear gradation in nitrate concentrations from low for the control sites, and increasing for impacted sites (see Fig. 4.5). On other occasions, nitrate was found to progressively decrease on moving away from the likely nutrient source, for example, the 10 February 2004 nitrate results (see Fig. 4.3) : QLT1 (Qalito) was the nearest site to the large Warwick Resort; QLT2 was about 50 m further west of QLT1, moving away from the resort. Within 50 m, from QLT1 to QLT2, the nitrate concentration decreased by half from about 8.5 uM NO3-N to about 4 uM NO3-N, while the phosphate concentration did not change (Fig. 4.3). On the other (about 100 m east) side of the resort, EWRC appeared to be also affected by the resort. Incidently, QLT was noted for the prevalence of the brown macroalga *Sargassum* which covered much of the reef flat at Qalito (QLT) for much of the year (see Section 5.3.3). The Warwick resort discharged its partly treated wastewater via a pipeline running from the resort past Qalito (Fig. 4.3), and the pipeline has been an issue of contention for the local people, because on several occasions, it has actually broken, releasing highly polluted wastewater at Qalito.

The size of the village or the resort appeared to be reflected in the nitrate results, e.g., the Hideaway resort is much bigger than the Beachouse resort (see Fig. 4.5).

The creeks and rivers always showed much higher nitrate concentrations compared to the receiving coastal waters, and sites close to the creeks often reflected this nitrate loading. In fact, during thunderstorms and associated heavy rainfall, the creeks and rivers are the main sources of nutrient pulses to the coastal waters and ecosystems. For example during the 8 June 2004 sampling, the Namatakula Creek recorded 4.29 and 4.19 uM $NO_3$ (average) at NMC1 (above the bridge) and NMC3 (mouth of creek) respectively, whereas at the Namatakula shore (NMT4), average nitrate was 0.87 uM N-NO3 (see Fig. 4.5 and Appendix B2). The Kula Ecopark (KUC1) recorded 17.18 uM N-NO3 on 2 August, 2004 (see Table 4.12), and the Votua creek (VOC3) and the Cabana Creek (CBC2) recorded 22.93 uM and 6.86 uM N-NO3 respectively (see Table 4.13).

The rivers are also significant sources of sewage pollution and sewage-related nutrients including nitrate. On 2 August 2004, the elevated nutrient concentrations at BUL2 and BUL3 may be due to sewage in the Bulu river, because faecal coliforms for these two sites were high, 710 and 3000 counts per 100 ml respectively (Table

4.12), values which exceeded the World Health Organisation recommended levels of 300 c/100 ml for recreational waters (WHO, 1983). These results reiterate the importance of catchment landuse and human activities, on the downstream water quality. In contrast, both TBK (Tubakula Resort) and OTR (Outrigger Resort) are not close to any large river or creek, thus their recorded nutrient concentrations were relatively low on this occasion.

**Ammonia concentration variation during wet weather events**

April 27, 2005 was a very wet day and the very high concentrations of nitrate and ammonia found at Valase (VLS ( C )) were something entirely new for this ‘control’ site (Table 4.13). The development at Valase, and along the coastline to the east and updrift of Valase had progressed quite rapidly since January 2004. Changes in the area included widening of the highway to accommodate a new resort and new residential lots east of Valase (Table 4.4). At Valase itself, additional ‘bures’ or huts have been built since January 2004, as this area is being developed as a backpacker tourist facility, and changes were seen in the water quality. The effects of development at Valase were also reflected also in the significantly higher phosphate concentration at Valase (0.37 *u*M PO4), a previously undeveloped site chosen to represent ‘control’ conditions. The other two ‘control’ sites at CBN and WVLS both recorded < 0.1 *u*M PO4 as would be expected for such sites, while the 3 resort sites all recorded > 0.1 *u*M PO4.

The exceptionally high ammonia concentration (25.47 uM) for Valase on 27 April 2005 Table 4.13) can only be linked to the physical works and the influx of workers in the area around Valase at the time of sampling (see Table 4.4). This quickly decreased to < 1 uM at WVLS, about 200 m downdrift and west of Valase. This pattern of variation pointed to the development at Valase and the Maui Bay resort site as being sources of ammonia on this occasion.

**Nutrient-limited biological productivity during wet/rainy weather.**

In terms of potential biological productivity, there were mixed results, depending on differential enhancement between nitrate or DIN, and phosphate under wet weather conditions. Interestingly, in cases where both nitrate and phosphate were elevated, most of the the N : P ratios were less than 16 indicating a nitrogen-limited environment for biological productivity (4 and 8 June 2004; 2 August 2004). The same observations were reported by Lapointe (1995) and McCook *et al*. (1997). Lapointe (1995) found that the N : P ratios for inshore, enriched *Sargassum natans* in the western North Atlantic ocean, was 10.2 while that for non-enriched, oceanic *S.natans* was 18.1. McCook *et al*., (1997) in their studies with *Sargassum* found that the enriched tissues, following exposure to nutrient enrichment, had average N : P ratio of 21.4, while the control (non-enriched) tissues had an average of 30.6. On 10 and 25 February 2004, nitrate was elevated but phosphate was generally low (< 0.1 uM P-PO4) and the resultant N : P ratios were all > 16 indicating a phosphorus-limited situation for biological productivity.

#### 4.3.2.5 Statistical analysis of differences among control, village and resort sites

*Is there is any significant difference in nutrient concentrations among control, village and resort sites during wet (> 25 mm/day) and rainy weather?*

The effect of rainfall on nutrient concentrations was evident in the results discussed above. To test the hypothesis that there are no significant differences in the phosphate and nitrate concentrations among the control, village and resort sites, all of the wet weather data for the sites were pooled into the 3 categories or groups: C, V and R. Altogether, pooling of the data gave a total of 17, 21 and 20 data points for the Control, Village and Resort categories respectively. These were then tested using the SPSS 14.0 statistical software program. The one-way Analysis of variance (ANOVA) test could not be used because the data failed the test for homogeneity of variance, one of assumptions for application of ANOVA (Dytham, 2003). The Levene's Test of Homogeneity gave a significant p of 0.001, so the non-parametric equivalent of one-way ANOVA, the Kruskall Wallis test, was used. The Kruskall Wallis tests showed that for pooled phosphate data, there was no significant difference (p = 0.914) among the control, village and resort sites at the 0.05 level of significance. Similarly for the wet weather nitrate data, the Kruskall Wallis test showed there was no significant difference among the three categories or groups of sites, at the 0.05 level of significance (p = 0.886). This broad similarity among the sites within the eight Localities can be confirmed by the summarised results in Table 4.3 (Section 4.3.1.1). Appendix C1 shows the results of the statistical tests described above.

While the pooled data did not show any significant difference among the sites, separating out the data into separate dates or sampling events was more likely to show up a different outcome. The June 2004 results were tested using the Kruskall Wallis test again, since the Levene's Test for homogeneity gave a significant p value of 0.004, indicating that the data failed the homogeneity of variance test. This time the Kruskall Wallis test showed that there were significant differences among the control, village and resort sites with respect to phosphate concentrations (p = 0.006) and nitrate concentrations (p = 0.003) at the 0.05 level of significance. To identify which pairs of site/categories were significantly different, the Post Hoc Tests were performed and the results showed that for phosphate during the wet June 4$^{th}$ and 8$^{th}$ sampling, control sites differed significantly from village sites (p = 0.002) but not from resort sites (p = 0.146) at the 0.05 level of significance. However, the post hoc tests for nitrate showed that the control sites differed significantly from village sites (p = 0.039) and also from the resort sites (p = 0.049) at the 0.05 level of significance. This sort of significant variation in nitrate pulses during wet weather may be an explanation for variations in algal distribution among control and impacted sites (see Appendix C2).

#### 4.3.2.6 Comparisons between dry weather and wet weather nutrient results

One of research questions being investigated was whether there was any significant difference between wet weather and dry weather nutrient concentrations, in other words, does rainfall affect nutrient concentrations in the coastal waters along the Coral Coast. To address this question, two sets of results are presented in Tables 4.14 and 4.15, and discussed: the first set was collected in August 2004, and the second set of results was collected in April and May 2005. Following discussions of these results, statistical tests are presented on the nutrient data.

Table 4.14 Comparison Between Wet (August 2nd) and Dry (August 12th) Weather Nutrient Concentrations.

| Sites | **Nitrate (Av. uM)** | **Phosphate (Av. uM)** |
|---|---|---|
| BUL2 (C) – 2nd August | 10.7 | 2.72 |
| BUL2 (C) – 12th August | 0.35 | 0.18 |
| NMD (V) – 2nd August | 12.41 | 1.39 |
| NMD (V) – 12th August | 1.64 | 0.37 |
| TBK ( R) – 2nd August | 1.29 | 1.14 |
| TBK ( R) – 12th August | 0.86 | 0.41 |
| OTR ( R ) – 2nd August | 2.16 | 1.28 |
| OTR ( R ) – 12th August | 1.48 | 0.06 |

As can be seen in Table 4.14, the effects of rain flushing out nutrients was more significant for nitrate than for phosphate. This is to be expected because of the greater mobility of nitrate (Li *et al.,* 1997; Shuman, 2001). Phosphate which is less mobile was less enhanced by rainfall, and in some cases, phosphate concentrations were actually reduced, probably due to dilution during heavy rainfall. The effects of large rivers (for example, Bulu River on site BUL2, Table 4.12), and creeks, appeared to be generally more important than natural groundwater seepage during rain-induced flushing, because the extent of human impact in coastal villages is generally low; there is no intensive agricultural farming locally, and fertilizer use was hardly a concern at the time of sampling. The factors of beach profile and beach vegetation are also significant in assessing groundwater seepage.

The April/May 2005 set of comparative results are presented in Table 4.15.

Table 4.15 Comparison Between April 27th (wet) and May 16th (dry) Nutrient Concentrations.

| **Sites** | **Nitrate Conc. Av. *u*M** | **Ammonia Conc. Av. *u*M** | **Phosphate Conc. Av. *u*M** |
|---|---|---|---|
| VLS (C) April | 6.06 | 25.47 | 0.37 |
| VLS (C) May | 0.07 | 1.27 | 0.10 |
| CBN (C) April | 0.26 | 1.81 | 0.04 |
| CBN (C) May | 0.23 | 1.33 | 0.18 |
| HDW (R) April | 2.74 | 2.52 | 0.20 |
| HDW (R) May | 0.56 | 1.59 | 0.13 |
| BCH (R) April | 0.09 | 0.52 | 0.31 |
| BCH (R) May | 1.72 | 1.52 | 0.36 |

The most significant changes were in the concentrations of nitrate and ammonia for Valase (VLS), a previously unimpacted site (control) which became an impacted site as a result of large scale changes taking place along the shoreland and also inland. In contrast, at the Cabana (CBN) control site, there was no major difference between nutrient concentrations during dry and wet weather. CBN has not undergone any physical alteration to the coastal landscape, and therefore no additional sources of nutrients occurred during the period of study. As expected, the nutrient concentrations were lower during the dry weather sampling in May, particularly for nitrate and ammonia. For phosphate, the pattern was not as clear cut and may tend to behave differently, lower during wet weather (dilution effects) and higher in the drier weather (concentration effects), possibly as a result of point sources such as sewage effluent (Jarvie *et al.*, 2006).

#### 4.3.2.7 Statistical analysis of difference between wet weather and dry weather nutrient results

Due to high variability in nutrient concentrations, the data was not pooled for statistical analysis. Instead, the sites were treated separately. The null hypothesis tested was whether there was any significant difference between the wet weather data and the dry weather data for a site. Valase (VLS), Namada (NMD) and Hideaway (HDW) were selected to represent control, village and resort sites because there was sufficient data to run the statistical tests. The SPSS 14.0 statistical software program was used. Since there were two groups being tested (wet versus dry), the Mann-Whitney Test (non parametric) was used (Dytham, 2003).

For Valase control site, the Mann-Whitney test comparing phosphate concentrations in wet weather versus dry weather produced a significant result (p value of 0.036), at the 0.05 level of significance. In other words, there was a significant difference in phosphate concentrations at Valase on wet, rainy days compared to dry days. In the case of nitrate as well, the Mann-Whitney test produced a highly significant result (p value of 0.000) meaning that there were highly significant differences in nitrate concentrations for Valse on wet days compared to dry days. This is to be expected since the more mobile nitrate would definitely respond more strongly to rainfall than the less mobile phosphate (see Appendix C3, VLSPHRAIN and VLSNITRAIN).

In the case of Namada village (NMD), the Mann-Whitney test for phosphate produced a borderline probability with a significance value of p=0.061. Such a result may indicate that with more samples, there may be a significant p value which would mean there was significant difference in phosphate concentration between wet and dry weather for Namada site. As it is, the p value meant that there was no significant difference in phosphate concentrations for Namada for wet and dry days. The test for nitrate yielded a significant p value of 0.021, meaning that there was a significant difference in the nitrate concentrations at Namada on wet days and on dry days. The wet weather nitrate concentrations were much higher than the dry weather values.

For the Hideaway resort site, again the Mann-Whitney test of difference between two groups was used. In the test for phosphate, the test yielded a non-significant result (p = 0.485), meaning that there was no significant difference in the phosphate concentrations at the Hideaway resort site on wet days and dry days. The test for nitrate, however, yielded a highly significant p value of 0.002, indicating that nitrate concentrations were significantly higher on wet days compared to dry days at Hideaway resort site (Appendix C3, HDWPHOS and HDWNITRA).

The results of the statistical analyses (see Appendix C3) are not surprising since the more mobile nitrate is more likely to be enhanced by rainfall compared to the less mobile phosphate.

#### 4.3.2.8 Summary of General Observations from Spatial Nutrient Variation Patterns

In reviewing all the information from the nutrient analyses for waters along the Coral Coast of Viti Levu, some general points can be made:

- In general, the control sites, i.e., those furthest from any large village or resort, had lower concentrations of nutrients compared to sites near villages and resorts.

- Statistical tests showed that for the June 2004 wet weather nitrate concentrations, control sites were significantly different from village sites and also from resort sites. For phosphate results, control sites were significantly different from village sites but not from resort sites.

- Where control sites showed high concentrations of nutrients, the reasons were generally linked to the influence of impacted sites updrift of the control sites, for example, NAQ (C) on October 12, 2004 (see Table 4.7). At other times, effects of creeks or river estuaries were likely to have caused exceptionally high nutrient concentrations, especially during periods of heavy rainfall, e.g., BUL (C) during August 2004 sampling (see Table 4.6).

- There appeared to be no clear correlation between season and the variation in nutrient concentrations. This may be due to the fact that temperature ranges are not that different during the Hot and Wet Season and the Cool and Dry Season, unlike in temperate environments where temperature variation is vastly different from season to season. In the Coral Coast of Fiji, temperatures ranged from about 25 $^{o}$C to about 27 $^{o}$C in the Cool season, and from about 28 $^{o}$C to about 31 $^{o}$C in the Hot season. Temperature affects the mobility of substances including nutrients (Lobban and Harrison, 1997). On the other hand, rainfall appeared to have the greatest influence on nutrient concentrations, and high rainfall (while more common in the wet season) can occur at any time of the year.

- In general, nitrate concentrations correlated positively with rainfall. Statistical tests showed that there was a significant difference in nitrate levels between wet weather data and dry weather data for contol, village and resort sites. The wet weather nitrate results were significantly higher than dry weather nitrate levels.

- Ammonia concentrations also showed a positive relationship with rainfall. Ammonia concentrations dominated the total dissolved inorganic nitrogen (DIN) concentrations in almost all of the sites, from about 60 % up to 95 % in some cases. This showed the significance of ammonia as a form of nitrogen in the coastal waters along the Coral Coast, and that it needed to be included in analyses, for a more accurate estimate of the status of the dissolved nitrogen in the water column.

- Phosphate concentrations did not behave in as predictable a way as nitrate did. In some cases, rain elevated phosphate levels and in others, phosphate was actually reduced during heavy rain. When phosphate concentrations decrease with increased flow following heavy rainfall, the variation is considered evidence that the sources of phosphate are point sources such as sewage effluent, rather than diffuse sources such as agricultural sources (Jarvie *et al.*, 2006). The statistical tests for phosphate concentration versus weather showed mixed results.

- It is of concern that most sites on many occasions exhibited nutrient concentrations above the recommended concentrations for 'healthy'reefs, i.e. 0.1 uM for phosphate and 1uM for nitrate or DIN (Bell, 1992). The DIN values showed concentrations much higher than 1 *u*M, often because of the ammonia content.

- The $NO_3$ : $PO_4$ and DIN : $PO_4$ ratios tended to indicate that the waters were nitrogen limited for primary biological productivity. Most of the ratios were < 16. These ratios increased during high rainfall events when nitrate and ammonia concentrations tended to be boosted much more than the phosphate concentrations.

- The influence of creeks and rivers was quite notable. The rivers and creeks were significant sources of nutrients and sewage pollution both in themselves and also to the coastal waters. Sites near estuaries recorded higher nutrient and faecal coliform concentrations compared to sites further away. During wet weather, the increased nitrate and ammonia loadings in creeks and rivers have the effect of boosting the N : P and the DIN : P ratios to > 16, and creating a potentially phosphorus-limited situation for biological productivity.

### 4.3.3 Temporal Variation in Nutrient Concentrations, $NO_3$:$PO_4$ and DIN:$PO_4$

One of the research objectives was to examine the patterns of temporal variation in nutrients for sites along the Coral Coast. For comparison purposes, this section presents results for 3 control sites, 3 village sites and 3 resort sites, all of which were assessed at least 5 times during the period of study. The results and discussion are presented as three subsections: control, village and resort sites.

#### 4.3.3.1 Temporal variation in nutrient concentrations among control sites

The three control sites to be examined are Naqau (NAQ), Cabana (CBN) and Valase (VLS). Tables 4.16, 4.17, and 4.18 present the nutrient results for these three sites.

##### 4.3.3.1.1 Discussion of nutrient temporal variation for control sites along the Coral Coast

**Phosphate temporal variation for control sites along the Coral Coast**

The phosphate concentrations for the three control sites studied (along the Coral Coast) can best be summarised as variable. In some instances, phosphate was

Table 4.16 Temporal Variation in Nutrient Concentrations for NAQ Control Site

| **Date of Sampling** | **Season** | **Weather** | **PO4 Av *u*M** | **$NO_3$ Av *u*M** | **$NH_3$ Av *u*M** | **DIN Av *u*M** | **$NO_3$:$PO_4$** DIN: $PO_4$* |
|---|---|---|---|---|---|---|---|
| 2 Aug ‘03 | Cool/Dry | Dry | 0.28 | 0.12 | 0.27 | 0.39 | 0.43<br>1.39* |
| 25 Feb ‘04 | Hot/Wet | V.Wet | 0.02 | 10.89 | nd | _ | 544.5 |
| 25 Mar ‘04 | Hot/Wet | Dry | 0.06 | 0.08 | nd | _ | 1.33 |
| 13 May ‘04 | Cool/Dry | Dry | 0.10 | 0.06 | nd | _ | 0.6 |
| 25 May ‘04 | Cool/Dry | Dry | 0.03 | 0.71 | nd | _ | 23.67 |
| 8 June ‘04 | Cool/Dry | Dry | 0.07 | 0.60 | nd | _ | 8.57 |
| 11 Aug ‘04 | Cool/Dry | Dry | 0.88 | 0.28 | nd | _ | 0.32 |
| 12 Oct. ‘04 | Cool/Dry | Dry | 0.04 | 18.76 | nd | _ | 469 |
| 7 Jan ‘05 | Hot/Wet | Dry | 0.30 | nd | nd | _ | _ |
| 23 Mar ‘05 | Hot/Wet | Bit Wet | 0.72 | 0.04 | 1.97 | 2.01 | 0.06<br>2.79* |
| **Average** | | | **0.25** | **3.50** | **1.12** | | High variation |

Table 4.17 Temporal Variation in Nutrient Concentrations for CBN Control Site

| Date of Sampling | Season | Weather | $PO_4$ Av. uM | $NO_3$ Av. uM | $NH_3$ Av. uM | DIN Av. uM | $NO_3$:$PO_4$ | DIN:$PO_4$ |
|---|---|---|---|---|---|---|---|---|
| 4 Aug. '04 | Cool/Dry | Dry | 0.27 | nd | nd | _ | _ | |
| 13 Oct. '04 | Cool/Dry | Dry | 0.13 | 0.35 | nd | _ | 2.7 | |
| 6 Jan '05 | Hot/Wet | Dry | 0.41 | 1.31 | 4.44 | 5.75 | 3.2 | 14.0 |
| 27 Apr '05 | Hot/Wet | V. wet | 0.04 | 0.26 | 1.81 | 2.07 | 6.5 | 51.8 |
| 16 May '05 | Cool/Dry | Dry | 0.18 | 0.23 | 1.27 | 1.50 | 1.3 | 8.7 |
| **Average** | | | **0.21** | **0.54** | **2.53** | **3.13** | **3.4** | **24.8** |

elevated during wet weather (second highest for NAQ, Table 4.16; and for VLS, Table 4.18), and in other instances, phosphate was lowest during wet weather sampling (lowest for NAQ, CBN and VLS). A lot of factors would have been in control, for example the amount of rainfall at the time of sampling, the weather conditions prior to sampling and a multitude of ecological factors at the sites at the time of sampling.

Table 4.18 Temporal Variation in Nutrient Concentrations for VLS Control Site

| Date of Sampling | Season | Weather | PO4 Av. uM | $NO_3$ Av. uM | $NH_3$ Av. uM | DIN Av. uM | $NO_3$:$PO_4$ DIN:$PO_4$ |
|---|---|---|---|---|---|---|---|
| 2 Aug. '03 | Cool/Dry | Dry | 0.35 | 0.46 | 0.35 | 0.81 | 1.33 2.38 |
| 22 Jan. '04 | Hot/Wet | Dry | 0.25 | 0.13 | nd | _ | 0.52 |
| 10 Feb. '04 | Hot/Wet | Wet | 0.03 | 3.6 | nd | _ | 120 |
| 13 May '04 | Cool/Dry | Dry | 0.08 | 0.19 | nd | _ | 2.38 |
| 8 June '04 | Cool/Dry | Wet | 0.05 | 0.42 | nd | _ | 8.4 |
| 11 Aug. '04 | Cool/Dry | Dry | 0.90 | 0.34 | nd | _ | 0.38 |
| 13 Oct. '04 | Cool/Dry | Dry | 0.11 | 0.19 | Nd | | 1.73 |
| 4 Feb. '05 | Hot/Wet | Dry | 0.32 | 0.13 | 2.3 | 2.43 | 0.41 7.59 |
| 27 Apr. '05 | Hot/Wet | V. wet | 0.2 | 6.06 | 25.4 | 31.53 | 11.65 60.63 |
| 16 May '05 | Cool/Dry | Dry | 0.10 | 0.07 | 1.27 | 1.34 | 0.70 13.4 |
| **Average** | | | **0.27** | **1.16** | **7.35** | | **4.28** |

For NAQ, phosphate concentrations showed few changes over the years, and values have generally been low ranging from 0.02 *u* mol P-PO4/L to 0.88 *u* mol P-PO4/L. The high (0.88 *u* mol P-PO4/L) concentration was most probably linked to the KMV creek updrift, which also recorded high phosphate concentration (1.30 uM) on the same day (see Table 4.5). There appeared to be no significant influence of season, but rainfall seems to have caused an increase on one occasion (23 March, 2005 results, Table 4.16). The overall average of 0.25 *u* mol P-PO4/L was above the threshold concentration of 0.1 uM for good reef health (Bell, 1992), but within other proposed guidelines of up to 0.3 uM (Crossland, 1983; Bell *et al.*, 1987).

At CBN, phosphate concentrations did not show any major change over time, and remained relatively low, ranging from 0.04 – 0.41 *u* mol P-PO4/L. This is to be expected because during the monitoring period, there were no major changes in the physical or terrestrial surroundings at Cabana. The average of 0.21 *u* mol P-PO4/L was above the threshold proposed by Bell (1992) but within the range (up to 0.3 *u*mol/L) suggested by Crossland (1983), and Bell *et al.*, (1987), for good coral reef health. Again there appeared to be no association between seasons and phosphate levels, but high rainfall coincided with the lowest phosphate for this site (0.04 *u* mol P-PO4/L) on 27 April, 2005 (see Table 4.17).

The VLS (Valase) Control site presented a unique opportunity to monitor changes in water column nutrients, in an area where there was on-going physical disturbance to the adjoining coastal area. The changes were not anticipated at the start of the research. Phosphate concentrations were generally low, ranging from 0.03 – 0.90 *u* mol P-PO4/L, but 50 % of the ten results were > 0.1 *u* mol P-PO4/L, indicating that this site is not as pristine as one would have expected (see Table 4.18). This is not surprising since the area was progressively developed since the first sample was collected in August 2003. Examination of the phosphate data shows wide variations over time.

**Nitrate temporal variation for control sites along the Coral Coast**

The patterns of nitrate variation were clearer with all control sites recording the highest nitrate concentrations during wet weather. In the case of CBN, the highest nitrate was recorded on 6 January, 2005, a day without significant rainfall. In fact, the highest phosphate and ammonia levels were also recorded on this day. Other sites like Namada village also recorded high nutrients on this day. It appeared that weather conditions (rain) prior to this day had an effect on nutrients, and this would not be surprising for this time of the year in Fiji.

Nitrate concentrations for the NAQ Control site were also generally low with > 70 % of values being < 1 *u*mol N-NO3/L. The exceptions were the result of heavy rainfall and its flushing effects, as well as the effects of a flooded creek updrift of this site (10.89 and 18.76 *u*mol N-NO3/L respectively).

For VLS, nitrate concentrations ranged from 0.07 to 6.06 *u* mol N-NO3/L. The average nitrate concentration of 1.16 *u* mol N-NO3/L is a fair representation of the nitrate status, as 80 % of the results were < 1.0 *u* mol N-NO3/L. The other 20% (3.60 and 6.06 *u* mol N-NO3/L) occurred during heavy rainfall, confirming the significance of rainfall in mobilising nitrate from the land.

**Ammonia temporal variation in control sites along the Coral Coast**

One of the points of concern from this study was the prevalence of high concentrations of ammonia at most sites. Almost all ammonia results were > 1 uM and following on from that, most DIN values were > 1, exceeding the threshold suggested by Bell (1992). Out of the three control sites, Valase presented the exceptionally high ammonia concentration of > 25 uM N-NH3 on a very wet 27 April 2005. Of the three control sites, Valase was the site under intensive physical alteration, with clearing of vegetation and construction of buildings.

At NAQ, the average ammonia concentrations from 2 results (2 sets of 3 independent replicates) was also low at 1.12 *u*mol N-NH3/L. Likewise the average DIN (from 2 results) of 1.20 *u*mol/L was also relatively low and within acceptable range for good reef health (Crossland, 1983; Bell *et al.*, 1987).

The ammonia concentrations at CBN from the limited data collected were also relatively low (compared to other Coral Coast sites) with an average of 2.53 *u* mol N-

NH3/L. The average dissolved inorganic nitrogen (DIN) was also relatively low at 3.13 *u* mol /L, but already this was above the threshold level of 1 uM, for good coral growth (Bell, 1992).

At Valase, the concentrations of ammonia clearly showed the significance of this nutrient for an accurate assessment of the nutrient status of inshore coastal waters. The proportion of DIN present as ammonia was quite high, more than 80 % in all cases for this site. Again the wet weather was associated with not only the highest concentrations of nitrate, but also the highest concentration of ammonia (25.47 *u* mol N-NH3/L).

As far as NO3 : PO4 and DIN : PO4 ratios are concerned, most ratios are < 16, suggesting nitrogen limitation for biological productivity. This situation supports the suggestion that in the coastal waters of the Coral Coast, elevated nitrate and ammonia concentrations associated with wet weather may quickly enhance algal production. The only times that the N : P and DIN : P ratios exceeded the ideal (16) were during wet weather, especially for sites close to river estuaries and creek mouths.

#### 4.3.3.2 Temporal variation in nutrient levels for village sites.

The three villages that will be examined are Navola (NVL), Namatakula (NMT) and Namada (NMD). Tables 4.19, 4.20 and 4.21 present the results (averages) of nutrients over time, for these three village sites.

Table 4.19 - Temporal Variation in Nutrient Concentrations for NVL Village Site

| **Date of Sampling** | **Season** | **Weather** | **PO4 Av. uM** | **NO3 Av. uM** | **NO3 : PO4** |
|---|---|---|---|---|---|
| 25 Feb. 04 | Hot/Wet | V. Wet | 0.01 | 5.39 | 539 |
| 25 Mar. ‘04 | Hot/Wet | Dry | 0.08 | 0.05 | 0.63 |
| 13 May ‘04 | Cool/Dry | Dry | 0.48 | 0.21 | 0.44 |
| 4 June ‘04 | Cool/Dry | V. Wet | 0.20 | 1.04 | 5.20 |
| 11 Aug. ‘04 | Cool/Dry | Dry | 1.28 | 0.37 | 0.29 |
| 12 Oct. ‘04 | Cool/Dry | Dry | 0.72 | 0.31 | 0.43 |
| **Average** | | | **0.46** | **1.23** | **2.66** |

Table 4.20 - Temporal Variation in Nutrient Concentrations for NMT Village Site

| Date of Sampling | Season | Weather | PO4 Av. uM | NO3 Av. uM | NH3 Av. uM | DIN Av. uM | NO3 : PO4<br>DIN : PO4 |
|---|---|---|---|---|---|---|---|
| 25 Mar. ‘04 | Hot/Wet | Dry | 0.11 | 0.03 | nd | _ | 0.27 |
| 13 May ‘04 | Cool/Dry | Dry | 0.7 | 0.05 | nd | _ | 0.07 |
| 4 June ‘04 | Cool/Dry | Wet | 0.31 | 4.4 | nd | _ | 14.19 |
| 8 June ‘04 | Cool/Dry | Wet | 0.12 | 0.87 | nd | _ | 7.25 |
| 12 Oct. ‘04 | Cool/Dry | Dry | 1.73 | 0.36 | nd | _ | 0.21 |
| 6 Jan. ‘05 | Hot/Wet | Dry | 0.54 | 0.87 | 5.6 | 6.47 | 1.61<br>11.98 |
| 23 Mar ‘05 | Hot/Wet | Wet | 2.48 | 0.12 | 7.71 | 7.83 | 0.05<br>3.16 |
| **Average** | | | **0.86** | **0.96** | **6.66** | **7.15** | **1.12**<br>**8.36** |

Table 4.21 - Temporal Variation in Nutrient Concentrations for NMD (Namada) Village Site

| Date of Sampling | Season | Weather | PO4 Av. uM | NO3 Av. uM | NH3 Av. uM | DIN Av. uM | NO3 : PO4 | DIN : PO4 |
|---|---|---|---|---|---|---|---|---|
| 22 Jan. ‘04 | Hot/Wet | Dry | 0.05 | 0.25 | nd | _ | 5.0 | |
| 23 Jan. ‘04 | Hot/Wet | Dry | 0.02 | 0.16 | Nd | _ | 8.0 | |
| 10 Feb. ‘04 | Hot/Wet | Wet | 0.01 | 7.22 | nd | _ | 720 | |
| 2 Aug. ’04 | Cool/Dry | Wet | 1.39 | 12.41 | nd | _ | 8.9 | |
| 12 Aug. ‘04 | Cool/Dry | Dry | 0.37 | 1.64 | Nd | | 4.4 | |
| 13 Oct. ‘04 | Cool/Dry | Dry | 1.45 | 10.72 | nd | _ | 7.4 | |
| 6 Jan. ‘05 | Hot/Wet | Dry | 1.06 | 1.16 | 9.05 | 10.21 | 1.1 | 9.6 |
| 4 Feb. ‘05 | Hot/Wet | Dry | 0.29 | 0.29 | 1.27 | 1.56 | 1.0 | 5.4 |
| **Average** | | | **0.58** | **4.23** | **5.16** | **5.89** | **7.3** | **10.2** |

#### 4.3.3.2.1 Discussion of temporal variation among village sites

**Phosphate temporal variation for village sites along the Coral Coast**

Phosphate concentrations for the three village sites were also variable. For Navola and Namada villages, the highest phosphate results were recorded on dry days (1.28

uM, 1.45 uM respectively). For these two villages, the lowest phosphate results were recorded on wet days (<0.01 uM). For Namatakula, the highest phosphate result was recorded on a wet day (2.48 uM). All phosphate results for Namatakula, one of the larger villages along the Coral Coast, were > 0.1 uM, exceeding the threshold of 0.1 uM (Bell, 1992).

At Navola, phosphate concentrations were variable, but on the whole, higher than those recorded for the control sites (see Tables 4.16, 4.17 and 4.18). The concentrations ranged from 0.01 to 1.28 *u* mol P-PO4/L. Of interest also was the fact that generally, the phosphate concentrations were increasing with time. While there was no clear association with season, there was definitely a link with the weather at time of sampling; phosphate concentrations were lowest during high rainfall (dilution effects), and highest during dry days with no rainfall (concentration of phosphate in the water column).

Phosphate concentrations for NMT (Namatakula) Village were also are highly variable, but all were > 0.1 *u* mol P-PO4/L, and the high average for this site (0.86 *u* mol P-PO4/L) meant that coral reefs in the area were definitely at risk of degradation.

At Namada, phosphate concentrations ranged from 0.01 to 1.45 *u*mol P-PO4/L. While 4 out of 8 results were < 0.3 *u* mol P-PO4/L, the average concentration of 0.58 *u* mol P-PO4/L indicated a problematic situation for coral reef health (Crossland 1983; Bell and Greenfield 1987).

**Nitrate temporal variation in village sites along the Coral Coast**

As in the case of control sites, the nitrate behavior was more consistent over time. The highest nitrate results were obtained during wet weather sampling for all of the village sites, and some of these were very high (Namada, 12.41 and 10.72 uM N-NO3). For Namada village, five of the eight results were > 1.0 uM N-NO3.

At Navola, nitrate concentrations also showed a link with the weather, but not with season (see Table 4.19). On dry days with no rainfall, nitrate concentrations were < 1 *u* mol N-NO3/L (67 % of results) and on wet days, nitrate concentrations were > 1 *u* mol N-NO3/L (33% of results). While the actual amount of rainfall that fell would be important, the data for NVL (Navola) Village showed that the Wet Season/wet day nitrate concentration (5.39 uM N-NO3) was higher than the Dry Season/wet day results (1.04 uM N-NO3). There are no ammonia results as analysis for ammonia only started from December 2004.

At Namatakula village, nitrate concentrations were also highly variable, ranging from 0.03 to 4.4 *u* mol N-NO3/L with the highest being recorded during a wet day. Although the average nitrate concentration was 0.96 *u* mol N-NO3/L, the reefs at this site were degraded to varying degrees (observations by this author). The Namatakula reef is exposed to high nutrient and sediment loading via the Namatakula river, during flood events. This situation for Namatakula demonstrates the inadequacy of water column nutrient concentrations for assessment of total ecological health status in an area.

NMD (Namada) Village presents an interesting case in that the nitrate concentrations were some of the highest recorded during the study. Five out of eight results are > 1.0 *u* mol N-NO3/L and 3 of these are > 5.0 *u* mol N-NO3/L. However, the corresponding faecal coliform counts were low, some of the lowest recorded during the study. There appeared to be no relationship between sewage pollution and the high nitrate concentrations at this site. At this point, it would seem that the source of nitrate was something else and it is worth investigating the coral harvesting operations taking place but further to the west and downdrift of this site. The fact that this site has been set aside as a ‘no take’ or *tabu* zone may help explain this unusual phenomenon. The abundance of fish and the relative absence of macroalgae may be a possible explanation for the persistence of nitrate in the water column (observations by this author). This requires further investigation.

**Ammonia temporal variation for village sites along the Coral Coast**

The few ammonia results obtained for these sites were all high (5.60 uM, 7.71 uM and 9.05 uM N-NH3). The resulting DIN values therefore were all high, exceededing the guideline threshold of 1 uM (Bell, 1992). This is further evidence of the need to monitor ammonia along with phosphate and nitrate in village sites.

At Namatakula village, the high ammonium concentrations and the high DIN, with averages of 6.66 umol/L and 7.15 umol/L respectively are of concern and may be indicative of sewage as a major source of nutrients. Faecal coliform counts made on 6 January 2005 were TNTC (too numerous to count). This site also receives water discharged from the creek which drains the village where numerous livestock including pigs and chickens are kept. The high faecal coliform count was therefore not surprising.

At Namada village, the ammonium concentrations were variable and once again dominated the DIN concentrations: 90 % of DIN consisted of ammonium for the results in January and February 2005 (Table 4.21).

The situation with NO3 : PO4 and DIN : PO4 was no different from the control sites. Almost all ratios indicated nitrogen-limitation for primary biological productivity (ratio < 16), and the only exceptions were results of wet weather samplings when elevated nitrate and ammonia increased the ratio to > 16. It is suspected that this N-enrichment is quickly transferred to tissue nitrogen in macroalgae such as *Sargassum* (McCook *et al.*, 1997), and the situation reverts back to one of N-limitation.

#### 4.3.3.3 Nutrient temporal variation for resort sites

The three resort sites examined are Beachouse resort (BCH), Qalito (QLT) and the Hideaway resort (HDW). Tables 4.22, 4.23 and 4.24) present the average nutrient concentrations for these three sites, over time.

Table 4.22 Temporal Variation in Nutrient Concentrations for BCH Resort

| **Date of Sampling** | **Season** | **Weather** | **PO4 Av. uM** | **NO3 Av. uM** | **NH3 Av. uM** | **DIN Av. uM** | **NO3 : PO4** | **DIN : PO4** |
|---|---|---|---|---|---|---|---|---|
| 25 Mar. ‘04 | Hot/Wet | Dry | 0.07 | 0.03 | nd | | 0.43 | |
| 13 May ‘04 | Cool/Dry | Dry | 0.14 | 0.08 | nd | | 0.57 | |
| 25 May ‘04 | Cool/Dry | Dry | 0.12 | 0.40 | nd | | 3.33 | |
| 4 June ‘04 | Cool/Dry | Wet | 0.13 | 1.48 | nd | | 11.4 | |
| 11 Aug. ‘04 | Cool/Dry | Dry | 0.95 | 0.06 | nd | | 0.06 | |
| 12 Oct. ‘04 | Cool/Dry | Dry | 0.30 | 0.43 | nd | | 1.43 | |
| 27 Apr. ‘05 | Hot/Wet | Wet | 0.31 | 0.09 | 0.52 | 0.61 | 0.29 | 1.97 |
| 16 May ‘05 | Cool/Dry | Dry | 0.36 | 0.57 | 1.52 | 2.09 | 1.58 | 5.81 |
| Average | | | **0.30** | **0.39** | **1.02** | **1.35** | **2.39** | **3.89** |

#### 4.3.3.3.1 Discussion of temporal nutrient variation among resort sites

**Phosphate temporal variation for resort sites**

As found for the control and village sites, phosphate results for the resort sites were also variable. For the Beachouse and Hideaway sites, the highest phosphate

Table 4.23 Temporal Variation in Nutrient Concentrations for QLT Resort Site

| **Date of Sampling** | **Season** | **Weather** | **PO4 Av. uM** | **NO3 Av. uM** | **NH3 Av. uM** | **DIN Av. uM** | **NO3: PO4 DIN : PO4*** |
|---|---|---|---|---|---|---|---|
| 2 Aug. ‘03 | Cool/Dry | Dry | 1.00 | 0.06 | 10.32 | 10.38 | 0.06<br>10.38* |
| 10 Feb. ‘04 | Hot/Wet | Wet | 0.05 | 5.66 | Nd | _ | 113.2 |
| 25 Mar ‘04 | Hot/Wet | Dry | 0.10 | 0.06 | nd | _ | 0.6 |
| 13 May ‘04 | Cool/Dry | Dry | 0.13 | 0.25 | nd | _ | 1.92 |
| 4 Feb. ‘05 | Hot/Wet | Dry | 0.33 | 0.54 | 1.36 | 1.90 | 1.64<br>5.76* |
| 23 Mar ‘05 | Hot/Wet | V. Wet | 6.75 | 1.25 | 13.36 | 14.6 | 0.19<br>2.16* |
| 27 April ‘05 | Hot/Wet | V. Wet | 0.18 | 0.05 | 0.13 | 0.18 | 0.28<br>1.00* |
| 16 May ‘05 | Cool/Dry | Dry | 0.41 | 1.19 | 1.28 | 2.47 | 2.90<br>6.02* |
| **Average** | | | **1.12** | **1.13** | **4.03** | **4.79** | **15.10**<br>**5.06*** |

Table 4.24 Temporal Variation in Nutrient Concentrations for HDW Resort Site

| **Date of Sampling** | **Seasn** | **Weather** | **PO4 Av. uM** | **NO3 Av. uM** | **NH3 Av. uM** | **DIN Av. uM** | **NO3: PO4 DIN : PO4*** |
|---|---|---|---|---|---|---|---|
| 5 May ‘04 | Cool/Dry | Dry | 0.18 | 0.17 | nd | | 0.94 |
| 8 June ‘04 | Cool/Dry | Wet | 0.10 | 2.06 | nd | | 20.60 |
| 4 Aug. ‘04 | Cool/Dry | Dry | 0.32 | 0.50 | nd | | 1.56 |
| 22 Dec. ‘04 | Hot/Wet | Dry | 0.15 | 0.24 | 3.42 | 3.66 | 1.60<br>24.40* |
| 6 Jan. ‘05 | Hot/Wet | Dry | 1.01 | 0.72 | 8.33 | 9.05 | 0.71<br>8.96* |
| 27 April ‘05 | Hot/Wet | V. Wet | 0.29 | 2.74 | 3.72 | 6.46 | 13.70<br>26.30* |
| 16 May ‘05 | Cool/Dry | Dry | 0.13 | 0.56 | 1.59 | 2.15 | 4.31<br>16.50* |
| **Average** | | | **0.30** | **1.00** | **3.97** | **4.96** | **3.34**<br>**19.04*** |

concentrations were recorded on fine, dry days (0.95 *u*M and 1.01 *u*M P-PO4 respectively). On the other hand, at Qalito, the highest phosphate concentration was recorded on a wet day (6.75 uM P-PO4). What is of concern was the fact that most of the results were > 0.1 uM P-PO4 (Bell, 1992).

At the Beachouse site, phosphate concentrations ranged from 0.07 to 0.95 *u* mol P-PO4/L and almost all were > 0.1 *u* mol P-PO4/L. Beachouse is a relatively small resort with proper waste management practices. The average PO4 concentration of 0.30 *u* mol P-PO4/L is borderline as far as coral reef health is concerned (Crossland, 1983; Bell and Greenfield, 1987). There appears to be no link between phosphate concentration and either season or weather.

For QLT, phosphate concentrations were variable but all results except one (0.05 *u* mol P-PO4/L) were > 0.1 *u* mol P-PO4/L. The average concentration of 1.12 *u* mol P-PO4/L was the highest obtained for the sites discussed in this Section. This site gets affected by wastewater being discharged from the Warwick Resort, along a concrete pipeline that passes less than 100 m offshore.

The Hideaway resort is a large resort with proper wastewater treatment practices in place. The phosphate concentration range was from 0.1 to 1.01 *u* mol P-PO4/L. All results were > 0.1 *u* mol P-PO4/L and the average of 0.30 was above the threshold of 0.1 uM (Bell, 1992) but within levels generally acceptable for good coral reef health (Crossland, 1983; Bell and Greenfield, 1987). There is no clear pattern of variation with either season or weather. However, if coral reefs are to be conserved, measures need to be put in place to ensure phosphate concentrations do not increase above those at present.

**Nitrate temporal variation for resort sites along the Coral Coast**

Again, as was found for the control and village sites, the highest nitrate concentrations were recorded during wet weather, for all three resort sites. The pattern of nitrate variation was more consistent.

In general, the nitrate concentrations for the Beachouse resort site were relatively low, ranging from 0.03 to 1.48 *u* mol N-NO3/L, with a mean of 0.39 *u*mol/L. Season did not seem to have any influence on the results, although, all dry weather nitrate concentrations were < 1 *u* mol N-NO3/L. The only high value was that recorded during a period of heavy rainfall in June 2004 (1.48 *u* mol N-NO3/L). The low nitrate concentration recorded for 27 April 2005 was unexpected, and this may be due to delay in the laboratory analysis while waiting for a new FIA cadmium column to be delivered from Australia.

The range of nitrate concentrations for QLT was 0.05 to 5.66 *u* mol N-NO3/L. While there was no clear link between nitrate concentrations and season, there was definitely a positive link between weather and nitrate concentrations, with high rainfall leading to nitrate enrichment of coastal waters. The low nitrate concentration for 27 April 2005 (a wet day) may be due to delayed analysis, as discussed above.

At the Hideaway resort site, there was no clear link between nitrate concentration and season, but as with the other cases, high rainfall contributed to high nitrate concentrations. This site lacks any large rivers and so the maximum nitrate concentration of 2.74 *u* mol N-NO3/L was lower than for most other sites.

**Ammonia temporal variation for resort sites along the Coral Coast**

The highest ammonia concentrations were recorded on wet days as would be expected. The high levels of ammonia recorded for QLT (13.36 uM), and Hideaway resort sites (8.33 uM), are of concern. The much smaller Beachouse resort site recorded much lower ammonia levels.

At Qalito, ammonia results were also variable and the highest results were recorded during heavy rainfall (13.36 *u* mol $N\text{-}NH_3/L$). The significance of ammonia as a form in nitrogen in inshore coastal waters is very clear in all of the results for the Coral Coast. For QLT, ammonia makes up > 80 % of DIN in all of the results. At the Hideaway resort site, ammonia concentrations ranged from 1.59 to 8.33 *u* mol N-NH3/L, and contributed at least 60 – 90% of the DIN in this site.

The NO3 : PO4 and DIN : PO4 ratios for the resort sites were no different from the control and village sites, i.e., most of the ratios were less than the Redfield-Richards ratio of 16, indicating that nitrogen was likely to limit primary biological productivity for algal species. As mentioned above, this situation implied that there was an excess of phosphate in the water column, and any elevation of nitrogen would boost primary production. It had been suggested that carbonate-rich reefs had high DIN : PO4 ratios (above 16) and so were phosphate-limited, because the phosphate was strongly-adsorbed onto the carbonate in the reef structure and therefore not available in the water column for biological production (Lapointe, 1997). In the case of the Coral Coast reefs which are definitely carbonate-type reefs, it would appear that the nitrogen-limiting situation has been the result of nitrogen uptake by the array of benthic algae on the reef flats.

#### 4.3.3.4 Summary of Results for Temporal Nutrient Variation

An overview of the main features of the nutrient results is now presented for comparison with previous work. The three (or two in some cases) values in each cell represent the averages for the three (or two) sites, whether control, village or resort.

The summary presented in Table 4.25 showed that sites isolated from human impacts generally have lower concentrations of phosphate. However, the average PO4 concentrations at these control sites were already above what would normally be considered suitable for 'healthy' reefs (0.1 *u*M). Where the phosphorus concentrations were elevated in dry weather and decreased in wet weather, the sources of the variation can reasonably be linked to point sources such as sewage discharges (Jarvie *et al*., 2006)

The low concentrations recorded for the Great Astrolabe Reef Lagoon (GAR) correlated well with the absence or low levels of human impacts during those times in these isolated islands (Morrison *et al.*, 1992).

While individual results showed a link between rainfall and nitrate concentrations, the influence of rivers and creeks was a major factor in the extent of nitrate

Table 4.25 Summary of Nutrient Concentrations among control, village and resort sites, and comparison with other work*

| Nutrient | Control | Village | Resort | Coral Coast * | GAR Lagoon** |
|---|---|---|---|---|---|
| PO4 uM (Av. For 3 sites) | 0.25<br>0.21<br>0.27 | 0.46<br>0.86<br>0.58 | 0.30<br>1.12<br>0.30 | 0.21 | 0.07 |
| NOx uM<br><br>(Av. For 3 sites) | 3.50***<br>0.54<br>1.16 | 1.23<br>0.96<br>4.23 | 0.39<br>1.13<br>1.00 | 1.69 | 0.81 (adding $NO_3$ and $NO_2$) |
| NH3 uM | 1.12<br>2.53 | 6.66<br>5.16 | 4.03<br>3.97 | | 0.12 |
| DIN uM | 3.13 | 7.15<br>5.89 | 4.79<br>4.96 | | |
| DIN : P | 2.09<br>24.8 | 8.36<br>10.2 | 3.73<br>16.6 | | 13.5 |

* Coral Coast (Mosley and Aalbersberg, 2003)
** Great Astrolabe Reef Lagoon (Morrison *et al.*, 1992).
*** KMV Crk and KMV Village effects (see Table 4.7).

enrichment, even for control sites, as seen for NAQ CON site (3.50 *u*M). With increasing clearing of vegetation in catchment and coastal areas, the levels of nitrate can be expected to increase. However, the low nitrate concentrations in the water column can be misleading, (even to the extent that the waters are classified as being potentially nitrogen-limited) as this nutrient is rapidly taken up by primary producers. It is important that any assessment of nitrate status should take into account the presence of primary producer organisms, especially the macroalgae.

The relatively high concentrations of ammonia at all sites show the significance of this nutrient in the inshore, coastal waters of the Coral Coast. Comparison of the Coral Coast sites with the relatively pristine Great Astrolabe Reef (GAR) shows there is a clear pattern, in that control sites have less $NH_3$ than resorts which have less $NH_3$ than the villages, but all have higher ammonia than the GAR. i.e., GAR<<C<R<V.

The inshore waters of the Coral Coast can be described as being potentially nitrogen-limited, because the DIN : PO4 ratios were generally below the ideal Redfield-Richards ratio of 16.

### 4.3.4 Spatial variation in nutrient concentrations and water quality from creek to coast to off-reef waters.

#### 4.3.4.1 Introduction and methods

The effects of catchment activities on the downstream water quality and therefore biological communities has been investigated and documented in the more developed countries (Brodie, 2000). For this research, one of the objectives was to assess how land based sources of pollution affected the water quality, not only in the coastal waters, but also further off the coasts over the fringing reefs. The role of nutrients in coral reef health is well-recognized (Koop *et* al., 2001), and because nutrients are subjected to a multitude of factors such as dilution, dispersion, assimilation by marine organisms, the status of nutrients may be very different in the inshore waters compared to the waters over the reefs.

To address this objective, sampling of off-reef waters was carried out from a boat hired from one of the resorts, on four occasions in December 2004, and on January 6th and 7$^{th}$ 2005. Sampling of inshore waters was completed on the same day as the off-reef waters, except for the January 6$^{th}$ and 7$^{th}$ sampling when logistical difficulties made it impossible to sample on the same day.

#### 4.3.4.2 Results and Discussion

The results of the water quality and nutrient concentration analyses are tabulated separately by dates (see Tables 4.26, 4.27 and 4.28)

##### 4.3.4.2.1 Results and discussion for inshore vs off-reef nutrient and water quality – Locality 1 (Namaqumaqua), 14 December 2004.

December 14 2004 was a wet and rainy day, and this was reflected in the nitrate concentrations. The highest and second highest concentrations of nitrate (5.63 uM and 5.09 uM) were recorded for sites closest to the village and the resort (see Table 4.26). All the other inshore nitrate concentrations were well below these concentrations. The village site also recorded the highest phosphate concentration (1.30 uM).

Comparing the inshore nutrient concentrations with the corresponding off-reef data showed some interesting results. While there was variation in the nitrate concentrations, there appeared to be consistent increases for the phosphate concentrations from inshore to off-reef waters. The highest phosphate concentration for all of the sites was recorded at CVB4 (3.03 uM) which was also the most-eastern site, and closest to the Vitawatawa Pass (see Locality 1 Map, Appendix A1). This site also recorded the second highest nitrate concentration for the off-reef sites (see Table 4.26). On moving westward away from the Pass, there appeared to be decreases in both nitrate and phosphate concentrations. This result may be indicating the significance of catchment activities, the effects of which were conveyed to the coastal waters by large rivers and dispersed via reef passes such as the Vitawatawa Pass in this case.

Also important was the fact that all phosphate results for this date 14 December 2004, were above 0.1 uM PO4-P, the threshold level for healthy coral reefs. All of the NO3 : PO4 ratios were below 16, indicating a nitrogen-limited situation for biological production, but in the absence of ammonia data, nitrogen limitation of biological productivity cannot be confirmed.

Table 4.26 presents nutrient and water quality results from the inshore waters and waters just off the edge of the fringing reefs at Locality 1 sites, on 14 December 2004.

Table 4.26 Comparison of inshore and off-reef water quality and nutrient concentrations for Locality 1 (Namaqumaqua) sites, on 14 December 2004.

| **Site/ Station** | **Inshore PO4 Av.uM** | **Inshore NO3 Av.uM** | **Inshore FC c/100mL** | **Inshore NO3:PO4** | **Off-RF PO4 Av.uM** | **Off-RF NO3 Av.uM** | **Off-RF FC c/100mL** | **Off-RF NO3:PO4** |
|---|---|---|---|---|---|---|---|---|
| NMQ4 (V) | 1.30 | 5.63 | 90 | 4.33 | 0.54 | 0.99 | <1 | 1.83 |
| CVB1 | 0.53 | 1.08 | <1 | 2.04 | 3.03 (CVB4) | 2.05 | 7 | 0.68 |
| CVB2 | 0.40 | 1.20 | <1 | 3.00 | 0.63 (CVB5) | 1.14 | <1 | 1.81 |
| NMQ1 | 0.48 | 0.73 | 37 | 1.52 | 0.97 (NMQ5) | 1.57 | <1 | 1.62 |
| NMQ2 | 0.45 | 0.58 | 14 | 1.29 | 0.80 (NMQ6) | 2.42 | <1 | 3.03 |
| CRS1 | 0.59 | 5.09 | 30 | 8.63 | 0.64 (CRS3) | 2.02 | <1 | 3.16 |
| CRS2 | 0.69 | 1.06 | 13 | 1.54 | 0.94 (CRS4) | 0.71 | <1 | 0.76 |
| *Range* | 0.40 – 1.30 | 0.58 – 5.63 | <1 - 90 | 1.29 – 8.63 | 0.54 – 3.03 | 0.71 – 2.42 | <1 - 7 | 0.68 – 3.16 |
| *Average* | 0.63 | 2.20 | | 3.19 | 2.22 | 1.56 | | 1.84 |

**4.3.4.2.1.1 Statistical analysis of nutrient data - Namaqumaqua (Locality 1), 14 December 2004**

*Is there any significant difference in nutrient concentrations between inshore waters and waters off the fringing reefs?*

All of the inshore data were combined as group 1 and the off-reef results were combined into group 2. Since there were two groups (inshore versus off-reef waters), the test of difference used was the non-parametric Mann-Whitney Test because the Test of Homogeneity of Variances (an assumption of parametric tests such as the students t test) gave a significant p value of 0.043. The SPSS 14.0 statistical software programme was used for the statistical analysis.

For phosphate concentrations, the Mann-Whitney Test of difference did not give a significant result (p value of 0.804, 2-tailed), implying that there was no significant difference in the phosphate concentrations between the inshore waters and waters off the fringing reefs. This result may be indicating that on wet and rainy days, phosphate derived from land sources of pollution was reaching the reefs. The influence of large rivers as significant sources of phosphate direct to the reefs cannot be ignored, as discussed above.

The Mann-Whitney Test on nitrate also produced a non-significant result (p value of 0.426) indicating there was no significant difference between the nitrate concentrations for inshore and off-reef waters.

It may be necessary to sample further off-shore in order to assess more accurately the influence of land-based sources of nutrients on the reefs. Nevertheless, the results from the single sampling event for this Locality showed that the reefs were already exposed to nutrient concentrations much higher than the levels suggested for healthy coral reefs (Bell, 1992).

#### 4.3.4.2.2 Results and discussion for inshore vs off-reef nutrient and water quality – Localities 4 and 5, December 2004.

Table 4.27 shows the results of nutrient and water quality analyses, for sites in Locality 4 (Votua) and Locality 5 (Hideaway-Tagaqe).

For Locality 4 sites sampled on 20 December 2004, there appeared to be no major difference in nutrient concentrations between the inshore and off-reef waters. All of the DIN concentrations exceeded the 1 uM threshold for healthy coral reefs. The average phosphate concentrations were either close to or exceeded 0.1 uM P-$PO_4$. One point of interest though, was the high phosphate reading for site MKD2, at the reef passage (0.63 uM), and this may be indicating freshwater or land-based origin of phosphate in this area. There are a number of potential sources of phosphate on land including the Votua Housing Commission, the Votua village and creek and the Vilisite restaurant (VIL1) to the east. In terms of water flow and movement in this area, it appeared that the reef passage (MKD2) influenced the dispersal of nutrients from land sources, for example, site VOT2 to the west of the Votua creek (that drains the Votua Housing Commission) recorded lower phosphate, ammonia and nitrate

Table 4.27 Comparison of inshore and off-reef water quality and nutrient concentrations for sites in Localities 4 and 5. Locality 4 sites were sampled on 20 December 2004. Locality 5 sites were sampled on 22 December 2004.

| Site/Date | Inshore PO4 Av.uM | Inshore NH3 Av.uM | Inshore NO3 Av.uM | Inshore DIN Av.uM | Off-RF PO4 Av.uM | Off-RF NH3 Av.uM | Off-RF NO3 Av.uM | Off-RF DIN Av.uM |
|---|---|---|---|---|---|---|---|---|
| MKD1 20 Dec. | 0.11 | 2.50 | 0.26 | 2.76 | 0.63 (MKD2) | 3.29 | 0.83 | 4.12 |
| VOT1 20 Dec | 0.15 | 2.41 | 0.31 | 2.72 | 0.10 | 2.52 | 0.24 | 2.76 |
| VOT2 20 Dec | 0.13 | 2.23 | 0.13 | 2.36 | 0.13 | 2.22 | 0.29 | 2.51 |
| VIL1 20 Dec | 0.27 | 2.63 | 0.31 | 2.94 | 0.22 | 2.24 | 0.38 | 2.62 |
| Range | 0.11 – 0.27 | 2.23 – 2.63 | 0.13 – 0.31 | 2.36 – 2.94 | 0.10 – 0.63 | 2.22 – 3.29 | 0.24 – 0.83 | 2.51 – 4.12 |
| Average | 0.17 | 2.44 | 0.25 | 2.70 | 0.27 | 2.57 | 0.44 | 3.00 |
| HDW1 22 Dec | 0.15 | 3.42 | 0.24 | 3.66 | 0.13 | 4.85 | 0.21 | 5.06 |
| TGQ1 22 Dec | 0.04 | 3.58 | 0.16 | 3.74 | 0.13 | 4.18 | 0.14 | 4.32 |
| TGQ2 22 Dec | 0.19 | 3.67 | 0.21 | 3.88 | 0.16 | 4.04 | 0.31 | 4.35 |
| TGQ3 22 Dec | 0.09 | 3.84 | 0.16 | 4.00 | 0.14 | 4.02 | 0.30 | 4.32 |
| HDW3 22 Dec | 0.11 | 4.26 | 0.24 | 4.5 | 0.16 | 4.03 | 0.33 | 4.36 |
| BCN Pt. 22 Dec | 0.12 | 3.80 | 0.19 | 3.99 | 0.13 | 4.85 | 0.21 | 5.06 |
| Range | 0.04 – 0.19 | 3.42 – 4.26 | 0.16 – 0.24 | 3.66 – 4.50 | 0.13 – 0.16 | 4.02 – 4.85 | 0.21 – 0.33 | 4.32 – 5.06 |
| Average | 0.12 | 3.76 | 0.20 | 3.96 | 0.14 | 4.33 | 0.25 | 4.58 |

concentrations compared to VOT1, located to the east and closer to the reef passage (see Locality 4 Map). This pattern of nutrient variation implied that the Votua creek and pollutants derived from the Housing Commission were carried towards the reef passage in the east and hence affected the foreshore and water quality in front of the Votua village.

#### 4.3.4.2.2.1 Statistical analysis of nutrient data for inshore and off-reef waters at Votua

*Is there any significant difference in nutrient concentrations between inshore waters and waters off the fringing reefs at Votua?*

All the inshore data were grouped into group 1 and those for off-reef waters were grouped into group 2. The Levene's Test for Equality of Variance for the three nutrients (phosphate, ammonia and nitrate) showed non-significant results ($p = 0.589$; $p= 0.577$ and $p = 0.383$ respectively), indicating that the data satisfied the assumption for equality of variance for parametric tests. The Students T test of difference was then used to test if there were any significant difference between inshore and off-reef waters with respect to nutrient concentrations. The t-test for equality of means for the two groups (inshore versus off-shore) produced non-significant p values for each of the three nutrients (p values > 0.05). At the 0.05 level of significance, there was no significant difference in phosphate, ammonia and nitrate concentrations between inshore waters and off-reef waters at sites in Locality 4 on 20 December 2004. However, for nitrate, the significance value was 0.079 and this borderline case may warrant more samples being analysed before final conclusions can be reached.

For the sites in Locality 5, sampled on 22 December 2004, again there appeared to be no major difference between the inshore waters and off-reef waters with respect to nutrient concentrations. The sampling of inshore and off-reef waters was carried out during high tide to enable unobstructed movement of the boat over the reefs. The relatively homogeneous pattern of nutrient distribution may be due to the high tide during the time of sampling. As in previous discussion, the high DIN values, all of which exceeded 1 uM should be of concern. Most phosphate concentrations also exceeded 0.1 uM P-PO4. No statistical analysis was carried out on the data, as the patterns of variation were very similar to the previous datasets which yielded no significant difference between inshore and off-reef waters with respect to nutrient concentrations.

#### 4.3.4.2.3 Results of nutrient and water quality tests for inshore waters and off-reef waters at sites in Localities 4 - 8, December 2004, and January 2005

Table 4.28 presents the results for nutrients and faecal coliform tests on inshore waters and waters off the fringing reefs, at a number of sites from Locality 4 through to Locality 8. The sites in Locality 8 were sampled on December 31, 2004. The inshore sites for Localities 4 – 7 were sampled on January 6, and the corresponding off-reef sites were sampled on January 7, 2005. The weather on these days was dry.

For the sites sampled on 31 December 2004 (of Locality 8), again there appeared to be no major difference in the nutrient concentrations between inshore and off-reef waters. Of significance though, was the fact that all phosphate concentrations and DIN concentrations exceeded the threshold levels of 0.1 uM and 1 uM respectively, both inshore and off-shore. This area has the highest density of commercial operations in the study region, including restaurants, motels, hotels, a 5-star resort and semi-urban residential population. The exceptionally high phosphate concentration of 1.82 uM at Malevu village (MLV3) indicates that this site may be a nutrient hot spot. The phosphate concentration decreased to 0.32 uM at the corresponding off-reef site, indicating the importance of villages as sources of phosphate in waters (and coral reefs) along the Coral Coast.

The results from sampling on 6$^{th}$ and 7$^{th}$ January 2005 again showed that the Coral Coast coral reefs were already exposed to nutrient concentrations well above the threshold suggested for healthy coral reefs (Bell, 1992). All of the phosphate concentrations exceeded 0.1 uM (ranged from about 0.3 to >3 uM for inshore waters), and the ammonia concentrations alone ranged from about 4 uM to about 12 uM, far exceeding the guideline for DIN of 1 uM (Bell, 1992). The two hot spots with exceptionally high phosphate concentrations were sites near the Tambua Sands resort (TBS1) and Namada village (NMD3), recording 1.62 uM and 3.56 uM P-PO4 respectively. Their corresponding off-shore sites recorded 0.39 uM and 0.38 uM P-PO4 respectively. Such patterns of variation indicated the significance of villages and resorts as sources of phosphate to the inshore waters and the related fringing reefs. TBS1 and NMD3 also recorded the highest and second highest concentrations of ammonia (11.83 and 9.05 uM). These decreased to 4.66 and 4.26 uM respectively.

The Mann-Whitney U test was used (since Levene's Test of Homogeneity of Variances gave a significant p value of 0.002), to test the null hypothesis that there was no significant difference between inshore and offshore phosphate levels on dry days as these. The test gave a non-significant p value of 0.579, thus it can be concluded that generally on fine dry days, there is no significant difference in PO4 levels, inshore and offshore, except for nutrient hot spots. Appendix C4 shows the results from the statistical tests.

Table 4.28 Comparison of inshore and off-reef water quality and nutrient concentrations for sites sampled on 31st December 2004 (Locality 8), and 6th and 7th January 2005 (several sites across Localities 4 – 7). Ammonia was analysed for in all the samples but no faecal coliform tests were done for the 31 December samples.

| **Site/Date** | **Inshore PO4 Av.uM** | **Inshore NH3 Av.uM** | **Inshore NO3 Av.uM** | **Inshore DIN Av.uM** | **Insh FC c/100mL** | **Off-RF PO4 Av.uM** | **Off-RF NH3 Av.uM** | **Off-RF NO3 Av.uM** | **Off-RF DIN Av.uM** | **Off-RF FC c/100mL** |
|---|---|---|---|---|---|---|---|---|---|---|
| TBK1 31 Dec | 0.44 | 4.78 | 0.57 | 5.35 | | 0.75 (TBK2) | 4.55 | 0.51 | 5.06 | |
| MLV3 31 Dec | 1.82 | 3.28 | 0.38 | 3.66 | | 0.32 (MLV4) | 4.75 | 0.47 | 5.22 | |
| OTR1 31 Dec | 0.32 | 2.45 | 0.38 | 2.83 | | 0.34 (OTR2) | 2.74 | 0.99 | 3.73 | |
| CRW1 31 Dec | 0.37 | 4.61 | 0.53 | 5.14 | | 0.48 (CRW2) | 4.03 | 1.10 | 5.13 | |
| Range | 0.32 – 1.82 | 2.45 – 4.78 | 0.38 – 0.57 | 2.83 – 5.35 | | 0.32 – 0.75 | 2.74 - 4.75 | 0.47 - 1.10 | 3.73– 5.22 | |
| **Average** | **0.74** | **3.78** | **0.47** | **4.25** | | **0.47** | **4.02** | **0.77** | **4.79** | |
| WRC1 6 Jan | 0.35 | 5.51 | 1.55 | 7.06 | 3300 | 0.38 | 4.37 | 0.82 | 5.19 | <1 |
| MKD1 6 Jan | 0.30 | 5.04 | 0.62 | 5.66 | | 0.31 (MKD2- 7 Jan) | 3.90 | 0.5 | 4.40 | <1 |
| VLS1 6 Jan | 0.27 | 7.40 | 0.91 | 8.31 | | 0.35 (VLS3 – 7 Jan) | 5.74 | 0.53 | 6.27 | |
| NMD3 6 Jan | 3.56 | 9.05 | 1.16 | 10.21 | 2 | 0.38 (NMD4- 7 Jan) | 4.26 | 1.17 | 5.43 | 10 |
| TBS1 6 Jan | 1.62 | 11.83 | 1.08 | 12.91 | 2200 | 0.39 (TBS3 – 7 Jan) | 4.66 | 1.11 | 5.77 | ND |
| *VTK1* 6 Jan | 0.50 | 10.81 | 0.66 | 11.47 | 18 | 0.35 (VTK2 – 7 Jan) | 4.86 | 1.13 | 5.99 | ND |
| **Average** | **1.1** | **8.3** | **1.0** | **9.3** | | **0.36** | **4.6** | **0.9** | **5.5** | |

## 4.4 GENERAL SUMMARY

The nutrient concentrations in the water column were highly variable. For tropical regions where nutrients are usually delivered in pulses to the marine environment (McCook, 1997), water column nutrient can be expected to be highly variable, even within very short distances of a few meters. Despite the variability, there were clear patterns of variation that spanned the eight Localities from Namaqumaqua in Serua, to Korotogo in Nadroga.

In general, phosphate concentrations in waters of the Coral Coast were above the threshold concentration of 0.1 uM P-PO4 (Bell, 1992), recommended for the health of coral reefs. Given this situation, the current status of the fringing reefs, and the ‘phase shift’ being witnessed or described by local people is not surprising. The behaviour of phosphate was found to be unpredictable. In some cases, phosphate concentrations increased with increased flow in the creeks, rivers and in coastal areas nearby, following heavy rain, and in other cases, phosphate concentrations actually decreased during heavy rain. It has been suggested that when phosphate concentrations decreased with increased flow, it may be indicative of point sources of phosphate such as sewage, as opposed to diffuse sources such as agricultural sources (Jarvie *et al.*, 2006).

Nitrate concentrations were generally low, even below the suggested threshold of 1 uM N-NO3 (Bell, 1992). However, ammonia dominated the DIN concentrations at all sites, and ammonia was relatively high, mostly above the threshold of 1 uM (Bell, 1992). The behaviour of nitrate and ammonia was more predictable: increasing with rainfall. The creeks and rivers were found to the most significant sources of nutrients, particularly nitrate and ammonia, during wet weather and flood events. Statistical tests for Valase (control), Hideaway (resort) and Namada (village) all showed significant differences ($p < 0.05$) in the nitrate concentrations between dry weather and wet weather data. There was no significant difference in the phosphate results between dry and wet weather for Namada and Hideaway ($p > 0.05$), but there was a significant result for Valase control site ($p < 0.05$). Nitrate is more mobile than phosphate, thus the differential effects of rainfall on these nutrients.

In general, the control sites recorded lower nutrient concentrations than the impacted sites. Wherever control sites showed elevated nutrients, the causes were usually linked to updrift impacted sites or creeks or rivers. There appeared to be no major difference in nutrient content between inshore waters and waters just off the fringing reefs. Statistical tests confirmed this observation, i.e., there was no significant dilution or dispersion of nutrients from inshore to off-reef waters. This observation should be cause for concern because it indicated that the reefs were being affected by land-based nutrient sources.

The results from nutrient studies showed that the reefs were under threat from nutrient sources on the shoreline, as well as those in the catchment areas, through nutrient loading in the creeks and rivers. Any efforts to reduce nutrients in the inshore waters of the Coral Coast must include addressing the catchment activities. The fact that the control sites recorded lower nutrient results than the village and resort sites, indicated that anthropogenic factors needed to be identified and mitigative measures implemented to reduce nutrients and restore the health of the coral reefs.

# CHAPTER 5 – VARIABILITY IN CORAL REEF BENTHIC COMMUNITIES IN RELATION TO ANTROPOGENIC IMPACTS ALONG THE CORAL COAST OF SOUTHERN VITI LEVU, FIJI ISLANDS

This chapter presents the results of surveys conducted on the inner reef flats of the fringing reefs, along the Coral Coast of South-western Viti Levu in Fiji. The objective of this research was to assess how the different levels of human impacts on the land and coastal areas, affect the marine environment and the resources therein. Following an introduction which includes a brief literature review of the subject, the methods used for the surveys are described. The sites are the same as those sampled for water column nutrient concentrations (Section 4.2.1). The same sites that represented 'control' or unimpacted sites, in Chapter 4 (Water Quality and Nutrient Assessment) were surveyed and compared to sites close to villages and resorts. The results of the benthic surveys are then summarized and discussed.

## 5.1 INTRODUCTION

The coral reefs of the world are being threatened by anthropogenic impacts (Hutchings, 2001), such as increasing human populations, increasing agricultural activity and increasing coastal development (Hodgson, 1999; Wilkinson, 2000; Knowlton, 2001; GESAMP 2001). Different coral reefs have been degraded to varying degrees. In some cases, changes in the environment have led to certain coral species being favoured over others (e.g., Done, 1992; Hughes 1994a). However, the loss of corals, especially scleractinian corals, and their replacement with fleshy macroalgae appears to be the most common evidence of coral reef degradation in many locations (McCook, 1999; McCook, 2001; McCook *et al*., 2001). When one describes a coral reef as being degraded, it often means that a shift from coral dominance to algal dominance has been observed, the transition being referred to as the 'phase shift' (McCook, 1999). Coral reefs are affected by both natural and anthropogenic effects.  Effective management of coral reefs requires an understanding of the difference between these two categories or classes of effects (Grigg, 1995). While it is not possible to control or manage natural stress factors, it is often possible to manage and even mitigate against the effects of anthropogenic stress factors. Examples of this management can be seen in the case of the reefs in Kaneohe Bay and Mamala Bay in Hawaii (Smith *et al*., 1981; Grigg, 1995). Grigg

(1995) in his study of the 25 year case history of Mamala Bay off Honolulu, Hawaii, found that the effects of sewage being pumped out into the Bay were serious but localized, i.e., reef corals were adversely affected while fleshy macroalgae were favoured. However, upgrading the sewage treatment to advanced primary level, and extending the outfall to deeper waters in 1977, reversed this impact. This is an example of how anthropogenic stress factors can be mitigated. On the other hand, the two major hurricanes which hit the Mamala Bay in 1982 and 1992 caused large scale physical damage over a wide area of the coral reefs (Grigg, 1995).

Coral reef systems are unique ecosystems characterised by relatively high species biodiversity (Dubinsky, 1990). The high species diversity associated with ‘healthy’ coral reefs has challenged many researchers, because coral reefs thrive in oligotrophic waters (Dubinsky 1990; Miller, 1998). The phase shift occurring in coral reefs around the world has generated concerted research because the uniqueness and beauty of these precious ecosystems are being compromised, and human related factors have been blamed for the undesirable changes.

Macroalgae on coral reefs have been the focus of many recent scientific investigations because of their increasing prominence as a result of ‘phase shifts’. Not only are they seen to be replacing scleractinian corals, they are also undergoing species replacement, in that the turfing and calcified algae more commonly associated with healthy reefs are being replaced by fleshy, large, frondose macroalgae (e.g., Done, 1992; Hughes. 1994a; Adey, 1998). In trying to establish causes of the changes on coral reefs, most studies have focussed on water quality, in particular the nutrients nitrogen and phosphorus as the bottom-up controls on the abundance and distribution of macroalgae (Lapointe, 1997; Schaffelke and Klumpp, 1998). However, while nutrients play a very important role in the distribution and abundance of macroalgae, they are only one of the several factors that interact in the coral reef environment, to determine macroalgae abundance (see Section 2.4). The significance of nutrients (bottom-up) and herbivory (top-down) as the major controlling factors for coral reef communities has been established in a number of studies (Lapointe, 1997; Thacker, *et al*., 2001; Smith *et al*., 2001; Littler *et al*., 2006). Phase shift is exacerbated when nutrient enrichment is increased, while harvesting of herbivorous species continues unabated (Pedersen *et al*., 2005). The widespread occurrence of 'phase shift' can be seen in a summary presented in Table 5.1, although most of the invading algae are green macroalgae, in the case of temperate waters (Valiela *et al*., 1997).

Table 5.1 Selected examples of studies documenting 'phase shift' on reefs (from Valiela *et al*., 1997).

Please see print copy for Table 5.1

Research carried out in many locations confirmed the worldwide problem of reef degradation (Hodgson, 1999). In Australia, at the GBR, increased nutrients in the water column have led to increased macroalgae cover (Fabricius and De'ath, 2004). In the Florida coral reefs of the USA, higher nutrient levels and high phytoplankton production (measured through concentration of chlorophyll-a) were found closest to shore and decreasing as one moved offshore (Szmant and Forrester, 1996).

The few observational studies conducted in Fiji have also showed evidence of reef degradation possibly due to anthropogenic factors (Lovell and Tamata, 1996; Mosley and Aalbersberg, 2003). Lovell and Tamata (1996) found that the reefs downdrift of an outfall from the tuna cannery in Levuka, were proliferated with *Sargassum* sp. and the observations indicated the importance of currents and hydrological factors in the dispersal of *Sargassum* sp., and similar observations have been found elsewhere (Lapointe, 1995).

McCook (1997; 1999) suggested that invasion by *Sargassum* sp. will depend on the presence of an established adult *Sargassum* population in the area. The success of *Sargassum* sp. on the inshore reefs of the GBR has been linked to nutrient pulses to which these reefs are exposed to, especially in the summer, storm and wet weather events (Schaffelke and Klumpp, 1998). A number of studies have focused on *Sargassum* sp. on the GBR, to determine the nutrient levels that enhance this species (Schaffelke and Klumpp, 1998; McCook, 1999), and results from the studies have been varied. However, Schaffelke and Klumpp (1998) found that the growth of *Sargassum baccularia* almost doubled between the narrow window from 3 uM ammonium plus 0.3 uM phosphate to 5uM ammonium plus 0.5 uM phosphate (see Figure 5.1).

The effects of nutrients on corals has also been extensively studied (see Section 2.5.2). In the well known ENCORE studies, it was found that nutrient enrichment affected the corals at the organism level, i.e., the reproductive capacity of corals was reduced (Koop *et al*., 2001). The adverse effects of phosphate on coral calcification processes has also been established (e.g., Hawker and Connell, 1989; Koop *et al*., 2001).

**Phase shift on the fringing reefs of the Coral Coast of southern Viti Levu**

The fringing reefs of the Coral Coast have also been affected by anthropogenic impacts, and according to anecdotal information, the live corals that were once the pride of the Coral Coast (thus the name ‘Coral Coast’) have disappeared over time

Please see print copy for Figure 5.1

<u>Figure 5.1</u> *Sargassum baccularia* growth rates in varying nutrient concentrations (from Schaffelke and Klumpp, 1998a).

(pers. comm. /Tevita Love of Qalito, December 2003). In an earlier report on the fringing reefs near the Warwick resort by Raj *et al*. (1981), (Komave Reef, LOC 3 map in Appendix A3), there was no mention of dominance by macroalgae such as *Sargassum* sp., but instead, the report listed diverse groups of corals occupying the reef flats and the micro-atoll zone (Zone 4 in Table 5.2) on the fringing reefs near the Warwick resort. Also in the report by Raj *et al.* (1981), there was mention of a deepened swimming hole in front of the Warwick resort, and its connection to Korolevu Bay (west of Qalito, see map, Appendix A3), via an excavated boating channel. It appeared that the wastewater pipe that now runs along the excavated channel had not been put in place at that time. Raj *et al.*, (1981) made an interesting observation at that time which may explain the success of *Sargassum* sp. at Qalito, one of the resort sites sampled in this research. Qalito (QLT 1 in Appendix A3) is immediately west of, and downdrift of the Warwick resort (WRC1 in Appendix A3).

The artificially deepened swimming lagoon had a heavy sediment loading, poor visibility and was dominated by two macroalgae species, *Sargassum* and *Padina* sp, as well as the holothurian *Synapta maculata* (Raj *et al*., 1981). The survey conducted at Qalito in May 2004 for the current study, found that the two dominant species on the inner reef flats were *Sargassum* and the holothurian *Synapta maculata*. It has been suggested that the invasion of an area by *Sargassum* sp. requires the presence of an adult *Sargassum* population nearby (McCook, 1997, 1999). The proliferation by *Sargassum* of the reef flat at Qalito, may be linked to its dominance as early as 1981, in the artificially deepened lagoon at the Warwick resort. The survey site is shown in the map of Locality 3, Appendix A3.

As has been documented for many coral reefs around the world, the fleshy macroalgae have become more prominent while the live, scleractinian corals have disappeared on the fringing reefs of the Coral Coast. According to the local villagers interviewed, the brown macroalgae *Sargassum baccularia*, has been the more common of the algae that were taking over from the live corals (Community interviews by this author, Namada Village, 3 November, 2005). There have been no long-term monitoring studies of the fringing reefs of the Coral Coast to confirm what the local villagers have claimed. This present study was an attempt to investigate the occurrence of a 'phase shift' on the reefs at Coral Coast, at least on the inner reef flats. While it is not possible to ascertain what the 'before impact' situation was like on these reefs, the best estimate of such conditions would be those on reefs still isolated or removed from human impacts (Green, 1979). Such areas have been chosen as the 'control' sites in this study. These are the same as the water sampling sites (see Table 4.1).

The fringing reefs of the Coral Coast have been subjected to a number of different stress factors in varying degrees. Anecdotal information about the changing nature of the reef communities is common (e.g., Community interviews by this author, Namada Village, 3 November, 2005). However, very little scientific information on the condition of these reefs exists. In the current study, the assessment of the effects of anthropogenic factors on the inner reef flats of the Coral Coast fringing reefs has involved a survey of the benthic communities on the reefs at control sites (VLS1 in

Appendix A5), resort sites (QLT1 in Appendix A3), and village sites (NMD1, 2 & 3 in Appendix A6). Due to the heterogeneity of the reef communities, the three categories of sites (control, resort and village) will be treated separately in the presentation of the results, to address the research questions presented below.

- What are the patterns of **temporal variability** in benthic communities, within a control site, resort site or village site; and what are the possible causes of such variation?
- What are the patterns of **spatial variability along transects,** from shore towards the reef crest within a control site, resort or village site; and what are the possible causes of such variation?
- What are the patterns of **spatial variability across transects** from east towards the west; and what are the possible causes of such variation?
- On the basis of findings from the first three questions, what are the main differences among control, village and resort sites with respect to benthic community variability?
- How do the abundances of the macroalgae *Sargassum baccularia* compare with abundances of Live Coral within control sites, resort and village sites?

## 5.2 GENERAL METHODS

### 5.2.1 Study Area

The fringing reefs along the southern coast of Viti Levu have only been studied briefly before, back in the early 1980s (Morton and Raj, 1980). At that time, the aim of the study was to gather information about the inter-tidal communities (reefs, grass-flats and mangroves) for a handbook to be used by senior undergraduate students of Marine Biology at the University of the South Pacific and the University of Auckland. This earlier study and the resultant handbook briefly described the fringing reefs of Cuvu-Naevuevu, Namatakula Reef, Malevu and Korolevu reefs. Overall, the reefs at that time were very diverse and relatively healthy. Other studies on the same reefs and the whole of the Coral Coast fringing reef system recommended that parts of this reef system be protected because of the significant marine biodiversity (Dunlap & Singh, 1989), and the immense tourism value of these reefs (Ryland, 1981; Raj *et al.*, 1981). Despite this earlier interest and concern for these reefs, no action was taken by the relevant authorities, until about 2004 with the establishment of an initiative called the Locally Managed Marine Areas (LMMA). In LMMAs local communities, in collaboration with the University of the South Pacific, are actively surveying the reefs and setting aside “no-take” or “tabu” areas in the reefs.

Fringing reefs in general differ with respect to structural profiles, lengths of the reefs, and depths across the reef platforms. However, all have the same general structure and zones (Figure 5.2). For the Coral Coast, the fringing reefs can be broadly divided into geomorphological zones along a biophysical gradient from shore towards the wave break zone (Table 5.2). Each zone is subject to different physical regimes and comprises a distinct ecological unit.

Please see print copy for Figure 5.2

Figure 5.2 Generalised structure of fringing reefs (from Wikipidea, 2007).

The Coral Coast has been developed at a very fast rate in comparison to other similar areas in Fiji. New resorts have been built or expanded, highways constructed and village populations increased dramatically (see Section 3.2.4).

Table 5.2 Zones of the Coral Coast Fringing Reefs of Viti Levu

Please see print copy for Table 5.2

(Source: Ryland, 1981)

### 5.2.2 Survey Methods

The diversity of benthic communities has been viewed as a measure of the "health" of fringing reefs (Dubinsky, 1990; Birkeland, 1997). The benthic species composition is assessed using standard methods for biological communities – Line Transects and Point-Intercept (quadrat) methods. A reconnaissance survey was conducted as a pilot study of the area.

#### 5.2.2 a Reconnaissance Survey

The aim of the reconnaissance survey was to gain an overview of the general variation of the benthic communities and to select those sites which would be designated as impacted sites (close to resorts and villages) and those which would be designated as "control" sites. The basis of selection is primarily the **distance** from sources of impact, because of the non-availability of the scientific information on the "before impact" situation. In situations where the impact has already occurred and the "impacted" area is known, then the impact must be inferred from spatial patterns alone (Green, 1979). Ideally in impact studies, the BACI or the "before-after, control-impact" design first mooted by Green is the most appropriate. However, in the natural world, environmental pollution is usually unplanned and therefore, the "before impact" conditions are rarely assessed.

#### 5.2.2.b Valase control site – a BA (before-after) situation

In this study, one of the control sites, Valase (VLS) presented an opportunity for a 'BA' or 'before-after' study. During selection of control sites in mid-2003, Valase was relatively under-developed and was not close to any large village, resort or river, except for a small creek on the eastern boundary of the site. However, by mid-2004, changes were taking place for the development of the site for a backpacker resort (see Table 4.4). The change was not anticipated during the selection of control sites. However, the site was not abandoned and the results of water quality, nutrients and benthic surveys at Valase provide an example of a 'BA' or 'before-after' study, although at a small scale.

The sites for benthic surveys were selected on the basis of a number of criteria:

i) the site must have known sources of contamination (village or resort);
ii) the fringing reef must exhibit active growth in some parts;
iii) the site must be adequately protected from human interference and direct effects of cyclones;
iv) access must be reasonable;
v) some information on background nutrient levels or reef community status from earlier studies should be available;
vi) good reference sites need to be available close by, to represent 'control' or unimpacted conditions.

#### 5.2.2.c Line Transect and Quadrat Method

The main objective of the survey was to collect as much information as possible, on the variation in the types, and percent cover of benthic components, at each site, so that differences between control and impacted sites could be assessed. So for each survey, the aim was to maximise the use of available resources, particularly field assistance, within the constraints of time (and tide) to achieve this objective. Benthic components considered here included both biological and non-living material. The main species of interest was *Sargassum* sp. because of its increasing prominence along the Coral Coast in Fiji. Standard methods for assessment of abundance of benthic communities often involves measurement of percent cover. The Line Intercept Transect (LIT) method is one of the most commonly used survey methods (English *et* al., 1994), and can be used on its own, or in combination with other methods such as the Quadrat method (Hill and Wilkinson, 2004). This survey used a combination of line transects and quadrat methods.

The survey methodology involved laying out a minimum of 50 m and up to 100 m (given available assistance and field time) transects perpendicular to the shoreline, and randomly placing grided quadrats (0.25 $m^2$), at equal distances along the transects. For each quadrat, the point-intercept method was applied, where the benthic component directly underneath the grid of the quadrat was recorded. This methodology often required additional assistance and was time consuming. Initially when field assistance was difficult to maintain, only one transect (50 m) would be laid out right in the middle of the impact zone. This was the case during the 2004 and early 2005 surveys. Training of field assistants took some time and after securing more experienced assistance, more transects were able to be surveyed at any one time, for example, 3 transects instead of 1 at Valase in 2006; 4 transects instead of 3 for Namada in 2006. The lengths of the transects were also increased to 100 m during the 2006 surveys. It must be noted that the basic unit of sampling was the quadrat and not the transect. In other words, the transects actually represented independent sub-sites within a site. While the 1 $m^2$ quadrat was often used for coral reef assessment, the 0.25 $m^2$ quadrat was more appropriate for estimating cover of macroalgae (Green *et al*., 2000).

For precision and quality of the survey data, it was important that the 'correct' number of quadrats were surveyed (see Section 5.2.2.d). Each transect was laid out, starting at the point where there was obvious benthic life, i.e., the area which was "underwater" for most of the time during the tidal cycle. This point depended on the profile of the reef flat, so it varied from site to site. However, the main area of study was the mid-tide section of the reef flat which was characterised by moats and tidal channels (zones 4 and 5 in Table 5.2). This is the area where one would expect the highest diversity of life, even live corals where water depth was suitable, because of the good flushing of the water by the tides (Morton and Raj, 1980). Seaward from this mid-tide section was the consolidated reef crest, well-emergent at low tide, and delineated by the white line of breaking surge. Often the summit of this zone (shallow, not more than 50 cm depth at low water spring) is characterised by a stretch of a dense growth of the brown macroalgae *Sargassum* and *Turbinaria* sp. The persistence of this belt of macroalgae may be due to reduced grazing by the herbivorous fishes, as a consequence of depth (too shallow for intense grazing for much of the tidal cycle), and the high energy waves that impact this part of the reef from the surge.

At regular intervals (10 m or 25 m) along the transect, a study station was located. At each station, the metal quadrats measuring 0.5 x 0.5m with grids of 10 cm by 10 cm, were haphazardly placed around the station. A total of 5 quadrats was sampled at each station. Sampling was done by the “point-intercept” method, where the benthic component or feature underneath each grid point was noted. For the 0.25 $m^2$ quadrat, a total of 36 points were sampled. Therefore for 5 quadrats at each station, a total of 180 (36x5) data points or benthic features (living or non-living) were identified and recorded for each station.

#### 5.2.2.d Precision and Accuracy of Data

Ecological studies have established that for any survey methodology involving % cover as a measure of abundance, the ratio S.E./Average (% cover) must be less than or equal to 0.1, i.e., SE/AVERAGE = OR < 0.1, for high precision and high accuracy of data (Kaly, pers. communication, 2004). The high variability in abundance and distribution of the main benthic components of interest in this case (*Sargassum* and live coral), meant that the minimum number of quadrats required for high precision and high accuracy, would not be the same for different sites. To determine the optimum number of quadrats required to obtain a high precision and highly accurate estimation of *Sargassum* abundance, preliminary surveys were conducted at a number of study sites, with numbers of quadrats ranging from 25 to 50. The average % cover (and standard error, S.E.) of *Sargassum* was calculated, and the ratio

S.E./Average calculated for the different methodologies involving different numbers of quadrats (see Table 5.3). For the preliminary surveys, two sites (Naqau and Qalito) were initially surveyed. It was found that for the 0.25 sq.m quadrat size, the minimum number of quadrats required to attain a S.E./Average ratio of around 0.1 was 30. Generally, as the number of quadrats increased above 30, the ratio S.E/Average decreased below 0.1, indicating a better precision and accuracy of the abundance measure. However, given the limitations of time, personnel and other resources, the target of each survey was to sample at least 30 quadrats. The survey methodology therefore involved laying out a 50 m transect with survey stations at every 10 m along the transect (total of 6 stations), and randomly placing 5 quadrats around each station.

Table 5.3 Summary of calculations for determination of optimum quadrat number for survey of *Sargassum* sp. abundance.

| **Site/Date of survey** | **No. of quadrats** | **Av. % cover *Sargassum* sp.** | **SE** | **SE/Average** |
|---|---|---|---|---|
| NAQ – 11Oct.'03 | 30 | 32.6 | 2.4 | 0.07 |
| NAQ – 11Oct.'03 | 34 | 38.7 | 3.8 | 0.10 |
| NAQ – 23 Dec. '03 | 25 | 13.7 | 3.2 | 0.24 |
| NAQ – 23 Dec. '03 | 30 | 13.6 | 2.7 | 0.19 |
| NAQ – 23 Dec. '03 | 48 | 11.6 | 1.9 | 0.16 |
| QLT – 7 May '04 | 25 | 50.5 | 6.6 | 0.13 |
| QLT – 7 May '04 | 30 | 49.6 | 6.4 | 0.13 |
| QLT – 7 May '04 | 50 | 34.4 | 4.9 | 0.14 |

Based on the results (Table 5.3), 30 quadrats was the minimum required to give the best estimation of *Sargassum* sp. abundance, as it appeared to show a consistent SE/AV ratio of around 0.1.

Table 5.4 summarises the dates and sites of the surveys.

Table 5.4 Summary of sites and dates of benthic surveys.

| SITE/ LOC # | C (control) V (village) R (resort) | DATES OF SURVEY | SEASON |
|---|---|---|---|
| VLS Valase- LOC 5 | C -control | * 22 Jan. 2004<br>*31 Dec. 2005<br>* 17 July 2006 | Hot & Wet<br>Hot & Wet<br>Cool & Dry |
| NAQ Naqau – LOC 3 | C - control | *23 Dec. 2003<br>*14 Dec. 2005 | Hot & Wet<br>Hot & Wet |
| NMD Namada – LOC 6. | V - village | *23 Jan. 2004<br>*17 Dec. 2005<br>*17 July 2006 | Hot & Wet<br>Hot & Wet<br>Cool & Dry |
| BCH Beachous LOC 2 | R - resort | * May 2004 | Cool & Dry |
| TBS Tambua Sands – LOC 6 | R - resort | * 8 April 2005<br>* 2 Jan. 2006<br>* 17 July 2006 | Cool & Dry<br>Hot & Wet<br>Cool & Dry |
| QLT Qalito – LOC 3 | R - resort | * 7 May 2004<br>* 2 Jan. 2006<br>* 24 July 2006 | Cool & Dry<br>Hot & Wet<br>Cool & Dry |

## 5.3 GENERAL RESULTS AND DISCUSSION

This section starts off with a summary of the main findings from the study of benthic communities on the fringing reefs along the Coral Coast (sub-section 5.3.1). Following on from that are the more detailed results from the benthic surveys, presented and discussed to address the research questions (Section 5.1). To address the research questions, the three sites representing the control, resort and village situations are treated separately. This is necessary because of the natural heterogeneity of the reefs. Valase (VLS) control site will be examined first, followed by Qalito (QLT) representing resort impacts, and last to be examined is the Namada (NMD) village site. Each of these sites has a unique background. Each site also provides lessons to be learnt from the past (QLT), the present changes (VLS), and the benefits of sustainable management practices such as 'no take' zones (NMD). The presentation of the results is shown diagrammatically in Figure 5.3.

Fig. 5.3 Diagrammatic presentation of layout of results for benthic surveys

**Benthic Survey Results**

| **Section 5.3.2 Control Sites (Valase)** | **Section 5.3.3 Resort Sites (Qalito)** | **Section 5.3.4 Village Sites (Namada)** |
|---|---|---|
| Temporal variation | Temporal variation | Temporal variation |
| Spatial var. along transects | Spatial var. along transects | Spatial var. along transect |
| Spatial var. across transects | | Spatial var.across transect |
| *Sargassum* vs Live Coral (LC) | *Sargassum* vs LC | *Sargassum* vs LC |

### 5.3.1 General Findings

Before presenting the detailed results, there are a number of generalizations that can be made about the fringing reefs along the Coral Coast. The general findings are:

- There is low diversity of species on the reef flats studied (in comparison to results in Morton and Raj, 1980) – a few species dominated, namely *Sargassum* sp. and to a lesser extent, *Padina* and *Turbinaria* sp. where the substrate is hard or coralline. In the crevices nearer to the HWM, the black brittle stars *Ophiocomina scolopendrina* dominated the fauna. The holothurian *Synapta* was very common amongst patches or communities of *Sargassum* sp.

- A common feature of the inshore reef flats was the presence of the highly-localised, pockets of "primary impact zones", often manifested as dense, compact mats of *Enteromorpha* or *Sargassum,* depending on the substrate. Around these primary impact zones would be larger and more diverse communities still dominated by algal species and almost always devoid of any coral species. These areas would fall into the "secondary" impact zones. However, it was clear that *Sargassum* sp. was dominating these secondary impact areas, rather than any of the other macroalgae such as *Padina* and *Turbinaria.*

- *Sargassum* sp. dominated the impacted sites with abundances exceeding 40 % average cover in extreme cases such as Qalito in the wet season (January 2006). In control sites, the abundances rarely exceed 5 % average cover. The other macroalge species including *Padina* sp., *Turbinaria* sp. and turf algae were generally present in low to moderate abundances, up to 10 % average cover.

- The main species of live coral found in the study was *Acropora* sp. with low to moderate abundances of up to 30 % for the control site Valase (Fig. 5.5a – c), and greater than 30% on some occasions at Namada Reef site (Fig. 5.9c, Fig. 5.10a and Fig. 5.10b). No live coral was observed at the Qalito resort site during the study (Fig. 5.7a – c). Soft corals, mainly *Sinularia* sp. were more common in areas exposed to sediment loading, and were also in low abundances of about 15% at any given site. During the study, live coral included both hard and soft corals. The live corals were found in patches wherever the water quality and depth were suitable.

- While coral sand was a prominent feature in all of the reefs surveyed, rubble was more common in reefs that have been exposed to human impacts for a long time, for example, at Qalito (Fig. 5.7a – c). Rubble was virtually absent in control sites such as Valase (Fig. 5.4a – c).

### 5.3.2 Valase (VLS) Reef – A Before/After Impact Case

Valase was selected as one of the control sites, due to its isolation from any large village, resort or significant river or creek. At the start of the study in January 2004, the Valase site only had an unoccupied thatched hut or 'bure' on the land, with typical coastal vegetation like coconut trees and other larger trees including the 'dilo' fringing the shoreline. However, by the end of 2004, construction of other 'bures' was already underway, and the 'Valase Backpacker' tourist facility was starting up. This site represented a classic example (although on a much smaller scale than some other projects) of a 'BA' situation, i.e. a 'before-after' situation (Green, 1979). Table 4.4 summarizes the physical alteration of the site at Valase as well as the clearing of land and construction of the Maui Bay Resort immediately to the east of and updrift from Valase.

#### 5.3.2.1 Methods of benthic surveys at Valase (VLS) control site

The fringing reef at Valase was surveyed on three occasions: January 2004, December 2005 and in July 2006. In the 2004 and 2005 surveys, only one transect was laid out right in front of the Valase site. In 2006, with additional assistance, and with the need to survey for effects of a new impact source (the new Maui resort under construction to the east), three transects were surveyed. Transects 1 and 2 were placed on new 'sub-sites' to the east of Transect 3, and just downdrift from the new Maui Bay resort. Transect 3 (2006) was placed on the same 'sub-site' as the single transect from 2004 and 2005. For comparison of 'before' and 'after' effects, it is Transect 3 that is compared with Transects from 2004 and 2005.

#### 5.3.2.2 General findings from the benthic surveys at Valase

The results of the first survey in January 2004 represented a control or relatively unimpacted site (Fig. 5.4a). The December 2005 results showed the effects of the clearing that was on-going at the time, in the whole area (Fig. 5.4b). During December 2005, construction work on the highway, as well as the resort and the backpacker huts, were well underway. The effects of these changes included whole sections of the reef closer to shore being inundated and covered with fine, light brown silt or sediment. This material smothered the macroalgae, and covered the small patches of corals in that part of the shore. The July 2006 results showed how the area had recovered from the silt smothering, but with enhanced growth of the macroalgae (Fig. 5.4c).

#### 5.3.2.3 Results from 2004, 2005 and 2006 benthic surveys for temporal variation at Valase Reef.

The following figures show the average % cover for the main benthic components (biological and physical) from the 2004 (Fig. 5.4a), 2005 (Fig.5.4b) and 2006 (Fig.5.4c) surveys on Valase Reef.

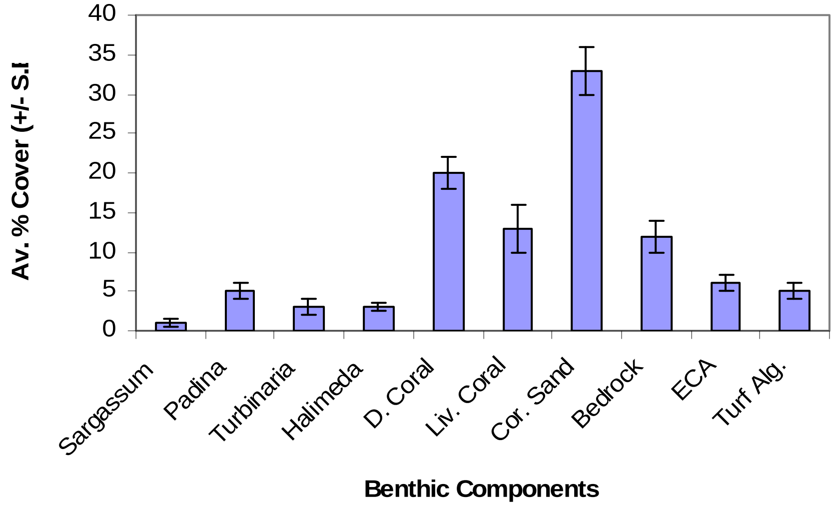



Figure 5.4a Benthic components cover (average %) for Valase Reef on 22 January 2004.

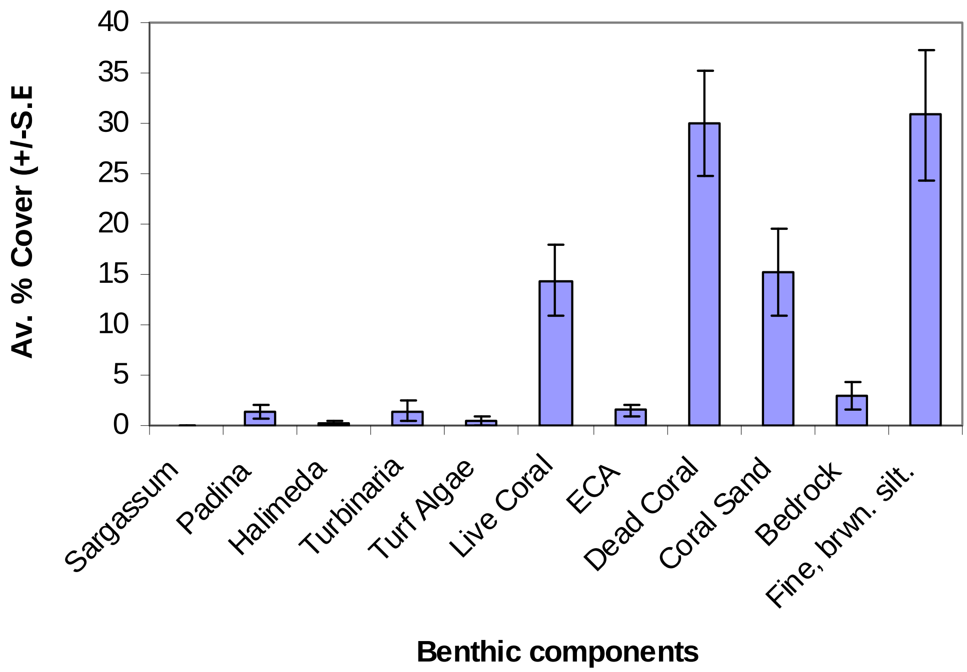



Figure 5.4b Benthic components cover (average %) for Valase Reef on 31 December 2004.

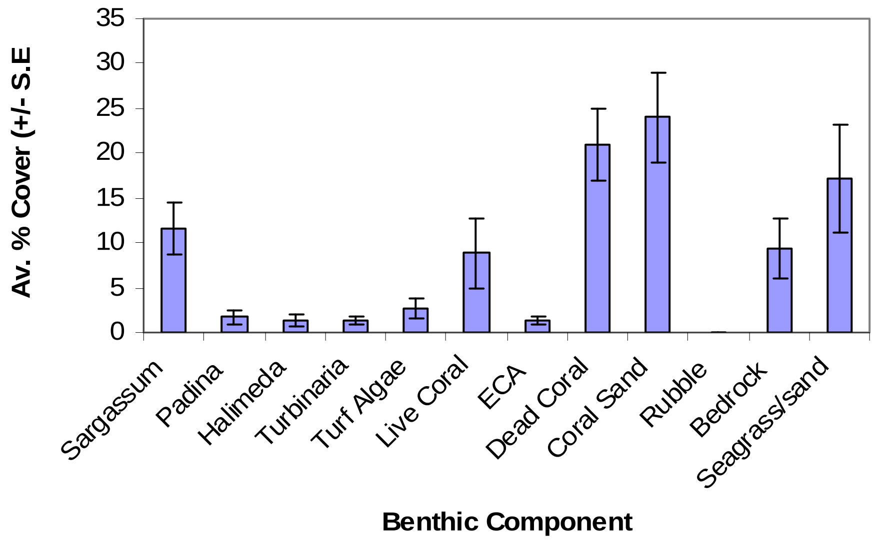



Figure 5.4c  Benthic components cover (average %) for Valase Reef 17 July 2006.

### 5.3.2.3.1 Discussion of temporal variation results for Valase Reef

The changes observed on the Valase inner reef flats show a reef becoming degraded over time. The first survey in January 2004 (Fig. 5.4a) recorded 1% cover for *Sargassum* sp. and 13% cover of live corals, which comprised both hard (*Acropora* sp.) and soft corals (*Sinularia* sp.). The results from the December 2005 (Fig. 5.4b) survey showed complete smothering of the macroalgae including *Sargassum*, *Padina* and *Turbinaria* sp. by fine sediment, which may have been discharged into the area from the physical construction works that were going on at that time. The results of the July 2006 (Fig. 5.4c) survey showed how the macroalgae had recovered, and the significant increase in *Sargassum* cover from 1 % to 12 %. At the same time, the average live coral cover had decreased from 13% to 9 %, and most of the corals were soft corals. The hard corals were noticeably less during the 2005 survey, as they were also smothered by the sediment layer that affected the area at that time.

#### 5.3.2.4 Spatial variation in benthic communities along transects at Valase

One of the research questions under investigation in this chapter was whether there was any clear pattern of spatial variation in the abundance and distribution of the main benthic species, along the transects, in the study area. This question was addressed by comparing the data at each sampling station along the transect, from near the high water mark (HWM), and moving towards the reef crest along the transect, perpendicular to the shore. The following three figures show results for the single transect in 2004 (Fig. 5.5a), 2005 (Fig. 5.5b), and Transect 3 from the 2006 survey (Fig. 5.5c). These three transects cover the same area of reef flat at Valase, and therefore can be compared and discussed together. The two additional transects surveyed in 2006 near the Mau resort development, are included in this sub-section (Fig. 5.5d and Fig. 5.5e)

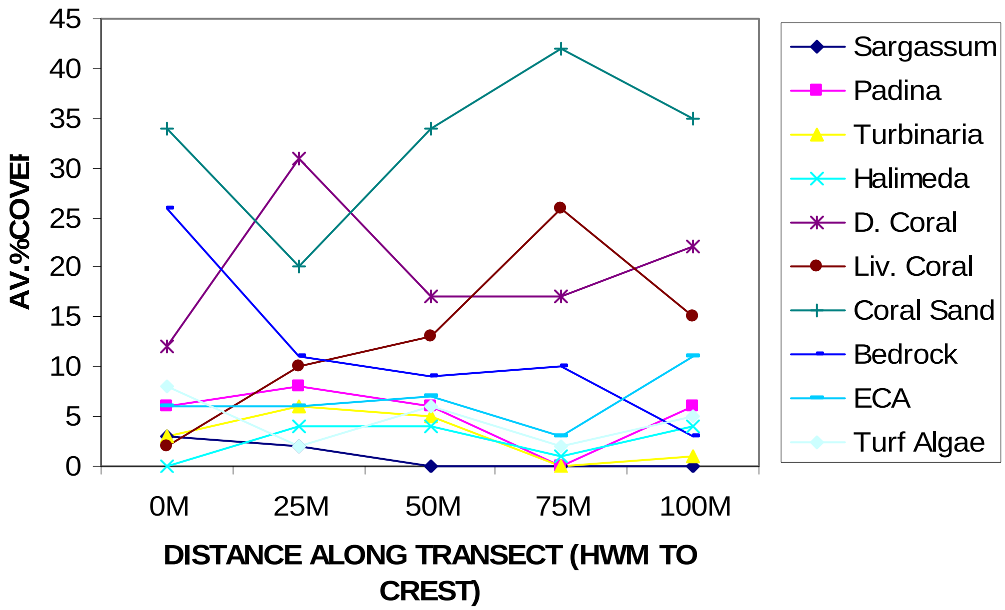



Fig. 5.5a Variation in benthic communities along the transect on Valase Reef, January 2004

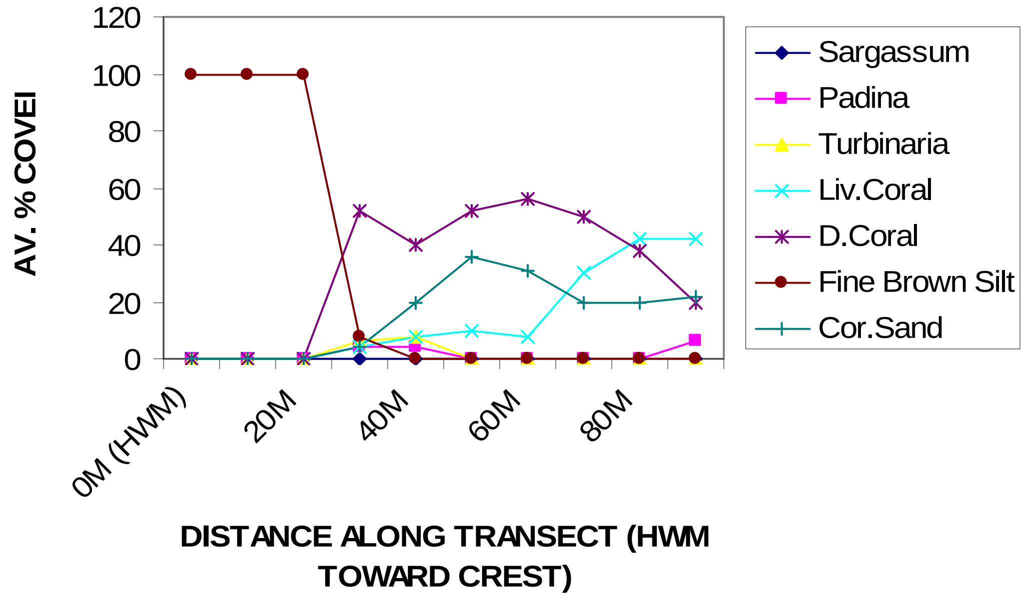



Fig. 5.5b Variation in benthic communities along the transect on Valase Reef, December 2005

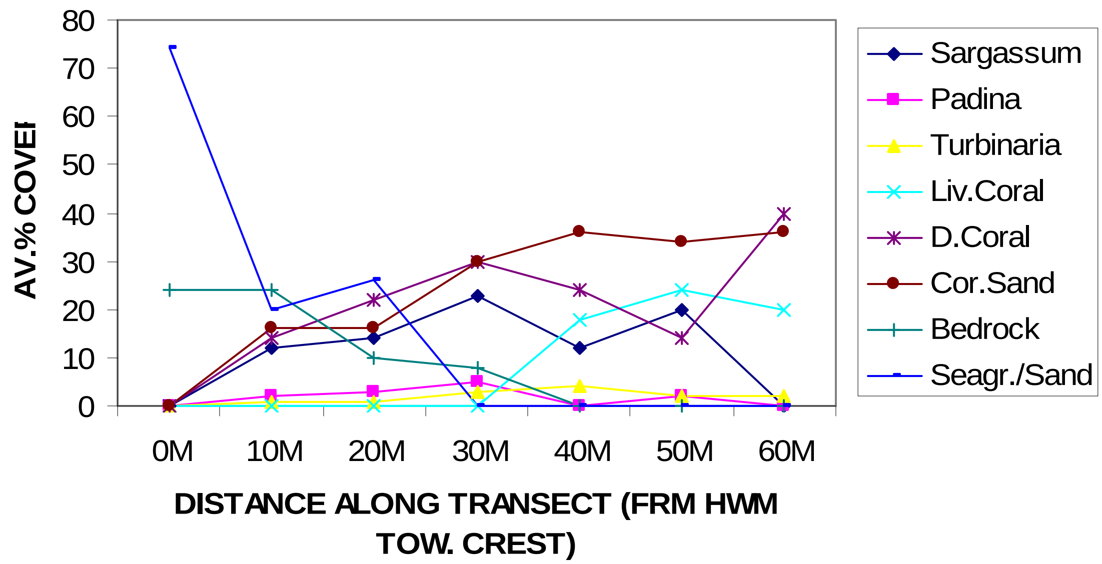



Fig. 5.5c Variation in benthic communities along the transect (Transect 3) on Valase Reef, July 2006

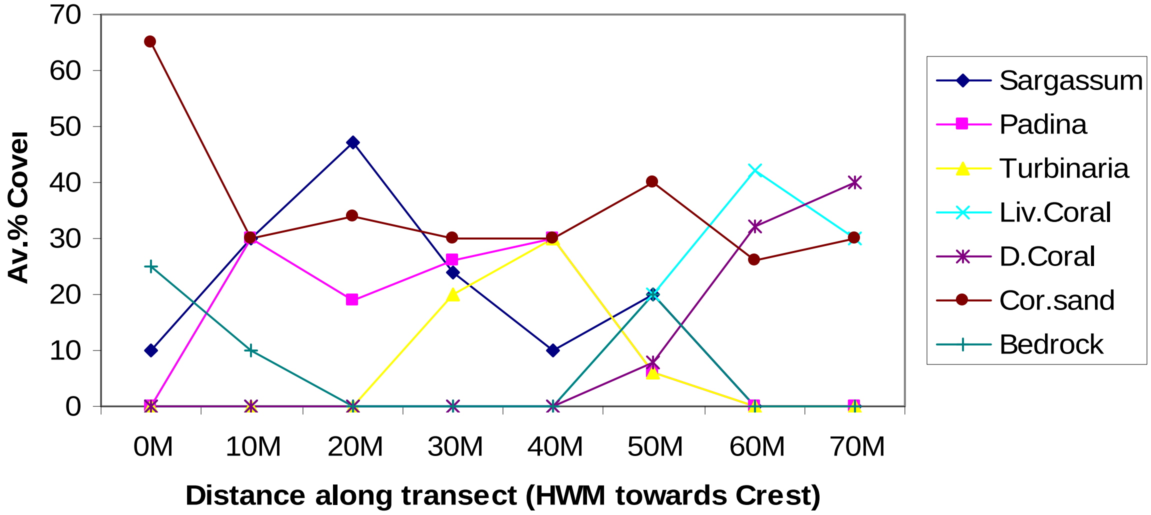



Fig. 5.5d Variation in benthic communities along Transect 1 on Valase Reef (adjacent to Maui Bay Resort site), July 2006

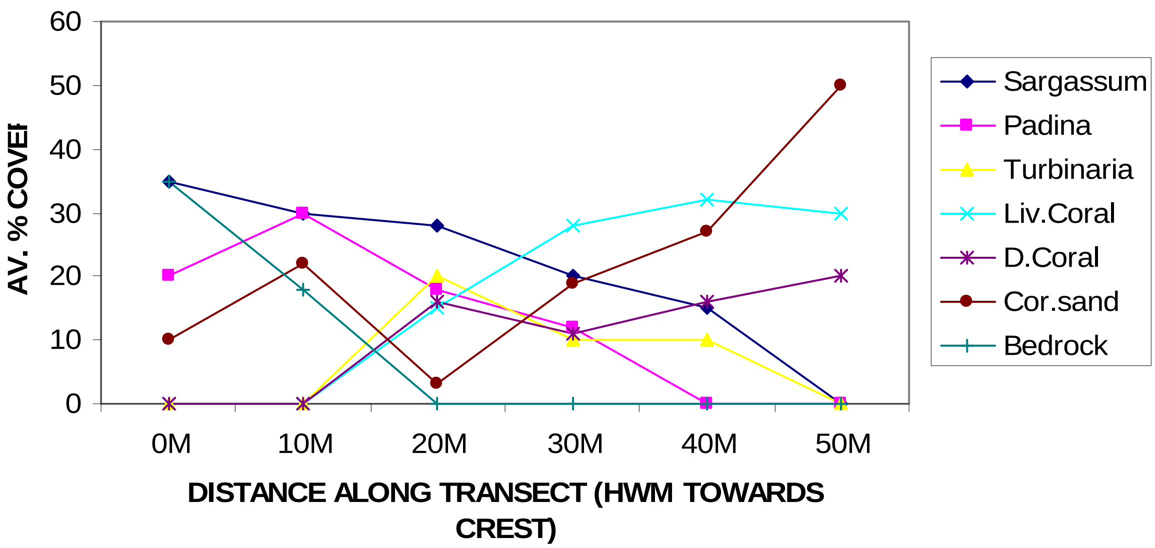



Fig. 5.5e Variation in benthic communities along Transect 2 on Valase Reef (west of Transect 1, near Maui Bay resort site), July 2006.

#### 5.3.2.4.1 Discussion of spatial variation along transects on Valase Reef

There are clear differences between the January 2004 (Fig. 5.5a) and the July 2006 results (Fig. 5.5c). The 2005 results were distinctly different from the other two because of the unusual, extensive sediment layer over part of the area (Fig. 5.5b). The December 2005 results clearly show how the inshore sections of the transect (up to 30m along the transect) were completely inundated and smothered by the fine, light brown sediment, which most probably originated from the physical works both at Valase as well as the area to the east (Suva side) at the Maui Bay resort development site. This fine sediment completely smothered the small patch of *Sargassum* as well as the other macroalgae *Padina* and *Turbinaria.* The live corals, in particular the *Acropora* sp. were also covered with the sediment layer. Although the survey did not differentiate between hard and soft corals, there was definitely less of the hard corals and more of the soft corals during the 2005 and also 2006 surveys. Live corals were observed quite close to shore in 2004 (Fig. 5.5a), but in the later surveys, they appeared to have been replaced by macroalgae (Fig. 5.5c). Generally, live corals thrived from beyond 30 m and increased in coverage on moving into deeper and more pristine waters (Fig. 5.5a).

The two additional transects surveyed in July 2006 both showed impacted reefs with prominence of macroalgae on the reef flats close to shore (Figs. 5.5d and Fig. 5.5e). *Sargassum, Padina* and to some extent *Turbinaria* were occupying much of the bedrock near the HWM during the July 2006 survey.

#### 5.3.2.4.2 Valase Reef changes: 'Before' (2004) vs 'After' (2006) Results

The Valase inner reef flat in January 2004 represented a relatively clean site; *Sargassum* was low in abundance (average 1% cover for whole study area) and concentrated towards the shore. In contrast, the other macroalgae *Padina, Turbinaria* and even *Halimeda* recorded higher abundances (5%, 3% and 3% respectively), and they were spread out along the transect, up to 100 m. Live corals, dead corals and coral sand and bedrock all featured along the transect (Fig. 5.5a). The 2006 results were very different and probably reflected the impacts of changes occurring on land

(Fig. 5.5c). Statistical tests (Mann-Whitney U) for differences in *Sargassum* cover in 2004 and 2006, gave a highly significant p value of 0.008, at the 0.05 level of significance, i.e., Sargassum cover was significantly higher in 2006, (see Appendix C5). ANOVA results for Live Coral cover did not show any significant difference between 2004 and 2006, ($p = 0.476$, Appendix C5). The main differences between the 2004 (before impact) and the 2006 (after impact) are listed in Table 5.5.

Table 5.5 Changes observed on Valase Inner Reef Flat, 2004 to 2006

| Feature | 2004 | 2006 |
|---|---|---|
| *Sargassum* av. % cover | 1 (whole reef) | 12 (whole reef) |
| Distribution of *Sargassum* | confined to in-shore<br>Low abundance (<2%) | more extensive<br>High abundance(>20%) |
| *Padina* av. % cover | 5 | 2 |
| *Turbinaria* % cover | 3 | 1 |
| Live coral % cover | 13 (hard and soft corals) | 9 (mostly soft corals) |
| Dead coral % cover | 20 | 21 |
| Bedrock (consolidated reef platform) | 12 % | 9% |

### 5.3.2.5 Spatial variation in benthic communities across transects at Valase

In July 2006, 3 transects were surveyed on Valase inner reef flats. The two additional transects (Transects 1 and 2) were laid out to the east and updrift of the usual site in front of the Valase Backpacker operation. It is important to note that during the time of the survey (July, 2006), construction work for the Maui Bay resort located to the east and updrift of Valase, was in an advanced stage. The Maui Bay resort project was not anticipated at the start of the research, and therefore no surveys were done to assess the 'before' impact situation. In order to differentiate between impacts arising out of the Maui Bay resort project, and the Valase Backpacker development, the two additional transects ('sub-sites') were placed between the two developments, and to the east of the usual transect site at Valase. The results from the two additional transects would help determine whether the changes being observed at Valase were due to the Valase project alone, or whether there was reason to place part of the blame on the Maui Resort project as well. Transect 1 was adjacent to the Maui resort site and Transect 2 was about 20 m west and downdrift of Transect 1. Transect 3 (usual site) was about 20 m further west and downdrift of Transect 2.

One of the research objectives was to investigate the patterns of spatial variation in benthic communities across transects, moving from east towards the west. Transect 1 (Fig. 5.6a), 2 (Fig. 5.6b) and 3 (Fig. 5.6c) from the July 2006 survey are compared to address this question for Valase Reef.

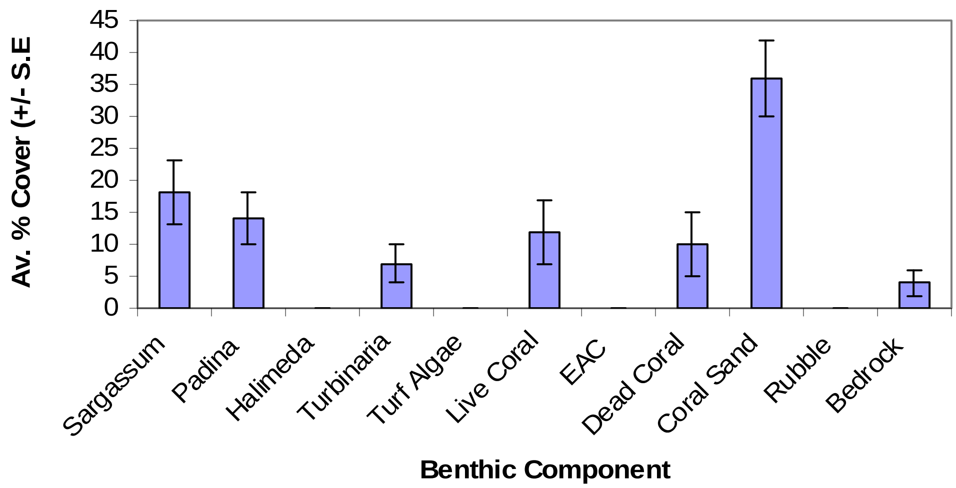



Fig. 5.6a Benthic components (av. % cover) for Transect 1, Valase Reef– July 2006

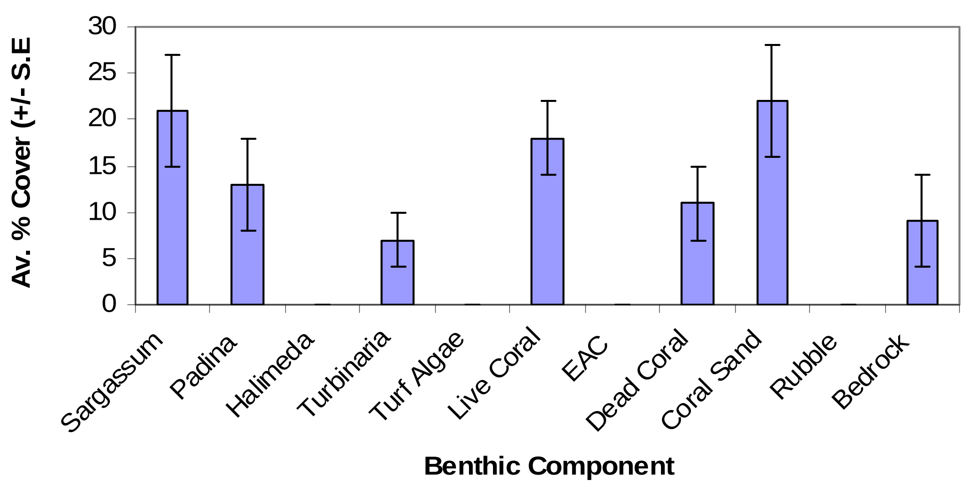



Fig. 5.6b Benthic components (av. % cover) for Transect 2, Valase Reef – July 2006

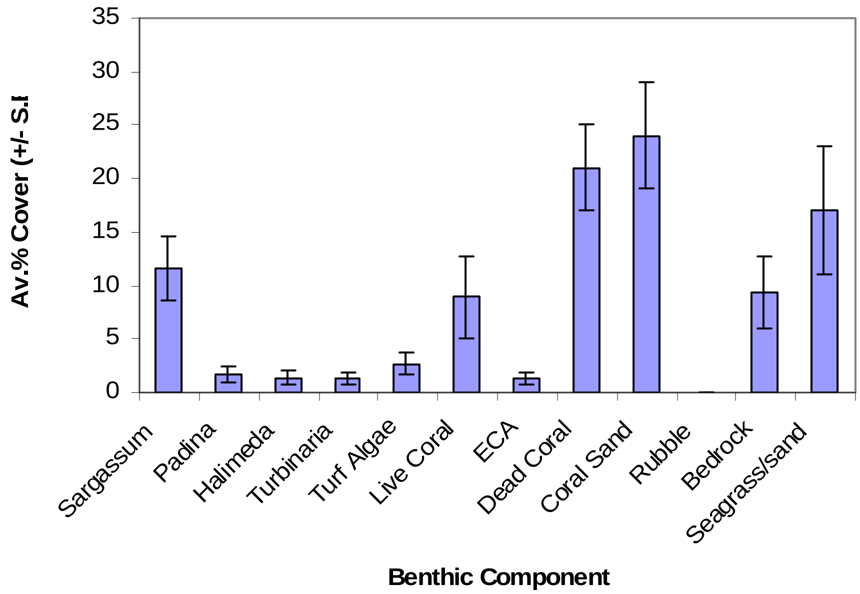



Figure 5.6c Benthic components (av. % cover) for Transect 3, Valase Reef – July 2006

#### 5.3.2.5.1 Discussion of spatial variation across transects on Valase Inner Reef Flat – July 2006

Table 5.6 summarises the variability in the main features of the benthic communities on Valase Reef, during the July 2006 survey.

Transects 1 and 2 are very similar in the abundances of the main macroalgal groups *Sargassum*, *Padina* and *Turbinaria* (see Table 5.6). Transect 2 is located 20 m west and downdrift of Transect 1, but both are adjacent to the new development at Maui, and updrift and east of Valase.  The small creek (mostly dry) next to Valase Backpacker operation is located just west and downdrift from Transect 2.

The reefs near the Maui Bay  Resort appeared to be definitely impacted, based on the prominence of macroalgae at Transects 1 and 2. For Transect 1, macroalgae made up about 39 % of the benthos, while Transect 2 made up 41 %  of the benthic communities (see Table 5.6). The abundance of macroalgae may be a sign of nutrient enrichment from the physical works of construction as well as human habitation. Incidently, the 2005 wet weather nutrient results for Valase were some of the highest to be recorded for the site (see Table 4.18). Prior to commencement of works in 2005, the area was under typical coastal vegetation with no clearing whatsoever.

Transect 3, further west of Transect 2 and directly in front of the smaller Valase Backpacker operation, recorded less macroalgae than the other two transects (see Table 5.6). The total macroalgae cover for Transect 3 was about 15%. The results for this site were compounded by the fact that the land was being developed and construction of buildings were taking place at the time of the surveys.

Table. 5.6 Summary of Spatial Variation Across Transects at Valase – July 2006

| Feature | Transect 1 (Maui) | Transect 2 (Maui) | Transect3 (Valase) |
|---|---|---|---|
| *Sargassum* av.cover | 18% | 21% | 12% |
| *Padina* av. cover | 14% | 13% | 2% |
| *Turbinaria* av. Cover | 7% | 7% | 1% |
| Live Coral av. Cover | 12% | 18% | 9% |
| Dead Coral av. Cover | 10% | 11% | 21% |
| Bedrock | 4% | 9% | 9% |
| Seagrass/sand | - | - | 17% |

#### 5.3.2.6 Summary of general patterns of benthic community variation at Valase Reef

There were clear patterns of spatial variation in the distribution and abundance of the main benthic components, on the reef flats at Valase, which reflected the extent of degradation of the reef. The January 2004 results represented a relatively unimpacted reef (‘control’ conditions), where macroalgae, in particular *Sargassum* sp. was of low abundance (% cover), while live corals thrived (Fig. 5.4a and Fig. 5.5a). Much of the bedrock was still unoccupied, and dead corals were still relatively low in abundance, and also unoccupied by frondose macroalgae. Instead of macroalgae, the turf algae, encrusting coralline algae and even *Halimeda* sp. occupied available space on some of the dead coral heads. Coral sand appeared to be the dominant substrate type taking over from bedrock from about 30 m onwards towards the reef crest.

On the other hand, the pattern of benthic community variation along the transect was very different for reefs that were degraded: macroalgae especially *Sargassum* sp. was more extensive and widespread, occupying any available, suitable substrate, which included dead coral heads and even the bedrock where crevices provided a niche for the holdfast (rhizome) of the plant (Fig. 5.6a, Fig. 5.6b and Fig. 5.6c). Live corals were being replaced by dead corals, most probably as a result of nutrient enrichment from land sources.

Valase Reef has shown clear signs of degradation, and the change from 2004 (before impact) to 2006 (after impact) provided an illustration of how human impacts on land affected the marine ecosystems, especially the inshore fringing reefs such as those at Valase.

### 5.3.3 Qalito – A case of a historical, environmental management mistake

#### 5.3.3.1 Introduction and background

During the study period from 2004 to 2006, the Coral Coast was the focus of much attention and activity involving several groups of stakeholders (community members, tourism industry operators and the scientific expertise), all working together to raise awareness about the need to protect the marine environment from land-derived pollutants including nutrients. This was the time when communities established ‘tabu’ or marine protected areas within their traditional fishing grounds, in an effort to restore fish stocks. The tourism operators and resort managers were also involved through a technical study to assess how the various sewage treatment plants used by the resorts, were performing. The issue of the broken wastewater pipe at Qalito was also highlighted to the management of the Warwick Resort, through the Integrated Coastal Management (ICM) Initiative of the Institute of Applied Sciences, University of the South Pacific in Suva. This resulted in an attempt to repair the pipe (June 2004).

In the current study, Qalito was selected as one of the impacted sites, because of its close proximity (<100 m) to the large Warwick Resort on the Coral Coast. A reconnaissance survey in December 2003 showed extensive communities of the macroalgae *Sargassum* sp. on the reef flats and shallow lagoon at Qalito, located west of and downdrift from the Warwick Resort. The reef at Qalito showed evidence of degradation, and from first presumption, part of the cause was the location of the wastewater pipeline running almost parallel to the shoreline and less than 100 m from shore, at Qalito. According to anecdotal information provided by community members of Qalito, the fringing reefs at Qalito were once very healthy with thriving live corals, and *Sargassum* was never a part of the reef community. An earlier study, revealed diverse communities of live coral, to the point of suggesting setting aside part of the reef for conservation (Raj *et al.*, 1981). According to Raj *et al.* (1981), the channel running from the marina and swimming lagoon at the Warwick Resort, was excavated out of the reef platform, to enable boats to be moved from Korolevu Bay to the marina in front of the resort. How the wastewater pipeline got placed in the channel is uncertain, but the recurring problems of the pipeline breaking up or coming apart at the joints, has been blamed by the residents of Qalito as being the main reason for the proliferation of the reef, with *Sargassum* sp. Discharging wastewater via an outfall, as in this case, was a mistake, because it did not take into account the depth of receiving water, the ecological value of the coral reefs that would be affected, and the hydrodynamic aspects such as the currents in the area. From observation of the disjointed pipeline, it appeared that the force of the currents dislodged the concrete base or shackles which held the pipeline in place. For the long term improvement of the coral reefs in the area, it would be worthwhile diverting the wastewater back to a treatment plant within the compound, and recycling treated water for other uses on land.

#### 5.3.3.2 Methods for benthic surveys at Qalito Reef

The reef at Qalito was surveyed on 7 May 2004, 2 January 2006 and 24 July 2006. One transect was surveyed each time. The reef at Qalito is not as wide as the other reefs surveyed in this study, and immediately adjacent to the reef on the western boundary is the Korolevu Bay and a large river estuary. Any additional transects to the west of the selected site would incorporate effects of the bay and estuary, and would not be representative of the Qalito reef. Following on from this, no comparisons could be made for variation across transects for Qalito reef.

#### 5.3.3.3 Temporal variation in benthic communities at Qalito reef

To assess temporal variation patterns in the benthic communities on Qalito reef, the results from the benthic surveys in May 2004 (Fig. 5.7a), January 2006 (Fig. 5.7b) and July 2006 (Fig. 5.7c) are presented and discussed. May marks the start of the cool season which lasts to October, while January falls in the hot and wet season. The growth of *Sargassum* sp. has often been described as seasonal, peaking in the summer weather and rescinding in the cool season through ‘die back’ (Vuki and Price, 1994). The results of temporal variation will also be discussed in relation to seasonality of *Sargassum* sp.. Figures 5.7a – c show the variation in benthic communities on the Qalito Reef from the three surveys.

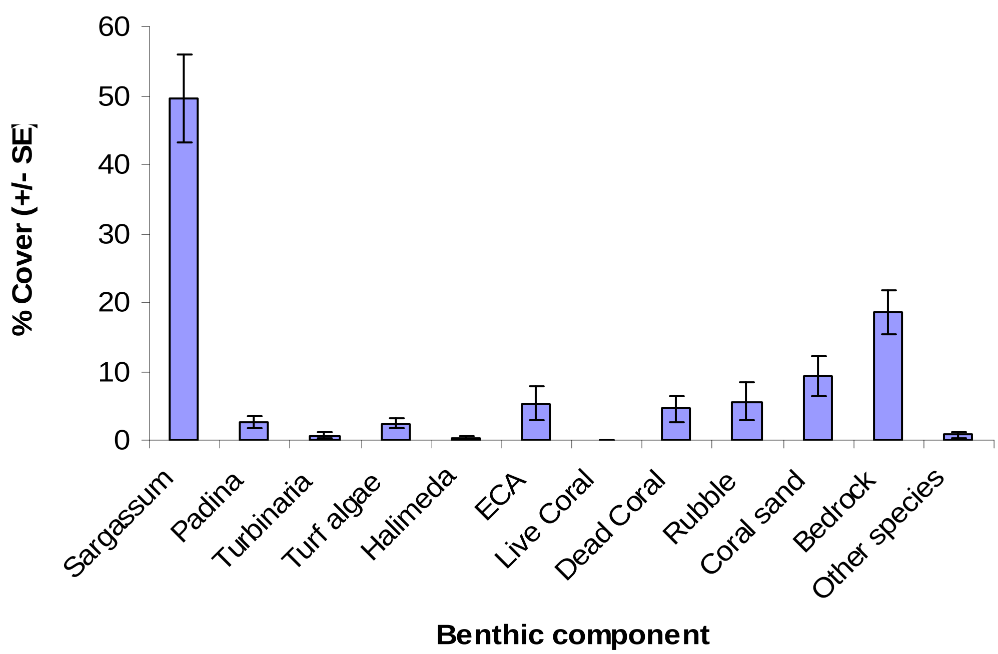



Figure 5.7a Abundance (av. % cover +/- SE) of the main benthic components on Qalito Reef on 7 May 2004.

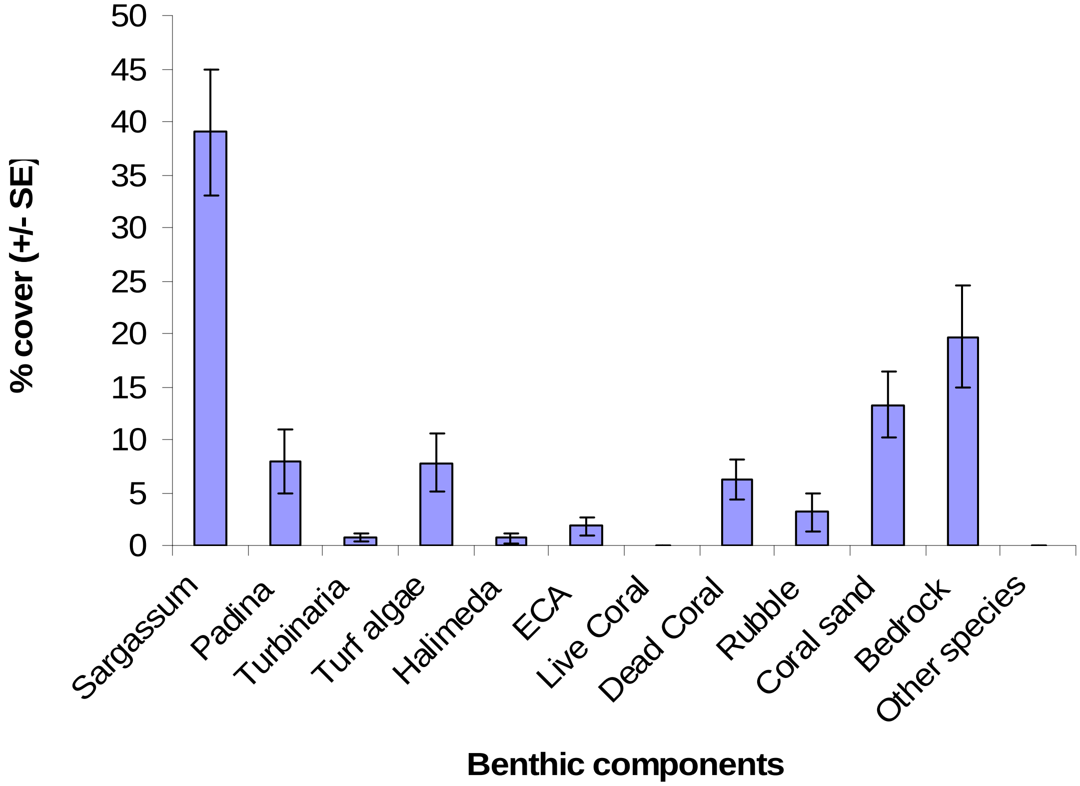



Fig. 5.7b Abundance (av. % cover +/- SE) of the main benthic components on Qalito Reef on 2 January 2006.

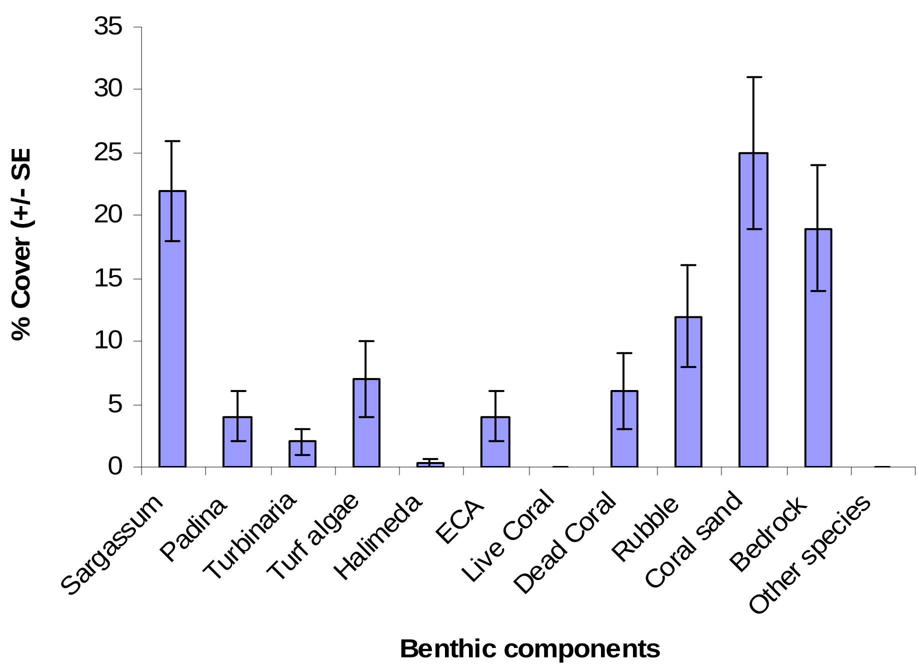



Fig. 5.7c Abundance (av. % cover +/- SE) of the main benthic components on Qalito Reef on 24 July 2006.

#### 5.3.3.3.1 Discussion of temporal variation in benthic communities on Qalito Reef

The changes in some of the main benthic communities on Qalito Reef over this period of sampling showed interesting results.

*Sargassum baccularia* variation appeared to be showing evidence of seasonality, with a relatively high abundance of 39 % average cover in January, and decresing to 22 % average cover in July of the same year, 2006 (Figs. 5.7b and c). The high abundance recorded in early May 2004 may appear unusual (Fig. 5.7a). However, considering that the survey was conducted in early May ($7^{th}$), and that the previous summer was marked by some heavy rain, it would not be unusual to find macroalgae such as *Sargassum baccularia* flourishing. In February 2004, heavy rain and thunderstorms affected the area and at Qalito nitrate concentrations reached a high 5.66 *u*M (see Table 4.3.2 h). Schaffelke and Klumpp (1998) showed through controlled experiments that the growth rates of *Sargassum baccularia* almost doubled when ammonium concentrations were between 3 *u*M – 5 *u*M (Fig. 5.1). Field observations during the water sampling trips in March 2004 noted the rapid expansion of *Sargassum* on the reef at Qalito (estimated at ~70 % of whole reef), compared to the situation observed during the site visit (for water sampling) on 10 February 2004. Nutrient enrichment from rain-induced flushing, (i.e., the nutrient pulse of February 2004) may have prompted the rapid expansion of *Sargassum* sp. During May 2004, the wastewater pipe was also broken, and this would have compounded the problem of nutrient enrichment. A significant observation during the May 2004 survey, was the beginning of 'die back' among the *Sargassum* sp. plants, despite the dominance of the species at the time.

Another of the common macroalgae species along the Coral Coast, *Padina* sp. appeared to show temporal variation consistent with season, i.e., low in the Cool Season (Fig. 5.7a and c) and high in the Wet Season (Fig. 5.7b). Live Coral was virtually absent during all three surveys. In the case of rubble and coral sand, an increase in cover of *Sargassum* sp, coincided with a decrease in these substrate components, and vice versa. This pattern of variation implied that the *Sargassum* sp. was well established on Qalito reef, and that in the Cool season when they appeared to have 'died out', the rhizoids of this species were in fact alive among the crevices in dead corals and in the bedrock. This proposition may need to be investigated further.

Following the first survey in May 2004, the matter of the broken wastewater pipeline was reported to management at the Warwick Resort and repair works commenced in June 2004. There was also an attempt to extend the pipeline further west of Qalito at that time. The reef was also declared a 'tabu' from January 2005. It would be of interest to investigate whether the 'tabu' would affect the abundance and distribution of *Sargassum* sp. on Qalito Reef.

#### 5.3.3.4 Spatial variation in benthic communities along transects at Qalito Reef

The transects laid out on the reef flat at Qalito crossed the excavated channel and wastewater pipeline at about 60 m from the HWM on the beach. The pipeline had recurring breakages at various times during the period of the study. The benthic communities at each station (10 m apart) along the transects are compared for patterns of variation along the transects, as one moved from the high water mark towards the reef crest. The results from the May 2004, January 2006 and July 2006 surveys are shown in Figures 5.8a, 5.8b and 5.8c.

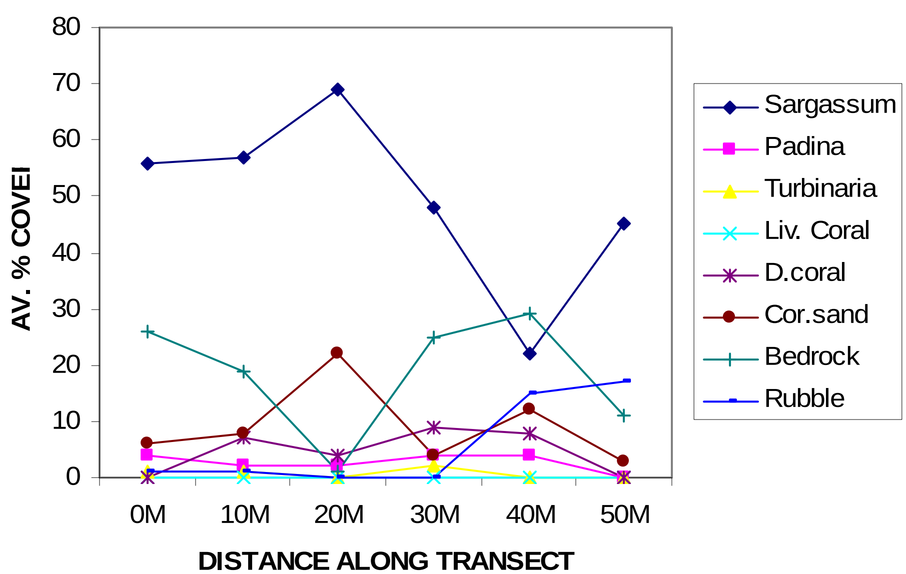
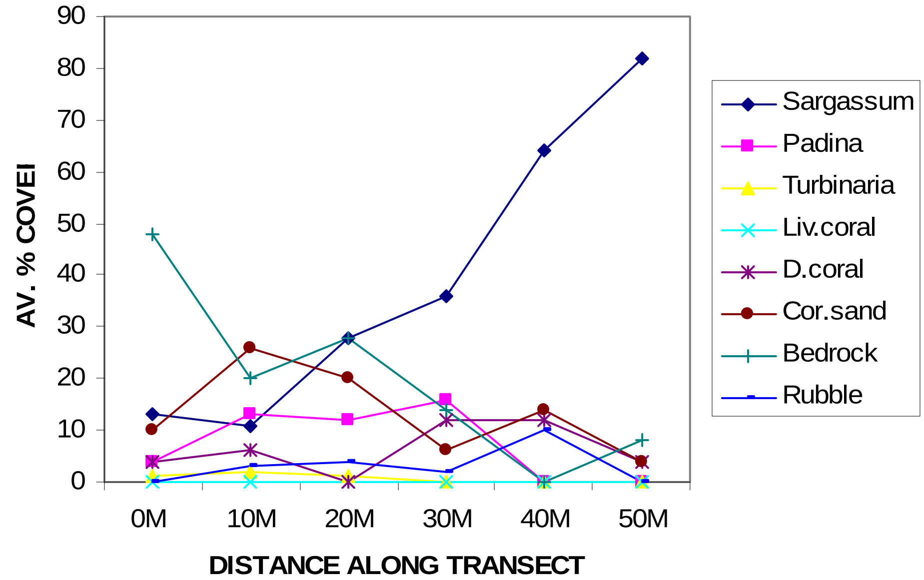
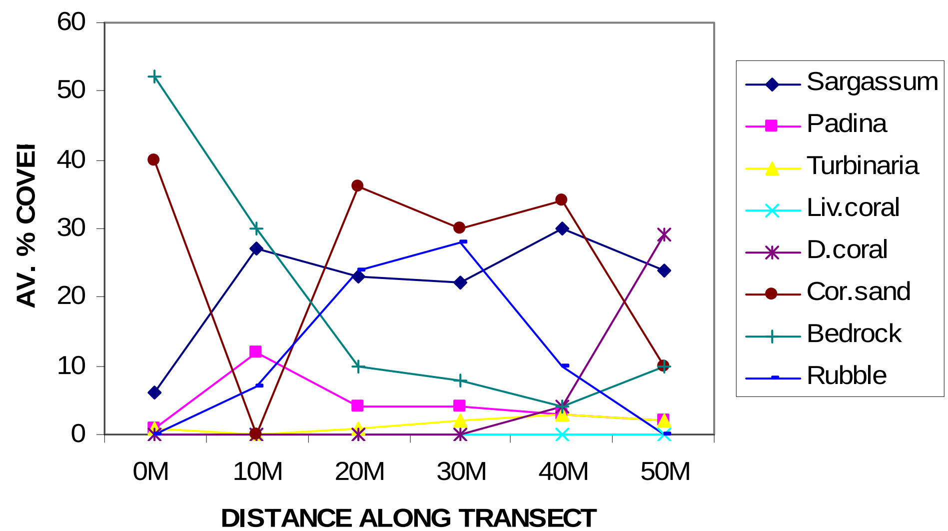



Figure 5.8a Variation of benthic communities along the transect at Qalito Reef-May 2004




<u>Figure 5.8b</u> Variation of benthic communities along the transect at Qalito Reef-January 2006.




<u>Figure 5.8c</u> Variation of benthic communities along the transect at Qalito Reef- July 2006.

#### 5.3.3.4.1 Discussion of spatial variation along transects on Qalito Reef

The results from the three surveys show the dominance of *Sargassum* sp. at Qalito, especially in the May 2004 (Fig. 5.8a) and January 2006 (Fig. 5.8b) surveys. While the other macroalgae *Padina* and *Turbinaria* remained in relatively low abundance along the transects (never exceeding 20% cover anywhere along the transects), the main benthic components that dominated were *Sargassum*, bedrock, coral sand and rubble. When *Sargassum* dominated, it covered most of the substrate. However, when it died out from various causes such as seasonal effects, epiphytic attack or insufficient nutrients as discussed in Section 5.3.3.3.1, the substrate which supported it recorded an increase in % cover. The prominence of rubble at Qalito is noteworthy, unlike the reef at Valase (a control site) which effectively had no rubble. This may be indicative of a long history of nutrient enrichment andother human impacts at Qalito reef.

The distribution of *Sargassum* sp. along the transects varied in an interesting way, as seen from comparing results from the three surveys. In May 2004, the pattern of distribution was one normally encountered for the fringing reefs along Coral Coast, i.e., highest % cover nearest to shore and decreasing further away from land (Fig. 5.8a). The suggested cause of the May 2004 proliferation was the high rainfall (and subsequent run-off) that raised nutrient concentrations in the area. In the January 2006 results, the pattern of distribution was reversed and highest abundance of *Sargassum* was found closer to the wastewater pipeline, suggesting this to be the source of nutrient enrichment at this time (Fig. 5.8b). The July 2004 survey showed a more even distribution, and lower total abundance (Fig. 5.8c). The results appeared to be supporting a seasonal pattern of growth for *Sargassum*, i.e., die back in the Cool Season (May to October), but high rainfall and the subsequent nutrient enrichment from run-off in the area can cause unusual patterns of abundance, particularly for *Sargassum* which appeared to thrive in highly nutrient enriched environments. In fact *Sargassum* may be an example of 'nutriphilic' species, according to Szmant (1997); these are species that thrive in very high nutrient environments.

#### 5.3.3.5 Summary of findings on variation in benthic communities on Qalito Reef

Generally speaking, the features that set Qalito apart from the other sites surveyed were the dominance of the macroalgae *Sargassum* sp. and the total absence of live corals on the Qalito inner reef flat. *Sargassum* sp. appeared to be seasonal, but nutrient pulses may cause unusual patterns of distribution and abundance for this macroalgae species (Fig. 5.7a). The prevalence of rubble may be indicative of a long history of reef degradation from factors such as nutrient enrichment, decreased salinity and bioerosion.

### 5.3.4 Namada (NMD) Reef – Village 'Tabu' site and a model for others

#### 5.3.4.1 Introduction and background

The Namada reef and surrounding waters had been set aside as a 'tabu' site or marine protected area, prior to the commencement of this study. The local community members had duly respected the 'tabu' and the abundance of fish and their non-aggressive behaviour towards people was a truly unique experience. The results of the surveys on Namada Reef may be seen as the best estimates of benthic cover, because the effects of fishing (which affects herbivory), and physical damage to corals (by trampling and other human-induced disturbances), are excluded or dramatically reduced within the 'tabu' area.

The Namada reef is far from any large resort or river. The major potential sources of nutrients are the village itself, the Tambua Sands Resort located about 1 km to the east (and updrift), and the large creek (dry most of the time) on the western boundary of the Tambua Sands Resort. The village itself is not immediately adjacent to the beach, it is higher up and back from the beach by at least 25 meters. The main highway and a stretch of coastal vegetation (coconut trees and typical beach leguminous, creepers and herbaceous plants) separate the village from the beach and the lagoon. These factors play a role in protecting the water quality of the Namada inshore waters from runoff and seepage from the village. The relatively deep lagoon, and the close proximity of the reef crest to land also ensured continued good flushing which favoured good coral growth on Namada reef. Another common feature of the fringing reefs along the Coral Coast are the uplifted reef platforms, running almost perpendicular to the beach and extending up to the reef crest. These often marked the boundaries of excavation effects from freshwater discharged from large rivers onto the reef flat. They often provide the perfect niche for various, low-profile algae including *Caulerpa* sp., juvenile forms of other macroalgae such as *Padina*, *Turbinaria* and *Sargassum.* At Namada, such a platform on the eastern boundary of the Namada village was the site of Transect 1 in the January 2004 survey.

#### 5.3.4.2 Methods of survey at Namada Reef

The Namada Reef was surveyed on three occasions: 22-23 January 2004, 17 December 2005 and 17 July 2006. In the first two surveys, 3 transects were surveyed. With additional assistance available in 2006, 4 transects were surveyed on 17 July 2006. The survey transects were laid out perpendicular to the shoreline, and at least 30 m apart, starting from the eastern boundary of the village and working towards the west. To address the question of variation between sites close to nutrient sources (impacted) and those well away from nutrient sources (control), the transects surveyed were considered as sub-sites, representing a gradation of conditions from impacted (eastern most and closest to Tambua Sands Resort and the l creek next the resort), to less impacted (western side of the reef) sites. As in the case of the control site (Valase), and the resort site (Qalito), variation in benthic communities along the transects, from HWM towards the reef crest was also studied, by comparing data in the stations along the transects.

The results from the three surveys are combined and discussed together under the sub-headings of : a) spatial variation across transects from east (impacted) moving west and further away from nutrient source (control); and b) spatial variation along the transects from HWM towards the reef crest.

#### 5.3.4.3 Spatial variability in benthic communities across transects or sub-sites for January 2004, December 2005 and July 2006 surveys

The average abundance (% cover) for the various benthic components on Namada reef, surveyed at different times are presented in Figures 5.9a – j. The January 2004 results are shown in Figures 5.9a, 5.9b and 5.9c. The results for the December 2005 survey are shown in Figures 5.9d, 5.9e and 5.9f. The results for the July 2006 survey are shown in Figures 5.9g, 5.9h, 5.9i and 5.9j.

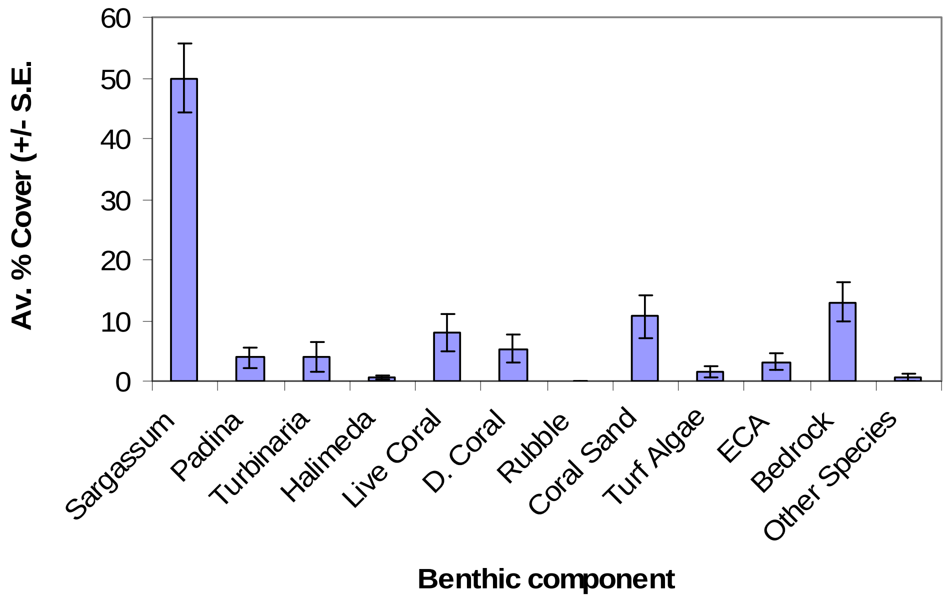



Figure 5.9a Abundance (av. % cover +/- SE) of the main benthic components on Namada Transect (sub-site) 1 – January, 2004.

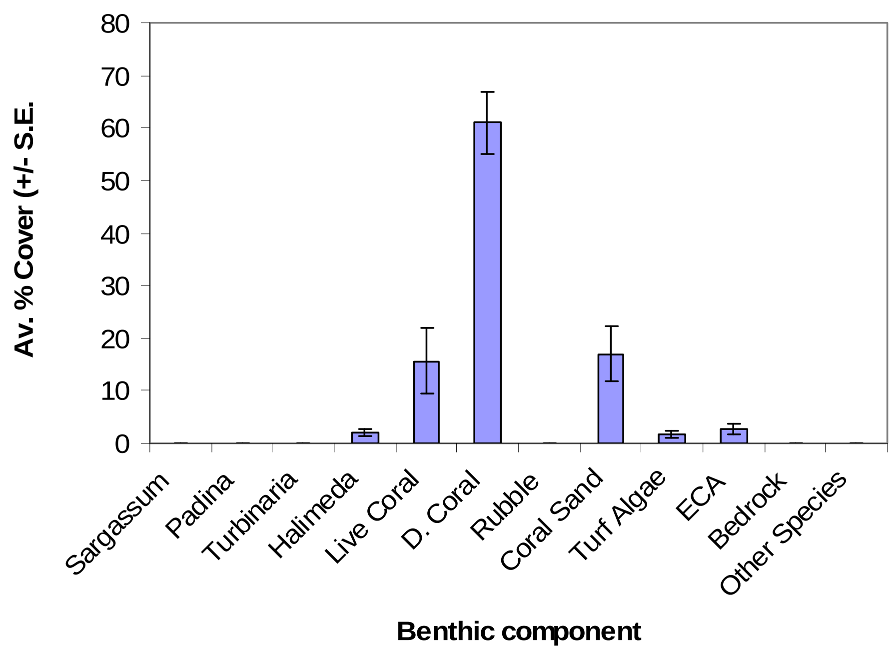



Figure 5.9b Abundance (av. % cover +/- SE) of the main benthic components on Namada Transect (sub-site) 2 – January, 2004.

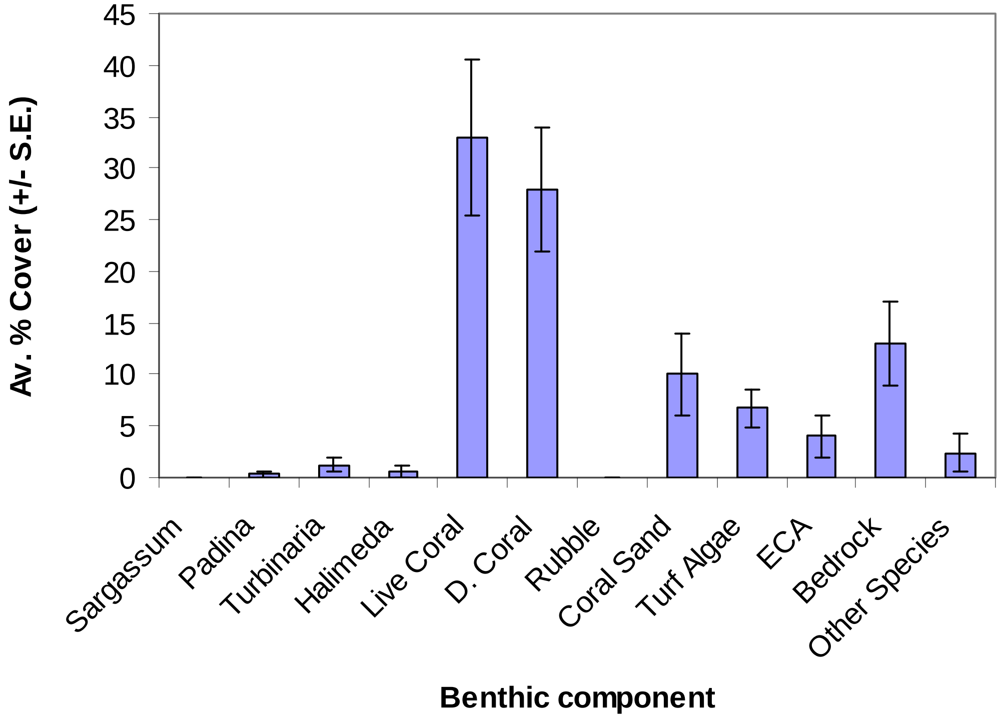



Figure 5.9c Abundance (av. % cover +/- SE) of the main benthic components on Namada Transect (sub-site) 3 – January, 2004.

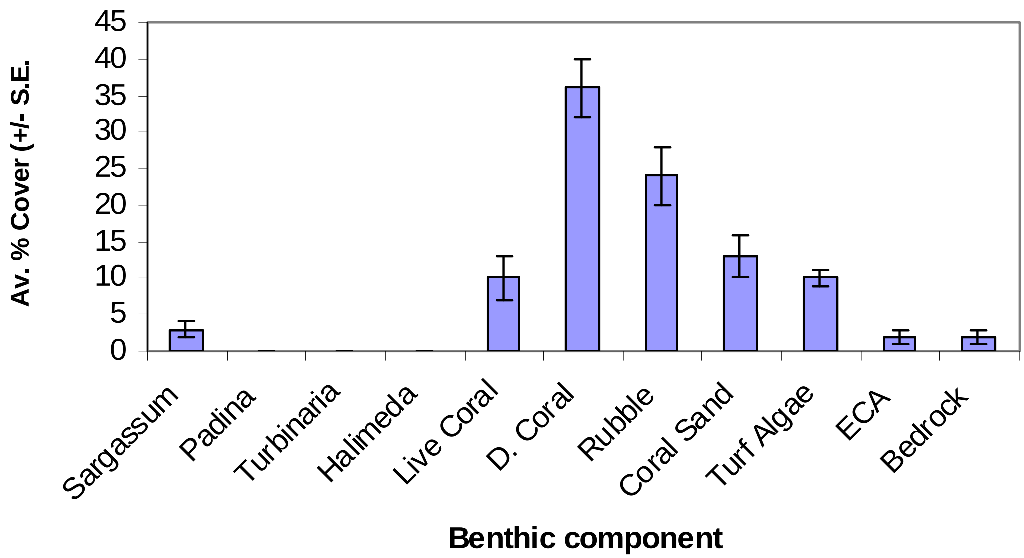



Figure 5.9d Abundance (av. % cover +/- SE) of the main benthic components on Namada Transect (sub-site) 1 – December 2005

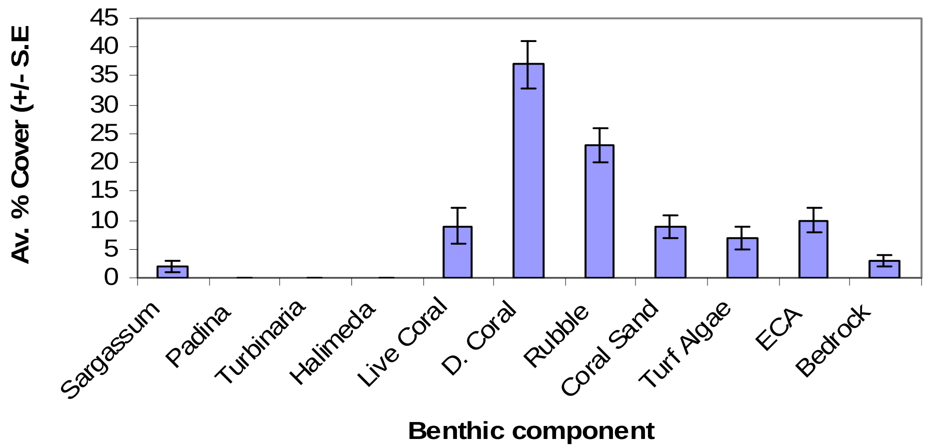



Figure 5.9e Abundance (av. % cover +/- SE) of the main benthic components on Namada Transect (sub-site) 2 – December 2005.

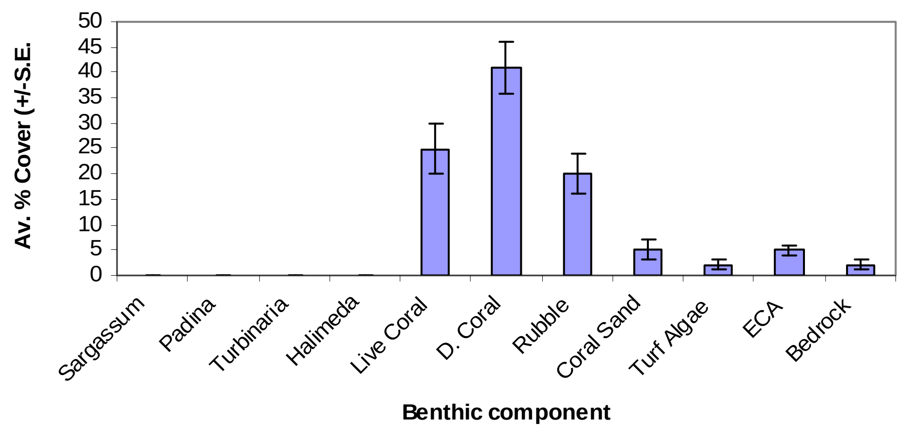



Figure 5.9f Abundance (av. % cover +/- SE) of the main benthic components on Namada Transect (sub-site) 3 – December 2005.

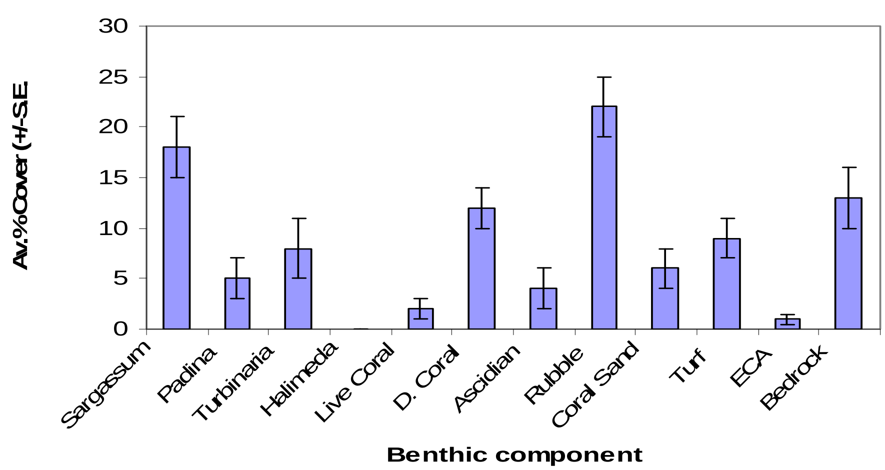



Figure 5.9g Abundance (av. % cover +/- SE) of the main benthic components on Namada Transect (sub-site) 1 – July 2006.

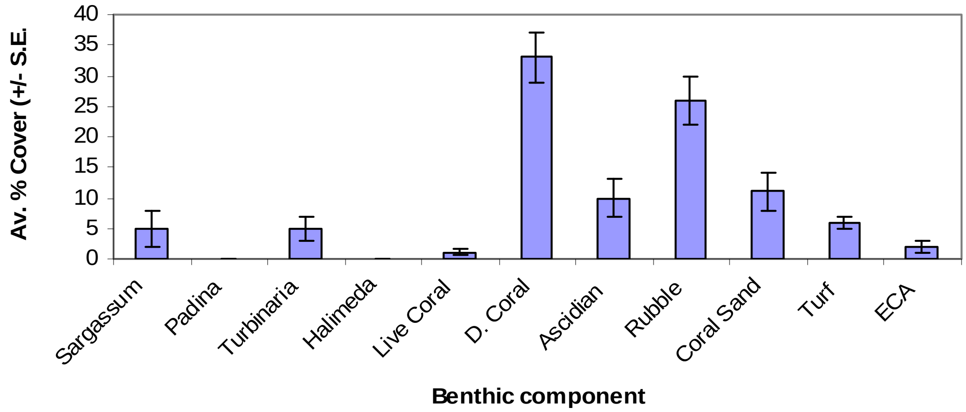



Figure 5.9h Abundance (av. % cover +/- SE) of the main benthic components on Namada Transect (sub-site) 2 – July 2006.

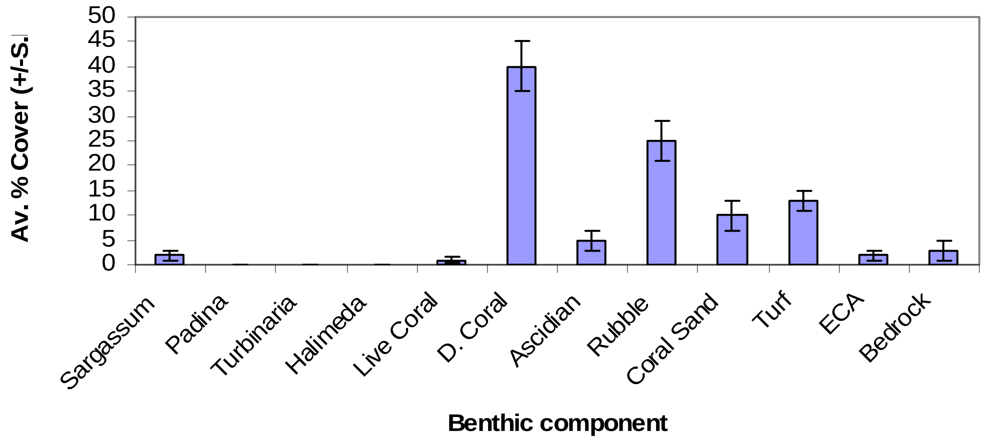



Figure 5.9i Abundance (av. % cover +/- SE) of the main benthic components on Namada Transect (sub-site) 3 – July 2006.

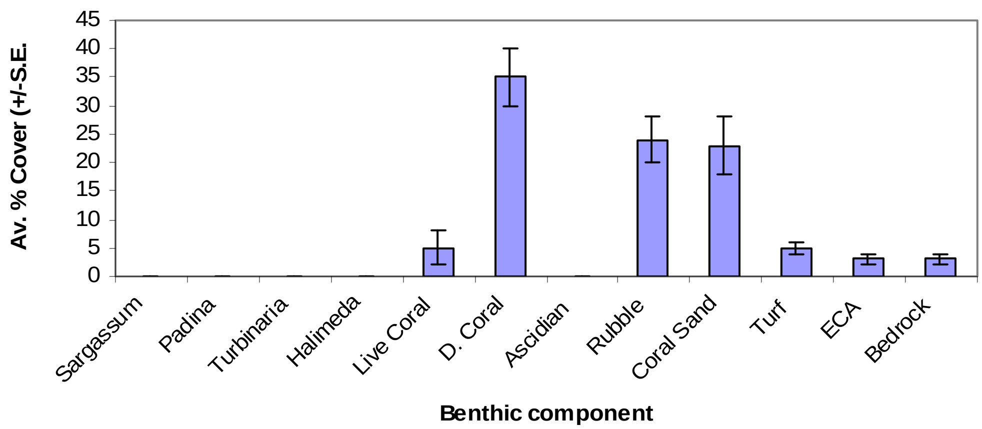



Figure 5.9j Abundance (av. % cover +/- SE) of the main benthic components on Namada Transect (sub-site) 4 – July 2006.

#### 5.3.4.3.1 Discussion of spatial variation in benthic communities between control and impacted sites/across transects at Namada

The January 2004 results (Fig.. 5.9a – Fig. 5.9c) for the Namada Reef survey showed a clear pattern of variation as one moved away from nutrient sources (from east towards west), as well as moving across transects. The influence of the S.E. Trade Winds and the westerly flowing long-shore currents appeared to be important in the spatial patterns of distribution of *Sargassum* during the January survey. Transect 1 was laid out on a partly raised platform running perpendicular to the shoreline. It appeared that the raised platform supported the survival and growth of *Sargassum* sp., most probably because of the trapped nutrients carried by the currents. The high % cover of *Sargassum* sp. may also be reflecting the seasonality of growth for this species (Fig. 5.9a). The most notable change observed on moving from east towards the west was the decrease in *Sargassum* cover from 50 % in Transect 1 (Fig. 5.9a), to 0 % in Transect 2 (Fig. 5.9b) and Transect 3 (Fig. 5.9c). Live coral cover on the other hand increased from 8% in Transect 1 (Fig. 5.9a) to 16 % in Transect 2 (Fig. 5.9b) and on to 33 % in Transect 3 (Fig. 5.9c). The decrease in *Sargassum* cover may be attributed to a number of factors: the possible reduction in nutrient concentrations as one moved away from the sources, and also the likelihood of increased herbivore activity controlling the macroalgae in the deeper part of the lagoon.

The three transects surveyed on 17 December 2005 were laid out as in the January survey: Transect 1 was located east of Namada Village, and moving west, Transects 2 and 3 were located in the deeper parts of the lagoon and further west of Transect 1(Fig. 5.9d – Fig.5.9f). The changes observed during the January 2004 survey were again seen in the December 2005 results; on moving from east to west, the frondose macroalgae such as *Sargassum* and *Padina* disappeared and live corals generally increased (10% to 25%). High coverage of dead coral (36%, 37% and 41%) was observed in all transects. Unlike other sites, there was no evidence of macroalgae colonization, even in summer (normally the peak growth period). This may be evidence to support the effectiveness of the 'tabu' in enhancing herbivore control on the macroalgae.

The survey conducted in July 2006 also involved placing the transects in order from east to west. Transect 1 was closest to sources of nutrient (Tambua Sands Resort and the creeks draining the village and the resort), and Transects 2, 3 and 4 move progressively away from the sources. The July 2006 survey showed similar results to the other two surveys, with respect to the macroalgae, in that they decreased in abundance from Transect 1 (Fig. 5.9g) towards Transect 4 (Fig. 5.9j), i.e., from east to west. As discussed above, this pattern appeared to coincide with distance from the nutrient sources on the east. However, unlike the earlier surveys, which showed increasing cover of live corals towards the west, this time, the live coral cover was low throughout, from 2 % in Transect 1 to 5 % in Transect 4. At the same time, there should be concern as the dead coral cover and rubble cover dominated the benthos, with high % cover (from about 20 – 40 %). In fact, dead coral and rubble together accounted for about 50 % of the benthic components. The fact that macroalgae such as *Sargassum* have not colonized the available substrate may be due to intense herbivory in the lagoon. Another possible explanation could be the low growth of the species during July, in the middle of the Cool season. The results appeared to support the concept that macroalgae do not outcompete live corals to bring about reef degradation or a phase shift. Rather, other stress factors such as nutrient enrichment may be killing off live corals before the macroalgae take over, utilizing the available, suitable substrate.

#### 5.3.4.4 Spatial variation in benthic components along transects at Namada Reef

The situation at Namada is such that the inshore waters and lagoon are protected to a certain extent by the relatively steep beach profile, the buffering effects of coastal vegetation and the distance between the village and the sea. In fact, live corals were observed within a few meters from the HWM at Namada. As before, the benthic communities at each station along the transects are compared, to assess patterns of benthic variation from the HWM towards the reef crest.

All of the results from the three surveys are presented followed by a brief discussion. The January 2004 survey results are shown in Figures 5.10a – 10c. The results for

December 2005 are shown in Figures. 5.10d – 10f, and the results for July 2006 are shown in Figures 5.10g – 10j.

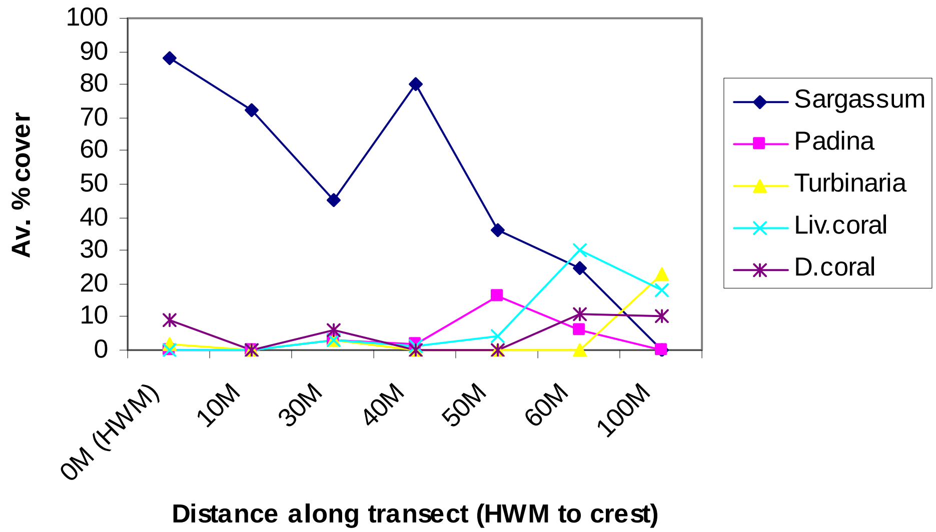



Figure 5.10a Spatial variation in benthic communities along Transect 1 - January 2004 on Namada Reef.

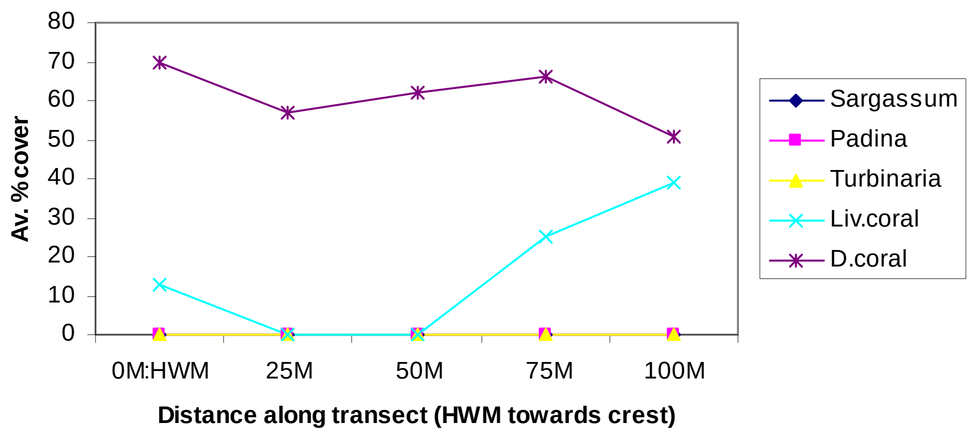



Figure 5.10b Spatial variation in benthic communities along Transect 2 - January 2004 on Namada Reef.

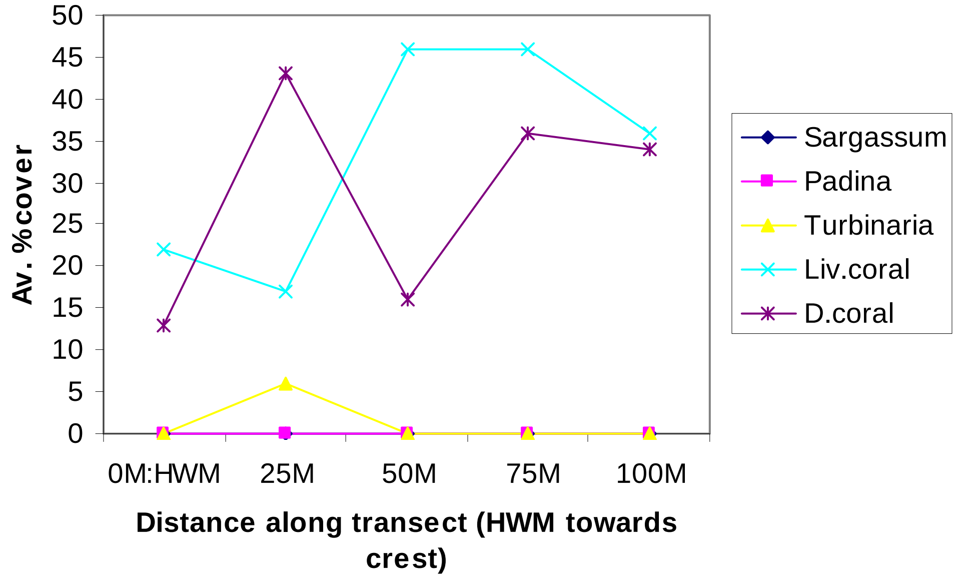



Figure 5.10c  Spatial variation in benthic communities along Transect 3 - January 2004 on Namada Reef.

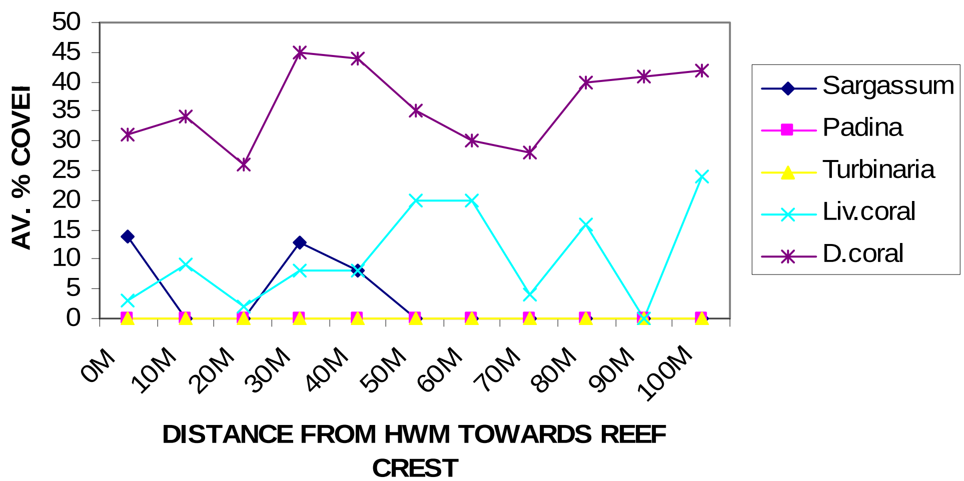



Figure 5.10d  Spatial variation in benthic communities along Transect 1 – December 2005 on Namada Reef.

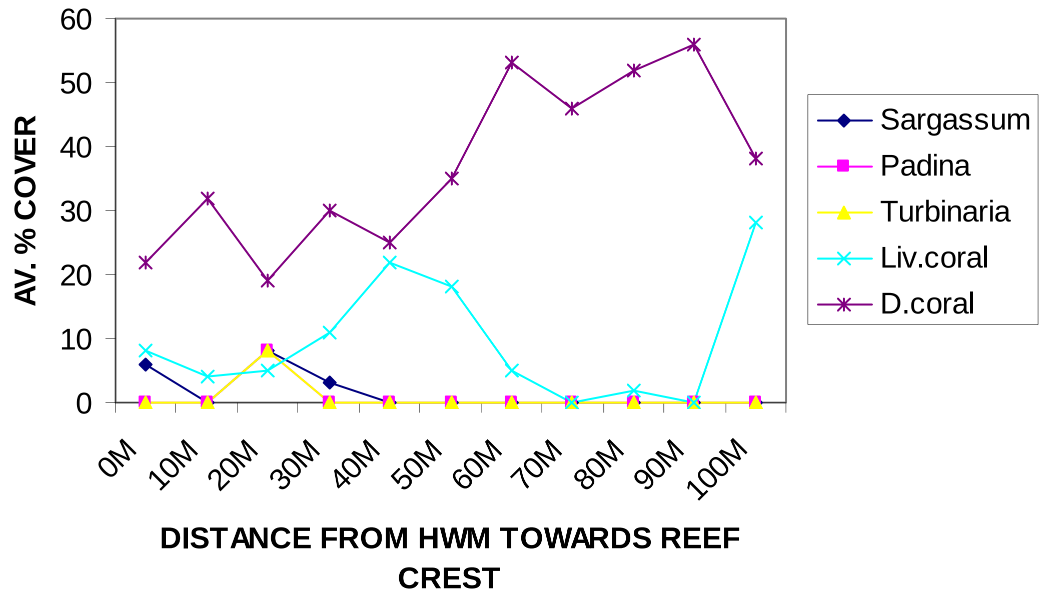



Figure 5.10e  Spatial variation in benthic communities along Transect 2 – December 2005 on Namada Reef.

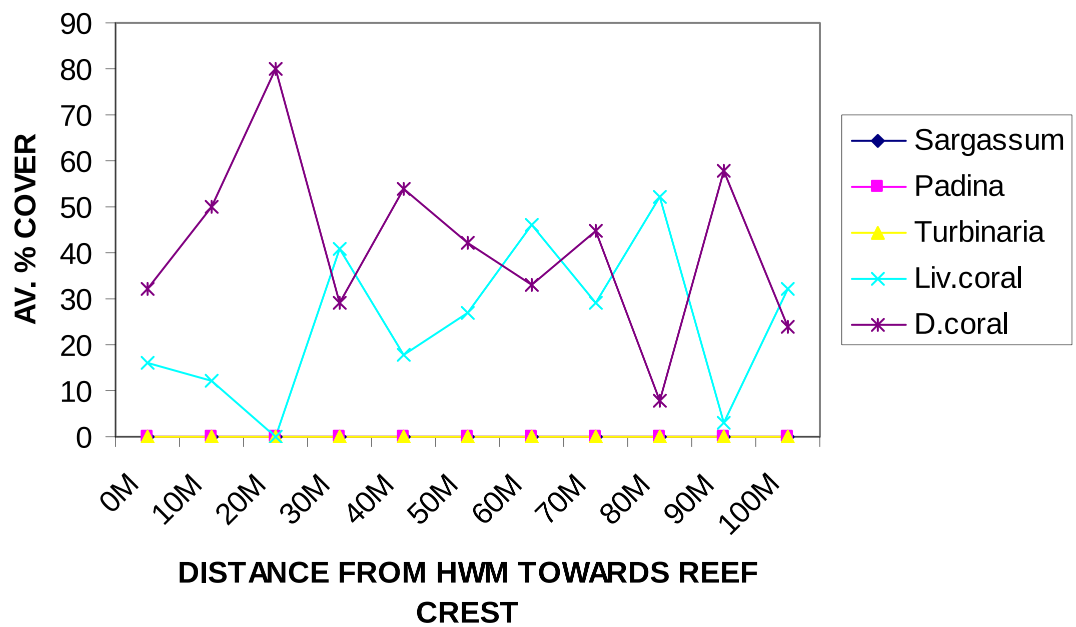



Figure 5.10f Spatial variation in benthic communities along Transect 3 – December 2005 on Namada Reef.

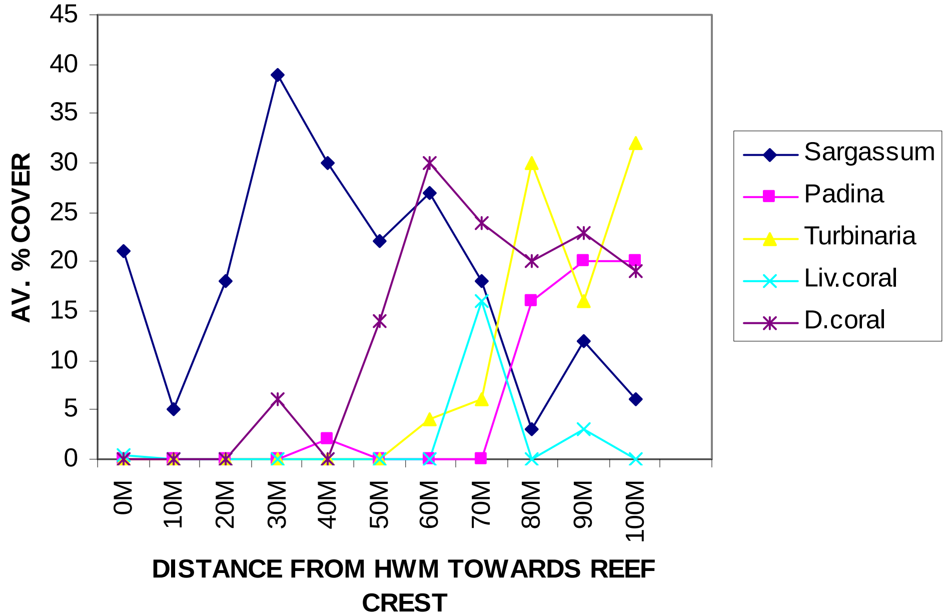



Figure 5.10g  Spatial variation in benthic communities along Transect 1 – July 2006 on Namada Reef.

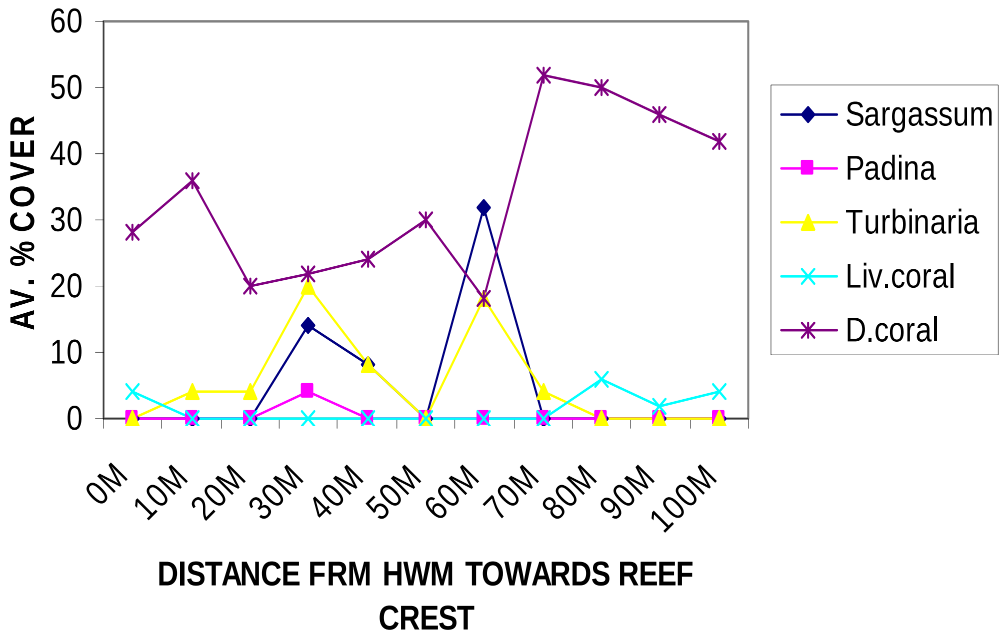



Figure 5.10h  Spatial variation in benthic communities along Transect 2 – July 2006 on Namada Reef.

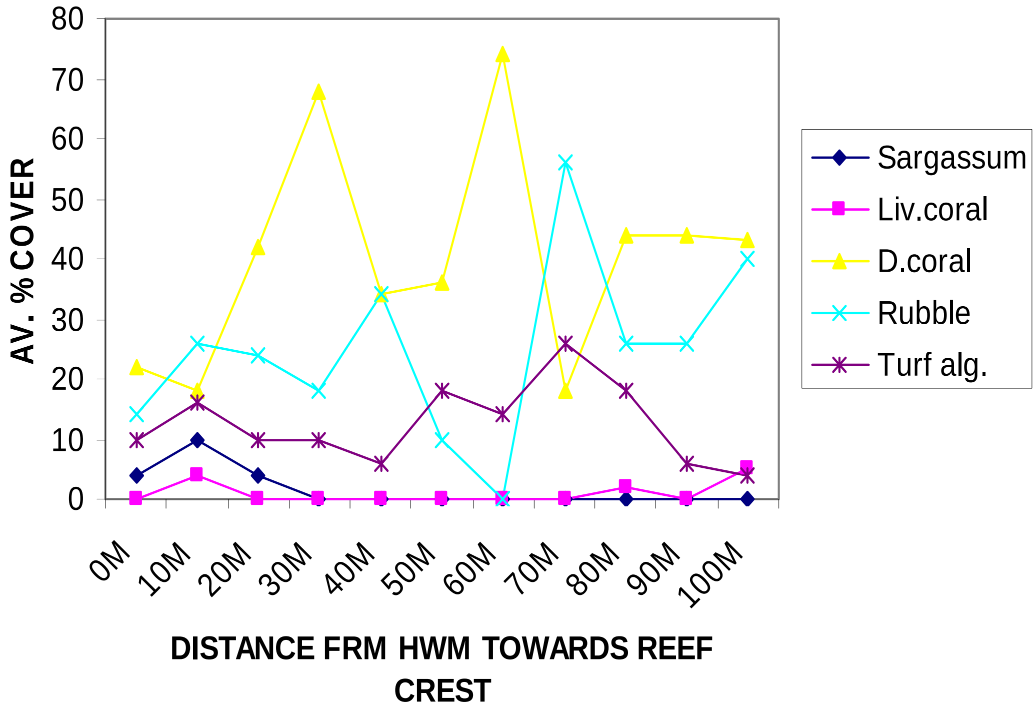



Figure 5.10i Spatial variation in benthic communities along Transect 3 – July 2006 on Namada Reef.

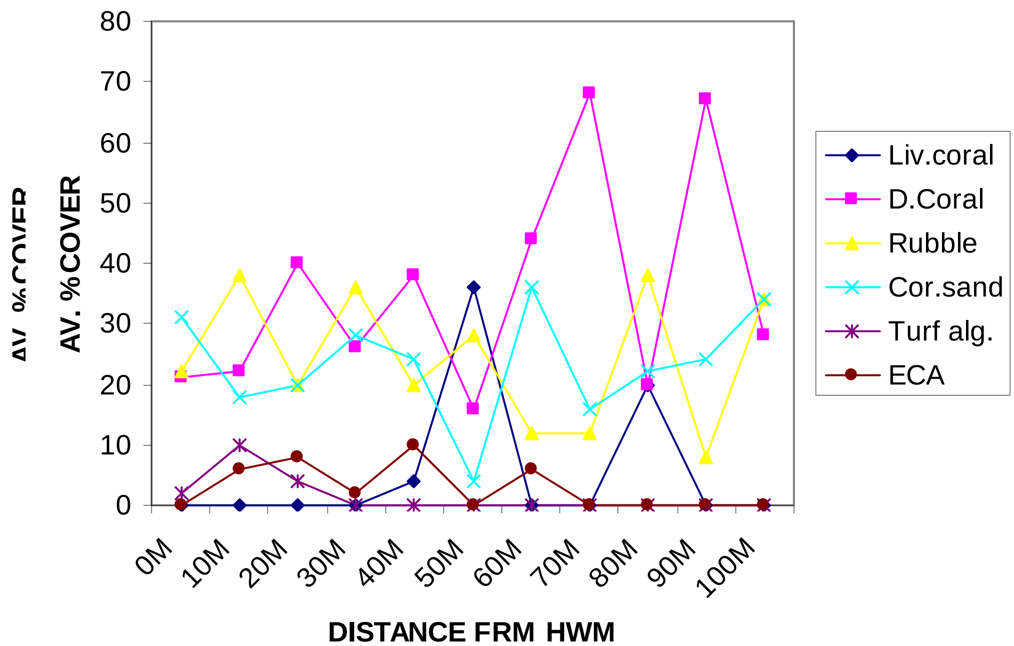



Figure 5.10j Spatial variation in benthic communities along Transect 4 – July 2006 on Namada Reef.

#### 5.3.4.4.1 Discussion of general patterns of spatial variation in benthic communities along transects, from HWM towards the reef crest.

The general pattern found for the other sites was also found at Namada Reef, i.e., the macroalgae were confined to shallower waters and closer to shore (Figure 5.10a). Live corals were found further along the transects away from the HWM, except for Transects 2 and 3 within the lagoon, where live corals were also found nearer to shore. The July 2006 results showed the extensive distribution and increasing prominence of dead corals and rubble, while live corals became less prominent (Figures 5.10h – j). This should be warning that the reef at Namada is becoming degraded, despite the imposition of the ‘tabu’. This situation calls for more action in monitoring and controlling the nutrients, and possibly suspended solids in the water column. Activities such as coral harvesting that was occurring on reefs to the west of Namada, may need to be monitored as these are likely sources of nutrients in the water column.

#### 5.3.4.4.2 General conclusions on status of Namada reef

The Namada reef and lagoon are potential havens for live corals because of a number of natural features already discussed: the relatively steep profile of the beach; the distance between the beach or lagoon and the village itself and the existence of coastal fringe of vegetation which act as barriers, to dilute or reduce effects of pollution generated in the village; and the raised reef platform on the eastern end of the village, which acts as a physical barrier to nutrients carried by westerly-flowing currents. The belt of *Sargassum* on this platform helps to take up nutrients from the water prior to entering the lagoon. The ‘tabu’ appeared to be having an impact on macroalgae in the lagoon by increasing the numbers of herbivorous fish. However, nutrient sources need to be identified so that the degradation of the corals may be reduced and actually reversed.

#### 5.3.4.5 General Patterns of Distribution and Abundance of Sargassum and Live Coral – an overview

As an overview of some of the clear patterns of distribution of *Sargassum* in contrast with live corals for the three main categories of sites surveyed, the results are presented in Figures 5.11a to 5.11c. There was overall dominance of *Sargassum* on inner reef flats close to resorts (Figure 5.11b), while at the same time, live corals were virtually absent. In contrast, the control sites showed low abundance of *Sargassum* but resonable abundance of live corals (Figure 5.11a).

The Namada reef which had been set aside as a 'no take' or 'tabu' site showed very interesting results (Figure 5.11c). The Namada Reef is discussed in detail in Section 5.3.4. As has been found in other studies, there is a clear inverse relationship between abundance of live corals and *Sargassum* (McCook, 1999). The same patterns of distribution were observed for the study sites along the Coral Coast (Figures 5.11a to 5.11c).

While most of the results were as expected, there were some exceptions. Naqau (NAQ), which was selected as a control site due to its relative isolation from any large village or resort on land, recorded relatively high abundance of *Sargassum* and low cover of live corals. This site recorded some of the highest nutrient concentrations that were unexpected for a control site (see Table 4.16), and the sources appeared to be the Komave Creek updrift of this site. This result indicated that the currents and flow regime in the inshore coastal waters play an influential role in the distribution of benthic species such as *Sargassum*.

The abundance of *Sargassum baccularia* is compared with that of live corals in the control sites (Fig. 5.11a), in the resort sites (Fig. 5.11b) and in the village sites (Figure 5.11c). On the graphs, the sites are represented by their codes, and the sampling dates are given by month and year, for example, JUL06 means July of 2006. The number after the date represents the transect number.

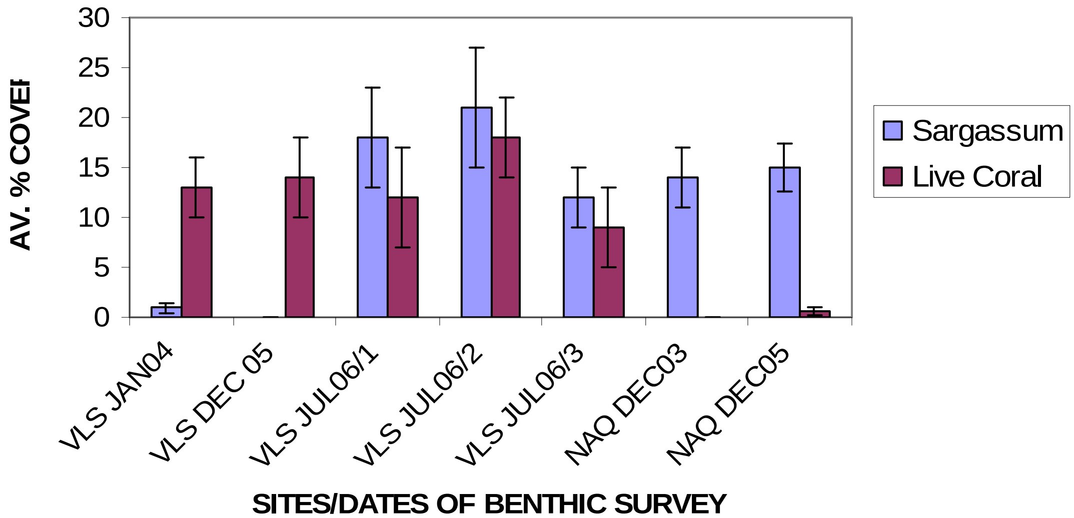



Figure 5.11a Comparison Between *Sargassum* and Live Coral Cover for Control Sites.

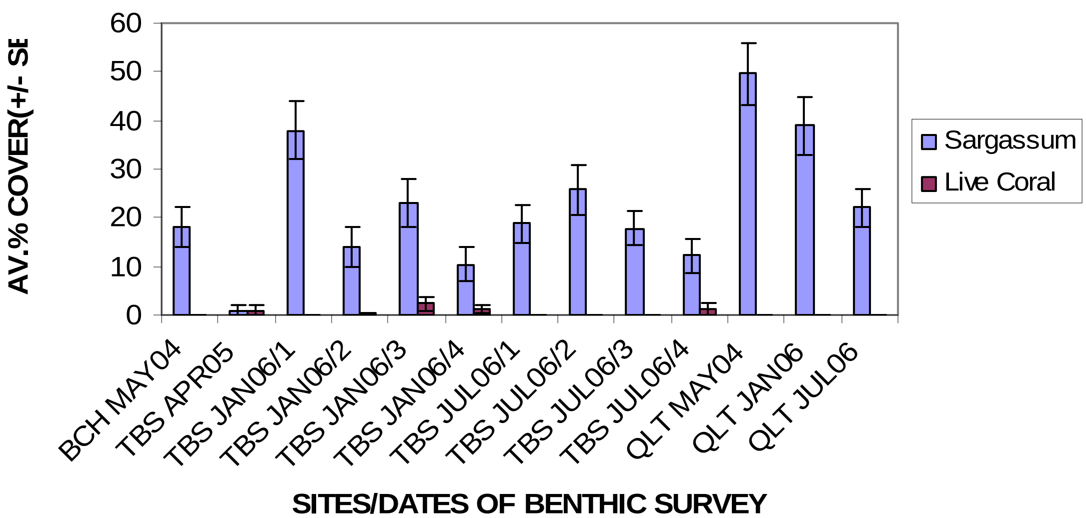



Figure 5.11b Comparison Between Sargassum and Live Coral Cover for Resort Sites.

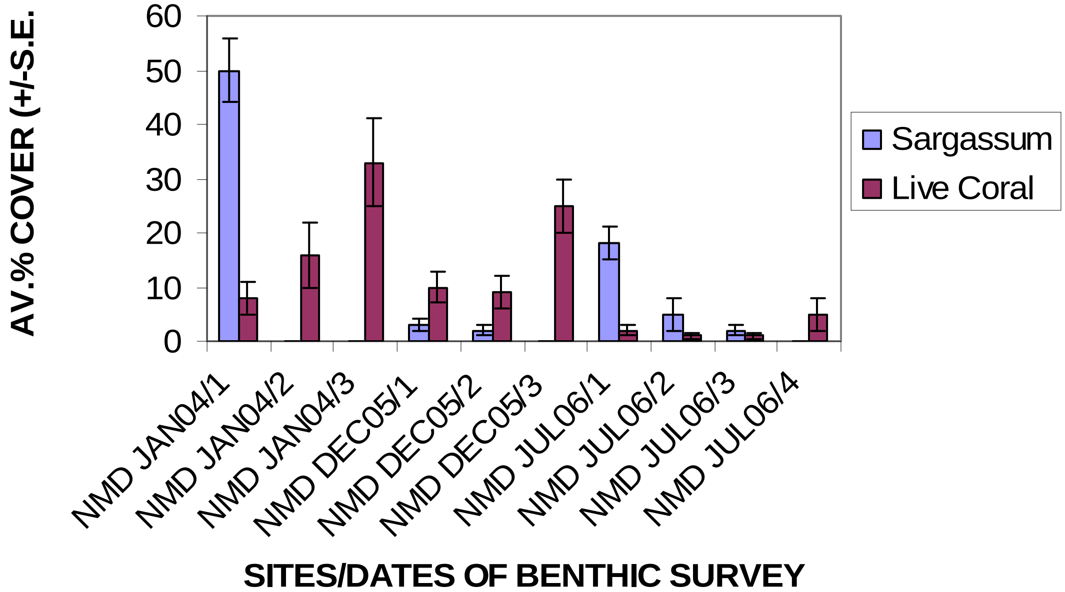



Figure5.11c Comparison Between Sargassum and Live Coral Cover for a Village/Tabu Site (Namada).

#### 5.3.4.6 General Discussion and Conclusions

In response to the research questions posed at the beginning of this chapter, the results of the surveys conducted on various reefs along the Coral Coast do show that there was a great deal of variability in the status of the reefs. The reefs at Valase represented a relatively unimpacted reef recording low macroalgae cover and a fair abundance of live corals, until recently when the new Valase Backpacker resort and the new Maui Bay Resort were built. On the whole, the reefs are being exposed to a number of different stress factors: nutrient enrichment from land sources; new development involving clearing of the coastal vegetation and construction of new buildings; ill-conceived plans such as the wastewater pipeline from the Warwick Resort; and, coral harvesting in some parts of the reefs.

However, there appeared to be clear patterns of benthic variation:

- *Sargassum* dominated reefs exposed to nutrient-enriched waters (e.g., Qalito)

- Live corals on the other hand abounded in relatively pristine waters further away from land sources, or further west and downdrift from nutrient sources (Namada Transects 2 and 3 in January 2004 and December 2005).
- Having a 'tabu' appeared to be effective in controlling macroalgae, even though suitable subtrate was available (Namada Transects 2 and 3, July 2006).
- However, having a 'tabu' did not fully protect the corals as live corals decreased while dead coral cover and rubble increased.

## 5.4 GENERAL CONCLUSIONS THAT ARISE FROM THE ECOLOGICAL STUDY INCLUDE:

- Overall, the status shows a set of reefs that have been impacted for a prolonged period of time, and the corals have been exposed to varying degrees of stress by a number of different factors – sediment, particularly in rivers and creeks after heavy rain; nutrient enrichment from a number of sources on land, especially sewage; increased water temperatures and exposure to direct sunlight; and the increasing human population all along the coast. Increasing human populations in coastal villages meant an increase in fishing intensity, as fishing and gleaning on the reefs were still popular, as alternative sources of income and for subsistence use. More recently though, in the last 2-3 years, there has been an increase in the number of pig-pens, privately owned by the villagers and located next to creeks and rivers. In the absence of concrete evidence at the moment, the most probable explanation for this trend is the search for alternative sources of income by the communities due to increasing financial hardship through limited employment opportunities.

- Spatial variation is generally high, even within a few meters, there can be very different communities. This is often an indication of a reef under stress. The example of the three transect/sub-sites at Namada village shows how the nutrients, probably from the Tabua Sands resort, and the main creeks located to the east of Namada, may be responsible for the dense mats of *Sargassum* sp between these two impact sources, making way for live coral growth in the shallow lagoon just in front of the village. Interestingly, the dense mats of *Sargassum* occupied an uplifted reef platform, in areas relatively shallower than the rest of the reef flat area at Namada.

- The degradation of the fringing reefs along the Coral Coast is evident by the increasing numbers of dead corals while the number of living corals decreased. This can be seen when comparing % cover of dead corals and live corals over time, for example, for Namada Reef Flats (see Figures 5.9c, 59f and 5.9i). While these changes were occurring for the corals, there was simultaneous changes occurring with the macroalgae, i.e., as live corals died out and dead corals increase, the % cover of *Sargassum* also increased.

- There are clear patterns emerging – where live corals thrive, macroalgae are not present (Namada transects/sub-sites 2 and 3, 2005). Where there is clear sewage pollution, *Sargassum* sp. dominates the flora and *Synapta* dominates the fauna. At Qalito, where the sewage pipeline from the Warwick resort passes only 58 m from the shore, this is the case.

- The macroalgae *Sargassum, Padina* and *Turbinaria* appeared to be more abundant on the bedrock or dead coral heads closer to shore. This pattern of distribution may be a consequence of higher concentrations of nutrients nearer to land, and also the lower frequency of herbivory activity, because at low tides, much of this area is too shallow for fish to swim or feed. In contrast, further away from land, these macroalgae become less abundant, and again the reasons may be due to decreased concentrations of nutrients in the water column, as well as the fact that in these deeper parts of the reef flat, herbivory activity was more intense, acting a a top-down control on the macroalgae. In place of the frondose macroalgae, the turf algae and encrusting, coralline algae appeared to dominate cover of the dead coral heads, as well as the bedrock material where it was exposed.

- The results of this research appeared to indicate that *Sargassum* has greater tolerance for higher concentrations of nutrients, compared to the other brown macroalge *Padina* and *Turbinaria*, both of which were also common in the study area. This can be seen in the patterns of distribution of these three macroalgal species, i.e., when *Sargassum* species dominated, the other two species *Padina* and *Turbinaria* decreased, and vice versa. These three macroalgae require firm and compacted substrate material as found in bedrock (coral limestone material that makes up the reef flat sections of fringing reefs), dead coral heads and to some extent rubble material compacted or cemented together by encrusting corraline algae (ECA). On the basis of this, it can be implied that a major portion of the fringing reef is a potential habitat for macrolgal proliferation. The exceptions are the sandy areas and the live corals.

- There was clear dominance of *Sargassum* in areas close to resorts and villages, provided the substrate was suitable, i.e., dead coral heads (*Porites*) or hard coralline bottom, e.g., at Qalito settlement, Namada village site 1 (between the village and Tabua Sands resort.

- There was little or no *Sargassum* in sites far from human population centres, even if the substrate was suitable, e.g., at Valase (VLS). Unfortunately, even at this site, benthic community structure  was found to be  changing, as more and more houses were being built on land.

- There appears to be clear positive relationship between nutrient enriched sites and the presence of the brown macroalgae *Sargassum*. At the same time, the results of this research appear to indicate that as one moves further offshore, the abundance of *Sargassum* decreases (see Spatial Variation Along the transects at Valase, Namada). This pattern of variation can be explained by two reasons at least:
    1. concentrations of nutrients decreased further away from land sources;
    2. in deeper waters, the activity of herbivorous fishes and other invertebrates such as sea urchins probably also increased.

- The results of this research also indicated that as one moves downdrift, or westerly from the nutrient source whether it be a village, a resort, a creek or river estuary, the abundance of *Sargassum* quickly decreases (see Section 5.3.2.5.1; Section 5.3.4.3.1). Perhaps the more obvious explanation for this pattern of *Sargassum* distribution is the decreasing concentrations of nutrient due to dilution, dispersion, and uptake by other primary producers in the water column. It must be noted, however, that in some sites, the tidal currents in combination with the location of the nutrient sources (village, resort or creek/river) and reef passages may actually cause the flow to be in an easterly direction, for example, at East Warwick (EWRC) and at Naqau (NAQ). The relatively high abundance of *Sargassum* at Naqau may well be due to easterly flowing currents moving nutrients from the Warwick Resort.

- The significance of herbivory as the top-down control on the abundance of macroalgae can be seen in the case of Namada Reef Flat benthic survey data (Figures 5.9h, 5.9i and 5.9j). At Namada, the fringing reef and the inshore lagoon in front of the village had been declared as 'tabu' or no-take zone since 2002. The results of the survey at Namada Reef and lagoon show very low abundance of the macroalgae *Sargassum* and also *Padina.* An important factor here also is the depth of the lagoon, i.e., the deeper the lagoon, the higher the probability of herbivory having a significant effect on the macroalgae, i.e., provided the herbivorous fish and invertebrates are present in relatively significant numbers.

The results of the benthic surveys on the Coral Coast fringing reefs on the whole, show some similarities to features observed on other reefs exposed to anthropogenic impacts (McCook *et al*., 1997; Schaffelke and Klumpp, 1998), but at the same time, the three surveyed sites (Valase, Qalito and Namada) provided unique lessons specific to each situation.

# CHAPTER 6 – EXPERIMENTAL INVESTIGATIONS ON NUTRIENT ENRICHMENT, HERBIVORE-EXCLUSION, NUTRIENT CONTENT AND $^{15}N$ CONTENT OF MACROALGAE LEAVES FROM THE CORAL COAST, FIJI.

This chapter presents the results from a number of additional experimental investigations and targeted laboratory and field experiments, conducted to assess how nutrient enrichment affected the macroalgae *Sargassum baccularia*, and whether herbivory was an important factor to consider in the complex interactions among coral reef communities along the Coral Coast. The introduction includes a brief literature review of the subject before each experiment is discussed. Each experiment has a specific objective, which is outlined at the beginning of each sub-section. In addition to the experiments, a one-off study was conducted to assess nutrient content of *Sargassum baccularia* collected from some of the study sites. In the final section of this chapter, a study to investigate concentrations of the $^{15}N$ isotope in *Sargassum baccularia*, and a few other species, is described and discussed.

## 6.1 INTRODUCTION

The increasing degradation of coral reefs in the last thirty years has prompted scientists to investigate the influence of 'bottom-up' controlling factors, and the 'top-down' controls, on the various groups of species found on coral reefs (Valiela *et* al., 1997; Smith *et* al., 2001; Thacker *et* al., 2001; Littler *et al*., 2006). The Relative Dominance Model (RDM, see Figure 2.3), which was first put forward by Littler and Littler (1984a), shows how the bottom-up controls such as nutrients, interact with top-down controls such as herbivory, to determine the relative abundances of the most common of coral reef species namely corals, crustose coralline algae or encructing coralline algae (CCA or ECA), the low growing turf algae, and the larger frondose macroalgae such as *Sargassum* (Littler *et al.*, 2006).

The role of nutrients as one of the main bottom-up controlling factors for coral reef communities has been extensively researched (e.g., Lapointe, 1997; Schaffelke and Klumpp, 1998; Fong *et al*., 2004; Raikar and Wafar, 2006). Some of these studies focused on the influence of nutrients on corals (e.g., Steven and Broadbent, 1997;

Koop *et al*., 2001), while others focused on the role of nutrients on the various groups of algae. The species of interest in this research is *Sargassum* and the experiments are based on this species.

This chapter has four sections based on the following experimental investigations:

- Nutrient enrichment and its effects on *Sargassum baccularia* growth in laboratory studies;
- Herbivore exclusion by caging, nutrient enrichment in the field, and the influence of these factors on survival and growth of *Sargassum baccularia* and *Turbinaria* sp. ;
- Nutrient content in tissues of *Sargassum baccularia;* and
- $\delta^{15}N$ of *Sargassum baccularia* from study sites along the Coral Coast, as a means of assessing the extent of sewage pollution.

## 6.2 Effects of nutrient enrichment on growth of *Sargassum baccularia* – a laboratory-based experimental investigation

### 6.2.1 Introduction

Fong *et al*. (2003) described the use of nutrient enrichment experimentation as being the only direct method of assessing nutrient limitation for macroalgae. The use of water column nutrient concentrations, and tissue nutrient concentrations are indirect methods (Fong *et al.*, 2003). Based on the atomic composition of phytoplankton (106C : 16N : 1P), the concentrations of nitrogen and phosphorus in the water column are assessed against the ratio 16 : 1 (Redfield-Richards ratio), and if N : P is < 16, then nitrogen is limiting biological primary productivity. Conversely, if the N : P in the water column is > 16, then phosphorus is limiting primary production (Redfield *et al*., 1963). There are limitations in using the water column N : P ratio to assess nutrient limitation for macroalgae productivity, especially for tropical environments where nutrients are usually delivered to the marine environment in pulses, associated with storm or cyclone events during the wet season (Schaffelke & Klumpp, 1998; McCook, 1999). Water column nutrient concentrations only provide a snapshot in time of the situation (Fong *et al*., 2003).

The success of *Sargassum* as an invasive species has been recognised by many researchers (e.g., Lapointe, 1995). The 'Sargasso Sea' in the North Atlantic Ocean got its name from the sea of floating seaweed, *Sargassum* that characterizes the area, since from the days of early explorers. In Australia, the increasing presence of this macroalgae on the inshore reefs of the GBR has led to several studies on this macroalgae (e.g., McCook *et al.*, 1997; Schaffelke & Klumpp, 1998). Vuki and Price (1994) studied *Sargassum* sp. on a fringing reef in the GBR region, to examine factors that may be causing the observed seasonality of this species. In Fiji, the fringing reefs along the Coral Coast are also being invaded by *Sargassum* sp. In all of these cases, nutrient enrichment of the water column by anthropogenic causes has been seen as one of the main contributing factors, i.e., a bottom-up controlling factor. Questions arise as to which particular nutrients, and what concentrations, enhance *Sargassum* growth. These questions have been addressed through experiments both in the field and in laboratories. Schaffelke and Klumpp (1998) found that the growth rate of *Sargassum baccularia* almost doubled within the narrow window of nutrient concentrations from 3 *u*M ammonium plus 0.3 *u*M phosphate to 5 *u*M ammonium plus 0.5 *u*M phosphate. Interestingly, outside of this window, the growth rate was reduced (see Fig. 5.1).

The experiments conducted by Schaffelke and Klumpp (1998) utilised continuous flow cultures, and so uptake of nutrients by the experimental *Sargassum baccularia* shoots was determined by the difference in nutrient concentrations between inflowing medium and outflowing medium. In the absence of such equipment, the current experiment involved extracting a small aliquot (5 mL, enough to fill the sample vial in the FIA), from the experimental jars at specified times.

The objective of this experiment was to compare growth responses in *Sargassum* shoots and rhizoids, under different treatment conditions. The reason for using rhizoids in the experiments was to avoid errors in measurement arising from loss of leaves during the experiment, as was found by Schaffelke and Klumpp (1998). Field observations also showed that while the distal, leafy shoots may be experiencing 'die-back' in the cooler months, the rhizoids of the *Sargassum* appeared to be intact and flourishing among the crevices of the substrate.

### 6.2.2 Pilot Study - Background

A pilot study was carried out to help in the design of the main experiment.

The initial tissue nutrient content of macroalgae affected their responses to nutrient enrichment (Fong *et al.*, 2003), and plants close to nutrient sources (e.g., sewage outfalls) were enriched and did not respond as strongly as those algae with depleted tissue nutrients (collected from sites further away from sewage sources). The algae with nutrient-depleted tissues responded to nutrient enrichment experiments by greater uptake of nutrients, and even uptake of dissolved organic nitrogen (DON) from the water, leading to increased tissue N. On the other hand, the algae with enriched tissues appeared to 'leak' ammonia into the water (Fong *et al.*, 2003). To control this factor, and also to determine the nutrient storage capacity of macroalgae, the experimental algae are often subjected to 'starvation', i.e., the macroalgae are kept in sea water with very little or no inorganic nutrients, while the algae sustain themselves using stored nutrients in the tissues (Schaffelke and Klumpp, 1998). The findings of Fong *et al*. (2003) may help explain the differing results from experiments or studies on nutrient limitation in macroalgae. While N is often quoted as the main limiting nutrient in macroalgae (Lobban and Harrison, 1997), it is more so for temperate environments, and P has been found to be the main limiting nutrient in some tropical environments (Lapointe, 1987, 1989, 1997). However, Schaffelke and Klumpp (1998a) found that both N and P stimulated growth of *Sargassum baccularia.* From another perspective (top-down control), McCook (1996) found that herbivory had greater influence on the distribution and abundance of *Sargassum baccularia* on the central GBR, compared to any other factor.

There is still much to be understood about nutrient limitation in macroalgae, for example, which species of N is taken up by which macroalgae species. There is a great deal of variation in this matter; some algae preferentially take up $NH_4^+$ while others take up $NO_3^-$, and others still take up either species equally well (e.g., Lotze and Schramm, 2000; Naldi and Wheeler, 2002). There is an advantage in taking up ammonium compared to nitrate. Before the absorbed $NO_3^-$ can be assimilated into tissues of macroalgae or plants in general, it must first be reduced into $NH_4^+$ by the nitrate reductase (Hurd *et* al., 1995). This step is not necessary when $NH_4^+$ is taken up by plants, and therefore, energy is saved for other metabolic processes. Cohen and Fong (2004) found in their studies with *Enteromorpha intestinalis* (L.) Link that there was preference for ammonium ($NH_4^+$) over nitrate ($NO_3^-$) in the nutrient uptake experiments.

Before conducting the nutrient enrichment experiments, it was necessary to identify the site from which experimental *Sargassum baccularia* would be selected. It was also important to test the feasibility of conducting such experiments in Fiji, given the lack of important facilities such as a continuous flow set-up (as in AIMS), or a water table by the sea for temperature regularisation in experimental aquaria (Fong *et al*., 2003), or a reliable, aeration system. The pilot study was conducted to address these needs. A pilot study consisted of two simple, short experiments described below as pilot studies A and B.

#### 6.2.2.1 Objectives of the Pilot Study A

The objective of the Pilot Study A was to ascertain if there was any difference between *Sargassum* sp. plants collected from two different sites, with regards to nutrient uptake capability. One site was continuously impacted by leaking wastewater from a pipeline from a resort (Qalito, QLT), and the other site was one of the 'control' sites (Naqau, NAQ). This was important for selecting which site the experimental *Sargassum* plants were to be collected from. Another objective of this pilot study was to assess the viability of setting up the experiments outdoors or indoors. In a similar study (Fong *et al*., 2003), the experiment was set up outdoors with jars opened for aeration, but with the jars sitting on water tables at a marine laboratory on the shore. Having the jars in contact with ambient seawater was one way of maintaining the temperature in the experimental jars near that of ambient sea water. This sort of facility was not available for the current experiment, so an alternative methodology was used.

#### 6.2.2.2 Methods of Pilot Study A

Seawater and *Sargassum baccularia* plants were collected from the two sites, Qalito and Naqau on 27 August, 2004. For ambient water nutrient concentrations, 3 replicate samples were collected and filtered on site according to standard procedures (see Section 4.2.2). At the time of collection, there were obvious effects of 'die back' of the *Sargassum baccularia* at sites which previously recorded high abundance of this macroalgae, for example, at Qalito (QLT). The month of August falls within the Cool season (May to October) in Fiji. The plants were kept in containers of seawater from their respective sites while being transported back to the laboratory.

At the laboratory, seawater was filtered and placed in small aquarium tanks (~30 x 15 x 15 cm): 4 tanks were used for the Naqau experimental set-up and 3 used for the Qalito set-up. There were only 7 tanks available at the time of this pilot study. Each tank was filled with 300 mL of filtered seawater from the sites. The 4 tanks for the Naqau set-up were for control (ambient water alone), N-enriched, P-enriched and N+P enriched experiments. For the Qalito set-up, the 3 tanks were for control (ambient water alone), N-enriched and N+P enriched experiments.

In the first experiment, about 10 *u*M N (as nitrate in $NaNO_3$) and 4 *u*M P (as phosphate in $Na_2HPO_4$) were added to the tanks. The Naqau set-up was placed on a bench in a shed, outdoor by the sea. The tanks were left open for aeration purposes, but temperature was not controlled as the tanks were sitting dry on the tables, unlike in Fong *et al* (2003). The Qalito set-up was placed indoors and aerated by pumps. One shoot was placed in each tank, with all shoots being about the same length. However the shoots were not secured, and so they floated about in the tanks. This would have been a cause of stress for the shoots and needed to be rectified in the major experimental run.

To assess uptake of the nutrients, water samples were extracted from the tanks over 3 days, and analysed on the FIA. Each day for 3 days, a sample was extracted and frozen to await analysis. At the same time, the plant shoot was removed from the tank, dabbed dry with tissues and the wet weight taken. Water was not changed during the 3 days of the pilot experiment.

#### 6.2.2.3 Results and Discussion for Pilot Study A

The changes in weights of *Sargassum* shoots, and the changes in water nutrient concentrations are shown in Tables 6.1 and 6.2 respectively.

Table. 6.1 – Changes in weights (g) of *Sargassum* shoots in Pilot Study A – August 2004

| Dates/Experiments | NAQ ( C ) | NAQ (+N) | NAQ (+P) | NAQ (+N+P) | QLT ( C ) | QLT (+N) | QLT (+N+P) |
|---|---|---|---|---|---|---|---|
| 27 Aug 2004 | 2.1 | 2.0 | 2.4 | 2.0 | 1.3 | 1.1 | 1.2 |
| 29 August 2004 | 2.1 | 2.1 | 2.5 | 2.0 | 1.4 | 1.1 | 1.2 |
| 30 August 2004 | 2.1 | 2.0 | 2.4 | 2.0 | 1.4 | 1.1 | 1.2 |

The algal shoots did not show any real change in weights (see Table 6.1). This is not surprising, as the experiment only lasted for 3 days.The response of plants to nutrient enrichment is always variable and complex (Fong *et al*., 2004; Cohen and Fong, 2004). Other reasons such as epiphytic effects, and stress from not being stationary or secured (as in the field) would have contributed to the results (Table 6.1). However, the changes in the nutrient concentrations in the tanks showed interesting results (Table 6.2).

From Table 6.2, it can be seen that nutrients were taken up by the *Sagassum* shoots in most of the tanks, as was expected. However, the responses of the *Sagassum* shoots from the two sites were very different, especially under pulse or enrichment conditions. The Naqau (NAQ) shoots showed both N and P limitation by an increased, immediate uptake of phosphate and nitrate in the enrichment experiments. For example, in the +N treatment, the nitrate concentration in the tank decreased from 11.07 to 1.70 uM in one day; and in the +P tank, phosphate concentration dropped from 4.74 to 0.33 uM (Table 6.2). Schaffelke and Klumpp (1998a) found that *Sargassum baccularia* growth was stimulated by both N and P.

An interesting observation was the response of the Qalito shoots to nutrient enrichment. Qalito is one the sites respresenting resort impacts in this research. In the Qalito control experiment (no enrichment), phosphate decreased (0.50 to 0.23 uM) but nitrate increased (0.10 to 0.90 uM), from the first (27 August) to the last analysis

(30 August). This may be an indication of nitrogen being ‘leaked’ into the medium from N-enriched algae, as was found by Fong *et al*. (2003). The results in the +N and also the +N+P enrichment tanks appeared to confirm that Qalito *Sargassum* shoots were ‘N-sufficient’ rather than being ‘N-limited’ because the concentrations of nitrate in the tanks did not decrease but remained constant at about 10 *u*M (Table 6.2). From the results for Qalito shoots, it appeared that the shoots were phosphorus-limited but nitrogen-sufficient.

While the weights of the *Sargassum* shoots did not show any change, the changes in the nutrient concentration in the water revealed critical differences between the two lots of shoots. The Naqau shoots from a ‘control’ site showed both N and P limitation, while those from Qalito (an impacted site) showed P-limitation but N-sufficiency. The behaviour of the shoots appeared to be reflecting the environments in which they grow. This pilot study showed the significant influence of nutrient content of experimental plants (which depends on ambient water nutrient concentrations) on nutrient uptake during pulse events.

Another observation from the experiment was the effect of epiphytic growth on the stalks of the *Sargassum* shoots. Interestingly, epiphytes were only observed on the Naqau experimental shoots set up outdoors, where they caused weakening of the stalks. They were absent from the shoots in the Qalito set-up indoors. The outdoor set-up was exposed to allow natural aeration (Fong *et al*., 2003), but it enhanced evaporation and led to concentration of the nutrients in the tanks. These issues were addressed in the second Pilot Study (B) and also in the main experimental run (C ).

The lessons learnt from pilot study A were:

- The experimental tanks should not be left open and exposed for aeration, especially in the warm temperatures of Fiji, and in the absence of a conditioning facility such as a water table for maintaining temperatures in the tanks (Fong *et al*., 2003).
    - Lesson: All experiments to be set up indoors, with access to light and aerated by peristaltic pumps.

Table 6.2 – Nutrient concentrations (*u*M) in experimental aquarium tanks – Pilot study A.

| **Date/ Site/Treatment** | 27 Aug '04 Ambient | 27 Aug '04 | 28 Aug '04 | 29 Aug '04 | 30 Aug'04 |
|---|---|---|---|---|---|
| NAQ (CONT.) **PO4** | 0.68 | 0.68 | 0.03 | 0.21 | 0.11 |
| NAQ (CONT.) **NOx** | 0.86 | 0.86 | 0.43 | 1.34 | 0.71 |
| NAQ (+N) **PO4** | | 0.65 | 0.04 | 0.26 | 0.09 |
| NAQ (+N) **NOx** | | 11.07 | 1.70 | 0.21 | 0.57 |
| NAQ (+P) **PO4** | | 4.74 | 0.16 | 0.43 | 0.33 |
| NAQ(+P) NOx | | 1.00 | 0.07 | 0.14 | 0.29 |
| NAQ (+N+P) PO4 | | 4.80 | 0.15 | 0.37 | 0.34 |
| NAQ (+N+P) NOx | | 4.90 | 7.60 | 16.00 | 8.90 |
| **QLT(CONT.) PO4** | 0.50 | 0.50 | 0.07 | 0.09 | 0.23 |
| **QLT(CONT.) NOx** | 0.01* | 0.01 | 0.14 | 13.90 | 0.93* |
| **QLT(+N)** PO4 | | 1.80 | 0.06 | 0.09 | 0.41 |
| **QLT(+N)** NOx | | 10.10 ** | 10.00 | 10.41 | 10.14 ** |
| **QLT(+N+P)** PO4 | | 4.20 | 1.70 | 0.97 | 0.82 |
| **QLT(+N+P)** NOx | | 10.20 ** | 10.00 | 10.14 | 10.07 ** |

* An increase in NOx may be indicating 'leaking' of ammonia into the water.

**No uptake of nitrate throughout 3 days indicating N-sufficiency in Qalito shoots.

- The immediate and large decreases in nutrient concentrations following addition of experimental shoots in the tanks meant, that 24 hours may be too long before sampling the water for nutrient content.
    - Lesson: Samples to be taken as soon as possible after adding shoots to the experimental tanks or jars.
- Running three days of experiment without changing the water in the tanks, is probably longer than adequate, because of senescence effects, i.e., nutrient

concentrations started to increase after 3 days and the change may be due to death and decay of micro-organisms in the water.

    - Lesson: If running the experiment for longer than 3 days, change the water every 2 or 3 days.

- Epiphytic attack on the *Sargassum* shoots prevents their growth under experimental conditions; and being unsecured created stress for the shoots.
    - Lessons: Treat the shoots according to established protocols (Schaffelke and Klumpp, 1998a) for removal of epiphytes. Secure shoots so they are stationary and submerged all the time in the tanks.
- The choice of experimental shoots and the site they grow in are critical in nutrient enrichment experiments, as the nutrient content in the plants affects uptake of nutrient from the water column.
    - For further nutrient enrichment experiments, the Naqau shoots should be used as they showed positive response to both N and P enrichment. Qalito shoots appeared to be P-limited but N-sufficient, and therefore would not be suitable.

The lessons learnt were addressed in pilot study B and in the main experimental run C.

### 6.2.3 Pilot study B

#### 6.2.3.1 Objectives of pilot study B

The objectives of pilot study B were to implement the lessons learnt from pilot study A, and observe changes in weights of shoots under different experimental conditions, as well as changes in the water column nutrients in the experimental tanks.

#### 6.2.3.2 Methods of pilot study B

Experimental *Sargassum* shoots were collected from Naqau site only, and treated according to established protocols for removing effects of epiphytes (Schaffelke and Klumpp, 1998a). The shoots with visible epiphytes were discarded and only those that appeared to be free of epiphytes were selected. These were then washed in filtered seawater a few times, wiped with soft tissue and left in filtered seawater awaiting commencement of the experiment. It must be noted that in the absence of a flowing seawater facility, the shoots had to be kept in filtered low nutrient seawater (LNSW) for a few hours, to recover.

As a starting point, the methodology followed as closely as possible that of Fong *et al.* (2003), in which the ambient, supposedly LNSW (collected from Dravuni, well away from human impacts), was enriched with 20 uM N and 2 uM P by addition of sodium nitrate and sodium phosphate (scientific grade) respectively. As in pilot study A, 4 treatments were used: control (no enrichment), N-enriched, P-enriched and combined N+P enrichment. The aquarium tanks were placed on the bench by the window, to allow as much light to reach the shoots, and aeration was achieved by use of pumps. The shoots were secured to pieces of coral with rubber bands, and placed in the tanks, to keep them submerged throughout the experiment.

#### 6.2.3.3 Results and discussion from pilot study B

The changes in the weights of the *Sargassum* shoots under various treatments indicated positive responses to enrichment (unlike pilot study A). There was no evidence of epiphytic attack on the shoots.

Almost all of the shoots gained in weight over the 4 days of the experiment. The gain in weight in the control set-up may be due to the fact that there was only one shoot, and therefore no competition, compared to the +N and +P enriched tanks. It also appears the LNSW already had elevated nutrients, with phosphate at 0.55 uM and nitrate at 3.75 uM (concentrations in the control set-up). Even though this LNSW was collected from offshore, there was no guarantee that the nutrients would be below detection limits as expected. Interestingly, these concentrations in the ambient water were within the most suitable range for a doubling of growth rate in *Sargassum*, according to Schaffelke and Klumpp (1998a). Other nutrient enrichment experiments had also found that nutrient addition did not lead to an increase in wet weight, but rather the control (and even nutrient removal) did (McCook *et al.*, 1997). From the studies by Schaffelke and Klumpp (1998a), it was found that nutrient concentrations much higher that the optimum range (3 uM $NH_4^+$/0.3 uM $PO_4$ to 5 uM $NH_4^+$/0.5 uM

Table 6.3 Changes in weights of *Sargassum* shoots (g) under various treatments in pilot study B – September 2004. (n=number of shoots in the tank)

| **Date/Treatment** | **Control** (n=1) | **+N** (n=3) | **+P** (n=3) | **Combined (+N+P)** (n=1) |
|---|---|---|---|---|
| Start (12 Sept.'04) | 2.1 | a) 2.0<br>b) 1.9<br>c) 2.0 | a) 1.8<br>b) 1.7<br>c) 2.1 | |
| 13 Sept. '04 | | | | 2.5 |
| 14 Sept. '04 | 2.3 | a) 2.2<br>b) 2.0<br>c) 1.9 | a) 1.8<br>b) 1.8<br>c) 2.3 | 2.6 |
| 15 Sept. '04 | 2.3 | a) 2.2<br>b) 2.1<br>c) 2.1 | a) 1.8<br>b) 1.8<br>c) 2.2 | 2.6 |
| End (16 Sept. '04) | 2.4 | a) 2.3<br>b) 2.1<br>c) 2.1 | a) 1.8<br>b) 1.8<br>c) 2.3 | 2.6 |
| Average change | 0.08 g/sht/day | 0.05 g/sht/day | 0.03 g/sht/day | 0.03 g/sht/day |

Table 6.4 Changes in nutrient concentrations (*u*M) in aquarium tanks under various treatments, in pilot study B – September 2004.

| **Date/ Treatment** | **Control. P-PO4** | **Control. N-NOx** | **+N. P-PO4** | **+N. N-NOx** | **+P P-PO4** | **+P N-NOx** | **+N+P P-PO4** | **+N+P N-NOx** |
|---|---|---|---|---|---|---|---|---|
| 12Sept. '04 | 0.55 | 3.75 | 0.56 | 23.90 | 3.26 | 3.56 | | |
| 13 Sept. '04 | 0.13 | 0.40 | 0.46 | 12.21 | 0.48 | 0.15 | 2.72 | 14.60 |
| 14 Sept. '04 | 0.18 | 0.17 | 0.34 | 0.20 | 0.54 | 0.12 | 0.41 | 4.39 |
| 15 Sept. '04 | BDL | BDL | BDL | BDL | 1.04 | 0.18 | 1.06 | 1.46 |
| 16 Sept. '04 | BDL | BDL | BDL | BDL | BDL | BDL | 0.25 | 0.66 |

$PO_4$) did not increase but led to a decrease in growth rate. The enrichment concentrations in this pilot study were above the optimum range, according to Schaffelke and Klumpp (1998a).

The consistent decrease in nutrient concentrations in all of the treatments showed that *Sargassum* shoots from Naqau were limited by both nitrogen and phosphorus. The concentrations of nutrients dropping to below detection limits (BDL) after the third day, confirmed that for experiments lasting longer than 3 days, the water needed to be changed and replaced with fresh supply of nutrients every 2 or 3 days. The lesson learnt from pilot study B was the need to replace the water in the experimental jars after 2 or 3 days, to supply fresh nutrients to the experimental shoots.

### 6.2.4 Growth responses of *Sargassum baccularia* under controlled (laboratory) nutrient enrichment - Experiment C

Following on from the two pilot studies, the main experiment (C) was conducted from 30 October to 16 November 2004. The experiment used the same methodology, but this time, there were 10 replicates of each treatment and the experiment was conducted for 12 days. One of the common problems with *Sargassum* growth experiments was the loss of leaves, which led to a decreased growth rate (by weight). This was also observed in the pilot studies. As an alternative, the rhizoid of the *Sargassum* plant was included with the leafy, distal part of the *Sargassum* in each experimental jar. There was also an interest in how the rhizoids responded to nutrient enrichment during the Cool season when *Sargassum* growth was normally expected to be low, due to its seasonality and 'die back' factors.

#### 6.2.4.1 Objectives of the nutrient enrichment (laboratory) Experiment C.

The objective of the main experimental run was to ascertain if there was any significant difference in the responses of the *Sargassum* shoots and rhizoids among the control, N-enriched, P-enriched and the combined N+P treatment.

#### 6.2.4.2 Methods for the main experimental run – experiment C.

For the main experimental run, 10 replicates of each treatment were set up on the bench by the window inside the laboratory. Each replicate consisted of 300 mL of seawater medium inside a 500 mL plastik jar, with the lid fitted with an aeration tubing attached to a peristaltic pump. In each jar, a *Sargassum* shoot and a rhizoid were each secured with rubber band, to a piece of coral to keep them stationary and submerged. The water was changed every three days. During change of water, the shoots and rhizoids were measured for length and wet weight. At the same time, water in the jars was sampled, and the samples frozen to await analysis for levels of nitrate and phosphate. For the first lot of samples, each jar was sampled, giving a total of 40 water samples to be run on the FIA. Three out of the 10 replicates were selected at random and sampled for nutrients. To ensure that the other water quality parameters were adequate for growth, 3 jars from each batch of ten (for each treatment) were selected randomly, and water temperature and dissolved oxygen (DO) inside the jars were measured. This was done at intervals throughout the experiment.

#### 6.2.4.3 Results and discussion of main nutrient enrichment (laboratory) experiment (C).

The results from the experiment consist of three components: the water quality parameters of temperature and dissolved oxygen in the jars; the changes in nutrient concentrations in the jars; and the changes in the lengths of the experimental shoots and rhizoids from the start to the end of the experiment. The results will be presented first, followed by discussion of the results.

Initially, there were mostly decreases in the weight and length of the *Sargassum* leafy shoots and rhizoids. The changes in weights were also highly variable throughout the experiment. The lengths of the distal, leafy shoots and the rhizoids showed more consistent changes than the weights. These initial decreases can be expected as the plants get acclimatized to the experimental conditions. Most shoots lost leaves and parts of the rhizoids also broke off in the first few days of the experimental run. For this reason, the results from 30 October to 5 November (6 days) are not included in the discussions, and only the results from 5 November to 11 November (6 days) are presented and discussed, (c.f., Schaffelke and Klumpp, 1998), to ensure correct interpretation of plant responses to nutrient enrichment. One other drawback in the experimental set-up was the disproportionate availability of light to the experimental jars and plants, i.e., the jars/plants nearest the window were at an advantage and showed more vigorous growth, while those further from the window did not, and were the ones that lost more leaves than the others. The jars were moved around to address this problem, but the limited space on the bench (for 40 jars) meant that some jars would still be affected at some time during the experimental run.

In order to address the objective of the experiment, the weights of the shoots and rhizoids are not included (due to high variability from leaf loss) in the analysis of the results, and only the lengths are considered. The changes in the lengths of rhizoids and lengths or heights of the shoots are tabulated, for the period from 5 November to 8 November, and from 8 November to 11 November (Table 6.7). The changes are pooled according to treatment, i.e., control, N-enriched, P-enriched and combined N+P enrichment. There appeared to be major differences in the responses of the rhizoids as opposed to the responses of the leafy, shoots, and this observation is discussed further, following the presentation of results.

The results of water quality monitoring for water in the jars are shown in Table 6.5.

Table 6.5 Average temperature ($^{o}$C) and dissolved oxygen (mg/L) for 3 replicates of each treatment over time, for nutrient enrichment (laboratory) experiment C.

| Date | Av. Dissolved oxygen (mg/L) (n=3) | | | | Av. Temperature ($^{o}$C) (n=3) | | | |
|---|---|---|---|---|---|---|---|---|
| | Control | +N | +P | +N+P | Control | +N | +P | +N+P |
| 29 Oct. 04 (1600 hrs) | 7.5 | 7.5 | 7.5 | 7.5 | 27.4 | 27.4 | 27.3 | 27.2 |
| 30 Oct. 04 (1800 hrs) | 7.7 | 7.5 | 7.2 | 7.4 | 25.9 | 25.8 | 25.9 | 25.9 |
| 31 Oct. 04 (1600 hrs) | 7.5 | 7.2 | 7.0 | 7.0 | 26.1 | 26.2 | 26.0 | 26.2 |
| 1 Nov. 04 (1500 hrs) | 5.5 | 5.7 | 5.9 | 5.6 | 26.8 | 27.0 | 26.7 | 26.8 |
| 2 Nov. 04 (1500 hrs) | 5.4 | 5.6 | 5.7 | 5.7 | 27.3 | 26.9 | 26.8 | 26.9 |
| 4 Nov. 04 (1100 hrs) | 6.1 | 5.9 | 6.0 | 5.5 | 25.0 | 25.3 | 25.3 | 25.5 |

The temperatures of the experimental water in the jars were generally adequate for the plants, ranging from 25.0 to 27.4 $^{o}$C during the experiment. These are the usual values during the Cool season in the coastal waters of Fiji. However, on the whole, the temperatures were decreasing with time and this is not surprising given the shade inside the laboratory. The levels of dissolved oxygen were generally satisfactory, ranging from 5.4 to 7.7 mg/L. Dissolved oxygen levels below 5 mg/L are considered unsatisfactory for aquatic life. The aeration of the jars with the use of peristaltic pumps was adequate in this case.

The changes in nutrient concentrations were monitored by sampling water from the jars themselves. Sampling was done as soon as possible following the addition of the shoots and rhizoids to the jars of sea water, during the changing of the water. The first few samples were lost due to spillage as the sampling bottles were not of standard type. This problem was rectified immediately with use of proper bottles. The average nutrient concentrations were calculated for each set or batch, and the time of sampling was carefully noted. Table 6.6 summarises the changes in nutrient concentrations in the jars.

The nutrient concentrations in the Control jars are relatively low, at times going below the detection limit (bdl). The main feature of the changes as presented in Table 6.6 is the rapid uptake of nutrients from the enriched water. Both nitrate in the N-enriched water, and phosphate in the P-enriched water quickly decreased in concentrations, indicating the speed at which these nutrients were taken up by the *Sargassum* shoots and rhizoids. This tends to confirm that the Naqau *Sargassum* shoots and rhizoids were N-limited and P-limited.

The changing of the water every three days, for the purpose of supplying fresh supply of nutrients to the experimental shoots and rhizoids appeared to succeed, in that there were corresponding changes in the lengths (and weights in some cases) of the plants at least. However, the limitation of space inside the jars, and the issues with lighting (and temperature effects) meant that two weeks was perhaps the longest that this experiment could be continued. The experiment started on 30 October and lasted to 16 November, 2004. However, by the 16$^{th}$, many shoots had lost all their leaves and the stalks were weaker, and in some cases, colour of shoots and also rhizoids had started to turn black. As a result, the results for the 16 November have been omitted from the discussions.

The results from monitoring of growth in the *Sargassum* shoots and rhizoids are presented in Table 6.7. As can be seen in Table 6.7, there appeared to be very different responses by the shoots, as opposed to the rhizoids, to the different treatments. The leafy shoots showed increased growth under very low nutrient concentrations in the control jars, whereas the rhizoids responded very positively to nitrate enrichment. McCook *et al*. (1997) found similar results working with adult *Sargassum*, from the GBR in experiments at the AIMS, Australia. That study found

Table 6.6 Average nutrient concentrations (*u*M) in the experimental jars in nutrient enrichment (laboratory) experiment.

| **Date/time after addition of plant to jars** | **CONTROL (Batch A)** | | **+ N (Batch B)** | | **+ P (Batch C)** | | **COMBINED (Batch D)** | |
|---|---|---|---|---|---|---|---|---|
| | **P-PO4** | **N-NOx** | **P-PO4** | **N-NOx** | **P-PO4** | **N-NOx** | **P-PO4** | **N-NOx** |
| 30 Oct. 04 *NW 4 hrs | 0.14 | 0.21 | Lost sample | Lost sample | Lost sample | Lost sample | Lost sample | Lost sample |
| 31 Oct. 04 27 hrs | 0.13 | 0.21 | 0.71 | 6.14 | 0.71 | 0.21 | 0.85 | 0.43 |
| 1 Nov. 04 | 0.23 | 0.50 | 0.19 | 0.21 | 0.26 | 3.36 | 0.29 | 0.29 |
| 2 Nov. 04 *NW 45 min. – 1hr | 0.03 | 0.24 | 0.11 | 20.76 | 3.05 | 1.46 | 1.40 | 11.00 (45 min.) |
| 3 Nov. 04 ~20 hrs | 0.16 | 0.17 | 0.10 | 0.30 | 0.36 | 0.17 | 2.23 | 1.79 |
| 3 Nov. ~ 48 hrs | 0.06 | 0.14 | 0.26 | 0.50 | 0.55 | 0.26 | 0.32 | 0.86 |
| 4 Nov. 04 ~72 hrs | 0.09 | 0.14 | <bdl | 0.21 | 0.90 | 0.21 | 0.10 | 0.21 |
| 5 Nov. 04 * NW 5 hrs after | <bdl | 0.14 | 0.03 | 12.48 | 2.10 | 0.14 | 0.84 | 6.44 |
| 11 Nov. 04 *NW 4 hrs after | 0.20 | 0.41 | 0.13 | 16.55 | 0.64 | 0.50 | 0.17 | 8.96 |
| 15 Nov. 04 ~90 hrs after | 0.05 | 0.49 | 0.06 | 7.27 | 0.18 | 0.50 | 0.04 | 0.50 |
| 15 Nov. 04 ~94 hrs. after | 0.03 | 0.37 | 0.07 | 4.24 | 0.15 | 0.47 | 0.05 | 0.58 |

***** NW – new water (+ nutrients) added to the jars

that nutrient enrichment inhibited growth which was measured as biomass increases of the algae. They also found that the maximum frond length of *Sargassum* was also significantly reduced (McCook *et al*., 1997). On the other hand, the positive effect of nitrate-enrichment on the rhizoid parts of *Sargassum* may be indicating why this macroalgae succeeds in invading available substrata, following pulse events as would follow heavy rainfall. Differential responses by different parts of *Sargassum* to nutrient enrichment is an area of further research.

Table 6.7 Pooled changes in length (mm) of *Sargassum* shoots and rhizoids (root) during two intervals from 5 November to 8 November (A) and from 8 November to 11 November, 2004 (B). (n=10)

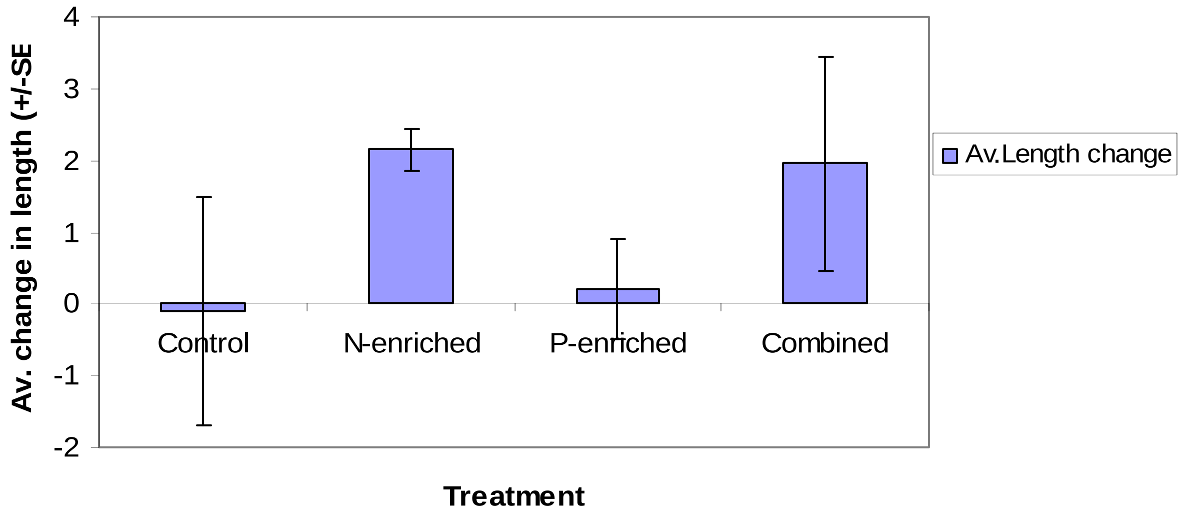
| # | **Control** | | **N-enriched** | | **P-enriched** | | **Combined** | |
|---|---|---|---|---|---|---|---|---|
| | **LEAFY** | **RHIZOID** | **LEAFY** | **RHIZOID** | **LEAFY** | **RHIZOID** | **LEAFY** | **RHIZOID** |
| A1 | 8 | 0 | 1 | 5 | 7 | 3 | 4 | 0 |
| A2 | 3 | 1 | 0 | 4 | 1 | 1 | 1 | 2 |
| A3 | 1 | -9 | 3 | 2 | 0 | 0 | 1 | 3 |
| A4 | 1 | 2 | 0 | 3 | 2 | 5 | 3 | 1 |
| A5 | 1 | 6 | 0 | 3 | -6 | -5 | 0 | -1 |
| A6 | 2 | 5 | 1 | 4 | 1 | 3 | 2 | -1 |
| A7 | 4 | 3 | 0 | 3 | 1 | 1 | 0 | 0 |
| A8 | 1 | 7 | 0 | 0 | 3 | 1 | 3 | 3 |
| A9 | 4 | 0 | 3 | 1 | 2 | 0 | 3 | 2 |
| A10 | 0 | 2 | 0 | 1 | 2 | 2 | 1 | 7 |
| B1 | 4 | 4 | -2 | 1 | -4 | 2 | 1 | -4 |
| B2 | 3 | 2 | 2 | 2 | -1 | -1 | -1 | 3 |
| B3 | 5 | 2 | 1 | 4 | 2 | 0 | 0 | 1 |
| B4 | 3 | -25 | 14 | 2 | 1 | 2 | -1 | 1 |
| B5 | 8 | 1 | 1 | 1 | -2 | -9 | 0 | -1 |
| B6 | 0 | -6 | 2 | 2 | 0 | -1 | 0 | 29 |
| B7 | -4 | 1 | 1 | 3 | 1 | 1 | 1 | 0 |
| B8 | 0 | 0 | 0 | 0 | -4 | 4 | -3 | -2 |
| B9 | 0 | -3 | 1 | 2 | -2 | 0 | 3 | 1 |
| B10 | 0 | 5 | 0 | 0 | -3 | -5 | 0 | -5 |
| **Av.**<br>**SE** | **2.20**<br>**0.64** | **-0.1**<br>**1.56** | **0.50**<br>**0.35** | **2.15**<br>**0.33** | **0.05**<br>**0.66** | **0.2**<br>**0.74** | **0.90**<br>**0.38** | **1.95**<br>**1.54** |

Figure 6.1 and Figure 6.2 show more clearly the different responses of the leafy shoots and the rhizoids, under the four different treatments.

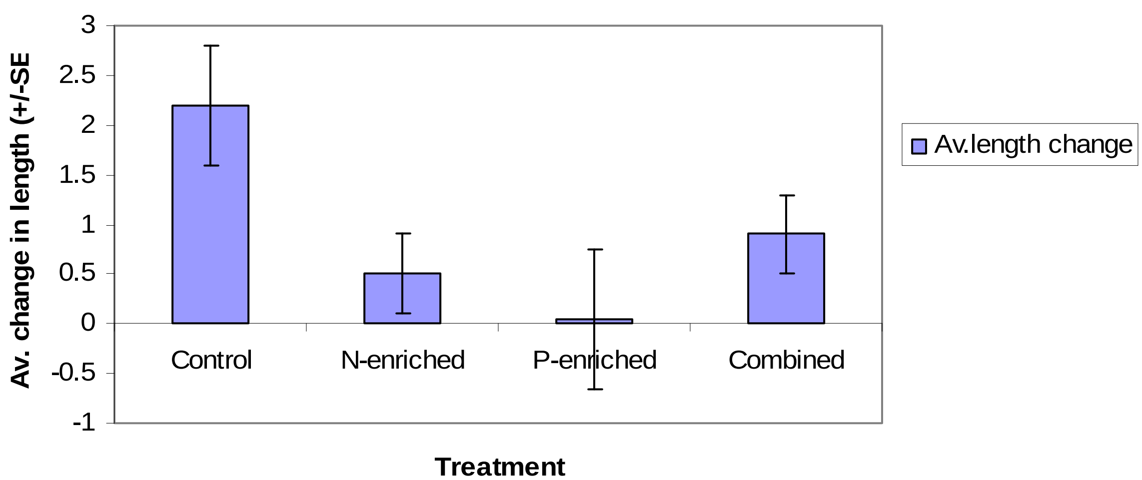
While the rhizoids appeared to be enhanced by nitrate enrichment, and also the combined N and P enrichment (Fig. 6.1), the One Way ANOVA statistical test conducted on the rhizoid data showed that there was no significant difference in rhizoid responses to the treatments, at the 0.05 level of significance ($p = 0.402$). For the leafy shoots, the Kruskal-Wallis Test (non-parametric) was used and it also yielded a non-significant p value of 0.097 (see Appendix C6).

### 6.2.5 General discussion and conclusions from nutrient enrichment experiments

The results from the Pilot study (experiments A and B) and the main experimental run (C) showed interesting and important points which must be considered for future




<u>Figure 6.1</u> Effects of nutrients on *Sargassum* rhizoid lengths. Bars are average changes (mm) in length of the shoots (+/- SE).




<u>Fig. 6.2</u> Effects of nutrients on *Sargassum* leafy shoot lengths. Bars are average changes in length (mm) of the rhizoids (+/- SE).

experiments involving *Sargassum* from the Coral Coast. *Sargassum* from impacted sites such as Qalito may not be suitable for nutrient enrichment experiments, because their tissues may already be enriched. *Sargassum* from control sites such as Naqau were more suitable because they were more likely to be N-limited and also P-limited. For this reason, it is best that the experimental algae be subjected to 'starvation' so that they use up stored nutrients, before exposing them to manipulated nutrient pulses (Schaffelke and Klumpp, 1998a).

For experiments, the level of enrichment is also critical and it may be better if concentrations were around the optimum concentrations for enhaced growth as suggested by Schaffelke and Klumpp (1998a). The enrichment concentrations used in this experiment were above the optimum range. McCook *et al.,* (1997) had also used enrichment concentrations above the optimum range, i.e., the mean of the DIN was 14.1 uM and the mean dissolved inorganic phosphate of 1.42 uM in the enriched tanks. In all cases, the nutrients were quickly taken up, but there was no significant growth effects in the shoots. As other studies have found, (e.g., McCook *et al*., 1997; Fong *et al.*, 2003), tissue nutrient content was enhanced in algae exposed to enriched water, even though they may not have exhibited growth increases. In the experiment described above (See Section 6.2.4.3), the shoots responded more positively to the low nutrients (some of which were closer to the suggested optimum levels) in the control. On the other hand, the rhizoids showed poor growth in the control tanks but positive growth with enrichment. This is an interesting observation which may explain the invasive success of *Sargassum* following nutrient pulses. The differential responses by the different parts of the same plant confirms the fact that uptake of nutrients by macroalgae is a complex process and much is still not well understood yet.

## 6.3 FIELD NUTRIENT ENRICHMENT AND CAGING EXPERIMENTS

### 6.3.1 Introduction

The role of herbivory as one of the main top-down controlling factors on abundance of macroalgae, has been recognized by researchers for a long time (e.g., McCook *et* *al*., 1997). Manipulative experiments involving use of cages to exclude herbivorous fish, have been quite common (e.g., Stimson *et al*., 2001; Thacker *et al*., 2001; Armitage and Fourqurean, 2006). More recently, manipulative experiments have progressed to the use of nutrient enrichment in combination with herbivore-exclusion cages (Thacker *et al*., 2001; Smith *et al*., 2001). Most of these studies have confirmed the prominent role of herbivory in controlling the abundance of macroalgae (e.g., McCook, 1996; Stimson *et al*., 2001). The abundance and distribution of *Sargassum* spp. on the GBR has been attributed mainly to the influence of herbivory (McCook 1996; Schaffelke and Klumpp 1997b). Investigating the role of herbivory through the use of herbivore-exclusion cages, is the subject of one of the experiments in this research.

No direct assessment of herbivore populations was done during the research. According to fish surveys conducted in late 2004 by Coral Cay Conservation team (CCC) in a number of 'tabu' (MPA) and non-'tabu' sites along the Coral Coast, the herbivorous parrotfishes (Scaridae), and the surgeonfishes (Acanthuridae) were quite common (pers. comm../James Comley of CCC, 2005), as is usually the case for coral reefs (Allen and Steene, 2002). At Namada and Tagaqe-Hideaway, there appeared to be more parrotfishes and surgeonfishes in the 'tabu' or MPA, compared to the non-MPA sites. At the Namada MPA, the average number of parrotfishes and surgeonfishes per transect were 28 and 14 respectively. In contrast, the average number of parrotfishes and surgeonfishes per transect at the non-MPA sites at Namada, were 19 and 11 respectively. For the Tagaqe-Hideaway MPA site, there was more surgeonfishes (average of 13), than in the non-MPA site (average of 11), but there were less parrotfishes (average of 17/transect) in the MPA than in the non-MPA (41/transect). At the time of the survey by CCC, the MPAs at Tagaqe and Namada were quite new (< 3 years in existence).

### 6.3.2 Objectives of the experiments

There were two main objectives of the experiments, each dealing with the one of the two controlling factors for macroalgae abundance: the bottom-up factor of nutrient enrichment, and the top-down control of herbivory. The objectives were:

- to investigate the effects of nutrient enrichment in the field, on the growth of *Sargassum* sp. and *Turbinaria* sp., under controlled herbivory; and
- to investigate the effects of herbivore-exclusion cages on the survivorship and growth of *Sargassum* sp.

### 6.3.3 Methods

The methods used in these experiments follow those used by other researchers (Schaffelke and Klumpp 1998; Thacker *et al*., 2001; Smith *et al*., 2001), but with modifications to suit the objectives, and the situation at the study sites (see Section 6.3.2).

#### 6.3.3.1 Nutrient enrichment experiment in the field

The experiment on nutrient enrichment was conducted at the Hideaway resort inshore lagoon, from 23 March to 13 May 2005, and involved the use of cages and NPK fertilizer. The cages were used to prevent herbivory from interfering with the experiment. The cages were made from 2 cm diameter galvanized wire mesh, and were circular with a diameter of about 30 cm, and height of about 40 cm. The tops of the cages were covered with finer, wire gauze material and secured with cable ties. Healthy shoots of *Sargassum* sp. and *Turbinaria* sp. were selected from the study site, and cut into lengths of about 5 to 10 cm from the distal end to the base, for use in the experiment. Each cage had two shoots of *Sargassum* sp. and two shoots of *Turbinaria* sp. attached (threaded) onto a piece of rope measuring about 50 cm long, such that the shoots fitted inside the cage. The rope was pulled tight across the cage and secured with cable ties onto the wire mesh of the cage. The NPK fertilizer (about 10g), contained in a pouch made from fine nylon material (panty hose material) was tied onto the middle of the rope with cable tie. Five cages had NPK fertilizer and five were without (control). In order to secure the cage onto the substrate or dead coral, another piece of fine wire gauze was attached onto the bottom end of the cage, with the other end loose for nailing the cage onto the hard substrate material, whether it be a dead coral head or the bedrock itself.

All of the cages were placed in a deep pool (~ 50 cm depth at low tide), between the large black rocks on the eastern end of the Hideaway resort lagoon. The cages with NPK were placed towards the west, on the resort side but behind 2 large rocks in the lagoon, to ensure the slow release of the fertilizer, while the control cages were in an open part of the lagoon towards the east on Tagaqe village side, directly in the path of westerly flowing currents from Tagaqe village and Valase, as well as the reef passage. It is worth noting that during the experiment, the Coral Coast, including the Hideaway resort site, experienced one the wettest days encountered during the research, the 27 of April 2005. On this day, the DIN at the Hideaway site was > 5 *u*M, while some sites such as Valase to the east recorded a high 31.53 uM DIN (see Table 4.13). The lengths of the experimental shoots were measured at the start (23 March 2005) and at the end (13 May 2005) of the experiment.

#### 6.3.3.2 Herbivore-exclusion caging experiment

In the second experiment, the objective was to investigate the effects of herbivore-exclusion (by caging), on the growth of *Sargassum* shoots. The first ten cages were set up inside an MPA ("tabu") in October 2004. This first run had to be abandoned for a number of reasons:

- The experimental shoots were being weighed and re-placed back in the water. However, survival was very low, most probably due to stress from being out of the water during the weighing. Most of the shoots did not survive and so the method of monitoring growth, was changed from weighing the shoots to measurement of length of the shoots in the water, keeping the plants in the water all the time.
- It was also found that the holothurian *Synapta maculata* was able to wriggle into the cages through gaps between the fine netting and the dead coral surface onto which the cages were nailed, thus interfering with the experimental *Sargassum* shoots inside the cages.
- The first lot of cages did not last as they were all washed ashore during a storm surge event in October 2004. All 10 cages were lost in the storm surge.

Changes were made to methodology for the new experimental runs in 2005. The next lot of herbivore-exclusion experiments were conducted from March to May 2005 at Tambua Sands resort site, and from May to June 2005 at Hideaway resort site and at the Namada 'tabu' site. The experiment was repeated at Namada from 3rd to 11th November 2005. The Tambua Sands resort site was an 'open fishing' zone, but was still less than 1 km from the Namada 'tabu' site. The other two sites were in the 'tabu' or no-take zones (Hideaway resort site and the Namada village site).

The design of the cages was modified to address earlier problems. Apart from the disturbance from the holothurian *Synapta* sp., it was also found that the cages were being dislodged by the currents on several occasions. The new design of the cages required more work on land, such as construction of concrete bases for the cages, and transporting them to the study sites. Instead of having open ends, the bottom of the cage was embedded into a concrete base, also circular and measuring about 40 cm in diameter and about 5 cm in height. This prevented *Synapta* sp. from entering the cages, and it also meant that the cages can be placed directly on the sand or substrate without the need for nailing. The concrete base was heavy enough to steady the cage in the water.

To address the objective of the experiment, one set of *Sargassum* sp. shoots was to be caged (preventing herbivory), while the other set or control was to be left open to herbivory. A method similar to that of Schaffelke and Klumpp (1998) was used to set up the *Sargassum* sp. shoots. The experimental shoots were fixed with rubber bands or small cable ties, to coloured pegs, also embedded into smaller concrete bases (about 15 cm in diameter and 3 cm high). The colour of the pegs and their order of placement in the concrete bases ('dishes') enabled tracking of the growth of the shoots. Each dish had 5 shoots, and one dish was placed into the cage, while the control dish or set was placed outside but adjacent to the cage and secured to the cage with cable ties. The top of the cage was closed off with wire gauze secured to the cage with cable ties. The advantage of this setup was the ease in which the growth of the shoots can be monitored, because all that was involved was opening up the top of the cage (by cutting the cable ties), removing the dish of shoots for measurement of heights, and then replacing the dish back in the cage before closing it off again.

Teams of two were trained to assist in the field, one member to measure the heights of the shoots while the other recorded the results on underwater or waterproof paper. At each site, ten cages were set up, with each cage containing a dish with 5 shoots. Thus in each site, there were 50 caged shoots and 50 uncaged shoots to be monitored. Two cages were lost in the experiment at Tambua Sands and two at the Hideaway resort sites during a tidal wave and storm surge at the end of May 2005.

### 6.3.4 Results of nutrient enrichment and caging experiment

The results from the nutrient enrichment experiment and the herbivore-exclusion caging experiments are presented in Sections 6.3.3.1 and 6.3.3.2 respectively.

#### 6.3.4.1 Results and discussion of field nutrient enrichment experiment

At the start of the experiment, 20 shoots (10 *Sargassum* and 10 *Turbinaria* ), were exposed to NPK fertilizer, and 20 were not (control). Out of the twenty shoots exposed to NPK enrichment, 12 survived to the end (survivorship of 60%), of which 6 were *Sargassum* and 6 were *Turbinaria*. Very similar results were found for the control (no NPK) set. The survivorship for the control was 65 %, and 7 of the surviving shoots were *Sargassum* and 6 were *Turbinaria* shoots.

In spite of the general similarity in terms of survivorship in the two groups, there are interesting observations in the individual results. There appeared to be major differences between the responses of *Sargassum* and *Turbinaria* to ambient nutrients, especially the pulse events that occurred during the experiment, and this appeared to be influenced to some extent by the location of the cages in relation to water flow (see Table 6.8).

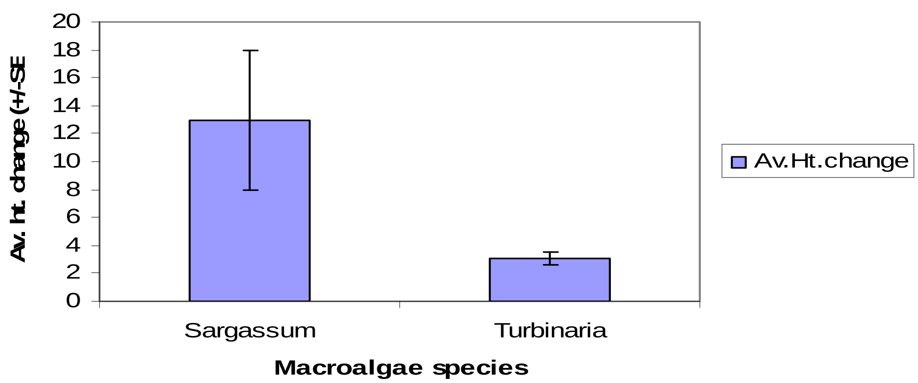
The results for individual shoots that survived to the end of the experiment are shown in Table 6.8. From Table 6.8, it is obvious that the shoots in the control cages increased much more than the shoots that were exposed to NPK fertilizer, and the shoots that showed exceptionally large increases were all *Sargassum* shoots. It was also interesting to note that in the cages where the largest increases occurred, the other shoots either did not survive, or showed very small increase in growth, for

Table 6.8 Changes in heights (cm) of *Sargassum* and *Turbinaria* shoots in NPK-enriched and control experiments from 23 March to 13 May 2005.

| **+NPK Treatment/ species** | **Ht. at start** | **Ht. at end** | **Ht. change** | **Control/ species** | **Ht. at start** | **Ht. at end** | **Ht. change** |
|---|---|---|---|---|---|---|---|
| *Sargassum* | 10 | 14 | 4 | *Sargassum* | 16 | 49 | 33 |
| *Sargassum* | 8 | 11 | 3 | *Turbinaria* | 9 | 12 | 3 |
| *Turbinaria* | 6 | 10 | 4 | *Sargassum* | 8 | 11 | 3 |
| *Sargassum* | 10 | 26 | 16 | *Turbinaria* | 8 | 9 | 1 |
| *Turbinaria* | 6 | 10 | 4 | *Turbinaria* | 5 | 7 | 2 |
| *Turbinaria* | 6 | 9 | 3 | *Sargassum* | 4 | 5 | 1 |
| *Sargassum* | 6 | 7 | 1 | *Sargassum* | 9 | 11 | 2 |
| *Sargassum* | 6 | 7 | 1 | *Turbinaria* | 6 | 11 | 5 |
| *Turbinaria* | 6 | 7 | 1 | *Turbinaria* | 8 | 13 | 5 |
| *Turbinaria* | 6 | 9 | 3 | *Sargassum* | 13 | 38 | 25 |
| *Turbinaria* | 7 | 8 | 1 | *Turbinaria* | 6 | 11 | 5 |
| *Sargassum* | 9 | 25 | 16 | *Sargassum* | 8 | 70 | 62 |
| | | | | *Sargassum* | 8 | 9 | 1 |
| | | | | | | | |
| **Range (av.)** | | | **1 – 16 (4.75)** | **Range** | | | **1 – 62 (11.38)** |

example, in the Control cage where the *Sargassum* shoot showed the largest increase in height (from 8 cm to 70 cm), the other *Sargassum* shoot only increased by 1 cm (8 – 9 cm), while both *Turbinaria* shoots in the same cage did not survive. These differential responses by these common macroalgae species may explain why *Sargassum* appeared to dominating and overtaking the other macroalge species such as *Turbinaria* along the Coral Coast of Fiji. A closer examination of the differences in growth of these two macroalgae species showed the dominance of *Sargassum* over *Turbinaria* (see Figure 6.3).

Fig. 6.3 Average change in height (cm) for *Sargassum* and *Turbinaria* shoots during nutrient enrichment (field) experiment. Error bars are standard errors. (N=13 for *Sargassum*, and 12 for *Turbinaria*)



From Figure 6.3, it appears that *Sargassum* responded more positively than *Turbinaria* to field nutrient concentrations in the study area. During the experiment, there was at least one pulse event associated with heavy rainfall.

While the NPK fertilizer may have been released slowly into the water column, it appeared to have no major effect on the growth of the macroalgae shoots. Part of the reason may be the increased particulate and suspended particles that were observed stuck on the leaves of the shoots, deterring their growth. It has been observed through other studies that *Sargassum* does not grow well where there is much suspended solids. The NPK-exposed shoots were protected from strong water motion because of their location behind the rocks. On the other hand, it appeared that the strong currents and the westerly-flowing waters (which would have brought in nutrients from sources updrift such as the Tagaqe village, and the Valase development), had a bigger effect on growth of the shoots. The largest increases in height of *Sargassum* (25 cm, 33 cm and 62 cm) were observed for the Control shoots (no NPK) located further east, and in the direct path of flow from the east and through the reef passage. This observation agrees with the findings of Edwards *et al.*, (2006) that nitrogen supply and uptake was affected by water flow, and that variation in these can be observed within centimeters.

The shoots that showed large increases in height were selected for further treatment and analysis for $\delta^{15}N$ content (see Section 6.5.2).

The results for the two groups appeared to indicate that nutrient enrichment by slow-releasing fertilizer in the field, does not always result in significant increases in growth, but that other factors such as water motion and pulse events may be more significant factors affecting growth of macroalgae in the field (Edwards *et al*., 2006). The results also appeared to show that *Sargassum* was the better competitor over *Turbinaria* during nutrient pulse events.

#### 6.3.4.1.1 Statistical analysis of nutrient enrichment results

The SPSS 14.0 statistical programme was used to test the two groups (+NPK and control) for any significant difference. The changes in heights for the shoots were pooled into two groups: NPK-enriched and control group. The student t test (parametric) could not be used because the Levene's Test of homogeneity of variance showed a significant p value of 0.015, and so the Mann-Whitney (non-parametric) test was used. The Mann-Whitney test showed that there was no significant difference between the shoots exposed to NPK treatment and the control (p value of 0.545) at the 0.05 level of significance (see Appendix C7). This result may be misleading because this statistical test ranks the values and thus ignores the extreme values which are critical in field nutrient experiments where pulse events have occurred and affected growth. Having more shoots may well qualify the data for a parametric test such as one-way ANOVA which would be more appropriate, because in ANOVA, the values are not ranked but treated as they are.

#### 6.3.4.2 Results of herbivore-exclusion caging experiments

The results (Table 6.9) showed very clear differences in the survival and growth of the caged shoots (herbivore-excluded), and the uncaged shoots exposed to herbivory. The heights of the shoots were measured at the start and at the end of the experiment. Survivorship of the shoots under the two treatments is given by the number of shoots surviving at the end of the experiment / number at the start of experiment. To assess the effects of caging, the survivorship was calculated for each set of caged and uncaged shoots for the three sites: the Hideaway resort site (HDW), Tambua Sands resort site (TBS) and Namada village 'tabu' site (NMD). For each set of caged shoots, there was a corresponding set of uncaged shoots right next to the cage (see Section 6.3.2). At the Tambua Sands site, the experiment was allowed to run from 17 March to 12 May 2005, with monitoring of heights *Sargassum* on 31 March and 13 April 2005. During the monitoring, shoots that were 'lost' were replaced, and continued to be monitored.

The results in Table 6.9 clearly show how caging has protected the shoots from presumably herbivorous fish. This result implies that herbivory was a significant factor controlling the distribution and abundance of *Sargassum* at these sites at least. It is also of interest that at the two 'tabu' sites at the Hideaway resort lagoon, and at the Namada village lagoon, the effects of herbivory appeared to more pronounced, i.e., the survivorship for the uncaged shoots at these two sites are lowest (15.6% and 11.7% for Hideaway and Namada respectively) compared to the open-fishing site at Tambua Sands resort site (31.1%). This result may be indicative of the success of 'tabu' sites in controlling *Sargassum* through the activities of herbivorous fish and possibly other grazers such as sea urchins.

At the Namada 'tabu' site, the additional cages set up in November 2005 showed interesting results. The experimental set that was placed between two rocks (marked * in Table 6.9) showed different results from the others. The rocks may have protected the shoots from herbivore attack and the all of the uncaged shoots survived the week (3 to 11 November, 2005). In contrast to this, the other cage that was not protected had 100 % survivorship for the caged shoots and 0 % for the uncaged shoots.

#### 6.3.4.2.1 Statistical analysis of caging experiment results

The results for the TBS ('open-fishing area') caging experiment were analysed statistically to see if caging affected the growth of the *Sargassum* shoots. The results for all caged shoots were pooled and treated separately from the uncaged shoots. The factor was time, and the effect was the height of the shoots, i.e., the heights of the shoots at the end of the experiment (t2) were compared with the heights at the start (t1). The results were treated as paired samples, and the Wilcoxon Signed Ranks Test (non-parametric equivalent of the Paired-samples *t* test) was used first for the caged set and then for the uncaged set of results. For the caged shoots, 32 of the 40 shoots (8 cages x 5 shoots per cage) showed positive ranks (an increase in height at t2), 5 showed negative rank (loss of shoot) and there were 3 ties. The heights of the shoots at the end of the experiment (t2) were significantly different from the start ($p=0.002$) at the 0.05 level of significance. Appendix C8 shows results of the tests above.

For the uncaged shoots, the heights of the shoots at the end of the experiment were significantly different from the start ($p<0.001$), but this time, the ranking was reversed. Out of 40 shoots, 32 showed negative ranking (a decrease in height or total loss of shoot), 5 showed a positive ranking (an increase) and there were 3 ties.

For the Namada site, the non-parametric Wilcoxon Signed Ranks Test was again used, (Levene's Test of Homogeneity of Variance gave a significant p value of 0.007). For the caged shoots, 35 of the 50 shoots showed a loss in height (either through herbivory or damage) at time 2. Part of the reason for this was the storm surge that damaged some of the cages in May 2005. For the uncaged shoots, 49 of the 50 shoots were either 'lost' to herbivory, or showed a decrease in height, and the Wilcoxon Test gave a highly significant p value of <0.001 (see Appendix C8).

For the Hideaway site caged shoots, 22 of the 40 shoots showed positive growth, and again damage to the cages from the storm surge of May 2005 caused some loss. The Wilcoxon Signed Ranks Test gave a borderline p value of 0.054. However, for the uncaged shoots, 34 of the 39 shoots were 'lost' during the experiment, and the Wilcoxon Signed Ranks Test gave a highly significant p value of <0.001 (Appen.C8).

Table 6.9 Survivorship (%) for the caged and uncaged *Sargassum* shoots at the 3 study sites. HDW and NMD are no-take ('tabu') sites. TBS is an open-fishing site.

| **Cage #** | **HDW caged** | **HDW uncaged** | **TBS caged** | **TBS uncaged** | **NMD caged** | **NMD uncaged** |
|---|---|---|---|---|---|---|
| 1 | 60 | 0 | 60 | 40 | 20 | 0 |
| 2 | 60 | 60 | 100 | 20 | 40 | 0 |
| 3 | 20 | 0 | 100 | 80 | 0 | 0 |
| 4 | 60 | 0 | 100 | 40 | 80 | 0 |
| 5 | 80 | 20 | 80 | 20 | 60 | 40 |
| 6 | 80 | 0 | 80 | 40 | 60 | 0 |
| 7 | 80 | 25 | 80 | 0 | 80 | 0 |
| 8 | 20 | 20 | 100 | 0 | 20 | 0 |
| 9 | | | 80(Nov. 05) | 40 | 40 | 0 |
| 10 | | | | | 60 | 0 |
| | | | | | 100 (Nov.05) | 0 |
| | | | | | 80* (Nov.05) | 100* |
| **Av. % survivorship** | **57.5** | **15.6** | **86.7** | **31.1** | **53.3** | **11.7** |

* Caged and uncaged shoots were placed between two rocks in the lagoon.

#### 6.3.4.2.2 Discussion and conclusions from caging experiment

The results of the caging experiment showed the significant role of herbivory in the abundance and distribution of *Sargassum* at the study sites along the Coral Coast.

Herbivory may well be the key factor to consider in any attempt to reduce and control abundance of *Sargassum* on inshore reef flats. The results of the experiments also appeared to show the effectiveness of the 'tabu' in controlling *Sargassum* at the sites chosen for the experiments, i.e., the two 'tabu' sites recorded lower survivorship (%) for the uncaged shoots.

## 6.4 NUTRIENTS IN MACROALGAE TISSUE

### 6.4.1 Introduction

Macroalgae take up nutrients from the water column for incorporation into their tissues, according to their specific molecular structure. Certain algal groups can form blooms because they have the ability to increase their uptake of nutrients from the water column when nutrients are released in pulses, as would occur in areas around point sources such as sewage effluent outfalls, or during heavy rainfall (e.g., Fong *et al.*, 2004). The increased uptake of nutrients during pulse events does not always result in growth. For macroalgae growing in oligotrophic waters, such as in tropical reef areas, nutrients taken up during pulse events are often stored for use during periods of low nutrient concentrations (Fong *et al.*, 2004; Raikar and Wafar, 2006; Edwards *et al*., 2006). Because of this, tissue nutrient concentrations tended to reflect the history of nutrient enrichment in an area, rather than an instantaneous water column measurement. Lapointe (1997) found that tropical macrophytes tended to be phosphorus-limited and temperate macroalgae tended to be nitrogen-limited, and these matched the average ambient N : P ratios. However, in general, growth of seaweeds is often limited by nitrogen (Lobban and Harrison, 1997).

### 6.4.2 Methods

The nitrogen and phosphorus contents in samples of the macroalgae *Sargassum baccularia*, collected from some of the study sites described in Table 4.1 were analysed. The objective was to compare results with published data from sites in other parts of the world, as this was the first time that nutrient content of this marine macroalgae (*Sargassum baccularia*) had been analysed, for samples from anywhere in Fiji. The only other marine macroflora data for Fiji was by Yamamuro *et al*.

(2003), who worked with seagrass collected from Dravuni Island in the Great Astrolabe Reef, south of Viti Levu.

**Sample Preparation and Analysis**

Nine samples of the macroalgae *Sargassum baccularia* were collected from nine stations within the study sites, from February to August of 2004. The samples collected were plants showing signs of good health and included growing tips and reproductive receptacles. The samples collected were rinsed in clean seawater and placed in small plastic bags for storage in the freezers awaiting further treatment. Prior to analysis, the samples were left to thaw at room temperature, cleaned with deionised water, oven-dried at 60 $^{o}$C for 48 hours and then ground into a powder form according to standard procedures (Lapointe, 1997). Analysis for nitrogen and phosphorus content of the macroalgaae was conducted by the Government Laboratory at Koronivia Research Station near Suva, Fiji in September 2004. Analysis followed standard procedures prescribed by IBSRAM, the International Board of Soil Research and Management (Shamsul-Islam *et al*., 1992). For each sample, two replicates were analysed, and the results are presented in Table 6.10

### 6.4.3 Results and Discussion

Table 6.10 shows the results for nutrient content in samples of *Sargassum baccularia* collected from some of the study sites along the Coral Coast.

The nutrient contents for the *Sargassum* samples collected from the study sites along the Coral Coast were similar to those obtained for the *Sargassum baccularia* plants from reefs around the GBR area in Australia (Schaffelke and Klumpp, 1998). The average nitrogen content for the nine Coral Coast samples is 1.31 % and the standard deviation is 0.20, indicating a low variability among the sites sampled. It is of interest to note that the highest % N values were recorded for samples collected from the Hideaway resort area (range of average from 1.26 – 1.62 %), and they were close to the average levels (1.89 % N) obtained for enriched *Sargassum* shoots in a study by McCook *et al.*, (1997). On the other hand, the low % N in Qalito samples may appear to be unusual, given the history of the site. However, Qalito is an area where

*Sargassum* flourishes on the reef flats, and one possible explanation for the low nutrient content of the tissues may be that growth and invasion of new areas have utilized the stored nutrients, i.e. large production of *Sargassum* dilutes the nutrient content in individual plants. This anomaly confirms the complex interactions between nutrients available to algae, and the responses by algae to these nutrients, given the options of storage, growth or invasion of available substrata.

Table 6.10 Tissue nutrient content for *Sargassum* samples from sites along the Coral Coast.

| ***Sample site/ Sample ID*** | Sample No. | % N | Av. % N | % P | Av. % P. Av. | N : P |
|---|---|---|---|---|---|---|
| HDW RES A | A1 | 1.47 | | 0.027 | | 54 |
| HDW RES A | A2 | 1.33 | 1.40 | 0.039 | 0.033 | 34 |
| HDW RES B | B1 | 1.19 | | 0.048 | | 25 |
| HDW RES B | B2 | 1.33 | 1.26 | 0.043 | 0.046 | 31 |
| HDW RES C | C1 | 1.47 | | 0.059 | | 25 |
| HDW RES C | C2 | 1.61 | 1.54 | 0.050 | 0.055 | 32 |
| HDW RES D | D1 | 1.33 | | 0.045 | | 30 |
| HDW RES D | D2 | 1.33 | 1.33 | 0.047 | 0.046 | 28 |
| HDW RES E | E1 | 1.61 | | 0.051 | | 32 |
| HDW RES E | E2 | 1.61 | 1.61 | 0.070 | 0.061 | 23 |
| VLS CONT F | F1 | 1.05 | | 0.036 | | 29 |
| VLS CONT F | F2 | 0.91 | 0.98 | 0.044 | 0.040 | 21 |
| QLT/WRC G | G1 | 1.05 | | 0.041 | | 26 |
| QLT/WRC G | G2 | 1.05 | 1.05 | 0.040 | 0.041 | 26 |
| NAQ CON H | H1 | 1.33 | | 0.065 | | 20 |
| NAQ CON H | H2 | 1.33 | 1.33 | 0.071 | 0.068 | 19 |
| NVL VIL I | I1 | 1.33 | | 0.058 | | 23 |
| NVL VIL I | I2 | 1.19 | 1.26 | 0.056 | 0.057 | 21 |
| *Average* | | | **1.31** | | **0.050** | **28** |
| *Range* | | | **0.98 – 1.61** | | **0.03 – 0.068** | **19 - 54** |
| *STD DEV* | | | **0.20** | | **0.012** | **7.95** |
| **Literature values** | | | **1.31 (control) * 1.89 (enriched)*** | | **~0.075 – 0.1 **** | **30 (control)* 21 (enriched)*** |

* McCook *et al.*, 1997. ** Schaffelke and Klumpp, 1998a

The highest average tissue phosphate levels were recorded for NAQ (0.068 % P) and HDW RES E (0.061 % P). On the whole, the % P content of the Coral Coast samples were lower than those for the GBR samples (see ranges in Table 6.10), and this may be reflecting the extent of human occupation and impacts from the land masses nearby. One major limitation in this one-off study is the under-representation of the control sites, only two samples were collected from the control sites in the Study area: VLS (Valase) and NAQ CON (Naqau). NAQ is often influenced by discharge from the Komave Creek flowing next to Komave Village, both of which are to the east and updrift of NAQ (and this may explain the high tissue % P from NAQ samples, see Section 4.3.2.2 and 4.3.2.4). VLS, on the other hand, is relatively free of such influence, and during the period of this study, Valase was still relatively underdeveloped, at the time of sampling. The lowest N % content was recorded for Valase (0.98 %), a significantly lower nitrogen content than for the other sites. Valase also recorded the second lowest % P level. At the other end of the spectrum, the highest N % were found in samples collected from around the HDW (Hideaway) Resort. The only village site sampled was Navola (NVL) and it is one of the smallest villages of all the villages along the Coral Coast. The macroalgae sample from NVL was one of the lowest values recorded (1.26 % N).

### 6.4.4 Conclusions

From this preliminary study, it can be reasonably concluded that nitrogen content of the macroalgae *Sargassum baccularia* does reflect ambient nitrogen concentrations in the water column. In fact it may be a more reliable indicator of nutrient enrichment in the coastal waters for some sites (see Section 4.3.3.1.1). The phosphate levels were generally lower than those found for *Sargassum baccularia* from the GBR and probably reflected the extent of human population and impacts. It would be interesting to re-sample Valase, because of the recent major transformation of the area, and to compare these early results with current nutrient content in algal tissue.

## 6.5 SEWAGE TRACING USING $\delta^{15}N$ OF MACROALGAE

### 6.5.1 Introduction

Nutrient enrichment of the coastal waters due to anthropogenic sources is well known, but, distinguishing between the different nutrient sources is a first step towards managing and controlling the sources of nutrient enrichment (Costanzo *et al*., 2005). The use of stable isotopes to trace or assess the extent of anthropogenic nutrient enrichment has become more popular since the mid-1990s (Cabana and Rasmussen, 1996; Hansson *et al*., 1997; Costanzo *et al*.,2001). The $^{15}N/^{14}N$ ratio or $\delta^{15}N$ concentration in macrophytes (or any organism that takes in DIN from the ambient environment) is used to assess the extent of anthropogenic effects or influence in that environment. A high $\delta^{15}N$ concentration means that a significant proportion of the DIN is derived from anthropogenic sources, as opposed to atmospheric sources, for example, which have negative $\delta^{15}N$ values (Yamamuro *et al*., 2003). The Moreton Bay sewage monitoring programme uses the red algae *Catenella nipae* which is deployed around the bay and then analysed for $\delta^{15}N$ concentration (Costanzo *et al*., 2001).

### 6.5.2 Methods

Thirty five (35) samples of *Sargassum baccularia*, 3 samples of *Padina commersoni*, and one sample of *Halimeda macroloba* were collected from the study sites over the period from December 2003 to May 2005. These samples were kept frozen while awaiting treatment and preparation for analysis. Apart from the samples of macroalgae, collected from the field, a few samples of *Sargassum baccularia* from a field nutrient enrichment experiment were also included in the tests. A total of 39 samples were used for this preliminary analysis. This is the first time for this technique to be used for *Sargassum* samples from anywhere in Fiji, although Yamamuro *et al*. (2003) analysed seagrass from the GAR for $\delta^{15}N$. The objective of the current experiment was to assess the viability of measuring $\delta^{15}N$ for samples from Fiji, and to compare results with published data, from other studies where $\delta^{15}N$ was used.

The samples were cleaned, dried, and ground to a fine powder using the electric blender, according to standard IBSRAM procedures for plant preparation for nutrient analysis (Shamsul-Islam *et al*., 1992). All of the plant preparation work was done at the University of the South Pacific laboratory in Fiji. The ground samples were then taken to the University of Queensland where the isotopic testing was completed using the methods described in Costanzo *et al*., (2001).

### 6.5.3 Results of $\delta^{15}N$ tests

Table 6.11 shows the results from analysis of macroalgae for $\delta^{15}N$ and $\delta^{13}C$.

<u>Table 6.11</u> Stable nitrogen isotope ratios ($\delta^{15}N$) and stable carbon isotope ratios ($\delta^{13}C$) in some macroalgae samples from study sites along the Coral Coast.

| **Macroalgae Species** | **Site of collection** | **Date of collection** | **Isotopic $\delta^{13}C$ ($^0/_{00}$)** | **Isotopic $\delta$ $^{15}N$ ($^0/_{00}$)** |
|---|---|---|---|---|
| *Padina commersoni* | NMQ - CON | 23 May '05 | -8.1 | 2.1 |
| *Padina commersoni* | CRS - RES | 23 May '05 | -7.8 | 4.5 |
| *Sargassum baccularia* | CRS - RES | 23 May '05 | -16.0 | 5.3 |
| *Halimeda macroloba* | CRS - RES | 23 May '05 | -5.3 | 0.9 |
| *Sargassum baccularia* | E.BCH - RES | 16 May '05 | -14.7 | 2.8 |
| *Sargassum baccularia* | W. BCH - RES | 16 May '05 | -15.0 | 2.7 |
| *Sargassum cristaefolium* | NVL VLG. CRK | 25 Feb.'04 | -16.4 | 2.3 |
| *Sargassum baccularia* | NVL VLG. SHR | 13 May '04 | -13.8 | 1.8 |
| *Sargassum cristaefolium* | NAQ CON SURGE ZONE | 22 Dec. '03 | -15.8 | 2.6 |
| *Sargassum baccularia* | NAQ CON SHR | 13 May '04 | -16.2 | 3.0 |
| *Sargassum baccularia* | E.WRC RES SHR | 13 May '04 | -17.3 | 2.0 |
| *Sargassum baccularia* | E.QLT RES | 16 May '05 | -14.6 | 2.8 |
| *Sargassum baccularia* | MID. QLT RES | 16 May '05 | -15.8 | 3.4 |
| *Sargassum baccularia* | W. QLT RES | 16 May '05 | -15.2 | 2.9 |
| *Padina commersoni* | MIKES DIVE/VOT VLG | 23 May '05 | -7.7 | 4.8 |
| *Sargassum baccularia* | CBN CON SHR | 16 May '05 | -15.3 | 2.7 |
| *Sargassum baccularia* | VLS CON SHR | 13 May '04 | -12.7 | 2.3 |
| *Sargassum baccularia* | E.VLS | 16 May '05 | -15.4 | 2.4 |
| *Sargassum baccularia* | VLS CON SHR | 16 May '05 | -13.7 | 2.7 |
| *Sargassum baccularia* | W.VLS | 16 May '05 | -14.4 | 2.6 |
| *Sargassum baccularia* | HDW1 RES SHR | 6 May '04 | -13.1 | 3.4 |
| *Sargassum baccularia* | HDW2 RES SHR | 6 May '04 | -14.3 | 3.7 |
| *Sargassum baccularia* | HDW3 RES SHR | 6 May '04 | -14.6 | 3.2 |
| *Sargassum baccularia* | HDW1 RES SHR | 13 May '04 | -14.6 | 2.8 |
| *Sargassum baccularia* | HDW2 RES SHR | 13 May '04 | -14.1 | 3.2 |

| | | | | |
|---|---|---|---|---|
| *Sargassum baccularia* | E. HDW RES | 16 May '05 | -14.3 | 5.8 |
| *Sargassum baccularia* | MID HDW RES | 16 May '05 | -12.9 | 6.2 |
| *Sargassum baccularia* | W. HDW RES | 16 May '05 | -13.4 | 4.8 |
| *Sargassum baccularia* | HDW-EXP (-NPK) | 13 May '05 | -17.0 | 3.5 |
| *Sargassum baccularia* | HDW-EXP (-NPK) | 13 May '05 | -15.5 | 3.6 |
| *Sargassum baccularia* | HDW-EXP (+NPK) | 13 May '05 | -18.5 | 2.8 |
| *Sargassum baccularia* | HDW-EXP (+NPK) | 13 May '05 | -15.7 | 3.2 |
| *Sargassum baccularia* | HDW-EXP(-NPK) | 13 May '05 | -14.5 | 3.0 |
| *Turbinaria ornata* | HDW-EXP(-NPK) | 13 May '05 | -12.5 | 2.2 |
| *Turbinaria ornata* | HDW-EXP (-NPK) | 13 May '05 | -13.7 | 4.1 |
| *Sargassum baccularia* | TBS1 RES | 5 April '05 | -15.0 | 3.3 |
| *Sargassum baccularia* | TBS2 RES | 5 April '05 | -16.8 | 3.0 |
| *Sargassum baccularia* | TBS3 RES | 5 April '05 | -15.6 | 2.6 |
| *Sargassum baccularia* | NMD VIL | 13 May '05 | -15.0 | 4.0 |
| Range of $\delta\ ^{15}N$ ($^0/_{00}$) | | | | 0.9-6.2 |
| Average | | | | 3.2 |
| Std.Dev. | | | | 1.1 |
| Average for C. nipae Moreton Bay (Australia) | | | | 2 ppt non-sewage impacted<br>6 – 7 ppt near pop. centers<br>10 ppt - at 3$^o$ STP discharge sites |

### 6.5.4 Discussion of $\delta^{15}N$ Results

In studies where *C. nipae* samples were deployed around the Moreton Bay area, it was found that $\delta^{15}N$ levels < 3 $^0/_{00}$ indicated no sewage effects, and $\delta^{15}N$ levels > 3 $^0/_{00}$ up to 10 $^0/_{00}$ indicated presence of sewage pollution (Costanzo *et al*., 2001). The highest values were found close to sewage outfalls. On the basis of that classification, 20 out of the 39 samples tested showed some presence of sewage pollution, even though the test species are different. All of the control sites, except for NAQ (SHR) recorded $\delta^{15}$ N < 3 $^0/_{00.}$ Interesting patterns of variation are seen in the case of Hideaway resort samples collected on 16 May, 2005. Comparing $\delta^{15}$ N levels in these samples, East HDW recorded 5.8 $^0/_{00,}$ MID HDW (middle of resort) recorded 6.2 $^0/_{00}$ and West HDW recorded 4.8 $^0/_{00}$. The sites close to sources of pollution (Tagaqe village, Valase development and Hideaway resort), tended to record higher levels of $\delta^{15}$ N (5.8 and 6.2 ppt) compared to sites further away (4.8 ppt at West HDW). Similarly, the patterns of $\delta^{13}C$ variation for the QLT sites followed what would be expected, i.e., the more polluted sites had more negative values (e.g. –15.8 for MID QLT) compared to sites further away (e.g., -14.6 for E QLT).

The lowest $\delta^{15}$ N was recorded for *Halimeda macroloba*, a calcareous, chlorophytic macroalga. This species may not be a good choice for stable nitrogen isotope methods, and this may be an indication of low nitrogen assimilation by this species. In a study to investigate effects of nutrient enrichment on fleshy and calcareous algae, it was found that nutrient enrichment enhanced productivity of fleshy macroalgae more than that of calcareous algae, one of which was a *Halimeda* species. It was found that, in fact, neither N nor P enrichment enhanced the growth of this calcareous species (Delgado and Lapointe, 1994).

Comparing the three species *Halimeda macroloba*, *Padina commersoni* and *Sargassum baccularia*, the results for samples collected from the CRS (Crusoe) Resort on 23 May 2005 showed that the plant type may have an influence on $\delta^{15}$N levels: *Sargassum baccularia* contained the highest concentration of $\delta^{15}$N (5.3 ($^{0}/_{00}$) , followed by *Padina commersoni* (4.5$^{0}/_{00}$), and the lowest was recorded for *Halimeda macroloba* (0.9 $^{0}/_{00}$). This pattern of variation may be indicative of *Sargassum baccularia* being the stronger competitor for nitrogen, over most other species, including the other brown macrolagae *Padina commersoni*, in conditions of high nitrogen influx, or during nutrient pulses, especially after heavy rainfall. Interestingly, the $\delta^{15}$N levels for seagrass species collected from Dravuni in the pristine Great Astrolabe Reef area south of Viti Levu were all negative, ranging from –0.06 to –1.41 (Yamamuro *et al.*, 2003), which these authors stated was an indication of minimal human impact. In fact, the results for Dravuni pointed to atmospheric N as being the source of DIN, rather than anthropogenic sources. N derived from atmospheric sources typically had negative $\delta^{15}$N values (Yamamuro *et al.*, 2003).

### 6.5.5 General conclusions on extent of anthropogenically-derived DIN including sewage pollution, with use of $\delta^{15}N$ levels.

The pattern of variation in $\delta^{15}N$ levels in the *Sargassum* reflected the variation in human impacts, i.e. the resorts and the village sites recorded higher $\delta^{15}N$ levels (> 3 $^{0}/_{00}$ ) indicating some degree of sewage pollution, while the control sites generally showed little or no sewage pollution (< 3 $^{0}/_{00}$ ). This technique certainly has value in mapping the extent of sewage pollution, because the stable isotopes reflect a time-integrated measure of assimilated nitrogen (Yamamuro *et al.*, 2003), instead of instantaneous values which may not include the significant effects of nutrient enrichment or pulse events.

## 6.6 OVERALL CONCLUSIONS

The series of experiments decribed in this chapter have generally complemented the results obtained from the nutrient studies (Chapter 4) and the biological surveys on the reef flats (Chapter 5). Chapter 7 will discuss the linkages among the results from Chapters 4, 5 and this chapter.

# CHAPTER 7 – GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

This chapter attempts to link the findings from the nutrient studies (see Chapter 4), and from the benthic community studies (see Chapter 5), and to examine relationships between the nutrient concentrations and the observed benthic communities on the inner reef flats of the fringing reefs along the Coral Coast. Observations made in the targeted laboratory and field experiments (see Chapter 6), are discussed in relation to the overall research objectives. The final section of this chapter presents the overall conclusions and possible management options for the conservation and restoration of the Coral Coast fringing reefs, including recommendations for further research.

## 7.1 INTRODUCTION

It has been suggested that wherever environmental impacts have already occurred, or are occurring, the extent of impacts can only be inferred from spatial variation patterns in variables of interest, for example, nutrients in the water column or biological communities on the fringing reefs as in this research. The extent of impact can only be inferred by comparing variability within impacted sites, with variability within control sites chosen purely on the basis of distance from the source of impact (Green, 1979; ANZECC, 2000). For the Coral Coast, this was the strategy followed in trying to determine the extent of human impact on the coastal waters and the inner reef flats of the fringing reefs. Variation in nutrients and biological communities within impacted sites are compared with variation patterns for the same variables in similar sites, but further from the source of impact, i.e., the control sites.

Due to logistical factors and resource availability, it was not always possible to conduct the nutrient analyses at the same time as the biological surveys, and this limited the opportunities for precise assessment of linkages between the water quality and biological assessment components. Linkage between nutrient data and biological survey results is therefore, primarily spatial, and to a less extent, temporal.

The following sections will discuss the general findings from studies on water column nutrient variability and link these with variability patterns in biological communities on the inner reef flats of the fringing reefs. The results from the laboratory and field experiments will be linked into the discussion on findings from the two main components of the research.

## 7.2 THE LOCAL SETTING

The research was conducted to address certain gaps in scientific information, and to raise awareness about the increasing threats to the coastal water quality, and the fringing reefs along the Coral Coast, south-western Viti Levu in Fiji, from anthropogenic factors. The Coral Coast continues to be developed for resorts (the most recent being the Maui Bay Resort near one of the control sites in the research, 2004 - 2007), and village sizes continue to expand (pers. observation, this author). The fringing reefs along the Coral Coast appeared to have been degraded over the years (pers. comm./Tevita Love of Qalito, 2003). From the few earlier scientific reports (see Section 3.2.7), the fringing reefs of the Coral Coast were described as being of high coral species diversity (Raj *et al.*, 1981). More recently, Mosley & Aalbersberg (2003) found nutrient levels near resorts, and in rivers, to be elevated above the suggested threshold concentrations of 0.1 uM for phosphate and 1 uM for nitrate or DIN (Bell, 1992). Anthropogenic factors were suspected of affecting the water quality and the biological communities in the inshore waters of the Coral Coast, but there was no scientific information to verify the suspicions. The need to gather such baseline scientific information was a primary driving force for the current research. One way to assess the extent of anthropogenic effects was to compare impacted sites with control sites. The impacted sites were grouped into two major types, the village sites and the resort sites.

## 7.3 GENERAL PATTERNS OF NUTRIENT VARIABILITY ALONG THE CORAL COAST

Generally speaking, the nutrient concentrations were highly variable in the inshore coastal waters along the Coral Coast. Part of the explanation for the high variability is the inherent nature of nutrient mobility in tropical areas, i.e., nutrients tended to be delivered in pulses to the coastal areas, following thunderstorms and heavy rain (McCook, 1999), and rivers and creeks/streams were the major sources of nutrient pulses to the coastal waters (Schaffelke and Klumpp, 1998**)**. For some of the control sites, the effects of pulse events raised nutrient concentrations to unusually high levels (e.g., Naqau on October 2004, Table 4.7). Apart from the high variability in nutrients, the other notable observation was the high phosphate concentrations, most of which exceeded the suggested threshold of 0.1 uM (Bell, 1992). Phosphorus has been found to reduce calcification in corals (Wilbur and Simkiss, 1968; Yamazato, 1970). This may well be part of the reason for the widespread degradation of the fringing reefs along the Coral Coast.

In general, the control sites (those not close to any large village or resort) recorded lower nutrient concentrations than the impacted sites (see Section 4.3.2.8). This pattern was more obvious for phosphate (see Table 4.25), than for nitrate, which tended to be low most of the time for all sites, except during wet weather (> 25 mm per day). The more mobile nitrate behaved in a more predictable way, increasing during wet weather and flood events, and remaining low otherwise. The behaviour of phosphate was not always predictable. In some cases, rain was associated with elevated phosphate (as in the case of nitrate and ammonia), and at other times, phosphate was actually reduced (dilution effects), and when the latter occurs, the sources of phosphate may be linked to point sources such sewage, rather than diffuse sources such as agricultural activities (Jarvie *et al.*, 2006).

There appeared to be no direct association between season and nutrient variability, but rainfall had a significant role, especially for nitrate and ammonia concentrations (see Section 4.3.2.4). In some instances, rainfall was associated with clear gradation in nitrate levels, from being low for control sites and increasing for impacted sites (see Fig. 4.5). Statistical tests showed that nitrate for control sites was significantly lower than for village and resort sites, at the 0.05 level of significance, (see Section 4.3.2.5). Such significant variability may be part of the explanation for variability in the biological communities for control sites in comparison with impacted sites (see Section 5.3.4.5). The effects of rain on water column nutrient levels, were exacerbated by the presence of creeks of rivers, which were significant sources of nutrients and faecal coliform, to the coastal waters. The creeks and rivers brought in very high concentrations of nitrate, often > 10 uM N-NO3 (see Fig. 4.4, Table 4.12, and Table 4.13). Such a high nutrient loading in the creeks and rivers, especially after heavy rain, is causing nutrient pulses into the coastal waters and the biological communities in the Coral Coast region.

The observation that control sites generally recorded lower nutrients than impacted sites supports the suggestion that anthropogenic factors were causing the deterioration of water quality in the inshore coastal waters of the Coral Coast.

## 7.4 BENTHIC COMMUNITY VARIABILITY ON THE CORAL COAST FRINGING REEFS (inner reef flats).

### 7.4.1 General patterns

To compare variation in benthic communities among control and impacted sites, three sites were selected, each representing the control (Valase, VLS), village (Namada, NMD) and resort (Qalito QLT) impacts respectively. The sites selected were unique in some way, in that they presented an insight into valuable lessons to be learnt, for the conservation and protection of fringing reefs. At these sites, benthic communities were assessed along the transects from shore towards the reef crest (up to 100 m), and also across transects moving from east to west. Clear patterns of community variation were observed as one moved from east towards the west, or from nutrient sources and away from the sources. The influence of westerly-flowing long-shore currents appeared to affect biological communities on the reef flats. Clear patterns also emerged as one moved away from nutrient sources such as villages or resorts, i.e., macroalgae abundances were higher nearer to the nutrient sources and decreased as one moved away. On the other hand, live coral was more abundant in deeper parts of the reefs, and away from the nutrient sources.

Valase represented the ‘control’ site which became an ‘impacted’ site, as the development of a backpacker operation took place on the site. The development was not anticipated at the start of the research (see Section 5.3.2). In addition to the backpacker operation, a larger resort, the Maui Bay Resort was developed to the east and updrift of the Valase site. The temporal variation in the biological communities, especially for the macroalgae *Sargassum* sp. and live corals on the Valase reef showed interesting patterns. Although the nutrient variability (temporal) for Valase did not show any clear deterioration in the water quality (see Table 4.18), the levels of ammonia and nitrate recorded for Valase in April 2005 were unusually high for the site, and may be indicative of the changes taking place in the area. Nevertheless, changes were definitely taking place on the reef flats. From 2004 to 2006, the main observations on the Valase reef flat were the increase in *Sargassum* sp. and a decrease in live coral abundance (see Section 5.3.2.6).

The reef at Qalito represented the effects of resorts on the reef flats. Qalito was usually characterized by flourishing beds of *Sargassum* sp. (see Sections 5.3.3.3 and 5.3.3.4). Qalito reef was unique because of the presence of the wastewater pipeline, from the Warwick Resort on the east, and running almost parallel to the shore at about 70 m from the shoreline. The pipeline had been a cause of concern for the Qalito community members because of its occasional breakage and subsequent release of nutrient-enriched wastewater into the lagoon. In fact, the proliferation of the reef flat with *Sargassum* sp. could well be linked to the wastewater pipeline from the Warwick Resort. The history of the channel along which the pipeline lies, is quite interesting (see Section 3.2.7). However, from results of biological surveys on the reef flats, it appeared that the pipeline was causing increased abundance of *Sargassum* sp. during the January 2006 survey (see Fig. 5.8b), i.e., the highest % cover of *Sargassum* sp. was recorded near the pipeline. The lessons to be learnt from the survey at Qalito reef flats, are that, discharging partly treated wastewater directly into a shallow lagoon via a pipeline such as at Qalito, was not environmentally sound. The depth of the lagoon and reef flats did not allow adequate dispersion and dilution of the wastewater, and the receiving water was bound to be polluted from leaking nutrient-rich water which degraded reefs and enhanced macroalgae such as *Sargassum* sp. For restoration of the corals on this reef, it may be worthwhile re-directing the wastewater into the sewage system of the resort, or into settling and aeration ponds, and re-using the water.

There appeared to be strong evidence of seasonality of *Sargassum* sp. from the temporal patterns of variation at Qalito, with strong growth in the Hot and Wet Season (see Figure 5.7b) and lower abundance in the Cool and Dry Season (see Figure 5.7c). However, the very high abundance of *Sargassum* sp. (~ 50 %) during early May 2004 (in the Cool Season when 'die back' was expected to be occurring), may have resulted from an input of nutrients following heavy rains in February 2004, when high nitrate was recorded for the site (5.66 uM N-NO3). Casual field observations during water sampling field site visit in March 2004, had noted a flourishing of *Sargassum* sp. on the Qalito reef. This observation may help explain how nutrient pulses can cause unusual patterns of abundance for macroalgae such as *Sargassum* sp.

The reef flats of Namada reef were surveyed to represent the village impacts. The reefs are within the 'tabu' or MPA (marine protected area). The site often recorded very high nitrate concentrations (see Table 4.21), yet there was a general absence of macroalgae from the available and suitable substrate (dead coral heads) during the study period. The absence of macroalgae such as *Sargassum* sp. may be evidence that the 'tabu' was effective in enhancing activities of herbivorous fish (see Section 5.3.4.3.1). The results of the caging experiment also supported this point, that herbivory was important at the Namada reefs (see Section 6.3.4.2). The survivorship for caged *Sargassum* shoots averaged around 53% whereas for uncaged *Sargassum* shoots, survivorship average at 12% (see Table 6.9).

The survey results at Namada from January 2004 through to July 2006 appeared to show gradual loss of live coral. The patterns of temporal variation in the *Sargassum* sp. and live coral, indicated a gradual deterioration of reef health. The specific causes of high nutrients at Namada reef lagoon need to be identified quickly and addressed, as this site was losing live corals.

The significance of hydrodynamic factors such as currents, direction of flow and depth of water became apparent in the studies at Namada reefs. The raised reef platform running perpendicular to the shorelone on the eastern boundary of Namada village, may have acted to trap nutrients carried by currents and flow from sources such as the Tambua Sands resort, and the creek, located to the east and updrift of the Namada lagoon. The platform supported a belt of *Sargassum* (50 % abundance, on Transect 1), according to survey results in January 2004 (see Section 5.3.4.3.1). Transects or sub-sites to the west of this platform (and moving further away from the nutrient sources), recorded less *Sargassum* and more live coral, and factors contributing to this pattern of variation included the increased distance from nutrient source, greater depth which favoured corals and also enhanced herbivore activity. Any effort to set up 'tabu' sites should take into account the hydrodynamic factors identified.

### 7.4.2 Linkage between nutrients and *Sargassum* sp., and between nutrients and Live Coral % cover.

With the exception of a few results (January 2004), water samples were not collected at the same time as the biological surveys were being conducted. Logistical factors simply did not allow this, as biological surveys took several hours, whereas water samples needed to be collected, filtered on site and transported back to the laboratory (several hours by road), and analysed the same evening, or as soon as possible after that. Transport facilities did not often allow for all the biological and water quality equipment, including freezer space to be taken to the field at the same time. However, while water column nutrients may vary considerably, the averages tended to fluctuate within a narrow range, and it is this 'range' of nutrient values that influenced the biological communities.

Plots of the closest temporal values between water column nutrients and *Sargassum* abundances or % live coral for different sites are shown in Figures 7.1 – 7.3 (*Sargassum*) and Figures 7.4 – 7.5 (live coral).

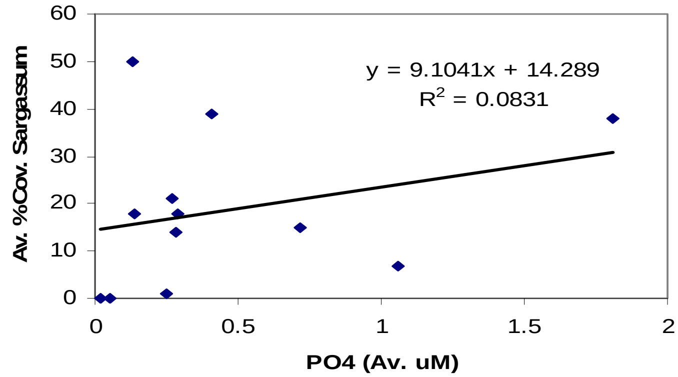



Fig. 7.1 Association between average phosphate concentrations and average % cover of *Sargassum* sp. for sites along the Coral Coast.

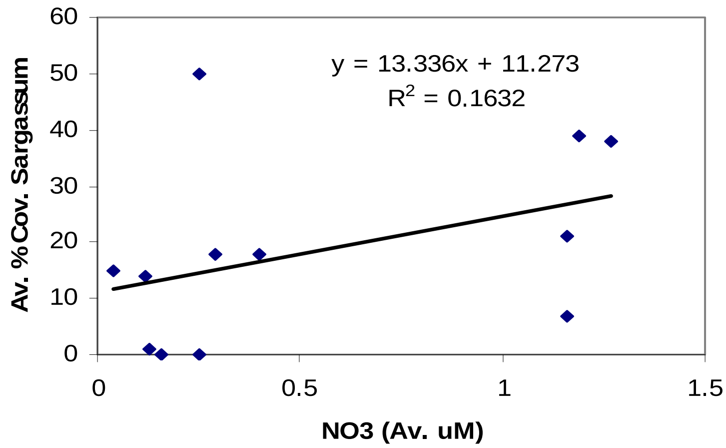



Figure 7.2 Association between average nitrate concentrations (uM) and average % cover of *Sargassum* sp. for sites along the Coral Coast.

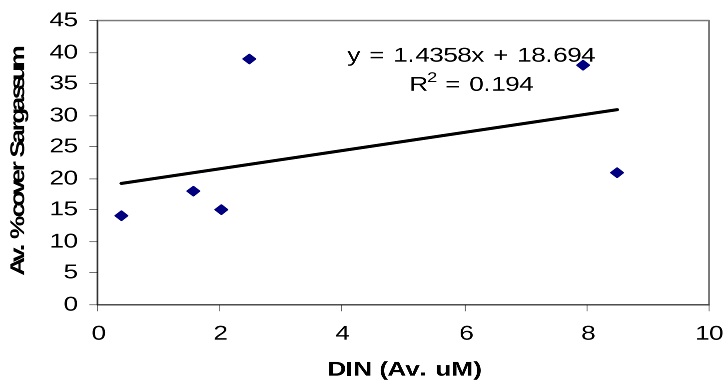



Figure 7.3 Association between average DIN (uM) and average % cover for *Sargassum* sp. for sites along the Coral Coast.

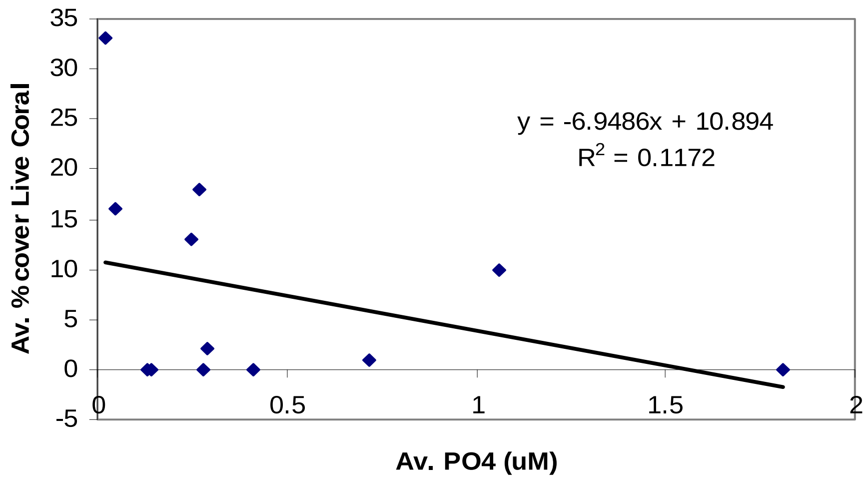



Figure 7.4 Association between average PO4 (uM) and average % cover for Live Coral, for sites along the Coral Coast.

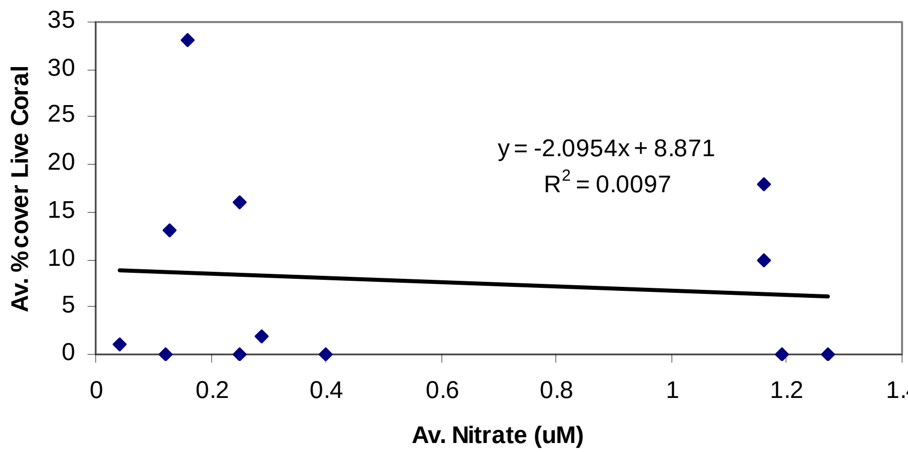



Figure 7.5 Association between average NO3 (uM) and average % cover for Live Coral for sites along the Coral Coast.

From Figures 7.1 to 7.3, the positive trend between *Sargassum* and nutrients is clear, and nitrate showed the stronger link with *Sargassum* sp.. The positive effects of nitrate on *Sargassum* may explain why this macroalgae is taking over much of the degraded reef flats and dead coral heads, and why proliferation of the reefs by

*Sargassum* often follows pulse events associated with heavy rainfall, for example, at Qalito in May 2004 (see Section 5.3.3.4.1).

The negative effect of phosphate on corals is shown in Figure 7.4, but there is no real effect due to nitrate, as shown in Figure 7.5. As discussed previously, the prevalence of high phosphate concentrations above the threshold level of 0.1 uM, for most of the sites, could have been contributing to the demise of corals on the Coral Coast fringing reefs.

Comparison of nutrient concentrations at the study sites in the inshore coastal waters, with waters just off the reef slope showed no major differences. This may need to be investigated further, as the live corals on the outer reef slopes may be exposed to nutrient levels above the threshold levels (Bell, 1992), just as the inshore corals were.

## 7.5 OUTCOMES FROM THE TARGETED LABORATORY AND FIELD EXPERIMENTS AND RELATING THESE TO NUTRIENT AND ECOLOGICAL STUDIES.

### 7.5.1 Uptake of nutrients by *Sargassum* under controlled laboratory conditions

The nutrient enrichment experiment using *Sargassum* from the Coral Coast, was the first of its kind in Fiji, and therefore, it was necessary to conduct some pilot studies before the main experimental run could be designed. The pilot study found that *Sargassum* plants from Naqau site, a control site in the current research, showed positive response to both nitrogen and phosphorus enrichment, whereas the plants from Qalito, an impacted site in the current research, only responded to phosphorus enrichment, and not to nitrate enrichment. The decision made was that only the Naqau plants were to be used in the main experimental run, because Naqau plants were both nitrogen and phosphorus limited, but the Qalito plants were phosphorus-limited but nitrogen-sufficient.

The lessons learnt from the pilot studies were implemented in the design of the main experimental run (Experiment C, see Section 6.2.4). Analyses of the results from the main experimental run showed that nutrients in the enriched tanks were quickly taken up from the water column by the *Sargassum* plants. Such observations may explain why water column nutrients (especially nitrate), are low, yet the area is overgrown with algae, for example, at Qalito (see Table 4.23). Even though tissue nutrient was not analysed for the enriched shoots, it is expected that tissue nitrogen and possibly phosphorus would be higher in the enriched plants, than for the control shoots, as was found by other researchers (McCook, *et al.*, 1997).

An important point that would need to be considered for any future research is the level of enrichment that is used, and that the enrichment supplied to the experimental plants should match the levels in the field during pulse events. Studies found that very high nutrient levels do not necessarily mean high growth rates for *Sargassum* (McCook *et al*., 1997; Schaffelke and Klumpp, 1998). The nutrient concentrations used in the current research (20 uM nitrate and 2 uM phosphate) were also much higher than what would normally be the case in a pulse event on the Coral Coast, for example, 10 uM N-NO3 and 1 uM P-PO4.

The differential responses of leafy shoots and rhizoids, was an interesting observation which may need to be researched further (see Table 6.7). The rhizoids showed more positive responses to nutrient enrichment, compared to the leafy shoots. One possible explanation for the observation could be the timing of the experiment, i.e., the experiment was being conducted during the ‘die back’ or ‘low growth’ season for *Sargassum*, when leafy portions of the plants die and break off from the holdfast. The response of the rhizoids may be indicating that during the ‘die back’ season, the rhizoids are actually enhanced by nutrient pulses, by growing laterally into available substrate, awaiting the new ‘peak growth’ season when the leafy shoots would grow vertically from the holdfast. This observation may explain why *Sargassum* appears to be highly invasive and dominating on the inner reef flats along the Coral Coast. Further research is needed to verify the observations from the current preliminary experiments.

### 7.5.2 General findings from field nutrient enrichment and caging experiments.

The findings from the field nutrient enrichment experiment did not show any clear evidence of increased growth for the *Sargassum* and *Turbinaria* shoots exposed to the NPK fertilizer, because the site was exposed to nutrient pulses from other sources (possibly to the east and updrift). The control cages which did not contain the NPK fertilizer, but were in direct pathway of westerly-flowing currents from sources such Tagaqe village and Valase development to the east, showed more positive results, as far as shoot lengths are concerned (see Table 6.8). The results of the experiment showed the importance of water motion, currents and nutrient pulses in the growth of *Sargassum* and *Turbinaria* in the field. Another interesting observation was the much greater increase in growth of *Sargassum* shoots, compared to *Turbinaria* shoots in the field. It appeared that *Sargassum* was more successful under situations where nutrient pulses occurred, but further research would have to be conducted to verify this observation. However, the observations seemed to provide an explanation for the apparent success of *Sargassum* over other macroalgae, in dominating the flora of the inshore reef flats along the Coral Coast, where nutrients are often delivered in pulses.

The results of the caging experiments showed the significance of herbivory in controlling *Sargassum,* for the sites studied along the Coral Coast. The survivor`ship was greater for the caged or protected shoots compared to the uncaged shoots. Another interesting observation was the fact that the two ‘tabu’ sites sppeared to show more intense herbivory, i.e., the survivorship for the uncaged shoots at the ‘tabu’ sites were lower than for the open-fishing area.

The results of the caging experiments support the need for ‘tabu’ areas, as a way to control abundance of *Sargassum* on the inner reef flats. Herbivorous fish activity, however, is dependent on water depth. For the shallower (< 50 cm depth at low tide), areas, the reef flats could be re-stocked with sea urchins such as ‘cawaki’, (a delicacy enjoyed by the local people), to control macroalgae including *Sargassum*. The findings of the experiment may imply that over-fishing of herbivorous fish such as the parrotfishe *Scarrus* sp., and sea urchins such as ‘cawaki’ (*Tripneustes gratilla*), as a result of the increasing populations in coastal villages (see Section 3.2.4), has contributed to the dominance of *Sargassum* on the reef flats in the recent times.

### 7.5.3 Nutrient and $\delta^{15}N$ contents of macroalgae samples from the Coral Coast

The results for tissue nutrient analyses (see Table 6.10), on the whole matched the water column nutrient concentrations (see Chapter 4). The highest tissue nitrogen concentrations, were recorded for the *Sargassum* samples, collected from impacted sites in the current research (near Hideaway resort and Tagaqe village), and the lowest average concentration was recorded for Valase (0.98 % N), a control site (see Table 6.10). At the time of sample collection (pre-August 2004), Valase was relatively under-developed, and conditions were quite pristine. It is also of interest to note that the tissue nitrogen values for the Hideaway samples, ranging from 1.26 – 1.61 % N, were just slightly lower than the average of 1.89 % N for enriched *Sargassum baccularia,* in the study by McCook *et al*. (1997). The tissue phosphorus contents however, were generally lower for the Coral Coast compared to results for the GBR, and this is to be expected given the difference in human occupation and impacts. The average tissue N : P for the Coral Coast samples (28) falls in between the range 21 (enriched) to 30 (control) observed by McCook *et al*. (1997) for the GBR samples. Most of the water column NO3 : PO4 ratios were < 16, and seemed to be indicating that biological productivity was being limited by nitrogen (see Chapter 4). However, the rapid uptake of nitrate from the water column, as demonstrated in the laboratory experiments (see Section 6.2.5), explains why nitrate may be low generally, in the water column, in areas of substantial *Sargassum* growth. An interesting point is that the tissue N : P ratios, being mostly > 16 (see Table 6.10), indicated a phosphorus-limited environment, and this agreed with the suggestion by Lapointe (1992) that tropical macrophytes tended to be phosphorus-limited. For the Coral Coast, the tissue nutrient data provide a more reliable estimate of N : P than the water column N : P, for the reasons discussed above.

The results of $\delta^{15}N$ analyses on macroalgae samples from the Coral Coast, showed a pattern of variation that agreed with the water column nutrient results, as well as tissue nutrient results, i.e., the impacted sites were enriched with nitrogen derived from anthropogenic sources. The highest $\delta^{15}N$ concentrations were found in macroalgae samples collected from around the resorts (Hideaway and Crusoe resorts), and the lowest were found in the control sites, although there was some degree of variation as well. On the basis of findings of the Moreton Bay sewage monitoring programme, the $\delta^{15}N$ concentrations in macroalgae from the Coral Coast appeared to indicate a degree of sewage pollution, ~ 50 % of the samples analysed recorded > 3 ppt $\delta^{15}N$, and all of the samples from control sites recorded < 3 ppt $\delta^{15}N$, except for Naqau (NAQ) shore, but Naqau was one site often impacted by the Komave creek and the village, located to the east and updrift (see Table 4.7). From the preliminary results of the current research, it was found that *Halimeda macroloba*, a calcareous chlorophyte had the lowest concentration of $\delta^{15}N$, of 0.9 ppt, even though it was collected from a resort site in which *Sargassum baccularia* recorded a relatively high $\delta^{15}N$ of 5.3 ppt, the third highest from the samples analysed. This result agreed with the finding by Delgado and Lapointe (1994), that calcareous algae were not enhanced as much as fleshy macroalgae like *Sargassum* during nutrient enrichment, and that *Halimeda* in particular was not enhanced by either P or N.

## 7.6 OVERALL CONCLUSIONS

The overall conclusions from the study are discussed in relation to the original objectives (Section 1.3).

Objective 1: *through long-term monitoring of the water quality including nutrients, establish baseline information on the physical and chemical characteristics of the in-shore coastal waters, and main creeks discharging into the coastal waters of the Coral Coast Region of South-western Viti Levu, Fiji Islands.*

There are clear differences in average nutrient concentrations between sites close to anthropogenic nutrient sources (the impacted sites), compared to sites further away, the control sites. The water column nutrient concentrations generally reflected the level of human impact on adjacent coastal areas, i.e., impacted sites were enriched (recorded higher nutrients) compared to control sites. This pattern of variation was matched by the *Sargassum* tissue nutrient concentrations, i.e., the impacted sites recorded higher % N (around the Hideaway Resort), and the lowest % N was recorded in samples from the control site, Valase. The nutrients were often delivered to the coastal waters in pulses, in association with thunderstorm and heavy rainfall events, and the rivers and creeks were the major sources of the nutrient pulses and sewage to the coastal waters.

Objective 2 *: through long-term monitoring of the fringing reef communities along the Coral Coast, determine the general physical and biological characteristics of the fringing reefs, in particular the distribution and abundance of the macroalgae Sargassum sp., and possibly the controlling factors.*

The biological communities on the inner reef flats of the fringing reefs also reflected the level of human impact, by way of the nutrients, in the water column. The reef flats close to anthropogenic nutrient sources, recorded higher % cover of macroalgae, particularly *Sargassum*, and less or absence of Live Coral; and the control sites recorded less *Sargassum* but a higher % cover of Live Coral. From the average nutrient concentrations recorded over several months of monitoring, a positive association emerges between nitrates in the water column, and *Sargassum* abundance on the reef flats, and there are also positive associations between phosphates and *Sargassum*, and between DIN and *Sargassum* sp.. As might be expected, there was a negative association between phosphate in the water column and Live Coral abundance, but the association between nitrate and live coral was unclear. Rubble was noticeably absent in control reef sites, but was a prominent feature on reefs exposed to consistent nutrient enrichment.

Objective 3*: conduct an assessment of the possible sources of nutrient pollution at the study sites.*

In the study, a number of resorts, villages, and creeks were monitored periodically for nutrients, and these were assessed against the control sites surveyed at the same time (see Chapter 4); the results generally confirmed villages, resorts and other anthropogenic locations as nutrient sources.

Objective 4: *conduct controlled experiments in the field and in the laboratory, to investigate nutrient uptake by Sargassum sp., effects of herbivory using caging experiments, variation in tissue nutrients and $\delta^{15}N$ concentrations in macroalgae from the study sites.*

The laboratory experiments indicated that *Sargassum* plants from nutrient-rich sites did not respond as strongly as plants from control sites, to nutrient additions. *Sargassum* plants responded to nutrient enrichment by immediate, rapid uptake of nutrients, even though there was no immediate growth response, and this was an indication of what happened in the field during nutrient pulses associated with heavy rainfall. The tissue nutrient content of *Sargassum* samples collected from impacted and control sites, showed a pattern of variation that generally matched the water column nutrient concentrations, i.e., samples from enriched sites had higher tissue nutrients than samples from control sites, with the exception of Qalito site which recorded a low % N. The the $\delta^{15}$N content of macroalgae samples collected from impacted and control sites along the Coral Coast, also showed variation that matched the variation of tissue nutrients and the general water column nutrients at these sites, i.e., the highest $\delta^{15}$N concentrations were found in *Sargassum* samples from impacted sites (resorts and villages). With ~ 50 % of the samples recording > 3 ppt of $\delta^{15}$N, there appeared to be a common occurrence of sewage pollution in the inshore coastal waters of the Coral Coast, and the influence of creeks, water currents and wind-driven long-shore westerly flow contribute to such a situation. Preliminary results from field experiments indicated that *Sargassum* was the stronger competitor over *Turbinaria* sp. during nutrient pulse events, and this may be part of the explanation for the success of *Sargassum* on the inner reef flats. Herbivore-exclusion experiments seemed to confirm the importance of herbivores in controlling *Sargassum* abundance in the deeper parts of the lagoons, and that the ‘tabu’ appeared to be effective in enhancing herbivory.

The results from fringing reef surveys at Namada, showed some important points regarding the ‘tabu’, and the critical role of nutrients in coral reef health, i.e., temporal changes showed an increase in dead coral and rubble cover at the expense of live coral, but there was no colonisation of available substrate by macroalgae, and this can be attributed to intense herbivory (as shown in caging experiments). The 'tabu' through enhanced herbivory, prevented algal proliferation, but did not prevent the death of live corals, and such observations on Namada reef proved that the bottom up controlling factors such as nutrients needed to be controlled first, before the top-down controlling factors like herbivory can bring about the desired outcome, which is a coral-dominated, healthy reef.

Objective 5: *from the results and findings of the research, put forward recommendations for improved usage of the coastal resources, better management of nutrient sources affecting this highly-valued asset of Fiji known as the Coral Coast, and suggest areas for further research.*

Section 7.7 lists some recommendations for reversing the phase shift occurring on the reefs along the Coral Coast, as well as propose areas for further research.

## 7.7 RECOMMENDATIONS FOR REVERSAL OF PHASE SHIFT ON THE CORAL COAST FRINGING REEFS, AND FOR FURTHER RESEARCH

### 7.7.1 Recommendations for Reversal of Phase Shift on the Coral Coast Fringing Reefs

**Management strategy**

The effects of anthropogenic factors on nutrient variability in the coastal waters of the Coral Coast, has been clearly shown from the results of the research, and the effects of the nutrient variability patterns in the water column, on the biological communities on the inner reef flats has been demonstrated. Results of tissue nutrient analyses, and $\delta^{15}N$ concentrations in macroalgae samples also exhibit patterns of variability that match those of average water column nutrients. One of the most important steps, therefore, to mitigate against a phase shift on the Coral Coast reefs, is to reduce the nutrients being discharged into the coastal waters. In Australia, the strategy followed is to develop 'end of catchment' water quality standards, that would ensure that the water quality is restored to pre-European conditions (Wooldridge *et* al., 2006). In Europe, the Water Framework Directive (WFD) is a collaboration by European countries, with the aim of achieving good ‘ecological’ status in all water bodies in Europe, by 2015. The WFD involves re-setting thresholds and standards to encompass ecological systems, and not just water quality or nutrient concentrations (Devlin *et al*., 2007). The WFD standards are based on the aim of restoring conditions, to those that prevailed in the absence of human impact (Devlin *et al*., 2007). For the Coral Coast, and for Fiji as a whole, a similar strategy is recommended, whereby, ‘ecological standards’, which include standards for both water quality and biologiocal systems such the fringing reefs, can be prepared, with the aim of restoring conditions to those in control sites. The setting up of such standards would require input from all stakeholders, especially from scientific expertise. Once standards are set, the stakeholders affected will have to comply, and they would need to be provided with the support they need from government, or even external concerned groups.

**Catchment activities**

Adoption of ‘best practice’ methodologies in agriculture, animal husbandry, forestry and other land-use activities in the catchment areas can go a long way to reducing nutrient loading in the rivers and creeks, and ultimately in the coastal waters. Establishing or replacing buffer strips of vegetation along the banks of rivers and creeks will assist in preventing soil erosion during heavy rainfall, reduce stormwater run-off and thereby reduce risk of polluting the creeks and rivers with sediment and associated nutrients. Proper disposal of all waste is fundamental to avoiding enrichment of the surface waters with nutrients. While the water problem is being addressed in larger communities in Fiji (Dick Watling, pers.comm.), much greater effort is needed in smaller communities where the problems should be easier to tackle.

**Coastal sources of nutrients – resorts and coastal villages**

The shallow reef flats of the fringing reefs are at risk of macroalgal proliferation because of nutrient enrichment from anthropogenic sources such villages and resorts, as well as low level of herbivory because of depth, and absence of herbivorous sea urchins. While depth of water is beyond human control, the affected reef flats can be re-stocked with sea urchins such as ‘cawaki’ and a ‘tabu’ be established in the area, to protect the herbivorous sea urchins. With impending sea level rise, the reef flats currently being affected because of exposure (to damaging sunlight and low level of herbivory), may even see a return of live corals, provided the nutrients are controlled on land. Improvement of sewage treatment in resorts, and the adoption of environmentally-friendly sewage disposal systems in villages, are essential for reducing nutrient enrichment from these sources.

The guidelines in the Resource Management Act for Fiji (2006), for building on coastlines, ought to be strictly followed, and monitored by the appropriate authorities. The Provincial Administration would be the authorities to implement such guidelines at the village level. Moving the buildings or houses as far back from the high water mark as is possible, has enormous benefits for the water quality in coastal waters, and establishing a coastal buffer zone of vegetation would act to trap nutrients and retain them on land. The case of Namada lagoon is evidence of this.

**Establishment of ‘tabu’ sites**

The importance of herbivory as a top-down controlling factor for macroalgae such as *Sargassum* was demonstrated in the caging experiments. Setting aside ‘tabu’ sites or MPAs has significant benefits for the fish stock, as well as the coral reefs through the control of algae. From a scientific perspective, it would be most effective to set up ‘tabu’ sites at or close to the enriched sites, so that the effects of nutrient enrichment can be immediately countered by herbivory, and not allow for proliferation of algae which may be difficult to control. Beyond the primary impact zone, factors such as currents and the longshore westerly drift would need to be taken into account when setting up the boundaries of the ‘tabu’. For conservation of pristine areas, it is also recommended that ‘tabu’ sites be set up in what would be classified as control or reference sites. The preservation of ‘control’ conditions is important, especially if national standards are to be based on such conditions, for the restoration of ‘ecologically-balanced’ systems, as the European WFD has embarked on. The significance of controlling nutrients in addition to setting up a ‘tabu’ site, was seen in the survey results for the Namada fringing reefs. Even though herbivory kept the algae abundances to a minimum, the live corals were still being replaced by dead corals and rubble, most probably as a result of nutrient enrichment.

In all of the recommended actions or strategies, extensive public awareness programmes and wide consultation with all key stakeholders should be undertaken before any action is implemented. Where grassroots and village people are concerned, the bottom-up approach would be the best way to go, whereby, the local residents are informed fully of the likely causes of the observed problems, the desired actions, and are allowed to voice any concerns, and contribute to the final design of action plans and strategies.

### 7.7.2 Recommendations for further research

1. For statistically sound scientific decisions, further research along the lines outlined below would be valuable:

    - The results of the experiments in this study, are mostly preliminary because of limited replication. Repetition of some of the experiments (e.g., nutrient enrichment experiments) with increased numbers of replicates would enable greater statistical confidence in the outcomes.
    - In the case of nutrient enrichment experiments, instead of just the one level of nutrient concentration, experiments using open ocean concentrations, prevailing ambient concentrations plus the observed pulse concentrations, would provide more information on algal responses.
2. The success of *Sargassum* needs to be investigated further, especially the reproductive alternatives of this macroalgae, and its interactions with other macroalgae in enriched areas.
3. Clear delineation of scientifically-sound boundaries for ‘tabu’ sites should be integrated with traditional knowledge and consent from the ‘I Qoliqoli’ owners.
4. Establishment of national ‘ecological’ standards for restoration of ‘pre-human’ conditions in the coastal waters and biological systems, using the WFD in Europe or the Australia ‘end of catchment’ strategies as a guide.

5. Establishment of a database of water quality information, and biological data, for future planning and setting of national standards, for improvement and preservation of coastal water quality and healthy reefs.

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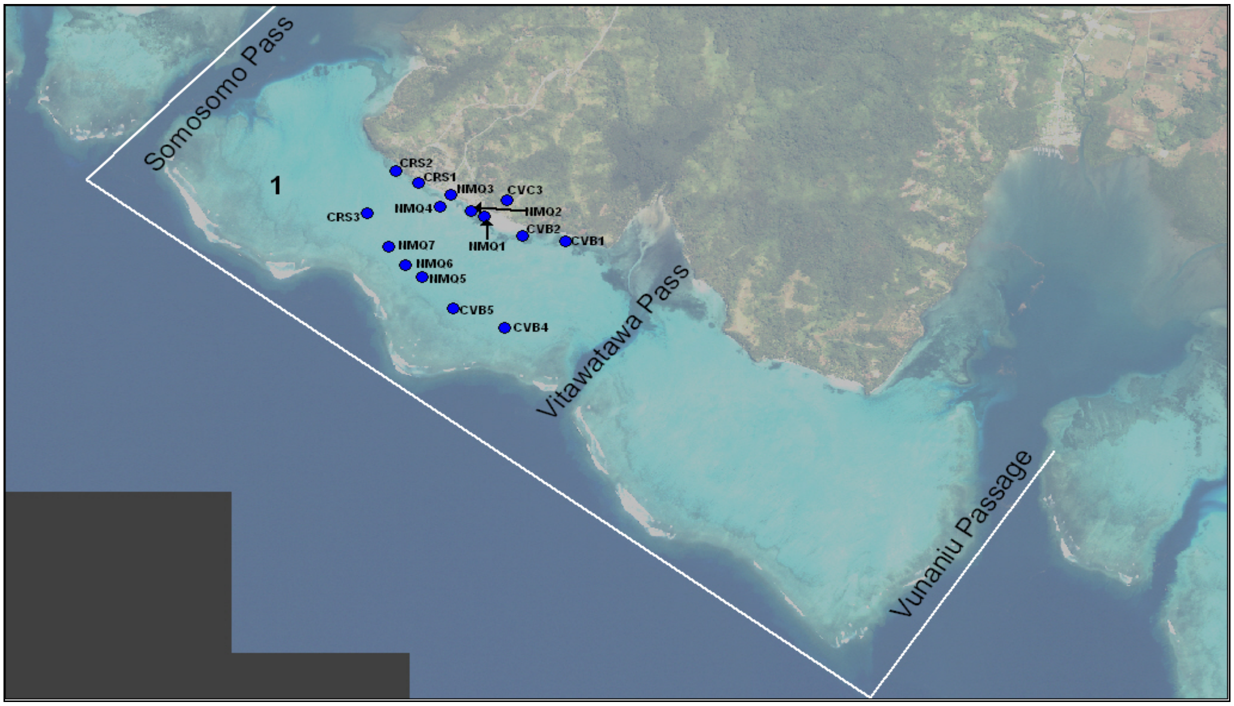
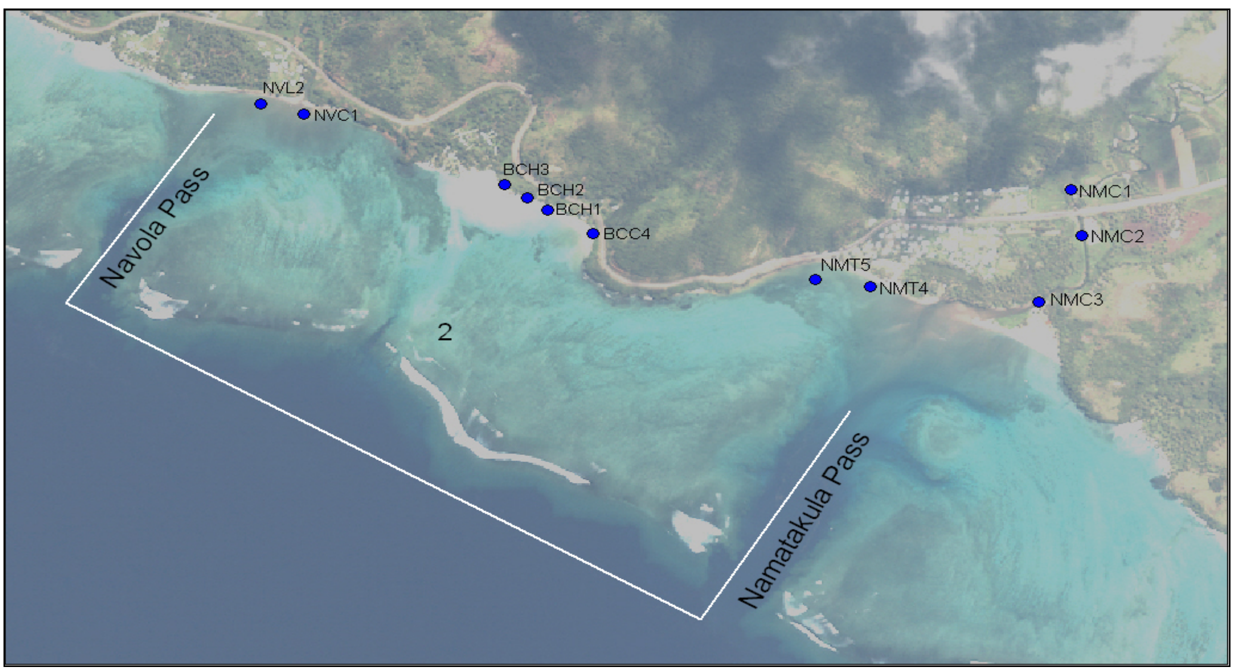
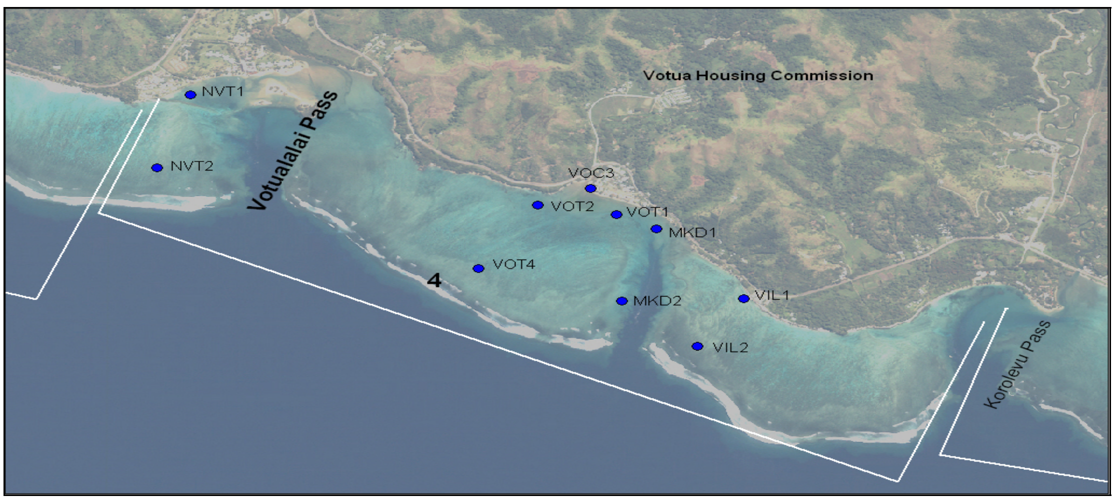



**<u>Appendix A1</u>: Map of the Locality 1 showing water sampling sites around Namaqumaqua Village and the Crusoe Resort on the left. Corresponding off-shore sites are shown.**

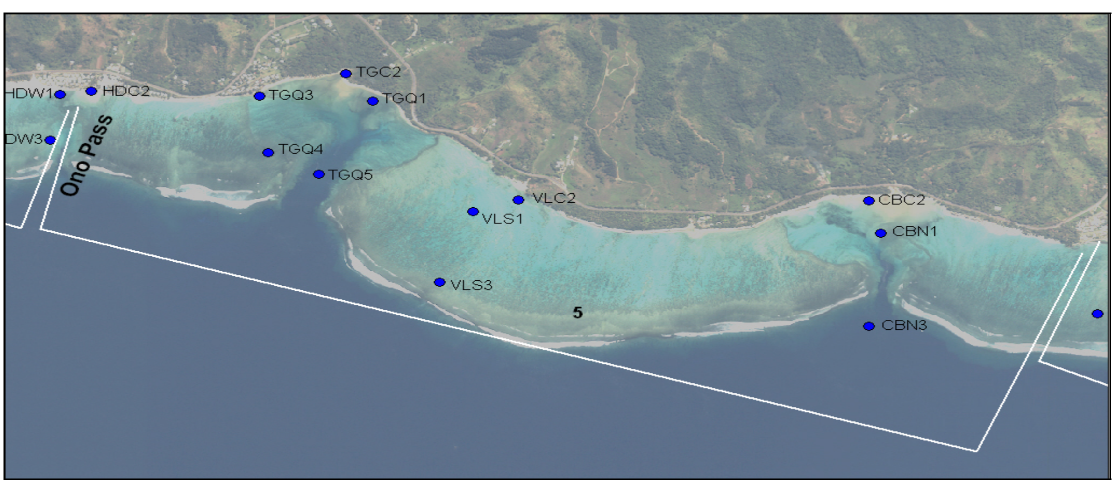



**<u>Appendix A2</u>: Map of the Locality 2 showing water sampling sites along Namatakula Creek (NMCI – 3) and shore (NMT4), and along Beach house foreshore (BCH), and at Navola Shore creek (NVCI).**

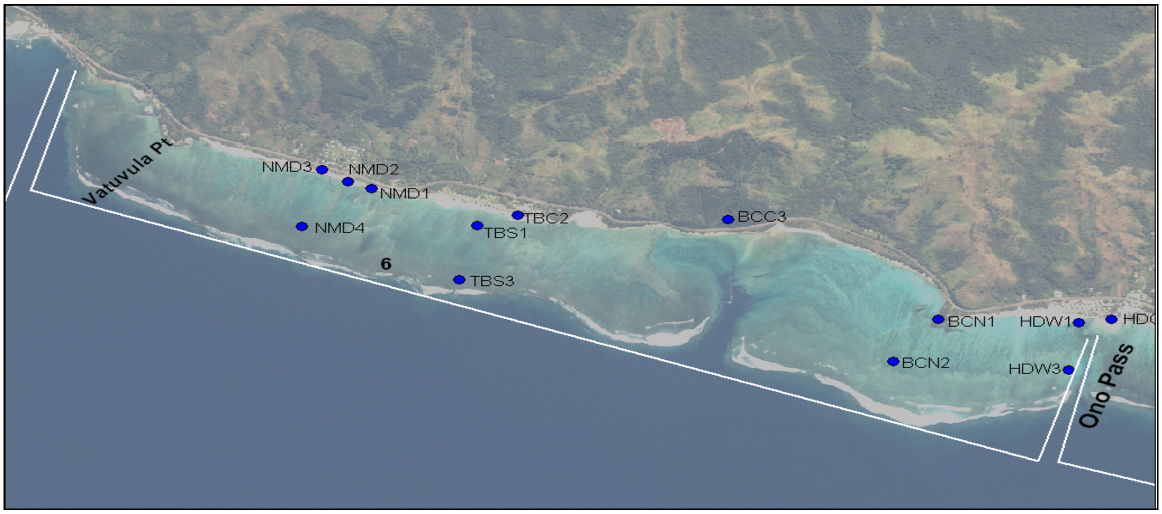

**Appendix A3: Map of the Locality 3 showing water sampling sites at NAQ, Komave and the Warwick (WRC) resort to the west.**



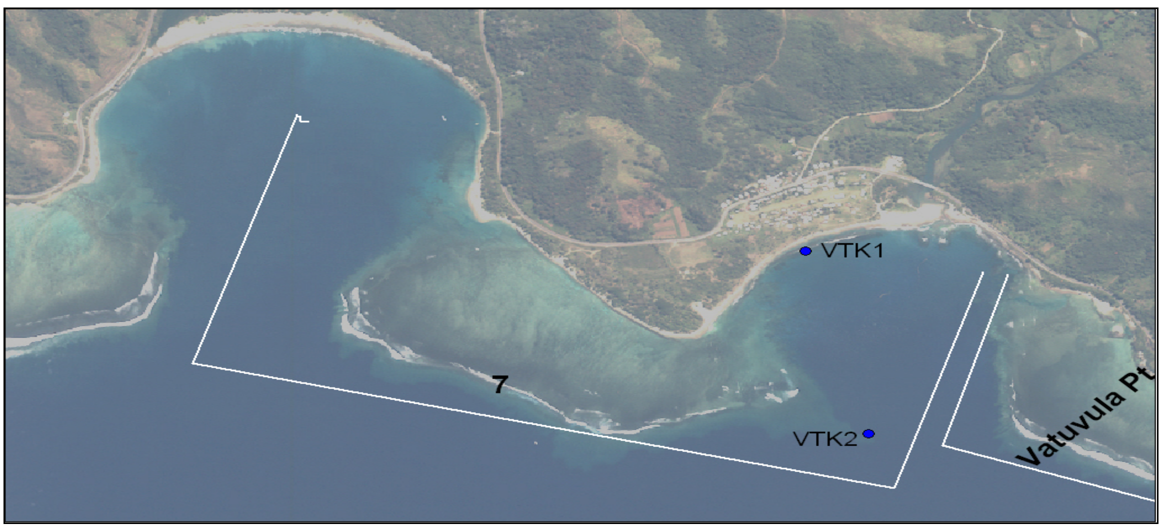

**Appendix A4: Map of the Locality 4 showing water sampling sites around Votua village, and Mike's Dive (MKD)**



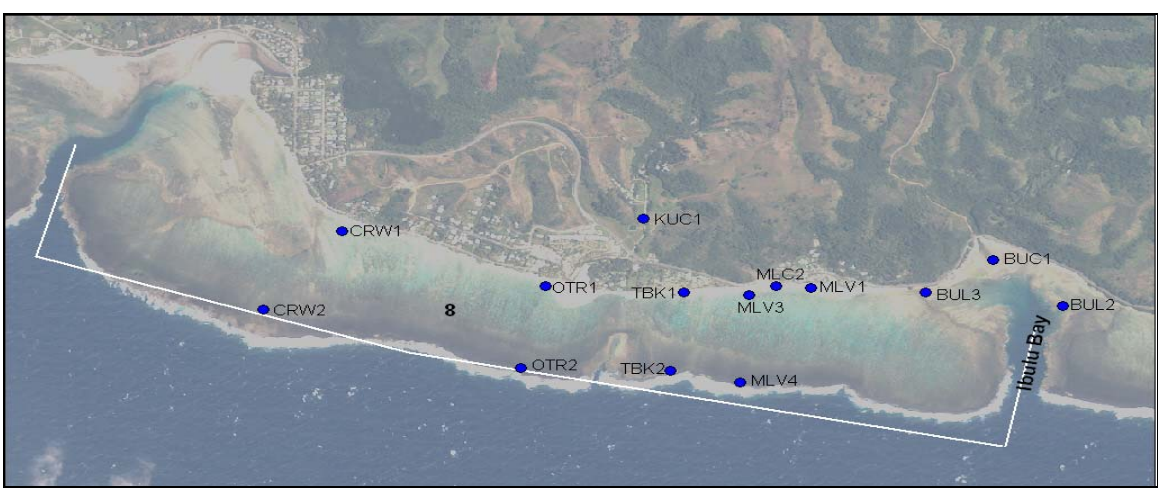

**Appendix A5: Map of Locality 5 showing water sampling sites around Valase (VLS), Tagaqe (TGQ) and the Hideaway (HDW) resort on the west of the map.**




**Appendix A6: Map of Locality 6 showing water sampling sites at Hideaway, Tambua Sands (TBS) resort and at Namada (NMD) Village on the left.**




**Appendix A7: Map of Locality 7 showing Vatukarasa (VTK) village sampling sites**.




**Appendix A8**: **Map of the Locality 8 showing water sampling sites at Bulu River**.

## APPENDIX B1 : NUTRIENTS FOR SITES IN LOCALITY 1

### LOCALITY 1 - SUMMARY TABLE FOR NUTRIENTS BY STATIONS WITHIN SITES

| SITE | DATE SAMPLED | RANGE PO4-PuM | AVERAGE PO4-PuM | RANGE NOx-N uM | AVERAGE NOx-N uM | RANGE NH3 uM | AVERAGE NH3 uM | AVERAGE DIN uM | DIN : P | NH3/DIN |
|---|---|---|---|---|---|---|---|---|---|---|
| CVB1 | 14-Dec-04 | 0.34 - 0.89 | 0.53 | 0.98 - 1.22 | 1.08 | | ND | | | |
| CVB2 | 14-Dec-04 | 0.36 - 0.44 | 0.40 | 1.11 - 1.24 | 1.20 | | ND | | | |
| | | | | | | | | | | |
| NMQ1 | 11-Aug-04 | 0.16 - 0.16 | 0.16 | 0.02 - 0.14 | 0.08 | | | | | |
| NMQ1 | 12-Oct-04 | 0.34 - 0.39 | 0.36 | 0.55 - 0.62 | 0.57 | ammonia | | | | |
| NMQ1 | 14-Dec-04 | 0.45 - 0.52 | 0.48 | 0.47 - 0.97 | 0.73 | analysis | 0.29 | 1.02 | 2.13 | 0.28 |
| | | | | | | was | | | | |
| NMQ2 | 11-Aug-04 | 0.14 - 0.84 | 0.49 | 0.06 - 0.21 | 0.14 | done | | | | |
| NMQ2 | 12-Oct-04 | 0.39 - 0.45 | 0.41 | 0.74 - 0.76 | 0.75 | by | | | | |
| NMQ2 | 14-Dec-04 | 0.43 - 0.49 | 0.45 | 0.48 - 0.70 | 0.58 | another | 0.3 | 0.88 | 1.96 | 0.34 |
| | | | | | | assistant | | | | |
| NMQ4 | 11-Aug-04 | 0.13 - 0.16 | 0.15 | 0.86 - 1.07 | 0.97 | and | | | | |
| NMQ4 | 12-Oct-04 | 0.03 - 1.29 | 0.52 | 1.57 - 19.8 | 15.72 | inidividual | | | | |
| NMQ4 | 14-Dec-04 | 1.07 - 1.67 | 1.30 | 5.34 - 6.08 | 5.63 | results | 3.53 | 9.16 | 20.36 | 0.39 |
| | | | | | | were | | | | |
| CRS1 | 11-Aug-04 | 0.01 - 0.10 | 0.06 | 1.71 - 2.43 | 2.07 | not | | | | |
| CRS1 | 12-Oct-04 | 0.02 - 0.13 | 0.08 | 0.21 - 0.43 | 0.32 | available, only | | | | |
| CRS1 | 14-Dec-04 | 0.51 - 0.64 | 0.59 | 5.06 - 5.10 | 5.09 | averages. | 0.28 | 5.37 | 9.1 | 0.05 |
| CRS2 | 14-Dec-04 | 0.45 - 1.10 | 0.69 | 0.81 - 1.26 | 1.06 | | | | | |
| | | | | | | | | | | |
| CVC3 | 11-Aug-04 | 1.23 - 1.39 | 1.31 | 0.57 - 0.64 | 0.61 | | FC:19000 | | | |
| (CRK) | 12-Oct-04 | 0.10 - 0.97 | 0.44 | 0.14 - 1.00 | 0.57 | | FC:TNTC | | | |
| CVC3 | 14-Dec-04 | 0.60 - 0.74 | 0.67 | 0.81 - 0.95 | 0.88 | | FC:46000 | | | |

**NOTES**

11 August and 12 October 2004 were fine, dry days.

14 December 2004 was a wet and rainy day.

CVC3 is a creek draining part of the village and the small Backpacker resort on eastern end of Namaqumaqua village. NMQ4 is downstream of CVC3

**APPENDIX B2 : NUTRIENTS FOR SITES IN LOCALITY 2**

**LOCALITY 2 - SUMMARY TABLES FOR NUTRIENTS FOR INSHORE SITES ONLY**

| SITE/CODE | DATESAMPLED | P-PO4 uM range | P-PO4 uM av | N-NH3 uM range | N-NH3 uM av | Nox-N uM range | Nox-N uM av | DIN range | DIN av | N : P OR DIN : P | NH3/DIN |
|---|---|---|---|---|---|---|---|---|---|---|---|
| BCH1 | 25-Mar-04 | 0.04 - 0.09 | 0.06 | | | 0.02 - 0.03 | 0.03 | | | 0.50 | |
| BCH2 | 25-Mar-04 | 0.01 - 0.12 | 0.07 | | | 0.02 - 0.03 | 0.03 | | | 0.43 | |
| BCH2 | 13-May-04 | 0.12 - 0.16 | 0.14 | | | 0.05 - 0.13 | 0.08 | | | 0.57 | |
| BCH2 | 25-May-04 | 0.06 - 0.2 | 0.12 | | | 0.12 - 0.57 | 0.4 | | | 3.33 | |
| BCH2 | 4-Jun-04 | 0.01 - 0.22 | 0.13 | | | 1.11 - 1.89 | 1.48 | | | 11.38 | |
| BCH2 | 11-Aug-04 | 0.85 - 1.14 | 0.95 | | | 0.01 - 0.18 | 0.06 | | | 0.06 | |
| BCH2 | 12-Oct-04 | 0.03 - 0.45 | 0.3 | | | 0.14 - 0.86 | 0.43 | | | 1.43 | |
| BCH2 | 27-Apr-05 | 0.26 - 0.35 | 0.31 | 0.45 - 0.58 | 0.52 | 0.02 - 0.15 | 0.09 | 0.47 - 0.73 | 0.61 | 1.97 | 0.85 |
| BCH2 | 16-May-05 | 0.19 - 0.49 | 0.36 | 1.09 - 1.83 | 1.52 | 0.29 - 0.84 | 0.57 | 1.38 - 2.67 | 2.09 | 5.81 | 0.73 |
| NMT4 | 25-Mar-04 | 0.001 - 0.35 | 0.11 | ND | | 0.02 - 0.04 | 0.03 | | | 0.27 | |
| NMT4 | 13-May-04 | 0.36 - 1.14 | 0.7 | ND | | 0.01 - 0.11 | 0.05 | | | 0.07 | |
| NMT4 | 4-Jun-04 | 0.3 - 0.31 | 0.31 | ND | | 4.38 - 4.42 | 4.4 | | | 14.19 | |
| NMT4 | 8-Jun-04 | 0.08 - 0.17 | 0.12 | ND | | 0.81 - 0.94 | 0.87 | | | 7.25 | |
| NMT4 | 12-Oct-04 | 0.03 - 3.42 | 1.73 | ND | | 0.29 - 0.43 | 0.36 | | | 0.21 | |
| NMT4 | 6th Jan-05 | 0.34 - 0.7 | 0.54 | 4.5 - 7.14 | 5.6 | 0.76 - 1.01 | 0.87 | 5.26 - 8.15 | 6.47 | 11.98 | 0.87 |
| NMT4 | 23-Mar-05 | 0.43 - 6.16 | 2.48 | 3.2 - 13.72 | 7.71 | 0.07 - 0.16 | 0.12 | 3.27 - 13.88 | 7.83 | 3.16 | 0.98 |
| NVL2 | 25-Feb-04 | 0.004 - 0.01 | 0.01 | ND | | 3.98 - 8.29 | 5.39 | | | 539 | |
| NVL2 | 25-Mar-04 | 0.03 - 0.19 | 0.08 | ND | | 0.03 - 0.06 | 0.05 | | | 0.63 | |
| NVL2 | 13-May-04 | 0.22 - 0.71 | 0.48 | ND | | 0.16 - 0.3 | 0.21 | | | 0.44 | |
| NVL2 | 4-Jun-04 | 0.11 - 0.34 | 0.2 | ND | | 0.54 - 1.49 | 1.04 | | | 5.20 | |
| NVL2 | 11-Aug-04 | 0.7 - 2.28 | 1.28 | ND | | 0.26 - 0.5 | 0.37 | | | 0.29 | |
| NVL2 | 12-Oct-04 | 0.1 - 1.13 | 0.72 | ND | | 0.21 - 0.5 | 0.31 | | | 0.43 | |

**LOC 3 SUMMARY TABLES FOR NUTRIENTS - INSHORE WATERS ONLY**

**APPENDIX B3 : NUTRIENTS FOR SITES IN LOCALITY 3**

| | | Range | Average | Range | Average | Range | Average | Range | Average | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SITECODE | DATE | P-PO4 uM | P-PO4 uM | N-NH3 uM | N-NH3 uM | Nox-N uM | Nox-N uM | DIN uM | DIN uM | DIN:P | N:P | NH3/DIN |
| KMV1 | 25-Mar-04 | 0.03 - 0.06 | 0.04 | | . | 0.01 - 0.02 | 0.02 | | | | 0.50 | |
| KMV1 | 13-May-04 | 0.01 - 0.13 | 0.09 | | . | 0.13 - 0.3 | 0.21 | | | | 2.33 | |
| KMV1 | 4-Jun-04 | 0.03 - 0.43 | 0.16 | | . | 0.39 - 0.5 | 0.46 | | | | 2.88 | |
| KMV1 | 12-Oct-04 | 0.02 - 0.19 | 0.08 | | . | 19.0 - 19.29 | 19.15 | | | | 239.38 | |
| KMV1 | 11-Aug-04 | 0.79 - 1.04 | 0.90 | ND | ND | 0.09 - 0.38 | 0.22 | | | | 0.24 | |
| NAQ1 | 2-Aug-03 | 0.26 - 0.29 | 0.28 | 0.08 - 0.55 | 0.27 | 0.06 - 0.23 | 0.12 | 0.14 - 0.78 | 0.39 | 1.39 | 0.43 | 0.69 |
| NAQ1 | 25-Feb-04 | 0.002 - 0.04 | 0.02 | | . | 5.24 - 13.42 | 10.89 | | | | 544.50 | |
| NAQ1 | 25-Mar-04 | 0.03 - 0.1 | 0.06 | | . | 0.06 - 0.11 | 0.08 | | | | 1.33 | |
| NAQ1 | 13-May-04 | 0.09 - 1.78 | 0.66 | | . | 0.05 - 0.07 | 0.06 | | | | 0.09 | |
| NAQ1 | 25-May-04 | 0.01 - 0.04 | 0.03 | | . | 0.46 - 0.92 | 0.71 | | | | 23.67 | |
| NAQ1 | 8-Jun-04 | 0.05 - 0.09 | 0.07 | | . | 0.58 - 0.64 | 0.6 | | | | 8.57 | |
| NAQ1 | 11-Aug-04 | 0.84 - 0.95 | 0.88 | | . | 0.22 - 0.35 | 0.28 | | | | 0.32 | |
| NAQ1 | 12-Oct-04 | 0.03 - 0.06 | 0.04 | | . | 17.93 - 19.29 | 18.76 | | | | 469.00 | |
| NAQ1 | 7th Jan-05 | 0.24 - 0.35 | 0.30 | | . | nd | cd colmn.dwn | | | | | |
| NAQ1 | 23rd Mar-05 | 0.66 - 0.77 | 0.72 | 1.81 - 2.12 | 1.97 | 0.02 - 0.05 | 0.04 | 1.83 - 2.17 | 2.01 | 2.79 | 0.08 | 0.98 |
| EWRC | 2-Aug-03 | 0.29- 0.31 | 0.30 | 0.26 - 1.71 | 0.9 | 0.34 - 0.47 | 0.38 | 0.60 - 2.18 | 1.28 | 4.27 | 1.27 | 0.70 |
| EWRC | 10-Feb-04 | 0.01 - 0.3 | 0.09 | nd | . | 4.2 - 6.54 | 5.35 | | | | 59.44 | |
| EWRC | 25-Feb-04 | 0.01 - 0.08 | 0.05 | nd | . | 14.07 - 15.0 | 14.73 | | | | 294.60 | |
| EWRC | 25-Mar-04 | 0.08 - 1.4 | 0.11 | nd | . | 0.04-0.04 | 0.04 | | | | 0.36 | |
| EWRC | 13-May-04 | 0.01 - 0.11 | 0.06 | nd | . | 0.005 - 0.18 | 0.06 | | | | 1.00 | |
| WRC1 | 4-Aug-04 | 0.34 - 0.49 | 0.41 | nd | . | 0.48 - 0.58 | 0.54 | | | | 1.32 | |
| WRC1 | 11-Aug-04 | 0.92 - 2.11 | 1.34 | nd | . | 0.0045 - 0.44 | 0.17 | | | | 0.13 | |
| WRC1 | 23rd Mar-05 | 0.42 - 2.04 | 1.23 | 1.59 - 3.86 | 2.72 | 0.79 - 1.64 | 1.12 | 2.38 - 5.50 | 3.84 | 3.12 | 0.91 | 0.71 |
| WRC1 | 27th Apr -05 | 0.63 | 0.63 | 0.27 | 0.27 | 0.38 | 0.38 | | 0.65 | 1.03 | 0.60 | 0.42 |
| WRC1 | 16th May -05 | 0.02 | 0.02 | 2.73 | 2.73 | 0.22 | 0.22 | | 2.95 | 147.50 | 11.00 | 0.93 |
| QLT1 | 2-Aug-03 | 0.85 - 1.10 | 1.00 | 6.43 - 18.49 | 10.32 | 0.03 - 0.09 | 0.06 | 6.46 - 18.58 | 10.38 | 10.38 | 0.06 | 0.99 |
| QLT1 | 10-Feb-04 | 0.03 - 0.07 | 0.05 | nd | . | 3.19 - 11.93 | 5.66 | | | | 113.20 | |
| QLT1 | 25-Mar-04 | 0.06 - 0.17 | 0.10 | nd | . | 0.04 - 0.09 | 0.06 | | | | 0.60 | |
| QLT1 | 13-May-04 | 0.10 - 0.15 | 0.13 | nd | . | 0.16 - 0.63 | 0.25 | | | | 1.92 | |
| QLT1 | 4th Feb-05 | 0.32 - 0.33 | 0.33 | 1.06 - 1.66 | 1.36 | 0.26 - 0.73 | 0.54 | 1.32 - 2.39 | 1.9 | 5.76 | 1.64 | 0.72 |
| QLT1 | 23rd Mar-05 | 4.58 - 10.48 | 6.75 | 11.03 - 17.98 | 13.36 | 0.89 - 1.54 | 1.25 | 11.92 - 19.52 | 14.61 | 2.16 | 0.19 | 0.91 |
| QLT1 | 27th Apr -05 | 0.08 - 0.28 | 0.18 | 0.11 - 0.14 | 0.13 | 0.03 - 0.07 | 0.05 | 0.14 - 0.21 | 0.18 | 1.00 | 0.28 | 0.72 |
| QLT1 | 16th May -05 | 0.24 - 0.57 | 0.41 | 0.16 - 2.39 | 1.28 | 0.31 - 2.06 | 1.19 | 0.47 - 4.45 | 2.47 | 6.02 | 2.90 | 0.52 |

**APPENDIX B4: NUTRIENTS FOR SITES IN LOCALITY 4**

**LOCALITY 4 - SUMMARY TABLE OF NUTRIENT CONCENTRATIONS FOR INSHORE SITES AND VOTUA CREEK**

| SITE | DATE SAMPLED | RANGE PO4-PuM | AVERAGE PO4-PuM | RANGE NH3 uM | AVERAGE NH3 uM | RANGE NOx-N uM | AVERAGE NOx-N uM | AVERAGE DIN uM | N : P | DIN : P | NH3/DIN |
|---|---|---|---|---|---|---|---|---|---|---|---|
| VIL1 | 20-Dec-04 | 0.03 - 0.65 | 0.27 | 2.20 - 3.49 | 2.63 | 0.29 - 0.36 | 0.31 | 2.94 | | 10.89 | 0.89 |
| MKD1 | 20-Dec-04 | 0.05 - 0.16 | 0.11 | 2.29 - 2.81 | 2.50 | 0.21 - 0.29 | 0.26 | 2.76 | | 25.09 | 0.91 |
| MKD1 | 7-Jan-05 | 0.25 - 0.36 | 0.30 | 4.23 - 5.80 | 5.04 | 0.60 - 0.63 | 0.62 | 5.66 | | 18.87 | 0.89 |
| VOT1 | 4-Aug-04 | 0.37 - 0.37 | 0.37 | ND | ND | 5.23 - 6.34 | 5.85 | | 15.81 | | |
| VOT1 | 13-Oct-04 | 0.03 - 0.06 | 0.04 | ND | ND | 0.14 - 0.14 | 0.14 | | 3.50 | | |
| VOT1 | 20-Dec-04 | 0.03 - 0.26 | 0.15 | 2.17 - 2.66 | 2.42 | 0.36 - 0.50 | 0.43 | 2.85 | | 19.00 | 0.85 |
| VOT2 | 20-Dec-04 | 0.06 - 0.19 | 0.13 | 2.05 - 2.56 | 2.23 | 0.03 - 0.21 | 0.13 | 2.36 | | 18.15 | 0.94 |
| NVT1 | 13-Oct-04 | 0.06 - 0.13 | 0.10 | ND | ND | 0.14 - 0.21 | 0.19 | | 1.90 | | |
| NVT1 | 7-Jan-05 | 0.24 - 0.32 | 0.28 | 3.96 - 4.00 | 3.98 | 0.54 - 1.19 | 0.85 | 4.83 | | 17.25 | 0.82 |
| VOC3 | 13-Oct-04 | 0.10 - 0.52 | 0.24 | ND | ND | 0.14 - 0.21 | 0.16 | | 0.67 | | |
| (CRK) | 27-Apr-05 | 0.51 - 1.42 | 0.97 | 1.24 - 4.02 | 2.81 | 7.36 - 8.00 | 7.64 | 10.45 | | 10.77 | 0.27 |
| VOC3 | 16-May-05 | 0.91 - 1.04 | 0.98 | 0.80 - 1.44 | 1.12 | 5.13 - 5.94 | 5.57 | 6.69 | | 6.83 | 0.17 |

**APPENDIX B5 : NUTRIENTS FOR SITES IN LOCALITY 5**

**LOCALITY 5 - SUMMARY OF NUTRIENT CONCENTRATIONS FOR INSHORE SITES ONLY**

| SITE/CODE | DATE SAMPLED | P-PO4 uM RANGE | P-PO4 uM AVERAGE | N-NH3 uM RANGE | N-NH3 uM AVERAGE | Nox-N uM RANGE | Nox-N uM AVERAGE | DIN uM RANGE | DIN uM AVERAGE | DIN:P | NH3/DIN |
|---|---|---|---|---|---|---|---|---|---|---|---|
| TGQ1 | 1-Aug-03 | 0.28 - 0.41 | 0.34 | 0.84 - 3.47 | 1.82 | 0.36 - 1.28 | 0.73 | 1.2 - 4.75 | 2.55 | 7.5 | 0.71 |
| TGQ1 | 16th May -05 | 0.07 - 0.12 | 0.09 | 0.68 - 2.83 | 1.57 | 0.08 - 1.64 | 0.83 | 0.76 - 4.47 | 2.4 | 26.67 | 0.65 |
| TGQ3 | 1-Aug-03 | 0.42 - 0.48 | 0.44 | 0.01 - 1.63 | 0.86 | 0.53 - 0.59 | 0.55 | 0.55 - 2.16 | 1.42 | 3.23 | 0.61 |
| | | | | | | | | | | | |
| TGQ1 | 22-Dec-04 | 0.04 - 1.03 | 0.37 | 3.36 - 3.76 | 3.58 | 0.14 - 0.21 | 0.16 | 3.5 - 3.9 | 3.74 | 10.11 | 0.96 |
| TGQ1 | 23-Mar-05 | 8.84 - 36.8 | 22.82 | 12.4 - 15.42 | 13.91 | 0.17 - 1.37 | 0.77 | 13.77 - 15.59 | 14.68 | 0.64 | 0.95 |
| TGQ1 | 27th Apr -05 | 0.05 - 0.5 | 0.21 | 0.39 - 1.34 | 0.81 | 0.18 - 1.34 | 0.57 | 0.57 - 2.68 | 1.37 | 6.52 | 0.59 |
| E.TGQ1 | 22-Dec-04 | 0.09 - 0.25 | 0.19 | 3.42 - 3.95 | 3.67 | 0.14 - 0.29 | 0.21 | 3.56 - 4.24 | 3.88 | 20.42 | 0.95 |
| MIDTGQ1 | 22-Dec-04 | 0.05 - 0.12 | 0.09 | 3.59 - 4.22 | 3.84 | 0.14 - 0.21 | 0.16 | 3.73 - 4.43 | 4.01 | 44.56 | 0.96 |
| E.TGC2a | 22-Dec-04 | 0.1 - 1.58 | 0.61 | 4.23 - 5.99 | 4.94 | 0.21 - 0.29 | 0.26 | 4.52 - 6.28 | 5.2 | 8.52 | 0.95 |
| E.TGC2b | 22-Dec-04 | 0.03 - 0.09 | 0.06 | 3.66 - 4.46 | 4 | 0.21 - 0.29 | 0.24 | 3.87 - 4.75 | 4.24 | 70.67 | 0.94 |
| TGQ3 | 6th Jan-05 | 0.97 - 1.38 | 1.14 | 3.88 - 4.51 | 4.09 | 0.51 - 0.58 | 0.55 | 4.41 - 5.07 | 4.65 | 4.08 | 0.88 |
| CBN1 | 4-Aug-04 | 0.26 - 0.28 | 0.27 | ND | ND | ND | ND | NA | NA | | |
| CBN1 | 13-Oct-04 | 0.06 - 0.19 | 0.13 | ND | ND | 0.21 - 0.64 | 0.35 | NA | NA | | |
| CBN1 | 6th Jan-05 | 0.36 - 0.45 | 0.41 | 4.29 - 4.71 | 4.44 | 0.89 - 1.74 | 1.31 | 5.18 - 6.45 | 5.75 | 14.02 | 0.77 |
| CBN1 | 27th Apr -05 | 0.03 - 0.04 | 0.04 | 1.0 - 1.54 | 1.27 | 0.25 - 0.26 | 0.26 | 1.2 - 1.79 | 1.53 | 38.25 | 0.83 |
| CBN1 | 16th May -05 | 0.11 - 0.27 | 0.18 | 0.20 - 2.99 | 1.33 | 0.14 - 0.41 | 0.23 | 0.34 - 3.4 | 1.56 | 8.67 | 0.85 |
| VLS1 | 2-Aug-03 | 0.34 - 0.35 | 0.35 | 0.08 - 0.62 | 0.35 | 0.36 - 0.56 | 0.46 | 0.44 - 1.18 | 0.81 | 2.35 | 0.43 |
| VLS1 | 22-Jan-04 | 0.05 - 0.16 | 0.11 | ND | ND | 0.08 - 0.17 | 0.13 | NA | NA | | NA |
| VLS1 | 10-Feb-04 | 0.01 - 0.06 | 0.03 | ND | ND | 1.09 - 5.64 | 3.6 | NA | NA | | NA |
| VLS1 | 13-May-04 | 0.07 - 0.09 | 0.08 | ND | ND | 0.15 - 0.23 | 0.19 | NA | NA | | NA |
| VLS1 | 8-Jun-04 | 0.04 - 0.05 | 0.05 | ND | ND | 0.40 - 0.46 | 0.42 | NA | NA | | NA |
| VLS1 | 11-Aug-04 | 0.9 - 1.68 | 1.16 | ND | ND | 0.18 - 0.52 | 0.34 | NA | NA | | NA |
| VLS1 | 13-Oct-04 | 0.06 - 0.16 | 0.11 | ND | ND | 0.14 - 0.29 | 0.19 | NA | NA | | NA |
| VLS1 | 4-Feb-05 | 0.28 - 0.38 | 0.32 | 1.58 - 3.62 | 2.3 | 0.07 - 0.17 | 0.13 | 1.65 - 3.79 | 2.43 | 7.59 | 0.95 |
| VLS1 | 16th May -05 | 0.01 - 0.2 | 0.10 | 0.29 - 0 .31 | 0.30 | 0.01 - 0.2 | 0.07 | 0.30 - 0.32 | 0.31 | 3.1 | 0.97 |
| W.VLS1 | 22-Jan-04 | 0.01 - 0.01 | 0.01 | ND | ND | 0.09 - 0.11 | 0.1 | NA | NA | NA | NA |
| HDW1 | 5-May-04 | 0.16 - 0.28 | 0.21 | ND | ND | 0.32 - 1.5 | 0.72 | NA | NA | N:P? | NA |
| HDW1 | 4-Aug-04 | 0.28 - 0.38 | 0.32 | ND | ND | 0.32 - 0.76 | 0.5 | | | | |
| HDW1 | 6th Jan-05 | 0.78 - 1.24 | 1.01 | 8.07 - 8.43 | 8.33 | 0.71 - 0.74 | 0.72 | | | | |

**CONT. LOCALITY 5 NUTRIENT CONCENTRATIONS**

| SITE/CODE | DATE SAMPLED | P-PO4 uM RANGE | P-PO4 uM AVERAGE | N-NH3 uM RANGE | N-NH3 uM AVERAGE | Nox-N uM RANGE | Nox-N uM AVERAGE | DIN uM RANGE | DIN uM AVERAGE | DIN:P | NH3/DIN |
|---|---|---|---|---|---|---|---|---|---|---|---|
| HDW1 | 27th Apr -05 | 0.18 - 0.39 | 0.29 | 1.59 - 5.85 | 3.72 | 1.24 - 1.42 | 1.33 | | | | |
| HDW1 | 16th May -05 | 0.01 - 0.03 | 0.02 | 0.96 - 1.00 | 0.98 | 0.22 - 0.49 | 0.36 | | | | |
| W.HDW1 | 8-Jun-04 | 0.07 - 0.15 | 0.1 | ND | ND | 1.65 - 2.41 | 2.06 | | | | |
| MID-HDW1 | 22-Dec-04 | 0.09 - 0.20 | 0.15 | 3.29 - 3.53 | 3.42 | 0.21 - 0.29 | 0.24 | 3.58 - 3.74 | 3.66 | | |
| E.HDW1 | 22-Dec-04 | 0.06 - 0.16 | 0.11 | 4.17 - 4.36 | 4.26 | 0.21 - 0.29 | 0.24 | 4.38 - 4.65 | 4.49 | | |
| BCN1 | 22-Dec-04 | 0.11 - 0.13 | 0.12 | 3.59 - 4.14 | 3.80 | 0.14 - 0.21 | 0.19 | 3.73 - 4.35 | 3.98 | | |
| BCN1 | 4-Feb-05 | 0.33 - 0.43 | 0.37 | 1.77 - 3.14 | 2.48 | 0.02 - 0.03 | 0.03 | 1.80 - 3.16 | 2.51 | | |

**APPENDIX B6 : NUTRIENTS FOR SITES IN LOCALITY 6**

**LOCALITY NUMBER 6 - SUMMARY OF NUTRIENT CONCENTRATIONS FOR INSHORE SITES ONLY**

| SITE/CODE | DATE SAMPLED | RANGE P-PO4 uM | AVERAGE P-PO4 uM | RANGE N-NH3 uM | AVERAGE N-NH3 uM | RANGE NO3-N uM | AVERAGE NO3-N uM | RANGE DIN *u*M | AVERAGE DIN *u*M | NO3:PO4 OR DIN:PO4* | NH3/DIN |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **TBS1** | 23-Jan-04 | 0.02 - 0.04 | 0.03 | ND | ND | 0.09 - 0.2 | 0.15 | NA | NA | 5.00 | |
| | 4-Aug-04 | 0.34 - 0.41 | 0.37 | ND | ND | 0.81 - 0.99 | 0.91 | NA | NA | 2.46 | |
| | 13-Oct-04 | 0.1 - 1.1 | 0.44 | ND | ND | 0.21 - 0.43 | 0.28 | NA | NA | 0.64 | |
| | 6th Jan-05 | 0.78 - 1.66 | 1.18 | 6.3 - 7.11 | 6.66 | 1.26 - 1.28 | 1.27 | 7.56 - 8.37 | 7.93 | 1.08/6.72* | 0.84 |
| **NMD1** | 22-Jan-04 | 0.03 - 0.07 | 0.05 | ND | ND | 0.15 - 0.34 | 0.25 | NA | NA | 5.00 | |
| | 23-Jan-04 | 0.01 - 0.03 | 0.02 | ND | ND | 0.13 - 0.18 | 0.16 | NA | NA | 8.00 | |
| | 10-Feb-04 | 0.01 - 0.02 | 0.01 | ND | ND | 4.15 - 11.07 | 7.22 | NA | NA | 722.00 | |
| | 2-Aug-04 | 1.04 - 1.69 | 1.39 | ND | ND | 11.75 - 13.43 | 12.41 | NA | NA | 8.93 | |
| | 12-Aug-04 | 0.35 - 0.39 | 0.37 | ND | ND | 1.57 - 1.71 | 1.64 | NA | NA | 4.43 | |
| | 13-Oct-04 | 1.45 - 1.45 | 1.45 | ND | ND | 10.64 - 10.79 | 10.72 | NA | NA | 7.39 | |
| | 6th Jan-05 | 0.47 - 1.64 | 1.06 | 8.86 - 9.50 | 9.05 | 1.14 - 1.19 | 1.16 | 9.94 - 10.69 | 10.21 | 1.10/ 9.68* | 0.89 |
| | 4-Feb-05 | 0.27 - 0.31 | 0.29 | 0.53 - 2.13 | 1.27 | 0.22 - 0.37 | 0.29 | 0.81 - 2.5 | 1.56 | 1.00 / 5.38* | 0.81 |
| **E.NMD1** | 6th Jan-05 | 1.03 - 2.22 | 1.23 | 9.5 - 13.29 | 11.83 | 1.04 - 1.14 | 1.08 | 10.54 - 14.36 | 12.92 | 0.88 / 10.50* | 0.92 |

## APPENDIX B7 : NUTRIENTS FOR SITES IN LOCALITY 7

### LOCALITY 7 - SUMMARY OF NUTRIENTS FOR INSHORE SITE

| SITE/CODE | DATE SAMPLED | RANGE P-PO4 uM | AVERAGE P-PO4 uM | RANGE N-NH3 uM | AVERAGE N-NH3 uM | RANGE NO3-N uM | AVERAGE NO3-N uM | RANGE DIN uM | AVERAGE DIN uM | NO3:PO4 OR DIN:PO4* | NH3/DIN |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **VTK1** | **2-Aug-04** | 0.92 - 1.94 | 1.35 | ND | ND | 3.51 - 3.84 | 3.64 | NA | NA | 2.70 | NA |
| | **12-Aug-04** | 0.10 - 0.23 | 0.15 | ND | ND | 0.36 - 0.50 | 0.41 | NA | NA | 2.73 | NA |
| | **14-Oct-04** | 0.02 - 0.03 | 0.03 | ND | ND | 0.14 - 0.21 | 0.18 | NA | NA | 6.00 | NA |
| | **6th Jan-05** | 0.47 - 0.53 | 0.5 | 10.07 - 12.0 | 10.81 | 0.64 - 0.69 | 0.66 | 10.73 - 12.69 | 11.47 | 1.32/22.94* | 0.94 |
| **VTK2** | **7th Jan-05** | 0.31 - 0.42 | 0.35 | 3.96 - 6.51 | 4.86 | 1.09 - 1.19 | 1.14 | 5.05 - 7.70 | 6.00 | 3.26/17.14* | 0.81 |

**APPENDIX B8 : NUTRIENTS FOR SITES IN LOCALITY 8**

**LOCALITY 8 - SUMMARY OF NUTRIENTS FOR INSHORE SITES**

| SITE/CODE | DATE SAMPLED | RANGE P-PO4 uM | AVERAGE P-PO4 uM | RANGE N-NH3 uM | AVERAGE N-NH3 uM | RANGE NO3-N uM | AVERAGE NO3-N uM | RANGE DIN uM | AVERAGE DIN uM | NO3:PO4 OR DIN : PO4* | NH3/DIN |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **BUL1** | 12-Aug-04 | 0.77 - 1.68 | 1.22 | ND | ND | 0.29 - 0.57 | 0.43 | NA | NA | 0.35 | NA |
| | 14-Oct-04 | 0.03 - 0.1 | 0.05 | ND | ND | 0.07 - 0.29 | 0.19 | NA | NA | 3.8 | NA |
| **BUL2** | 2-Aug-04 | 0.75 - 2.90 | 1.83 | ND | ND | 7.46 - 15.11 | 10.7 | NA | NA | 5.85 | NA |
| | 12-Aug-04 | 0.13 - 0.26 | 0.18 | ND | ND | 0.06 - 0.57 | 0.35 | NA | NA | 1.94 | NA |
| | 14-Oct-04 | 0.03 - 0.06 | 0.05 | ND | ND | 0.07 - 0.21 | 0.14 | NA | NA | 2.8 | NA |
| **BUL3** | 2-Aug-04 | 0.66 - 1.45 | 1.03 | ND | ND | 4.87 - 5.29 | 5.08 | NA | NA | 4.93 | NA |
| **MLV1** | 29-Jul-04 | 0.50 - 0.57 | 0.54 | ND | ND | 0.81 - 1.48 | 1.24 | NA | NA | 2.30 | NA |
| | 12-Aug-04 | 0.06 - 1.68 | 0.71 | ND | ND | 0.43 - 1.29 | 0.86 | NA | NA | 1.21 | NA |
| | 14-Oct-04 | 0.02 - 0.16 | 0.07 | ND | ND | 0.07 - 0.14 | 0.09 | NA | NA | 1.29 | NA |
| | 31-Dec-04 | 1.74 - 3.48 | 2.61 | 2.93 - 3.61 | 3.28 | 0.37 - 0.4 | 0.38 | 3.3 - 3.98 | 3.66 | 0.15/1.40* | 0.9 |
| **MLV3** | 2-Aug-04 | 0.88 - 0.97 | 0.91 | ND | ND | 0.96 - 1.74 | 1.25 | NA | NA | 1.37 | NA |
| **TBK1** | 29-Jul-04 | 0.55 - 0.56 | 0.56 | ND | ND | 0.86 - 0.89 | 0.87 | NA | NA | 1.55 | NA |
| | 2-Aug-04 | 0.87 - 1.47 | 1.14 | ND | ND | 1.06 - 1.70 | 1.29 | NA | NA | 1.13 | NA |
| | 12-Aug-04 | 0.26 - 0.58 | 0.41 | ND | ND | 0.5 - 1.36 | 0.86 | NA | NA | 2.10 | NA |
| | 14-Oct-04 | 0.03 - 0.03 | 0.03 | ND | ND | 0.14 - 0.14 | 0.14 | NA | NA | 4.67 | NA |
| | 31-Dec-04 | 0.27 - 0.79 | 0.44 | 3.91 - 5.99 | 4.78 | 0.56 - 0.59 | 0.57 | 4.50 - 6.55 | 5.35 | 1.30/12.16* | 0.89 |
| **OTR1** | 29-Jul-04 | 0.49 - 0.50 | 0.50 | ND | ND | 1.36 - 1.55 | 1.44 | NA | NA | 2.88 | NA |
| | 2-Aug-04 | 1.04 - 1.41 | 1.28 | ND | ND | 1.29 - 1.72 | 1.51 | NA | NA | 1.69 | NA |
| | 12-Aug-04 | 0.03 - 0.09 | 0.06 | ND | ND | 1.70 - 2.36 | 2.08 | NA | NA | 34.67 | NA |
| | 31-Dec-04 | 0.23 - 0.45 | 0.32 | 3.16 - 3.36 | 3.26 | 0.36 - 0.39 | 0.38 | 3.55 - 3.72 | 3.64 | 1.19/11.38* | 0.90 |
| **CRW1** | 29-Jul-04 | 0.48 - 0.51 | 0.50 | ND | ND | 0.57 - 0.57 | 0.57 | NA | NA | 1.14 | NA |
| | 2-Aug-04 | 1.40 - 2.34 | 1.87 | ND | ND | 2.16 - 3.09 | 2.57 | NA | NA | 1.37 | NA |
| | 12-Aug-04 | 0.35 - 0.52 | 0.44 | ND | ND | 0.21 - 0.57 | 0.39 | NA | NA | 0.89 | NA |
| | 14-Oct-04 | 0.03 - 0.03 | 0.03 | ND | ND | 11.86 - 12.64 | 12.25 | NA | NA | 408.00 | NA |
| | 31-Dec-04 | 0.31 - 0.48 | 0.37 | 3.66 - 6.0 | 4.61 | 0.51 - 0.55 | 0.53 | 4.17 - 6.55 | 5.13 | 1.43/13.86* | 0.90 |

# APPENDIX C – RESULTS FROM STATISTICAL TESTS

**APPENDIX C1 : Comparing pooled phosphate and nitrate data among the 3 categories of sites (control, village and resort) during wet weather sampling (refer Section 4.3.2.5)**

## Oneway

**Test of Homogeneity of Variances**

wetphos

| Levene Statistic | df1 | df2 | Sig. |
|---|---|---|---|
| 7.253 | 2 | 74 | .001 |

## NPar Tests

## Kruskal-Wallis Test

**Ranks**

| | site | N | Mean Rank |
|---|---|---|---|
| wetphos | 1 | 28 | 39.84 |
| | 2 | 22 | 37.32 |
| | 3 | 27 | 39.50 |
| | Total | 77 | |

**Test Statistics[a,b]**

| | wetphos |
|---|---|
| Chi-Square | .179 |
| df | 2 |
| Asymp. Sig. | .914 |

a. Kruskal Wallis Test

b. Grouping Variable: site

## NPar Tests

## Kruskal-Wallis Test

**Ranks**

| | site | N | Mean Rank |
|---|---|---|---|
| wetnitra | 1 | 28 | 37.48 |
| | 2 | 22 | 40.57 |
| | 3 | 27 | 39.30 |
| | Total | 77 | |

**Test Statistics[a,b]**

| | wetnitra |
|---|---|
| Chi-Square | .242 |
| df | 2 |
| Asymp. Sig. | .886 |

a. Kruskal Wallis Test

b. Grouping Variable: site

**<u>APPENDIX C2:</u> Comparing June 2004 (wet) phosphate and nitrate data among the 3 categories of site (C, V and R, refer page 109).**

# Oneway

**Test of Homogeneity of Variances**

wetjunphos

| Levene Statistic | df1 | df2 | Sig. |
|---|---|---|---|
| 7.435 | 2 | 19 | .004 |

**ANOVA**

wetjunphos

| | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Between Groups | .075 | 2 | .038 | 6.669 | .006 |
| Within Groups | .107 | 19 | .006 | | |
| Total | .182 | 21 | | | |

# NPar Tests

# Kruskal-Wallis Test

**Ranks**

| | site | N | Mean Rank |
|---|---|---|---|
| wetjunphos | 1 | 6 | 4.92 |
| | 2 | 9 | 15.89 |
| | 3 | 7 | 11.50 |
| | Total | 22 | |

**Test Statistics[a,b]**

| | wetjunphos |
|---|---|
| Chi-Square | 10.319 |
| df | 2 |
| Asymp. Sig. | .006 |

a. Kruskal Wallis Test

b. Grouping Variable: site

# NPar Tests

# Kruskal-Wallis Test

**Ranks**

| | site | N | Mean Rank |
|---|---|---|---|
| wetjunnitr | 1 | 6 | 4.17 |
| | 2 | 9 | 12.56 |
| | 3 | 7 | 16.43 |
| | Total | 22 | |

**Test Statistics[a,b]**

| | wetjunnitr |
|---|---|
| Chi-Square | 11.936 |
| df | 2 |
| Asymp. Sig. | .003 |

a. Kruskal Wallis Test

b. Grouping Variable: site

## Post Hoc Tests

**Multiple Comparisons**

Dependent Variable: wetjunphos
LSD

| (I) site | (J) site | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval Lower Bound | Upper Bound |
|---|---|---|---|---|---|---|
| 1 | 2 | -.14222* | .03956 | .002 | -.2250 | -.0594 |
| | 3 | -.06333 | .04175 | .146 | -.1507 | .0241 |
| 2 | 1 | .14222* | .03956 | .002 | .0594 | .2250 |
| | 3 | .07889 | .03782 | .051 | -.0003 | .1581 |
| 3 | 1 | .06333 | .04175 | .146 | -.0241 | .1507 |
| | 2 | -.07889 | .03782 | .051 | -.1581 | .0003 |

*. The mean difference is significant at the .05 level.

## Oneway

**Test of Homogeneity of Variances**

wetjunnitr

| Levene Statistic | df1 | df2 | Sig. |
|---|---|---|---|
| 6.987 | 2 | 19 | .005 |

**ANOVA**

wetjunnitr

| | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Between Groups | 6.444 | 2 | 3.222 | 2.978 | .075 |
| Within Groups | 20.559 | 19 | 1.082 | | |
| Total | 27.003 | 21 | | | |

# Post Hoc Tests

**Multiple Comparisons**

Dependent Variable: wetjunnitr
LSD

| (I) site | (J) site | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval Lower Bound | Upper Bound |
|---|---|---|---|---|---|---|
| 1 | 2 | -1.21500* | .54824 | .039 | -2.3625 | -.0675 |
| | 3 | -1.21548* | .57872 | .049 | -2.4268 | -.0042 |
| 2 | 1 | 1.21500* | .54824 | .039 | .0675 | 2.3625 |
| | 3 | -.00048 | .52422 | .999 | -1.0977 | 1.0967 |
| 3 | 1 | 1.21548* | .57872 | .049 | .0042 | 2.4268 |
| | 2 | .00048 | .52422 | .999 | -1.0967 | 1.0977 |

*. The mean difference is significant at the .05 level.

---

**<u>APPENDIX C3:</u> Comparing wet weather and dry weather nutrient results for Valase (VLS), Namada (NMD) and Hideaway (HDW) sites (section 4.3.2.7)**

# NPar Tests

# Mann-Whitney Test

**Ranks**

| | site | N | Mean Rank | Sum of Ranks |
|---|---|---|---|---|
| VLSPHRAIN | 1 | 10 | 8.05 | 80.50 |
| | 2 | 11 | 13.68 | 150.50 |
| | Total | 21 | | |

**Test Statistics**[b]

| | VLSPHRAIN |
|---|---|
| Mann-Whitney U | 25.500 |
| Wilcoxon W | 80.500 |
| Z | -2.089 |
| Asymp. Sig. (2-tailed) | .037 |
| Exact Sig. [2*(1-tailed Sig.)] | .036[a] |

a. Not corrected for ties.

b. Grouping Variable: site

# NPar Tests

# Mann-Whitney Test

**Ranks**

| | site | N | Mean Rank | Sum of Ranks |
|---|---|---|---|---|
| VLSNITRAIN | 1 | 10 | 16.20 | 162.00 |
| | 2 | 11 | 6.27 | 69.00 |
| | Total | 21 | | |

**Test Statistics**[b]

| | VLSNITRAIN |
|---|---|
| Mann-Whitney U | 3.000 |
| Wilcoxon W | 69.000 |
| Z | -3.664 |
| Asymp. Sig. (2-tailed) | .000 |
| Exact Sig. [2*(1-tailed Sig.)] | .000[a] |

a. Not corrected for ties.

b. Grouping Variable: site

# NPar Tests

# Mann-Whitney Test

**Ranks**

| | site | N | Mean Rank | Sum of Ranks |
|---|---|---|---|---|
| NMDPHOS | 1 | 8 | 6.00 | 48.00 |
| | 2 | 7 | 10.29 | 72.00 |
| | Total | 15 | | |

**Test Statistics[b]**

| | NMDPHOS |
|---|---|
| Mann-Whitney U | 12.000 |
| Wilcoxon W | 48.000 |
| Z | -1.870 |
| Asymp. Sig. (2-tailed) | .061 |
| Exact Sig. [2*(1-tailed Sig.)] | .072[a] |

a. Not corrected for ties.

b. Grouping Variable: site

# NPar Tests

# Mann-Whitney Test

**Ranks**

| | site | N | Mean Rank | Sum of Ranks |
|---|---|---|---|---|
| NMDNITRA | 1 | 8 | 10.50 | 84.00 |
| | 2 | 7 | 5.14 | 36.00 |
| | Total | 15 | | |

**Test Statistics[b]**

| | NMDNITRA |
|---|---|
| Mann-Whitney U | 8.000 |
| Wilcoxon W | 36.000 |
| Z | -2.315 |
| Asymp. Sig. (2-tailed) | .021 |
| Exact Sig. [2*(1-tailed Sig.)] | .021[a] |

a. Not corrected for ties.

b. Grouping Variable: site

# NPar Tests

## Mann-Whitney Test

**Ranks**

| | site | N | Mean Rank | Sum of Ranks |
|---|---|---|---|---|
| HDWPHOS | 1 | 6 | 5.67 | 34.00 |
| | 2 | 6 | 7.33 | 44.00 |
| | Total | 12 | | |

**Test Statistics[b]**

| | HDWPHOS |
|---|---|
| Mann-Whitney U | 13.000 |
| Wilcoxon W | 34.000 |
| Z | -.801 |
| Asymp. Sig. (2-tailed) | .423 |
| Exact Sig. [2*(1-tailed Sig.)] | .485[a] |

a. Not corrected for ties.

b. Grouping Variable: site

# NPar Tests

## Mann-Whitney Test

**Ranks**

| | site | N | Mean Rank | Sum of Ranks |
|---|---|---|---|---|
| HDWNITRA | 1 | 6 | 9.50 | 57.00 |
| | 2 | 6 | 3.50 | 21.00 |
| | Total | 12 | | |

**Test Statistics[b]**

| | HDWNITRA |
|---|---|
| Mann-Whitney U | .000 |
| Wilcoxon W | 21.000 |
| Z | -2.887 |
| Asymp. Sig. (2-tailed) | .004 |
| Exact Sig. [2*(1-tailed Sig.)] | .002[a] |

a. Not corrected for ties.

b. Grouping Variable: site

# Appendix C4: Comparing phosphate levels in inshore and off-shore waters (Section 4.3.4.2.3)

## Oneway

**Test of Homogeneity of Variances**

PO4

| Levene Statistic | df1 | df2 | Sig. |
|---|---|---|---|
| 13.424 | 1 | 18 | .002 |

**ANOVA**

PO4

| | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Between Groups | 1.513 | 1 | 1.513 | 2.566 | .127 |
| Within Groups | 10.611 | 18 | .590 | | |
| Total | 12.124 | 19 | | | |

## NPar Tests

## Mann-Whitney Test

**Ranks**

| | insh/offsh | N | Mean Rank | Sum of Ranks |
|---|---|---|---|---|
| PO4 | 1 | 10 | 11.25 | 112.50 |
| | 2 | 10 | 9.75 | 97.50 |
| | Total | 20 | | |

**Test Statistics**[b]

| | PO4 |
|---|---|
| Mann-Whitney U | 42.500 |
| Wilcoxon W | 97.500 |
| Z | -.568 |
| Asymp. Sig. (2-tailed) | .570 |
| Exact Sig. [2*(1-tailed Sig.)] | .579[a] |

a. Not corrected for ties.

b. Grouping Variable: insh/offsh

**<u>Appendix C5:</u> Valase Reef Data, Before (2004) and After (2006) the Maui Resort Development**

*<u>Comparing Sargassum % cover on Valase Reef in 2004 and 2006</u>*

# Oneway

**Test of Homogeneity of Variances**

VLSsargcov

| Levene Statistic | df1 | df2 | Sig. |
|---|---|---|---|
| 62.297 | 1 | 73 | .000 |

**ANOVA**

VLSsargcov

| | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Between Groups | 1978.974 | 1 | 1978.974 | 12.866 | .001 |
| Within Groups | 11228.546 | 73 | 153.816 | | |
| Total | 13207.520 | 74 | | | |

# NPar Tests

# Mann-Whitney Test

**Ranks**

| | before/after | N | Mean Rank | Sum of Ranks |
|---|---|---|---|---|
| VLSsargcov | 1 | 40 | 33.25 | 1330.00 |
| | 2 | 35 | 43.43 | 1520.00 |
| | Total | 75 | | |

**Test Statistics[a]**

| | VLSsargcov |
|---|---|
| Mann-Whitney U | 510.000 |
| Wilcoxon W | 1330.000 |
| Z | -2.642 |
| Asymp. Sig. (2-tailed) | .008 |

a. Grouping Variable: before/after

*Comparing Live Coral cover % on Valase Reef in 2004 and 2006*

# Oneway

**Test of Homogeneity of Variances**

LivCorCov

| Levene Statistic | df1 | df2 | Sig. |
|---|---|---|---|
| .161 | 1 | 73 | .689 |

**ANOVA**

LivCorCov

| | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Between Groups | 272.086 | 1 | 272.086 | .513 | .476 |
| Within Groups | 38713.061 | 73 | 530.316 | | |
| Total | 38985.147 | 74 | | | |

---

**APPENDIX C6 : Comparing responses of Sargassum rhizoids and leafy shoots to 4 levels of treatment (control; +N; +P; +N+P) in laboratory experiments**

*Rhizoid responses*

# Oneway

**Test of Homogeneity of Variances**

RhizLngth

| Levene Statistic | df1 | df2 | Sig. |
|---|---|---|---|
| 2.114 | 3 | 76 | .105 |

**ANOVA**

RhizLngth

| | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Between Groups | 81.300 | 3 | 27.100 | .991 | .402 |
| Within Groups | 2078.500 | 76 | 27.349 | | |
| Total | 2159.800 | 79 | | | |

*<u>Leafy shoot responses</u>*

**ANOVA**

SargLeafLngth

| | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Between Groups | 51.438 | 3 | 17.146 | 3.081 | .032 |
| Within Groups | 422.950 | 76 | 5.565 | | |
| Total | 474.388 | 79 | | | |

**Test of Homogeneity of Variances**

SargLeafLngth

| Levene Statistic | df1 | df2 | Sig. |
|---|---|---|---|
| 3.309 | 3 | 76 | .025 |

# NPar Tests

# Kruskal-Wallis Test

**Ranks**

| | NutriTreatmnt | N | Mean Rank |
|---|---|---|---|
| SargLeafLngth | 1 | 20 | 51.10 |
| | 2 | 20 | 36.18 |
| | 3 | 20 | 34.73 |
| | 4 | 20 | 40.00 |
| | Total | 80 | |

**Test Statistics[a,b]**

| | SargLeaf Lngth |
|---|---|
| Chi-Square | 6.332 |
| df | 3 |
| Asymp. Sig. | .097 |

a. Kruskal Wallis Test

b. Grouping Variable: NutriTreatmnt

**<u>APPENDIX C7</u> : Statistical Test Results for Caging/Nutrient Enrichment Field Experiments (Section 6.3.4.1.1)**

## Oneway

[DataSet0]

**Test of Homogeneity of Variances**

HTCHNGE

| Levene Statistic | df1 | df2 | Sig. |
|---|---|---|---|
| 6.914 | 1 | 23 | .015 |

**ANOVA**

HTCHNGE

| | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Between Groups | 268.341 | 1 | 268.341 | 1.429 | .244 |
| Within Groups | 4319.019 | 23 | 187.783 | | |
| Total | 4587.360 | 24 | | | |

## NPar Tests

[DataSet0]

## Mann-Whitney Test

**Ranks**

| | TREATMNT | N | Mean Rank | Sum of Ranks |
|---|---|---|---|---|
| HTCHNGE | 1 | 12 | 12.08 | 145.00 |
| | 2 | 13 | 13.85 | 180.00 |
| | Total | 25 | | |

**Test Statistics[b]**

| | HTCHNGE |
|---|---|
| Mann-Whitney U | 67.000 |
| Wilcoxon W | 145.000 |
| Z | -.606 |
| Asymp. Sig. (2-tailed) | .545 |
| Exact Sig. [2*(1-tailed Sig.)] | .574[a] |

a. Not corrected for ties.

b. Grouping Variable: TREATMNT

**<u>APPENDIX C8:</u> Statistical Tests for Caging/Herbivory Exclusion Field Experiments.**

*<u>Tambua Sands Site</u>*

# NPar Tests

## Wilcoxon Signed Ranks Test

**Ranks**

| | | N | Mean Rank | Sum of Ranks |
|---|---|---|---|---|
| TBSDAY2 - TBSDAY1 | Negative Ranks | 5[a] | 30.30 | 151.50 |
| | Positive Ranks | 32[b] | 17.23 | 551.50 |
| | Ties | 3[c] | | |
| | Total | 40 | | |

a. TBSDAY2 < TBSDAY1

b. TBSDAY2 > TBSDAY1

c. TBSDAY2 = TBSDAY1

**Test Statistics[b]**

| | TBSDAY2 - TBSDAY1 |
|---|---|
| Z | -3.027[a] |
| Asymp. Sig. (2-tailed) | .002 |

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

## NPar Tests

# Wilcoxon Signed Ranks Test

**Ranks**

| | | N | Mean Rank | Sum of Ranks |
|---|---|---|---|---|
| TSUNCDY2 - TSUNCDY1 | Negative Ranks | 32[a] | 21.36 | 683.50 |
| | Positive Ranks | 5[b] | 3.90 | 19.50 |
| | Ties | 3[c] | | |
| | Total | 40 | | |

a. TSUNCDY2 < TSUNCDY1

b. TSUNCDY2 > TSUNCDY1

c. TSUNCDY2 = TSUNCDY1

**Test Statistics[b]**

| | TSUNCDY2 - TSUNCDY1 |
|---|---|
| Z | -5.045[a] |
| Asymp. Sig. (2-tailed) | .000 |

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

*Namada site – caged Sargassum shoots*

**Test of Homogeneity of Variances**

NMDSargHttm2

| Levene Statistic | df1 | df2 | Sig. |
|---|---|---|---|
| 2.936 | 11 | 35 | .007 |

**ANOVA**

NMDSargHttm2

| | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Between Groups | 669.592 | 14 | 47.828 | .811 | .652 |
| Within Groups | 2063.528 | 35 | 58.958 | | |
| Total | 2733.120 | 49 | | | |

# NPar Tests

# Wilcoxon Signed Ranks Test

**Ranks**

| | | N | Mean Rank | Sum of Ranks |
|---|---|---|---|---|
| NMDSargHttm2 - NMDSargHttm1 | Negative Ranks | 35[a] | 25.06 | 877.00 |
| | Positive Ranks | 12[b] | 20.92 | 251.00 |
| | Ties | 3[c] | | |
| | Total | 50 | | |

a. NMDSargHttm2 < NMDSargHttm1

b. NMDSargHttm2 > NMDSargHttm1

c. NMDSargHttm2 = NMDSargHttm1

**Test Statistics**[b]

| | NMDSarg Httm2 - NMDSarg Httm1 |
|---|---|
| Z | -3.314[a] |
| Asymp. Sig. (2-tailed) | .001 |

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

*Namada uncaged Sargassum shoots*

# NPar Tests

# Wilcoxon Signed Ranks Test

**Ranks**

| | | N | Mean Rank | Sum of Ranks |
|---|---|---|---|---|
| NMDuncgTm2 - NMDuncgTm1 | Negative Ranks | 49[a] | 26.00 | 1274.00 |
| | Positive Ranks | 1[b] | 1.00 | 1.00 |
| | Ties | 0[c] | | |
| | Total | 50 | | |

a. NMDuncgTm2 < NMDuncgTm1

b. NMDuncgTm2 > NMDuncgTm1

c. NMDuncgTm2 = NMDuncgTm1

**Test Statistics**[b]

| | NMDuncgTm2 - NMDuncgTm1 |
|---|---|
| Z | -6.156[a] |
| Asymp. Sig. (2-tailed) | .000 |

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

*Hideaway caged Sargassum shoots*

**Test of Homogeneity of Variances**

HDWcagedSargTm2

| Levene Statistic | df1 | df2 | Sig. |
|---|---|---|---|
| 3.413 | 9 | 29 | .006 |

**ANOVA**

HDWcagedSargTm2

| | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Between Groups | 2322.792 | 10 | 232.279 | .938 | .514 |
| Within Groups | 7177.583 | 29 | 247.503 | | |
| Total | 9500.375 | 39 | | | |

# Wilcoxon Signed Ranks Test

**Ranks**

| | | N | Mean Rank | Sum of Ranks |
|---|---|---|---|---|
| HDWcagedSargTm2 - HDWcagedSargTm1 | Negative Ranks | 18[a] | 14.81 | 266.50 |
| | Positive Ranks | 22[b] | 25.16 | 553.50 |
| | Ties | 0[c] | | |
| | Total | 40 | | |

a. HDWcagedSargTm2 < HDWcagedSargTm1

b. HDWcagedSargTm2 > HDWcagedSargTm1

c. HDWcagedSargTm2 = HDWcagedSargTm1

**Test Statistics[b]**

| | HDWcaged SargTm2 - HDWcaged SargTm1 |
|---|---|
| Z | -1.930[a] |
| Asymp. Sig. (2-tailed) | .054 |

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

*Hideaway uncaged Sargassum shoots*

## NPar Tests

## Wilcoxon Signed Ranks Test

**Ranks**

| | | N | Mean Rank | Sum of Ranks |
|---|---|---|---|---|
| HDWuncagedSargTm2 - HDWuncagedSargTm1 | Negative Ranks | 34[a] | 22.49 | 764.50 |
| | Positive Ranks | 5[b] | 3.10 | 15.50 |
| | Ties | 0[c] | | |
| | Total | 39 | | |

a. HDWuncagedSargTm2 < HDWuncagedSargTm1

b. HDWuncagedSargTm2 > HDWuncagedSargTm1

c. HDWuncagedSargTm2 = HDWuncagedSargTm1

**Test Statistics[b]**

| | HDWuncagedSargTm2 - HDWuncagedSargTm1 |
|---|---|
| Z | -5.236[a] |
| Asymp. Sig. (2-tailed) | .000 |

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test