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Chapter 1

Introduction to the husbandry of corals in aquariums: A review

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ABSTRACT

Corals have been maintained in aquariums for hundreds of years, although long-term husbandry is a comparatively recent occurrence. The 1970s and 1980s witnessed the beginning of "reef" aquariums, where living substrates and biological processes were combined with increasing technological advances in maintaining water quality and providing essential environmental parameters in order to maintain corals in closed systems. Corals, comprising members of the classes Anthozoa and Hydrozoa, are highly diverse and numerous species with varying requirements for successful husbandry. The presence of intracellular symbionts, the phylogenetically diverse zooxanthellae, allows corals to be divided into two functional groups in terms of their husbandry; zooxanthellate and azooxanthellate. The former group, as a whole, can be maintained with a high degree of success since much of their metabolic energy can be provided by light. Advances in lighting technology have made such widespread success possible. The azooxanthellate corals, however, remain difficult to maintain, principally because of the difficulty in providing adequate nutrition. Advances in aquarium filtration, water movement, nutrition, habitat provisions, collection and transport, and communication between aquarists have allowed for rapid advances in coral husbandry. Today, almost all zooxanthellate corals can be propagated by asexual means, and virtually all have been kept in captivity. Sexual reproduction is becoming more common in aquariums, although synchronized mass spawning of broadcasting species is still uncommon and largely unpredictable. Other new issues have arisen in coral husbandry, however, including the occurrence, spread, and transfer of pathogens, parasites and predators. The major hurdles yet to be overcome are primarily in nutrition and in closing life cycles to allow for captive breeding programs. These issues and hurdles are the primary topics for this section on the husbandry of corals.

INTRODUCTION

The desire to maintain corals in aquariums traces its history back to Victorian times where early attempts of naturalists and socialites to keep corals alive were met with short-term survival of the collected species (Brunner, 2005). More successful attempts began in earnest in the middle of the 20th century. H.A.F. Gohar, despite his frustration with the husbandry of most corals, wrote that the Alcyonarians, especially members of the genus *Xenia,* were among the easiest to keep in aquariums by usingonly seawater exchanges and natural light (Gohar, 1940). Lee Chin Eng adopted a similar method in the Philippines by using tanks with natural reef substrates, water exchanges, and natural sunlight to keep a variety of corals over extended periods of time (Eng, 1961). Other descriptions of such early natural systems have been described (Straughan, 1959; Catala, 1964; Riseley, 1971). Despite the desire of home aquarists and public aquarists, the successful husbandry of corals in aquariums over longer time frames remained elusive. Technology and artificial filtration of the time proved largely unsuccessful in maintaining water parameters conducive to coral survival. Some of the earlier promising efforts with maintaining corals sprang from the Berlin aquarium society (Wilkens, 1973; 1975; 1976) and later successful culture of the sensitive genus, *Acropora*, by Stüber (1989) using these methods. Soon afterwards, Walter Adey (1983) described a system employing a multiple habitat design representing functional components of a reef ecosystem and the purification of a closed system using algae turf scrubbers at the Smithsonian Institution. This was soon followed by another natural method of filtration by Jean Jaubert at the Musee Oceanografique in Monaco using natural substrates and deep sand beds to integrate natural denitrification resulting in high water quality (Jaubert, 1989). Some of the best early efforts at maintaining corals in public aquariums were found at the Waikiki aquarium under the direction of Bruce Carlson (Carlson, 1987). Eventually, and despite these isolated cases of successful coral husbandry, real advances rapidly arose in the late 1980s and throughout the 1990s through the efforts of private aquarists who quickly began combining methods through trial and error, spurred mainly by efforts initially based on the Berlin methods and later through the rapidly increasing interest in private reef aquariums in the United States and Europe. During this time, coral husbandry reached a level where virtually all zooxanthellate corals were not only being maintained for many years, but were soon being propagated and traded between private aquarium owners and some public aquariums.

The advances of the aquarium "hobby," including the entrance of hobbyists into the public aquarium community, saw a similarly rapid rise in the success of public aquarium reef displays and an increased effort for public aquarium to include living reef displays as popular and important components of their facilities. We look back, with some notable exceptions in terms of both successes and failures, at a history of almost two decades of widespread success in the successful husbandry of almost all zooxanthellate coral species and the only slightly briefer history of propagation of these same species. Today, living coral reef exhibits have become global in distribution, and are more often being used as tools for education, conservation and science.

This paper is a review of the integral components of successful coral husbandry as well as an overview of areas that can benefit from improvement. Among the primary goals for the future are to advance the ability of all aquarists to contribute to furthering coral husbandry, increasing the number of displays representing habitat accuracy rather than "garden tanks," responsible and conservation-based efforts that extend beyond the displays and education therein, and future challenges and obstacles yet to be overcome in order to overcome limitations of species not yet able to be maintained with widespread success.

BASIC TENETS OF CORAL HUSBANDRY

Coral reefs are mostly defined as areas of high marine biodiversity limited mainly to tropical regions where conditions allow for the buildup of topographically complex carbonate frameworks due to the action of calcifying organisms, and they are primarily recognized by the proliferation of hermatypic (reef framework-building) scleractinian corals. This generalization is not entirely accurate since coral reefs also exist in locations outside the tropics and many variations of habitat exist that may include locally adapted coral populations, including those dominated by other nonscleractinian species, such as octocorals (soft corals). It is important, however, that despite exceptions such as marginal reef areas, temperate and deep water reefs, adjacent communities and other atypical coral reef habitats that coral reefs generally share certain environmental characteristics that allow for their success. These are summarized in table 1, and the characteristics listed are also generally ones that must be met in order to maintain the typical living reef displays of corals in aquariums.

COMMON ELEMENTS IN CORAL HUSBANDRY

The numerous methodologies, equipment, techniques and maintenance in order to successfully meet the husbandry requirements of corals are highly variable. Many variations work, although there are a few elements that most successful displays share. According to specific needs or species, even these may be not imperative, but the majority of successful coral displays, specifically those containing zooxanthellate species do have certain critical environmental parameters. These are:

1) the use of natural reef substrates or functional facsimiles (i.e. live rock, live sand);

2) the use of strong lighting, either natural or

Table 1: Average seawater values for reefs (after Kleypas et al.*, 1999) (SSI = sea surface irradiance)*

Variable	Limits	Time scale
Temperature (°C)	18	Annual minima
Salinity (ppt)	25-42	Continuous
Light ($\mu E.m^2.s^{-1}$)	30-40 % SSI	Limits reefs
	10 % SSI	Limits corals
Nutrients ($\mu mol.L^{-1}$)		
NO_3	0.5-3.0	Limits reefs
PO_4	0.1-2.0	Limits reefs and corals

artificial; and,
3) the maintenance of high water quality that can be accomplished by numerous means. It may seem surprising that these are indeed the main fundamental needs for coral husbandry, but they are. Other aspects are equally important, but the multiple means to provide them precludes their inclusion as essential. It is not my intention to discuss exceptional cases where success has been accomplished in the absence of these requirements. Water quality management occurs through many methods, including mechanical filtration (e.g sand filters), foam fractionation (protein skimming), natural nutrient uptake, export and regeneration methods (sand, algae, bacteria), water exchanges, and countless other types of additional equipment or technologies. The effectiveness of any given regimen depends on specific aspects of the display, the experience and efforts of the aquarists, and the intrinsic general effectiveness of the chosen method(s). Any choices or combination of choices has the potential to be adequate in maintaining high water quality but none of them will do so without exception. Therefore, choices made to address water quality are beyond the scope of this review and should be considered on an individual basis, according to system needs and experience of the staff, and the utilization of those methods with proven success in their respective functions.

WATER CHEMISTRY

Ideally, water chemistry in aquariums should replicate those found in nature where specimens in a display are found. It is difficult to characterize what the parameters of coral reefs are since local conditions or reef waters can vary significantly from mean oceanic values. It is also notable that oceanic and reef waters are now different from historical values, most notably in a reduction of the carbonate saturation state of surface waters from those of a century or so prior to today (Kleypas and Langdon, 2002; Eakin, 1996). It has also been found through laboratory experiments and practical experience that the growth of corals may be increased by pushing certain parameters to levels different from current or historical oceanic values (Langdon, 2000). Table 2 summarizes natural oceanic water values, acceptable ranges for coral husbandry, and idealized values for average coral reef displays. In my experience, certain water quality

Table 2: Various parameter ranges for seawater, aquariums, and ideal ranges for coral husbandry

Parameter	Seawater range	Acceptable range	Ideal range
Temperature (°C)	21-30	24-28	26-28
Salinity (ppt)	23-40	33-38	34-36
pH	7.4-8.4	7.8-8.8	8.2-8.6
NO_3	0.0-3.34 $\mu mol.L^{-1}$	0-10 $mg.L^{-1}$	0-1 $mg.L^{-1}$
PO_4	0.0-0.54 $\mu mol.L^{-1}$	0-1.0 $mg.L^{-1}$	0-0.03 $mg.L^{-1}$
PAR ($\mu E.m^{-2}.s^{-1}$)	0-2000	0-2000	250-1000
Calcium ($mg.L^{-1}$)	400-430	350-500	425-450
Alkalinity ($mEq.L^{-1}$)	2.0-2.5	2.5-4.5	3.5-4.0

parameters of aquariums are more critical than others to ensure successful coral husbandry, and these are summarized in Table 3.

I do not suggest that parameters absent from the most critical categories are indeed not essential to maintain for good coral health, but that some of them may naturally fall into acceptable ranges if other parameters are maintained, or if the system is properly designed and managed. Other parameters, such as some minor and most trace elements, are not easily measured, are impractical to address, or serve no known role in the metabolic requirements of corals. It should be mentioned, however, that some of these elements are known toxins and elevated levels may be deleterious to coral health. Equally concerning are the almost limitless number of organic and inorganic toxins that may be introduced to an aquarium or be produced by the inhabitants of an aquarium. Failure to thrive may be a result of the production of secondary metabolites by other corals and species within a display. The presence or absence of these many chemicals have different implications; some may have positive effects on coral health but most are far more likely to exert deleterious

Table 3: Common aquarium water parameters and their effects on coral health

Variable	Importance	Notes
Salinity	Critical rapid	Changes possible resulting in mortality
Temperature	Critical rapid	Changes possible resulting in mortality or coral bleaching
Alkalinity	Critical	Limiting to calcification; stabilizes pH
Oxygen	Critical	Respiration at night can result in hypoxia and mortality
Calcium	Essential	Constant replacement required for calcification
Phosphate	Essential	Reduces calcification, increases nuisance algae
Magnesium	Essential	Rapidly depleted and interferes with calcium alkalinity balance
pH	Important	Proper alkalinity and photosynthesis can selfregulate
Nitrate	Important	Can reduce coral growth, increases nuisance algae
Ammonia	Important	Toxic but normally not an issue unless there are system perturbations or mortalities
Nitrite	Important	Toxic but normally not an issue unless there are system perturbations or mortalities
Silicate	Not important to corals	May have display implications
Strontium	Not important to corals	Divalent substitute for calcium
Other minor and trace	Not important	Either not essential to elements corals or levels are rarely anomalous
TDS/organics	Questionable	Some may effect light penetration or be toxic; too many possible compounds to address
Redox	Questionable	General measure of water quality but no known impact to corals
Iron	Questionable	Typically chronically low but no known effect on corals

effects.

Is extensive and highly quantitative water quality analysis desirable for the many organic and inorganic compounds found in display seawater? I would argue that it is, but that cost and screening, especially for unknowns, is prohibitive and impractical. In practice, judicious caution in terms of potential inputs and careful observation in the case of corals failing to thrive despite otherwise apparently good water quality may warrant more extensive water quality analysis. Alternately, corals failing to thrive when other specimens are displaying apparent health may better be addressed by relocating the affected species to clean aged seawater or quarantine for observation and more careful examination of the specimen. In this way, the aquarist can more effectively determine the reasons for its condition, evaluate potential issues with the display, allow time to more thoughtfully address possible solutions, and prevent any issues emanating from an ailing specimen from affecting other specimens in a display.

A final condition to consider in regards to ater quality in a display is the source of seawater. Some aquariums have access to natural seawater and the quality of the source water may or may not be a source of problems. Coastal waters unfortunately may have levels of nutrients, pollutants, and potential xenobiotics that must be removed or treated through various means to prevent harm to sensitive species. Furthermore, salinity of coastal waters may be reduced and the water must be evaporated or have supplementation with additional salt to be brought to an acceptable salinity. If artificial seawater is used in a display by mixing synthetic sea salt mixes to fresh water, several issues arise. The source water must be sufficiently purified so as not to add unwanted elements and potential toxins to a display, and this can be accomplished using numerous commercial water purification systems. Perhaps more important is the use of artificial salt mixes, none of which are likely to represent a close facsimile to pure seawater (Atkinson and Bingman, 1998; Borneman, 2006).

Many of the elements of artificial salt mixes contain proportions of elements highly elevated or depressed from desired or natural values. The low cost of salt mixes has the unfortunate consequence of requiring the use of relatively low-grade materials, some of which have high levels of contaminants including heavy metals. While it is true that successful coral husbandry has been accomplished using both natural and artificial seawater, it is likely that the survival and growth of corals in less than ideal seawater has implications on their health and reproduction and may be more of a testimony to the inherent adaptability of the species than the quality of their medium.

SUITABILITY AND SUCCESS

In general, coral husbandry in aquaria is highly successful for almost all zooxanthellate species (those that contain the diverse photosynthetic endosymbiotic dinoflagellates). Despite numerous husbandry requirements across species, those which gain metabolic energy from light through translocated photosynthate of their zooxanthellae have proven to be widely successful in captivity. There are also many species, including highly desirable display species that are azooxanthellate and including many of the colorful seafans and gorgonians, some hydrocorals, and some scleractinian corals. These have proven to be very difficult to maintain over long periods because of the difficulty of providing appropriate and sufficient foods to meet their energy budgets. In most cases, the sources of nutrition to these species are not well known or known at all. In others, dedicated trials and feedings have allowed for some species to be maintained (e.g. *Tubastraea* spp., *Diodogorgia* sp., *Studeriotes* sp., and antipatharians). The single most important factor that limits our abilities for these species is the provision of the right amounts and types of food to sustain species (Fossa, 2006).

LIGHT

For zooxanthellate corals, light plays a variable but critical role in coral husbandry. Some species thrive across a wide range or irradiance values while others fail to thrive under irradiance that is too high or too low. If irradiance is too high, bleaching or polyp contraction are the more common responses along with potential damage to the coral polyp tissue or the endosymionts (especially photosystem II within the chloroplasts) by the production of toxic oxygen or damage from excess ultraviolet radiation. If irradiance is too low, tissue recession can occur as the metabolic carbon provided by photosynthesis fails to meet the species' requirements.

It is important to recognize that there is no single ideal irradiance value for most displays that contain a mix of species. Variations in the light field within a display for species with different lighting requirements can be met or compensated through appropriate placement within the display in relation to the light source. In cases where irradiance is suboptimal, it may be possible for coral energy budgets to be met through other means of nutrient acquisition. Lighting coral displays consists of using either natural sunlight or artificial luminaries. It is beyond the scope of this review to address all the potential options available. It is imperative, however, for accurate measurements to be made of the light available within a display, ideally at the surfaces of individual corals, using a submersible PAR meter. Given the critical importance of light in the maintenance of zooxanthellate corals and the dynamic, rapidly attenuating and variable light field within a display, data on irradiance is essential. In large or deep displays, the most difficult task, and perhaps an unachievable one, is to provide adequate irradiance at the bottom of the aquarium. Sunlight may be the best source for large displays, but the loss of light through thick, weather etched, poorly maintained, poor quality, or dirty overhead panels may factor heavily into limiting the effective solar irradiance reaching a display. Artificial luminaires, generally high intensity discharge metal halide lamps, are generally the most powerful lighting available. Unfortunately, poor reflector design is common since these lights are usually designed to simply illuminate large areas and not to allow maximal focused penetration into tank water.

As a result, bulbs that potentially could provide adequate light for displays may be lost through improper reflector design. Also impacting total irradiance to a display are poorly maintained luminaires and reflectors, aged bulbs, undersized wiring, ballast choices, and any glass, screen, or plastic covers over the display.

It must be noted, however, that relatively shallow displays using high wattage (>1000 W) daylight spectrum metal halides and high quality reflectors can produce PAR levels high enough to equal the light available to shallow water corals at noon.

Data are available for many of the light, allast, and reflector combinations available (www1). It can be said that, in terms of light levels, that aquarists are at least potentially able to meet the photosynthetic needs of the most-light demanding species.

A PAR value of approximately 250 $\mu E.m^{-2}.s^{-1}$ reflects a general rule of thumb in terms of known compensation points for most coral species studied.

There is a great deal of discourse on the implications of spectrum provided by various light bulbs, specifically on which provide the best growth or coloration. It is beyond the scope of this review to fully explore this topic. In summary, there are no strong data that support the view that certain spectra are more beneficial to corals than others. Coral coloration is a complex subject with references too numerous to include that involves genetics, environmental conditions, and aspects of cellular biology and functions not fully understood. It is certain that the perception of coral color changes depending on the spectrum of light used because of the excitation of various fluorescing proteins. For some species, PAR provides some control over the density of the zooxanthellae and the production of fluorescing proteins, while in others it does not seem to affect fluorescing protein content or distribution. Higher wavelengths tend to produce greater visual perception of many fluorescing proteins but may not affect the actual pigments present. Many species also alter or change their coloration in response to numerous environmental variables, including light variations. Some are predictable and some are not. In general terms of coral health and growth, PAR is the more important variable to coral physiology and spectrum is primarily an aesthetic component for coral or display appearance.

A final consideration of light in the aquarium by comparison with sunlight reaching a reef is that the sun moves across the sky, and both environmental variations (clouds, water vapor) and azimuth affect the intensity and spectrum of light reaching the reef. This dramatic diurnal variation, including extremely high pulses of light resulting from “glitter lines” as light is focused by waves, is rarely met by static light sources over aquariums. The results of static constant irradiance in aquariums are largely unstudied, but potential effects are the shading of some corals or the unrelentingly high and invariant irradiance that other corals receive, depending on their placement in a display. Despite successful husbandry of coral species, the standard static source illumination of displays, even those providing simulated “dusk and dawn" cycles, is highly aberrant compared to natural conditions yet in practice is adequate to maintain corals successfully.

WATER MOTION

Water motion is another critical parameter that is imperative to the health of corals. It affects the transmission of light through the water column, the delivery of all types of nutrition to corals, impacts water quality and provides direct and indirect effects on species physiology. Increased water flow increases rates of photosynthesis (Helmuth et al., 1997), respiration (Helmuth and Sebens, 1993), gas exchange, larval dispersal, waste removal, tissue growth and calcification rates (Houlbreque *et al*., 2003; 2004). It affects or modifies growth forms, coral health, habitat structure and species composition. It also decreases the effects of sedimentation damage and overgrowth by some competing species and disease consortiums, as well as providing a degree of bleaching resistance.

Water flow on reefs is provided by wind driven waves, tides, currents, upwellings, and internal waves. There is a general trend of mass flux across reefs and corals from turbulent flow, surge, and laminar currents ranging from 1-50 $cm.s^{-1}$ (Sebens, 1991; 1997; 1998) depending on reef zones. In terms of growth forms, water flow alters the colony growth form of species to maximize prey and light capture.

Low flow tends to provide habitat for both small and large-polyped corals that are encrusting, plate-like, phaceloid and fragile, including branching species with widespaced thin branches. High flow environments tend to harbor corals with upright branches, plates and ridges, and for mounding, encrusting and robust branching species. There is a maximum flow rate within or around a colony that limits further development called the saturation velocity (Chamberlain and Graus, 1975), and water flow around a colony controls a static water layer called the coral surface boundary layer. The thickness of this layer plays a role in the exchange of gas and nutrients, as well as the composition and growth of surface microbiota.

Water flow in display aquariums is provided by numerous means beyond the scope of this review. Some of these are reviewed in Sprung and Delbeek (2006), but include powerheads, pumps, oscillating valves, surge tanks, dump buckets, hydraulic devices, and others. Water flow is extremely important and often underestimated.

Because of limitations imposed by closed systems and the difficulty of providing mass flux in aquariums, it is perhaps even more important in aquaria than in the wild to provide flow that allows for food capture, ideal metabolic processes, and general health and growth. While there are many ways to provide water flow, the "best" ways are determined by considering individual displays or species requirements.

Oscillatory, random and turbulent flow tends to decrease boundary layers and is important to tissue and organisms within coral colonies. If the flow is sufficient, it can even result in energy surpluses. In the absence of good intracolony flow, hypoxia can occur especially at night when photosynthesis does not provide oxygen to coral tissue.

Other species (for example some of the azooxanthellate species) may thrive in unidirectional flow, yet even the velocity of the laminar flow may be important in determining if coral polyps extend in a feeding posture or are effective in prey capture in a given flow environment.

HETEROTROPHIC NUTRITION

Despite the potential ability of some zooxanthellate coral species to meet in excess of 100 percent of their metabolic carbon needs by endosymbiont photosynthesis, many cannot. All corals must supplement their metabolic energy requirements, particularly in respect to nitrogen in coral reefs waters generally vanishingly low in nitrogen. Polytrophic corals obtain energy from multiple sources,

and as sessile organisms they are unable to pursue prey sources and depend on water currents, cilia, mucus, direct absorption and specialized penetrant organelles (cnidocysts) to obtain required nutrition outside the symbiosis. At any given time, there may be prey available but no light, or light but no prey. Through feeding, absorption, and photosynthesis, corals require the energy for the following, in order of importance:

1) maintenance (respiration, metabolism, survival (including competition); 2) injury repair; 3) growth; and, 4) reproduction.

Hatcher (1988) states, "The quality and ates of coral primary production imply that xanthellae provide "junk food" to their hosts, and beg the question of nutrient limitation of coral growth rates under conditions of adequate light… On present evidence it seems clear that all corals need to supplement their diets with particulate organic matter from outside the symbiosis (heterotrophy) in order to meet these requirements." "By the end of the 1970's, it became clear that all hermatypic scleractinian corals, independently of the morphology of their colonies or the size of their polyps, make use with high efficiency of their mechanisms for predatory feeding, filter-feeding, "osmotic" feeding with DOM as well as of the autotrophic products translocated by their symbionts (Lewis and Price, 1975; Lewis, 1976; 1977; Sorokin, 1973a; 1973b; 1978; 1981; Falkowski *et al*., 1990; Bythell 1988; 1990).

While copepods seem to comprise the most abundant zooplanktivorous resource consumed by scleractinian corals (Hamner and Carleton, 1979; Sorokin, 1981), individual differences between species in prey items and capture mechanisms are common. This is especially true of the octocorals which lack efficient prey capture mechanisms and depend to a larger degree on sieving particulates and perhaps the utilization of phytoplankton and bacteria (Fabricius, 1995; Widdig and Schlichter 2001; Anthony, 1999; Bak *et al*., 1998; Mariscal and Bigger, 1977). The direct uptake of ammonium and nitrate is possible as a food source but may not be an ideal method of acquisition in terms of coral health, assimilation, growth, or regulation of zooxanthellae density (Bruno *et al*., 2003; Hoegh-Guldberg and Williamson, 1999; Steven and Broadbent, 1997; Marubini and Davies, 1996). It has also been found that most essential amino acids are able to be biosynthesized by the coral or its normal bacterial surface biota (Fitzgerald and Szmant, 1997).

Coral feeding depends on numerous interacting factors including the time of day (Elliot and Cook, 1989), night or day feeding, irradiance level, the oxygen content of water, water flow, acute chemosensory cues (1: 10,000,000 dilution) and the energetic cost of feeding and tentacle expansion (Borneman, 2000). Digestion generally takes 2-3 hours in scleractinian corals and 6-12 hours in octocorals with many species displaying linear ingestion rates to extremely high prey concentrations.

In terms of aquarium coral husbandry, several papers in this volume address experimental feeding trials and a comprehensive review of coral feeding in relation to aquariums is provided by Borneman (2002a-d; 2003a-c).

CORAL SELECTION AND NICHE HABITATS

Many aquariums, both public and private, tend to be "garden tanks," that contain many diverse species that may not normally be found existing together within the many zones that comprise the coral reef ecosystems of the world. While the ranges of some species can be quite broad, others are narrow, confined to subtidal, seagrass, deepwater or other specialized environments. Public aquariums, as rule, tend to be quite accurate in their commitments to habitat accuracy in display design. There is still considerable room for improvement in reef aquarium designs. While it is understandable to have dramatic displays of many interesting species, there are basic restrictions common to all coral reef displays. First, there is an issues with the biomass of an aquarium in a limited water volume by comparison with natural habitats. This leads to increased competition and crowding, in additional to potentially abnormal direct and indirect species interactions. Second, there is an issue of limited biodiversity, not only in terms of these system biodiversity but also in terms of the coral species availability through various traditional sources. Given the biomass present in most coral reef displays and the importance of food, a concomitant issue that must be addressed is providing adequate particulate and planktonic materials for the high density of species in a small water volume and may confound attempts to maintain high water quality. Another issue results from scale since many species grow far too large for all but the largest displays, and "bonsai" corals often result from trimming and pruning specimens over the lifetime of a long-term display. The result is often a display that is more of a biological diorama than a realistic coral reef display.

The various habitats found as part of larger reef areas are hard to describe without first hand experience. The Sulawesi aquarium of Mitch Carl at the Henry Doorly Zoo in Omaha emulates a small cross-section of a specific reef habitat (see chapter 23). One example of an interesting habitat is a harbor in Koror, Palau. Here, steep island hills covered with trees dropped leaf litter into the water, decomposing, and forming an organic benthic resource with areas of silt and decomposition underlying a benthic veneer of corals. *Pavona cactus* and *Anacropora* dominated and covered the bottom like a carpet, and the spatial heterogeneity at the bottom from dead understory colonies, coupled with the abundance of organically enriched material and the small fauna found there, provided perfect habitat for mandarinfishes (*Synchiropus splendidus*). It is my feeling that through providing for mate selection, natural and realistic niches and habitats that increased vigor and sexual reproduction may be more common than in less realistic settings, despite species abilities to thrive in unnatural surroundings. As an educational component, however, creating smaller, shallower and ecologically accurate habitats will likely encourage breeding efforts and well as enhancing proper educational components for visitors.

DISEASE, PREDATORS, AND PARASITES

It is beyond the scope of this review to comprehensively discuss the various diseases, parasites and predators that affect corals in captivity but several reviews exist (Borneman, 2000; 2004). There is relatively little known about coral disease and parasitism in the wild, and few of the natural diseases described or characterized occur in aquariums. In contrast, several uncharacterized disease conditions occur commonly in aquariums but are uncommon to unreported in the field. Several of these, such as “brown jelly” infections and rapid tissue sloughing (called by the misnomer, RTN, for rapid tissue necrosis), are contagious and can quickly cause the mortality of many specimens in a display. Parasitism occurs in wild corals, but field conditions and possibly natural controls tend to limit their effects. In aquariums with high stocking densities, parasites are contained within a space that facilitates their spread and impact, and natural controls may not be present. Their effect, therefore, may be much more acute and result in many specimens having partial to total mortality. Among the more common parasites and predators are various nudibranchs, ciliates, copepods and flatworms (see chapter 5). Many of these pests are direct developers and have prey preferences. Eradication once established is difficult, and prevention through quarantine and examination is far more effective than treatment - if effective treatment is even available or possible to use in a display.

Reproduction Closing life cycles of corals in captivity is still in its formative stages. The results of Project SECORE are described in papers in this volume and elsewhere (Petersen, 2005). Sexual reproduction in aquarium-reared corals is still an uncommon and largely unpredictable event. Reports are becoming more frequent and correspond well with reports from the field in terms of timing (Borneman, 2006b; Petersen *et al*., in press). In particular, aquarium coral spawnings are more frequent in the summer, as tank temperatures generally increase by a few degrees. The small size or young age of aquarium corals when first acquired may be a reason sexual reproduction is infrequently observed (Kojis and Quinn, 1985).

The regular fragmentation of many captive species is likely to be a factor in the relatively low spawning frequency of colonies that have been maintained for many years. Corals undergoing fragmentation typically lose reproductive viability for 4-6 months, even if fragments are of a reproductively viable age and size (Wallace, 1985; Szmant-Froelich, 1985; Smith and Hughes,1999). Additionally, many coral spawning events occur at night and may be missed by aquarists. Several reports of multiplespecies spawnings occurring over one night or consecutive nights, as well as synchronous mass spawning involving many species (including non-coral taxa) have been reported. These events are rare, although regular and predictable annual spawnings by captive specimens are becoming more common as aquarists are better able to maintain stable tank conditions over long periods of time, and as captive colonies become older and mature (see chapter 35).

Many factors have been implicated in coral sexual reproduction, including temporal changes (annual, seasonal, diurnal, nocturnal), lunar periodicity, tidal changes, latitudinal differences, nutritional effects, and temperature. It is entirely possible that such effects may not be duplicated or represented in aquaria. Although aquaria are now capable of microprocessor level control of temperature and lighting, plankton substitutes and dosing systems are quite well developed, and moonlight simulation is widely in use, there is still a lack of data to determine if these factors are adequately replicated. Scleractinian corals, corallimorpharians and octocorals utilize multiple modalities of reproduction and can be gonochoric or hermaphroditic (Harrison and Wallace, 1990). In addition to sexual reproduction by broadcast spawning and the production of internally or externally brooded larvae, many forms of asexual reproduction have been reported, as well as more recently reported asexual reproductive behaviors including those of aquarium corals are reviewed in Borneman (2006). Various means of asexual reproduction have previously been reported as taxon-specific, and tradeoffs may exist between sexual and asexual reproductive strategies within species (Wallace, 1985; Soong and Lang, 1992; Smith and Hughes, 1999).

CONSERVATION

It is in the interest of coral husbandry to limit mortality to reduce the needs for collections of specimens from wild populations. There obviously exists an inherent interest in the survival of individual specimens in their own right. Several papers in this volume discuss aspects regarding the conservation of species and the use of public aquariums in that role. These topics will not be covered further except to state that the intent of this review on coral husbandry is meant to act as a conservation tool by serving as a guideline to help ensure successful maintenance, growth and reproduction of corals through proper husbandry.

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INTERNET RESOURCES

www1. Joshi, S. 2007. Sanjay’s reef lighting info pages: http://www.reeflightinginfo.arvixe.com/