

Chapter 11

Ecological purification in the captive reef – natural approaches to water quality management

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ABSTRACT

Advances in the husbandry of coral organisms in captivity have been underpinned by an evolution in the understanding of the natural processes occurring within closed systems. This has facilitated a more refined approach to water quality management, informed by studying nutrient cycling processes and ecosystem function in nature. Life support system technology has been adapted to function alongside these natural processes, often in contrast to fish-only systems, avoiding an over-reliance on equipment intensive, synthetic chemical filtration. Natural methodologies can be employed to manage nitrogenous and other metabolic by-products which can be detrimental to closed coral systems. This paper reviews the biological processes utilised by natural filtration methods and how these processes are being adapted for use in coral life support systems.

INTRODUCTION

Understanding the requirements of captive coral reef organisms is an evolving science inseparable from the technologies and philosophies employed in the provision of conditions appropriate to their welfare. In contrast to fish-only systems, a more diverse array of potentially deleterious compounds must be monitored and managed if the successful maintenance of corals, in closed systems, is to be achieved: Compounds which do not physiologically impair fish are often detrimental to corals.

Characteristically corals form only part of the biological community inhabiting a coral reef exhibit, often in direct contrast to fish-only systems where other biological representation is either actively discouraged or is incidental to the main focus of the exhibit. Thus the water quality management of fish-only systems is focused exclusively on the removal of pollutants resulting from the metabolic processes of the fish it supports. Coral exhibits support a more diverse assemblage of organisms, where the origin of potentially harmful substances has more diverse origins. However, this biological complexity provides opportunities for nutrient management pathways unavailable within

fish-only systems and where there is a greater reliance upon nutrient cycling rather than the physical removal of accumulating pollutants either chemically or physically by performing water changes. It is, therefore, a necessity to create systems for coral exhibits where the provision of substrates and other habitats encourages the development of these beneficial nutrient pathways.

This paper avoids prescriptive recommendations of acceptable limits of nitrogenous and other potentially detrimental compounds, rather it aims to explore how wild ecosystems facilitate nutrient cycling and attempt to explain how we as aquarists can adapt these processes to assist in creating captive environments suitable for corals to thrive. It provides a brief overview of the commonly used natural methods before discussing the biological processes underlying their success. Unlike wild coral reefs, closed systems are not continually flushed with oligotrophic water from the surrounding ocean, and have a tendency to become eutrophic (Spotte, 1979). If the risk of eutrophication is to be mitigated, it is incumbent upon the aquarist to understand the path of nutrients within wild ecosystems and adopt husbandry

and life support techniques which allow similar processes to function. However, it should be noted that our understanding of ecosystem functioning in the field is based upon scientific study, the same cannot be said of captive systems. To date, there has been very little experimental analysis to elucidate how natural methodologies function in a captive environment.

NATURAL SYSTEMS – A BRIEF OVERVIEW

Natural systems can be defined as those that do not rely on synthetic substrates for processing nitrogenous and other potentially harmful waste (Pecorelli *et al.*, in press). Whilst the bacterial conversion of ammonia to nitrite and finally nitrate (nitrification) forms part of the overall nutrient management strategy, many other pathways can be integrated across different trophic levels. This pluralistic approach is a key difference between natural systems and those which rely on aerobic bacterial nutrient management, usually occurring within a dedicated biofilter. However, natural methodologies are flexible in their application, and can be adapted to work alongside more traditional life support technology, as discussed later.

Traditionally, natural methods have relied upon the use of 'live' sediments, 'live' rock and various algal species as the primary nutrient management centres ('live' in the sense that they support a community of micro and macrofauna). Both 'live' sediments and 'live' rock integrate the processes of nitrification and denitrification utilising micro-faunal communities located within the pore structures of these substrates where both aerobic and suboxic/anoxic conditions persist in close proximity, minimising the flux of nitrogenous waste into the water column during processing. Algae have the ability to assimilate nitrogenous waste directly although uptake is variable according to the availability of nitrogen and the affinity of individual species for ammonia or nitrate, as discussed further later. Descriptive work on the application of natural methods began in the 1950s and early 1960s with the hobbyist Lee Chin Eng who pioneered the use of 'live' rocks and sediments to maintain water quality sufficient for corals (Eng, 1961), together with high rates of water circulation and strong illumination. The live substrates were taken directly from the ocean, with minimal collection

and transport disturbance ensuring the desired biological communities remained intact.

Subsequently natural systems have evolved into several distinct types, each with defining characteristics. In practice although the systems are defined according to their original description, many Aquarists adopt a hybrid approach, integrating many of the techniques within a single system. However, it is instructive to look at some of the major and more recent developments in the evolution of natural systems from Eng's starting point. Readers are directed towards Pecorelli *et al.* (in press), Delbeek and Sprung (2006) and Tyree (2000) for further discussion of the merits and drawbacks associated with each of these systems.

Sediment systems

The focus of sediment-based nutrient management systems began with Jaubert's description of the plenum technique which featured a layer of coral sand under which a void space (the plenum) facilitated the formation of an oxygen gradient through the profile of the sediment (Jaubert, 1989). Aerobic processes occurred in the upper layers whilst hypoxic conditions within the plenum and in the sediment layers above encouraged denitrification. An additional cited benefit was the biogeochemical release of calcium and carbonate materials as interstitial pH values would be lowered by microbial activity (see chapter 12). Subsequently sand beds have been deployed both with and without the addition of a plenum (Toonen and Wee, 2005). Recently commercial systems which actively manipulate the biochemical conditions within sediment beds have become available (the EcoDeco[®] system, although to date these are in the early stages of development for use in public aquaria, being more commonly used in laboratory based experimental systems (Sipkema *et al.*, 2005; Khalesi *et al.*, 2007). By controlling the pH and dissolved organic carbon concentration of the water passing through the sediment, it is tendered that optimal conditions for denitrification and biogeochemical dissolution of calcium can be achieved.

Algal systems

Methods which rely on algal species as the primary nutrient management strategy include the Algal Turf Scrubber[™] system (Adey and Loveland, 1998) where various species of turf algae are grown on a screen flushed periodically with system water. Nutrient export is achieved

by harvesting the growing algae to ensure that the turfs are kept in an exponential growth phase where nutrient uptake is maximized.

Leng Sy's Ecosystem method® hybridizes many of the techniques of other natural systems utilizing a layer of 'miracle mud®' substrate over which a bed of macroalgae (such as *Caulerpa* spp.) is grown within a refugium separate from the main display (described in Paletta, 2001). Lighting regimes above the algal turf scrubber (ATS) and Ecosystem refugium are commonly reversed or prolonged (perpetual lighting regimes have been used on Ecosystem™ refugia) to facilitate optimal oxygen and carbon dioxide levels within the exhibit. It should be noted that the Ecosystem method is most commonly used on small private aquaria and has received very little experimental investigation and it is unclear whether the mud plays any significant role in nutrient processing (see below for further discussion).

Other natural methods

Although not commonly employed as a strategy for water quality management in public aquaria, Tyree's tri-zonal method utilises the abilities of cryptic sponges to remove dissolved organic nutrients (Tyree, 2000). Areas within the exhibit are created such that sponge growth and reproduction are encouraged. It remains to be seen, however, how much of the nutrient processing can be directly attributed to the sponges. Indeed, whilst sponges uptake particulate organic matter, they also release inorganic nutrients (Richter *et al.*, 2001), and that associated bacterial populations perform do not facilitate either denitrification or anammox (Southwell *et al.*, 2008).

The Berlin method relies on 'live' rock to provide both aerobic and anaerobic conditions (Tulloch, 1997). However a foam fractionator was used remove dissolved organic compounds and other particulate waste. The issue of integrating natural methods with other life support system (LSS) strategies will be explored further later, however, the foam fractionator was a key component of the system and as such the balance between nutrient management within the natural substrates and the fractionator is unknown.

Whilst it is important to understand the practical applications of natural methodologies, it is equally important to have a firm understanding of the biological processes occurring within them to harness their abilities to best effect. The following sections review how wild sediment and

algal systems function and how acknowledge of the functional characteristics can lead to more effective management practises in closed systems.

Nutrient dynamics in sediment systems

Sediment systems have a fundamental role in ocean nutrient cycling (Pecorelli *et al.*, in press). The interaction between grain size and composition, and the micro and macroscopic communities living within the sediment are the key determinants of nutrient processing. In general terms, sediments with finer grain size support greater biodiversity than those with larger grains, as they are better able to avoid excessive nutrient flushing (Adey and Loveland, 1998). Estuarine sediments support some of the highest levels of biological activity found in any sediment type, however their fine structure and propensity to accumulate organic material leading to the development of anaerobic regions close to the surface (aerobic depths can be as shallow as 6.5 mm (Revsbech *et al.*, 1980) makes them a poor model for captive systems. Marine sediments associated with coral reefs are a more suitable choice for a model system. They are typically coarser grained and are less prone to be clogged by organic detritus (Hallock, 1997). However, these sediment beds are dynamic with varying characteristics according to hydrodynamic gradients, and as such are not homogenous in either composition or nutrient retention. Lagoon and back reef systems are the primary location for sediment nutrient processing where relatively high inputs of coral derived materials couples with rapid rates of organic recycling. Up to 15 % of lagoon water permeates through the underlying sediment per day, which acts as a bio-catalytic mineralising filter (Wild *et al.*, 2004, 2005).

In order for a sand bed to facilitate both nitrification and denitrification, a vertical stratification of oxygen creating both oxic and anoxic layers must form. The boundary between the oxic and anoxic zones is called the Redox Discontinuity Layer (RDL) above which oxidative reactions occur and with reductive reactions taking place below. However, research has suggested that sediment beds are in continual flux where particularly intense microbial activity leads to anoxic microsites forming within otherwise oxic zones (Day *et al.*, 1989).

Nitrogen cycling

Nitrogenous compounds are in continual flux

within the sediment and between the sediment and the overlying water column. Ammonia is a primary excretory product of macrofauna and is released from complex proteins and amino acids by microbial action. In the upper aerobic layer, autotrophic and heterotrophic bacteria oxidize ammonia to nitrite and then nitrate (nitrification) a process which may be significantly enhanced by the bioturbation (the turnover of sediment by organisms dwelling within) of infaunal organisms (Henriksen *et al.*, 1983; Herbert, 1999; Hylleberg and Henriksen, 1980; Kristensen, 1985). Indeed polychaete burrows have been shown to harbor between 10-70 % of all sediment nitrification and help to increase the aerobic volumes by 30-50 % (Kristensen *et al.*, 1985).

An additional mechanism for ammonia removal is via the recently discovered anammox reaction (Strous *et al.*, 1999, see figure 1), where under anaerobic conditions, ammonium and nitrite are converted to dinitrogen (N_2). However, this process is more common in sediments containing high levels of organic carbon. (Trimmer *et al.*, 2003) and its role in nitrogen cycling in reef systems has yet to be demonstrated, although this may change upon further investigation given its ubiquity in other habitats (Kuypers *et al.*, 2005; Devola *et al.*,

2006).

Nitrate released by nitrification can either flux into the water column or remain within the sediment where, under suboxic or anoxic conditions, heterotrophic bacteria reduce it to atmospheric dinitrogen (N_2). The coupling of both aerobic and anaerobic processes limits the diffusion of nitrate into the water column as the closure of the nitrogen cycle effectively removes nitrogenous waste from the system. Rates of nitrogen removal in wild sediments can be extremely rapid (up to $1401 \text{ mg N.m}^{-2}.\text{d}^{-1}$; reviewed in Herbert, 1999), however in closed systems performance will obviously depend on the dynamics of the individual system, as described below.

Dissimilatory nitrate reduction, where bacteria convert nitrate to ammonium, is a fermentive process that is a potential problem in closed systems (see figure 1). However, studies have shown that this occurs primarily when sediment nitrate concentrations are comparatively low (Herbert and Nedwell, 1990), a situation unlikely to occur in nitrogen eutrophic aquariums. Nitrous oxide is an intermediate product of denitrification and a side reaction of nitrate ammonification, however, it is of relatively little consequence as it is fluxed from the air/water interface in the same way as dinitrogen.

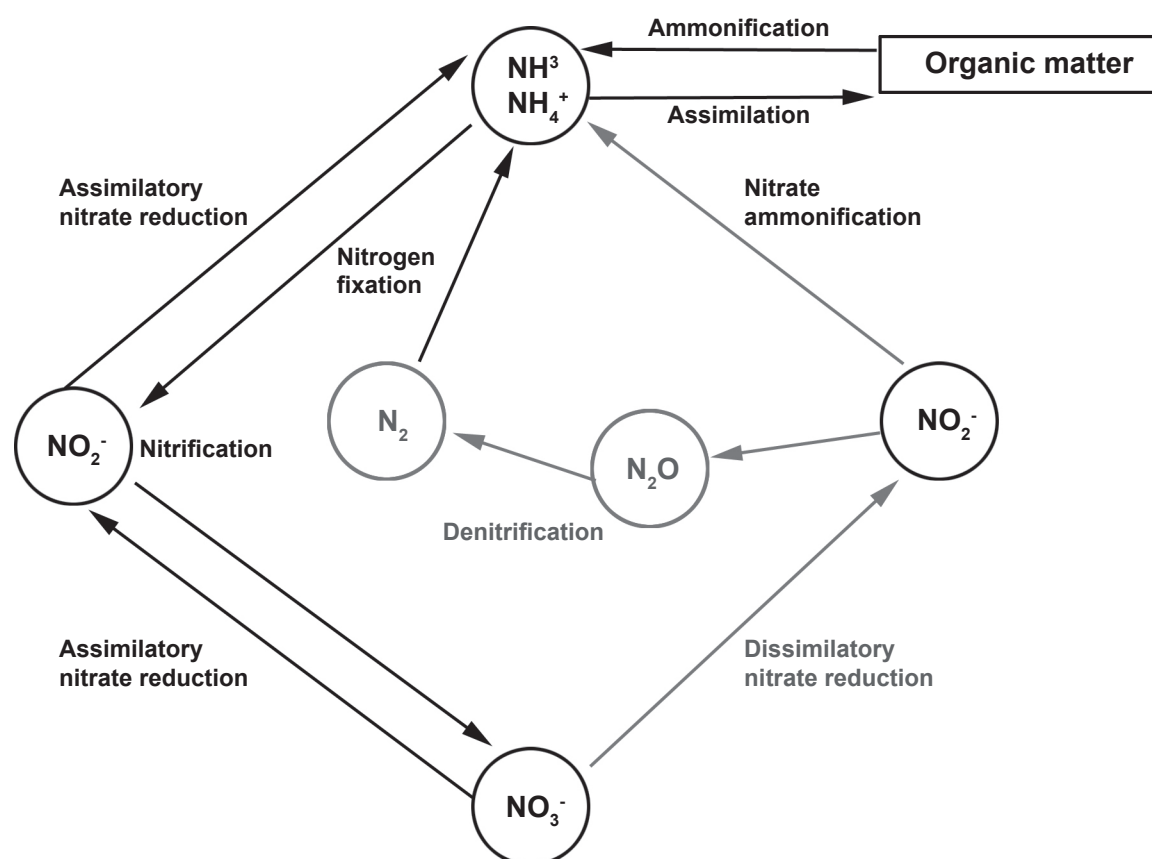


Figure 1: The nitrogen cycle in aquatic environments. Anaerobic processes are shown in grey.

Although the primary role of deep sand beds in captive reef systems is usually associated with the management of nitrogenous wastes, their role in the biogeochemical cycling of phosphates and organic carbon must also be considered. Organic carbon is either mineralized by both aerobic and anaerobic bacterial communities (as a source of electron donation). Nevertheless, some compounds are extremely resistant to microbial breakdown and may remain in the sediment (Arnosti and Holmer, 2003) and hence accumulate over time. High levels of organic input into sediment systems can also be detrimental to the aerobic functioning of the system by encouraging the proliferation of high levels of heterotrophic oxygen consuming bacteria (Kube, 2006). Orthophosphate meanwhile, tends to be bound to ferric oxides in aerobic substrates and released under anaerobic conditions where bacteria use iron oxides as terminal electron receptors (Day *et al.*, 1989). This suggests a degree of flux between the sediment and the overlying water. Phosphates may also bind within aragonite based substrates during crystal formation. However, these may be released during biogeochemical activity at reduced pH levels (Toonen and Wee, 2005). Carbonates are released by biochemical processes from sediment systems associated with reef environments (Charpy-Roubaud *et al.*, 1999; Leclercq *et al.*, 2002; Yates and Halley, 2006), thereby supporting coral calcification. Carbonate release is also facilitated by the actions of organisms boring into the skeletons of both live and dead corals (Londoño-Cruz *et al.*, 2003; Tribollet and Golubic, 2005), and also live rock (Zundeleovich *et al.*, 2006).

Theoretical concepts and practical realities

In practical terms, the performance of sand bed systems, either with or without the presence of a plenum, shows substantial variation between individual exhibits (e.g. Toonen and Wee, 2005; Delbeek and Sprung 2006). Toonen and Wee (2005) examined the interaction between grain size, sediment depth and the presence/absence of a plenum in small scale sediment systems to determine how variation in the physical characteristics of the sand bed affected nutrient processing, both with and without an assemblage of live organisms. No significant differences were detected between the nutrient processing performance of sediments overlying a plenum and those

placed directly onto the tank bottom, both with and without animals. Over the course of the trials lower nitrate concentrations and reduced animal mortalities were associated with deeper finersediments (approximately 9 cm deep, grain size 0.2 mm diameter) than shallower courser substrates (approximately 2.5 cm, grain size 2 mm diameter). The relatively short assessment period of the trials (114 days without animals and 118 days with animals) and the very small size of the replicate systems (27x17x30 cm) are two important shortcomings. However this is the first replicated study of sediment systems as practiced in closed system nutrient management.

Various other factors can also affect sand bed performance such as infaunal diversity (Raffaelli *et al.*, 2003a) and sediment input. Indeed the observed clogging of the sediment pore structure with bioclasts and refractory organic material may be directly related to the composition of the detritus being generated by the overlying community. Delbeek and Sprung (2006) explore the impact of flow dynamics, sediment topography and tank contents on nutrient processing. Potential stochasticity due to biological community variation is discussed later.

LIVE ROCK

The potential for nutrient management offered by the addition of live rock to a reef aquarium depends on two different modes of action. Firstly the physical structure of the rock facilitates both aerobic and anoxic/suboxic microbial activity to develop in close proximity in a stratification analogous to deep sand beds. The cavity structure of the rock may also act as a sink for dissolved organic carbon (Goeij and Duyl, 2007). Secondly, the live rock is an excellent biodiversity carrier although the biological communities carried within and on the rock surface will depend on both transit times from the reef (as the rock is shipped damp, not immersed) and the prevailing conditions at the site of collection. Tullock (1997) provides an excellent review of the organisms commonly found on live rock.

The use of cultured live rock is becoming increasingly common as concerns with collection practices grow (Wabnitz *et al.*, 2003). Nutrient processing rates associated with cultured rock do not appear to differ from wild harvested rock (Sharp, unpublished

data), although as with all live rock, the amount of living material surviving harvesting and transportation may effect its ability to function as an effective substrate for nutrient management.

ALGAL NUTRIENT MANAGEMENT

Repeated observations confirm that turfs of filamentous and small fleshy algal species are the major contributor to the primary productivity of reef systems (reviewed by Hatcher, 1997; Adey and Loveland, 1998). As such they form one of the key nutrient processing centers in reef ecosystems facilitating the flow of energy from primary production upwards throughout the trophic structure of the reef community. The rapid growth rates of turf species, particularly when maintained in an exponential growth phase through grazing pressure, can support high levels of production – 20 to 50 g dry weight.m⁻².d⁻¹ which translates to the assimilation of 0.3-1.2 g total nitrogen.m⁻².d⁻¹ (Adey and Loveland, 1998). Macroalgae tends to enter microbial food webs as detritus rather than supporting macrofaunal production *in situ* (Hatcher, 1997). High rates of nutrient uptake by both micro and macroalgal species have lead to their use in both aquaculture and aquaria. This is primarily in the management of nitrogenous waste, but also to control orthophosphate levels.

Nutrient assimilation rates across different algal communities vary widely depending on a variety of environmental factors with fast growing and opportunistic species tending towards the highest rates of nutrient uptake (Neori *et al.*, 2004). Uptake rates for some

macroalgal species commonly maintained in captivity are well described in the field (e.g. Pedersen and Borum, 1996; Larned, 1998; Menédez *et al.*, 2002, see table 1) and vary widely according to ambient nutrient concentrations, however the mode of nutrient acquisition varies between species and local environment.

In wild reefs inorganic nitrogen rather than phosphate may be a limiting factor restricting algal growth, leading to competition with zooxanthellae for inorganic nitrogen. However, in all but the most lightly stocked of reef systems, this situation is unlikely to occur (see chapter 16). *Caulerpa racemosa* (Forsskål), *C. sertularioides* (Gmelin) and *C. cupressoides* (Vahl) overcome nutrient limitation by extracting inorganic nitrogen and phosphate directly from the pore water of underlying sediment (Larned, 1998), trapping a layer of enriched water between the algal mat and the substrate effectively preventing nutrient flux into the water column. The biochemical environment created around algal rhizoids may assist in the transfer of nutrients from the sediment to the algae with the rhizoids having the ability to uptake phosphorus from calcareous sediments (Chisholm and Jaubert, 1996) and fix nitrogen in the anoxic rhizosphere (Chisholm and Jaubert, 1996). Other algal species are entirely reliant on nutrients extracted directly from the water column and are dependant on a rapid advection of nutrients caused by high current flows. Indeed where current flows are insufficient to advect the required nutrients, there is a net decrease in algal biomass (Larned, 1998; Hernandez *et al.* 2002) and a release of nutrients. Total uptake of both

Table 1: Nitrogen and phosphate concentrations (% dry weight) in macroalgal species in field conditions. These figures may vary temporally and are specific to collection sites at the locations described within the references.

| Species | Nitrogen | Phosphorus | Source |
|--------------------------------|-------------|-------------|--------|
| <i>Caulerpa racemosa</i> | 5.3 ± 3.3 | 0.08 ± 0.03 | 1 |
| <i>Caulerpa sertularioides</i> | 12.7 ± 1.13 | 0.14 ± 0.08 | 1 |
| <i>Codium edule</i> | 1.46 ± 0.13 | 0.10 ± 0.01 | 1 |
| <i>Sargassum echinocarpum</i> | 1.32 ± 0.08 | 0.08 ± 0.01 | 1 |
| <i>Ulva fasciata</i> | 2.69 ± 0.29 | 0.12 ± 0.01 | 1 |
| <i>Chaetomorpha linum</i> | 5.5* | 0.65* | 2 |

* These are the maximum values recorded over the course of a year

1 Larned, 1998

2 Pedersen and Borum, 1996

inorganic nitrogen and phosphate varies between species depending on their individual storage capacities - nutrient availability in the water column may be a poor predictor of assimilated nutrients (Lobban and Harrison, 1994; Larned, 1998). Aquarists may therefore want to encourage those species with high nutrient storage capabilities and fast growth rates to maximize nutrient removal such as *Chaetomorpha* sp., and *Caulerpa* sp.. Based on the results published by Larned (1998), Holmes-Farley (www1) calculated that 10 g of dry weight *Caulerpa racemosa* contained the equivalent of 24 mg of phosphorus and 2.5 g of nitrate when collected from the reef. However, it should be noted that typical ammonia/nitrite/nitrate ratios found within closed systems are typically enriched with nitrate, whereas the water surrounding wild reefs is more evenly balanced. This may or may not translate into switching between inorganic nitrogen sources, although some species are able to assimilate ammonia and nitrate simultaneously (Ahn *et al.*, 1998).

Microalgae cultivation

A recent experiment demonstrated the possibility of using a species of microalgae (*Nannochloropsis* sp.) as a nutrient management strategy in a recirculating system (Kube, 2006). Although the culture system was considerably higher in dissolved inorganic nitrogen than is desirable for coral systems, the algae were cultivated in a continual flow through photobioreactor on a bypass loop from the main LSS path. The water entering the culture vessel was pretreated by fractionation

with the application of ozone to avoid bacterial contamination, before entering at a rate predetermined to ensure sustainable amounts of algae were washed out of the vessel without a net loss of biomass. Nutrient uptake rates were considerable ($\text{PO}_4\text{-P}$ $0.294 \text{ mg}\cdot\text{L}^{-1}\cdot\text{h}^{-1}$, N-NO_3 $0.186 \text{ mg}\cdot\text{L}^{-1}\cdot\text{h}^{-1}$) within the culture vessels. In systems where foam fractionation is necessary to manage levels of suspended particulates this method offers a potentially exciting way of transferring pollutants directly into planktonic production with high nutritional value, although further development and refinement would be required before integrating photobioreactors into coral exhibit LSS. Maintaining sustainable populations of phytoplankton in coral systems, designed to be low in inorganic nitrogen and phosphorus, is a challenging proposition.

Heavy metal removal

Whilst some metals are important trace elements, algae can be an extremely effective removal mechanism for potentially harmful concentrations of most heavy metals. Uptake rates may be proportional to metal concentration in the surrounding water (Chan *et al.*, 2003), thereby rapidly nullifying toxic events. Various mechanisms for metal assimilation have been proposed (Maeda and Sakaguchi, 1991), however the most significant appears to be adsorption of the positively charged metal ions to the negatively charged fibrils of algal cell walls (Adey and Loveland, 1998). Aquarists can choose to deploy algal purification opportunistically if metal contamination is suspected.

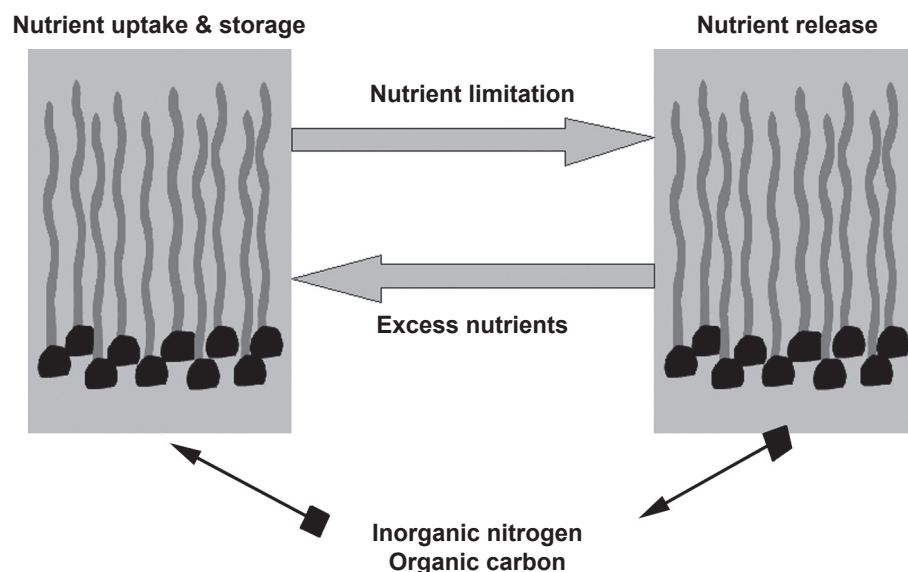


Figure 2: The dynamic relationship between algal nutrient uptake and release.

Nutrient release

As previously discussed algal nutrient uptake is a two-way process with nutrients being released under suboptimal growth conditions. Significant nutrient release may also occur during the reproductive events of certain algal species (i.e. *Caulerpa* spp.) where the release of gametes may cause a substantial nutrient spike and subsequent deoxygenation event. Although this may be a short-lived event with little long-term damage (Sprung, www2), corals have been observed to retract and partially bleach, particularly in smaller systems during reproductive events (Sharp, pers. obs.). A secondary metabolite of *Caulerpa* spp. (caulerpenyne) may also have toxic effects at a cellular level in higher organisms (Boudouresque *et al.*, 1996; Amade and Lemee, 1998), although such effects may be limited in wild ecosystems as caulerpenyne is quickly inactivated in seawater.

Case studies

Both the Ecosystem and ATS methods rely primarily or substantially on algal nutrient processing and further discussion of the systematics of both systems can be found in Delbeek and Sprung (2006) and Pecorelli *et al.* (in press). In a case study conducted within the large reef exhibit (2.5×10^6 liters) at Reef HQ, Townsville, Australia, the total biomass of algae supported directly on the ATS screens was approximately 0.5 % of the total algal biomass within the system (Pecorelli *et al.*, in press). Consequently when the ATS was taken offline, the ability of the mesocosm to process nitrite and nitrate was not significantly affected. Indeed orthophosphate levels were significantly lower after the removal of the ATS, suggesting that the rupturing of the algal cells during harvesting was causing orthophosphate to return to the system. Nevertheless, the nutrient processing capabilities of algae within any exhibit will depend upon a multitude of factors such as grazing pressure and light levels, therefore the use of remote vessels such as the ATS screens and refugia remain extremely useful tools to optimize algal growth.

Higher plants

Whilst mangroves are sometimes planted in captive systems their role in nutrient cycling is minimal when compared to other natural filtration methods. However, with careful management, the stability of the assimilated

nutrients minimizes the risk of nutrient flux back into the system.

BIODIVERSITY CONSIDERATIONS

One of the underpinning tenets of the mesocosm approach, (as described by Adey and Loveland, 1998) is the establishment of a trophic structure and energy flow incorporating nutrient cycling within living biomass. The need, therefore, for other forms of nutrient management supported by artificial substrates is minimized. A key to this process is the diversity of organisms unlocking a variety of nutrient pathways and a complexity which may confer stability and a resistance to sudden changes in nutrient levels. Natural methodologies can encourage the formation of a functioning trophic structure within closed systems in multiple ways.

Firstly, primary productivity is supported in the form of algal growth. Secondly natural substrates provide an abundance of habitat types (Shimek, www3) that, assuming that nutrients are not a limiting factor, will allow a wide range of niche utilization. Obviously the relative abundance of organisms will depend on predation pressure and if natural systems are to be considered functionally balanced, energy flow from producers to consumers must be sufficient to support the needs of the apex predators.

Biodiversity vs. Ecosystem function

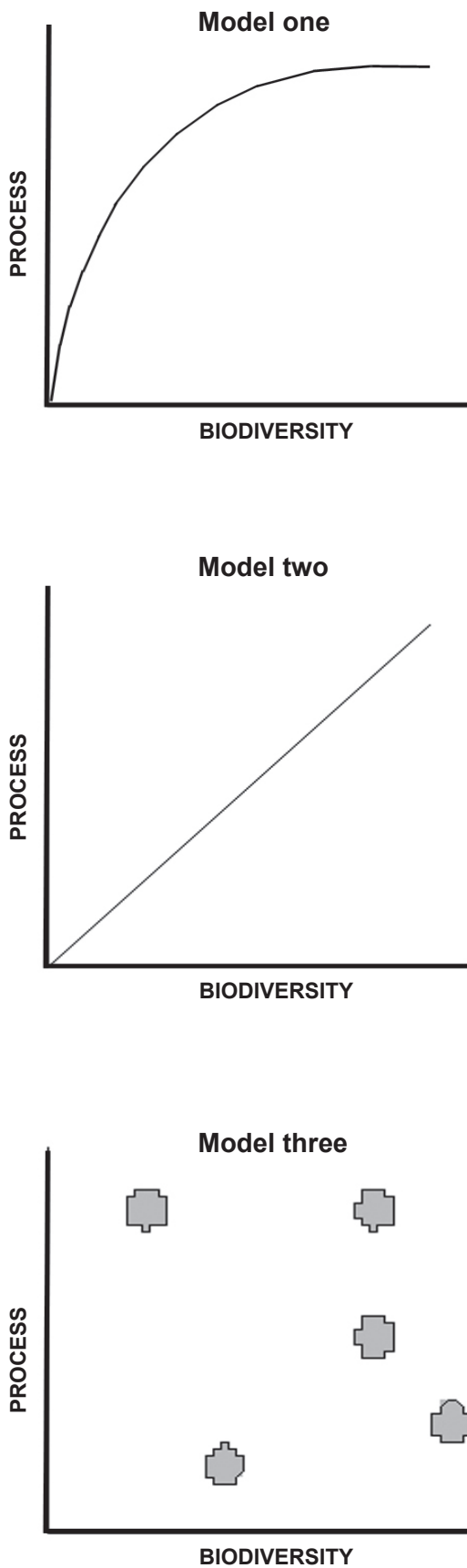
Ecosystem processes are mediated through the functional traits of the component species, rather than species richness *per se* (Raffaelli *et al.*, 2003b). This raises the question of whether increasing levels of biodiversity within closed systems improves nutrient processing rates. This has yet to be experimentally tested in a coral reef type exhibit, however there are three possibilities (figure 3). Model One suggests a cumulative exponential relationship linear relationship between species richness and nutrient cycling, Model Two a linear relationship, whilst Model Three is potentially the most troubling for captive situations as it suggests a random interaction, with maximal nutrient processing rates dependent on the establishment of a random assemblage of organisms. Only experimental manipulation of the type conducted within wild ecosystems (e.g. Hooper and Vitousek, 1998) can elucidate which of these models is applicable to captive

situations, the results of which would have important implications in the management of

closed system dynamics.

Questions of scale

The construction of large coral reef exhibits has provided opportunities for the creation of multiple habitats within a single envelope. Two of the largest coral reef exhibits (see chapter 9 and 31) aim to create multiple habitat types within one exhibit, supporting the highest diversity of reef organisms possible. However, large systems create problems of scale not necessarily associated with smaller systems. Natural methods may not be able to maintain turbidity levels acceptable to the viewing public, necessitating the addition of mechanical filtration.



INTEGRATING NATURAL METHODS AND LIFE SUPPORT SYSTEM HARDWARE

Whilst natural systems in their purest sense rely solely on the processing abilities of the biological communities within the system, real world issues often dictate that other LSS components are added either to rectify specific water quality concerns such as turbidity, or as 'failsafe' devices as circumstances dictate. Those planning LSS systems for large scale coral reef exhibits tend to incorporate natural systems within the matrix of a larger scale LSS design in order to provide the best possible chance of delivering the required water quality parameters. Foam fractionation, with or without the addition of ozone and rapid sand filtration, are commonly used on larger coral exhibits (see chapter 10).

As previously stated, elements of ecological purification can be successfully incorporated with other techniques, particularly if the refugium principle is followed. Therefore, natural systems must be considered as a continuum stretching from heavily managed and LSS intensive systems at one end, to those operating without extraneous LSS filtration components (Toonen and Wee, 2005). Even here the scale is complicated as even systems with no traditional forms of biological, chemical or physical waste management must provide both water circulation and temperature regulation which often necessitates the use of pumps. Therefore, to maximise the performance of natural elements within the LSS matrix the interactions between their biological communities and other LSS must be understood.

Figure 3: Conceptual models of nutrient processing vs biodiversity (adapted from Raffaelli et al., 2003)

Foam fractionation, mechanical and chemical filtration

Foam fractionation ('protein skimming') is often employed to remove suspended solids, proteins and other hydrophobic compounds before bacterial activity and chemico-physio leaching can release nutrients into the water column (Kube, 2006). However, in addition to the removal of pollutants, fractionation will remove potentially beneficial material, including virtually all algal material (Kube, 2006). Ozone is commonly injected into the air/water mix within foam fractionators to aid the coagulation of small particulate matter and to kill free living bacteria (but see Kube and Rosenthal, 2006), improving the efficiency of the skimming process. Mechanical filtration has a similar mode of action, being necessarily unselective. Adey and Loveland (1998) compared their action to that of a giant filter feeder, effectively competing for nutrients with organisms utilising similar material.

The physical removal of particulate material from the water column will impact upon the viability of organisms with planktonic life histories. This will occur both directly through damage and removal of the organisms themselves and through removal of their food source. Inevitably this will truncate foodwebs relying on the supply of such material unless supplementary food is supplied (Adey and Loveland, 1998). This will alter the mass balance of nutrients entering the system leading to a system leaning heavily towards heterotrophy.

Centrifugal pumps have also been blamed for causing damage to planktonic organisms ('plankton shear') although the author has observed relatively large copepods passing unharmed through the impellor chamber of both large and small pumps. They may however prevent the natural co-agulation and settlement of particulate waste, keeping smaller particulates in suspension for longer. Adey and Loveland (1998) extensively used Archimedes screw pumps to minimise potential damage, although 'low impact' pumps are now available which claim to minimise shear forces and enable plankton transfer (e.g. www4).

LSS sequencing

The uncertainty inherent in relying on purely natural methods and the desire to maximize stocking densities often necessitates more intensive management techniques. With careful consideration the integration of natural methodology with other forms of LSS can

mitigate the negative interactions of one upon the other. To an extent the impact of the LSS will depend on turnover rates through individual items of equipment, with slower turnover times minimising the potential for disruption to planktonic organisms. In situations where organisms within the main exhibit may damage the functioning of a natural nutrient management system, the use of remote inline refugia can allow their application to be considered. Ideally refugia should be installed such that the outflow of the vessel is gravity fed, rather than pumped, back to the display. The species composition of the refugia can be tailored towards maximal food output rates by including organisms producing planktonic material such as *Lysmata wurdemanni*.

SUMMARY AND FUTURE DIRECTIONS

Natural methods provide successful and flexible options for water quality management in closed coral systems. Whilst research undertaken in wild ecosystems has led to a detailed understanding of nutrient pathways in the wild, our knowledge of captive equivalents is lagging behind. Much of the evidence for the success of natural methods is based around anecdotal reports from single exhibits and systems. Replicated and statistically rigorous study to explore some of the functional relationships between systems based on natural methods and nutrient processing rates are few and far between (Toonen and Wee, 2005) and more are required to identify where and how nutrients are being processed. A 'modular' approach may be one method of exploring the relative contribution of different nutrient processing centres (see for instance Kube, 2006) such as algal beds, sediment systems and live rock. Nutrient processing within separate vessels could be calculated by monitoring influent and effluent water quality.

The individuality of public aquaria dictates that no two systems or exhibits are directly comparable. Inevitably this feeds back into a relatively cautious approach to exhibit design and management, and a tendency to remain faithful to practices which have been successful in the past. However, increasing demands for environmental sustainability and reducing energy loads of public aquaria mean that serious consideration must be given to increasing the role of natural systems in reef tanks.

ACKNOWLEDGEMENTS

This paper was greatly improved by the comments of Olivia Walter, Dr Heather Koldewey of the Zoological Society of London and two anonymous referees.

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