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Project Report

The Iconic Philippine Coral Reef at Steinhart Aquarium: The Husbandry, Welfare, Behavior, and Veterinary Care Considerations of a Large Multi-Taxa Living Coral Reef System

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Abstract: In 2008, Steinhart Aquarium at the California Academy of Sciences in San Francisco, CA, USA, unveiled a brand new facility with the 212,000 gallon Philippine Coral Reef habitat as its iconic centerpiece. Designing and managing a system that consists of a living reef this large, with associated invertebrates and teleosts, has been a challenge for the aquarium's husbandry and veterinary teams. Establishing appropriate lighting, water quality, and flow has required a scientific approach and resulting adjustments to the original habitat design. The medical management of reef species has required an in-habitat approach as well as trial-and-error therapeutics. Determining the criteria for assessing the welfare of corals and other tank inhabitants has been a shifting process that has heavily utilized photography-tracked changes and other quantitative parameters as baselines. This report details the successes and limitations of establishing the environmental and veterinary management of this mesocosm. The consideration of interplay between species is discussed, and recommendations for monitoring welfare both on an individual and tank level are made. Making adjustments for the benefit of the exhibit and its animals is key for the unique aquarium displays that comprise captive coral reef systems.

Keywords: coral reefs; public aquariums; animal welfare; coral husbandry; aquatic animal medicine

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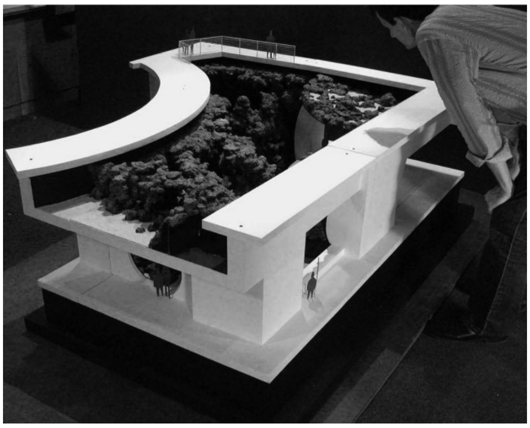
1. Introduction

Most public aquaria have at least one tank featuring corals. Coral reef ecosystems are vital to global health, and their display is an invaluable tool for public education and outreach [1]. Additionally, corals make for captivating displays favored by hobbyists and public aquarium visitors alike. The well-being of coral reefs and corals themselves has been a focus of the scientific community for years, but especially recently, given progressive climate changes that threaten their extinction [1].

Steinhart Aquarium has been a part of the California Academy of Sciences in San Francisco, CA, USA, since 1923. The aquarium is a leader in the ongoing scientific effort to understand, regenerate, and educate about natural coral reefs, including deeper water mesophotic coral ecosystems. In 2008, the California Academy of Sciences unveiled a brand new facility, with the Philippine Coral Reef habitat (hereafter referred to as PCR) as its iconic aquarium centerpiece (Figure 1). The tank is 25 feet (7.6 m) deep and contains 212,000 gallons (802,507 L; 800 m^3) of seawater. The habitat boasts over 100 genera of invertebrates, including 84 genera of corals. There are also over 700 fish representing 53 genera. A summary of the animals that can be found in this tank is provided in Table 1.

Designing and managing a captive living reef system this size has been a challenge for the husbandry and veterinary teams responsible for its care. The aim of this report is to provide an overview of the successes and challenges that Steinhart Aquarium has faced with the PCR since its opening in 2008. As for any coral reef aquarium, husbandry has been vital to maintaining the health of the mesocosm. Steinhart's approach to behavioral, welfare, and veterinary considerations for this system will also be discussed.

(a)



(b)

Figure 1. (**a**) Photograph of a diver in the primary viewing window of the Philippine Coral Reef habitat at Steinhart Aquarium, California Academy of Sciences in San Francisco, CA, USA. (**b**) An example of one of the scale models used during the planning stages of the habitat, with human figurines to scale.

Table 1. Fauna within the Philippine Coral Reef habitat at Steinhart Aquarium, California Academy of Sciences in San Francisco, California, USA.

Class of Animal	Number of Genera in the PCR
Bivalvia (clams)	1
Crustacea (crustaceans)	4
Echinoidea (urchins)	4
Gastropoda (snails)	4
Hexacorallia (corals and sea anemones)	65
Holothuoidea (sea cucumbers)	1
Hydrozoa (hydrozoans)	1
Octocorallia (corals)	19
Osteichthyes (bony fish)	53
Stelleroidea (sea stars)	5

2. Approach

2.1. Husbandry

The successful maintenance of captive coral reefs relies heavily on the physical parameters surrounding them, namely, water and light. The ultimate goal of appropriate water chemistry and light sourcing is to provide reef biota what is needed to carry out their natural physiological functions, resulting in a healthy and healthy-appearing coral reef ecosystem. Detailed discussions of the ideal water and light parameters for captive reef systems can be found in numerous sources, only one of which will be used for citation here [2]. The PCR is the major iconic tank of the new California Academy of Sciences building. Designing the tank and the building as a whole offered an opportunity for the Steinhart team to reevaluate husbandry approaches for the coral reef exhibits, including water and light sourcing.

For nearly 100 years, Steinhart Aquarium relied on a source of natural seawater from a sub-sand Ranney collector located at the nearby Ocean Beach in San Francisco. However, the quality of the incoming water was variable, with low salinity and high orthophosphate (PO_4^{3-}) concentrations. The incoming water was treated with lanthanum chloride when phosphates were elevated, and commercially available artificial sea salts were being used to compensate for the low salinity. Ultimately, it was decided that the existing infrastructure was not sustainable for the long-term supply of seawater to the aquarium, and two years after the debut of the PCR, the decision to switch from natural seawater to synthetic seawater was made.

A comparison of the salt formulations from zoos and aquariums successfully housing corals throughout the U.S.A. was conducted and then compared to potential saltwater blends made utilizing chemicals from different providers [3]. Lastly, once a salt formulation was chosen and the chemicals sourced, a basic bioassay was conducted over 30 days utilizing the new saltwater and an existing coral reef exhibit. This way, the aquarium was able to ensure that there were no toxic contaminants, no deficiency in desired ions, and no interference from trace elements—and the living coral reef community thrived.

It is important to note that the primary goal when creating the Steinhart Aquarium's salt blend was to tailor it to this aquarium's specific collection. The saltwater is made by brining dechlorinated municipal freshwater with a blend of major, minor, and trace elements mixed in a 16,000 gallon (60,567 L; 60.6 m^3) cistern. As municipal freshwater supplies frequently contain traces of some elements, the incoming water is analyzed frequently to guide the amounts, if any, of additional trace elements to be added to the aquarium's salt formulation (Table 2) [3]. Sourced chemicals are of the highest possible purity, and the primary component, sodium chloride, is a "food grade" iodine-free salt obtained from Morton Salt (Newark, CA, USA). Every newly mixed batch of seawater is analyzed for ammonia, nitrite, nitrate, salinity, alkalinity, calcium, potassium, magnesium, phosphate, bromine, and chlorine concentrations. The newly made seawater is then transferred and kept in a 30,000 gallon (113,562 L; 114 m^3) saltwater cistern for general aquarium use. When saltwater is added to the PCR specifically, trace elements and mineral supplements such as manganese (II) citrate, iron (II) citrate, and potassium iodide are dosed directly into the tank in order to achieve a final saltwater formulation that is a close approximation of the concentration of elements found in naturally occurring Philippine coral reefs (Table 3) [3–5].

Table 2. The formulation of artificial seawater, detailing major, minor, and trace elements, developed for use in Steinhart Aquarium, California Academy of Sciences in San Francisco, CA, USA. This formula is to make 1000 gallons (3.79 L) of saltwater. Note that the amount of sodium bicarbonate added varies based on the alkalinity of incoming dechlorinated freshwater.

Chemical	Unit Added for 1000 Gallons (3.79 L)
sodium chloride ($NaCl$)	100.05 kg
magnesium sulfate ($MgSO_4$)	14.33 kg
magnesium chloride ($MgCl_2$)	8.35 kg
calcium chloride ($CaCl_2$)	4.45 kg
potassium chloride (KCl)	2.80 kg
boric acid (H_3BO_3)	93.75 g
strontium chloride ($SrCl_2$ $6H_2O$)	57.50 g
potassium iodide (KI)	566.5 mg
zinc sulfate hepta ($ZnSO_4$ $7H_2O$)	261.5 mg
cobalt sulfate hepta ($CoSO_4$ $7H_2O$)	196 mg
sodium molybdate (Na_2MoO_4 $2H_2O$)	0.11 g
sodium bicarbonate ($NaHCO_3$)	750 g (varies)

Corals are sessile organisms that rely on water flow to bring them dissolved nutrients and gasses and carry away by-products of digestion and respiration [1,2]. Aquaria housing corals require not only the proper water chemistry but the proper water flow rate and type of motion [5]. Given the size of the PCR, the flow of the water from the standard aquarium loop was insufficient for living corals. To achieve appropriate flow, three Fybroc pumps (CECO Environmental, Dallas, TX, USA) on a closed loop provide additional water circulation within the habitat. The water from these pumps is split into five separate returns that are controlled by motorized butterfly valves. This allows the aquarium team to control direction of water flow, as well as the strength of the flow, within the PCR using automated building systems controls (RCK Controls, Inc. Systems, San Diego, CA, USA). Lastly, in-water ECM75 Hydro Wizard® pumps (Panta Rhei, GmbH, Wedemark, Germany) are utilized to target areas of water flow concern as needed. In combination, these pumps allow the team to target specific areas of the tank and create strong currents within the tank.

Table 3. A summary of frequently monitored water quality parameters and their targeted ranges for the Philippine Coral Reef at Steinhart Aquarium, California Academy of Sciences in San Francisco, CA, USA.

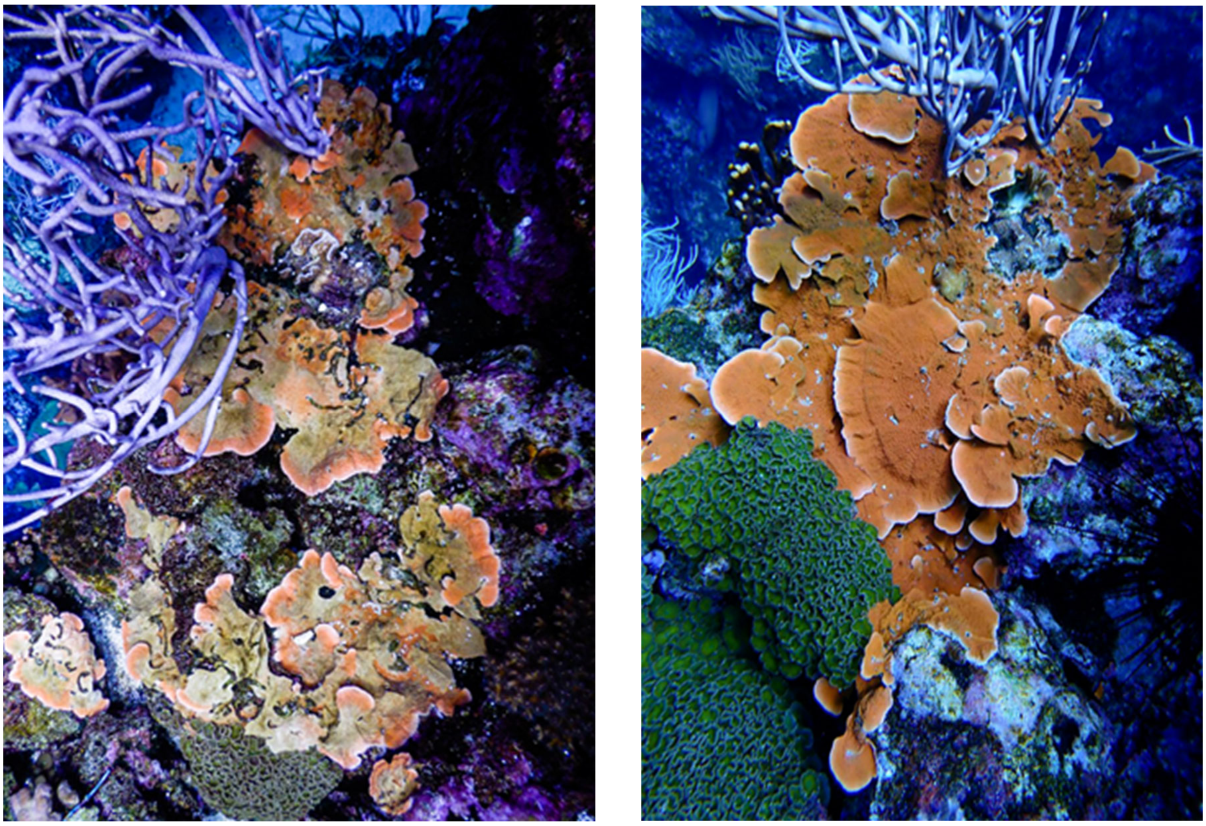
Water Quality Parameter	Targeted Range
salinity	33–36 ppt
temperature	76–79 °F (24–26 °C)
pH	8.0–8.4
alkalinity	3.0–3.5 mEq/L
$NH4^{+}$	<0.01 mg/L
NO_2^{-}	<0.01 mg/L
NO_3^{-}	<10 mg/L
Ca^{2+}	400–460 mg/L
Mg^{2+}	1300–1400 mg/L
PO_4^{3-}	<0.15 mg/L
Cl^{-}	<0.01 mg/L
K^{+}	340–380 mg/L

Besides the water chemistry and motion, the most critical design aspect for a coral reef habitat is the lighting. The California Academy of Sciences is a U.S. Green Building Council Leadership in Energy and Environmental Design Platinum-certified building, indicating its commitment to sustainability. As such, energy-efficient changes are made throughout the building as technology and strategies arise. One sustainability feature was to illuminate habitats in a sustainable manner. In keeping with this goal, the PCR was designed to be lit with as much natural sunlight as possible. A scientific study was conducted to model the amount of sunlight reaching various areas of the building over the course of the calendar year, and habitats with the highest light requirements—including the PCR—were placed in areas with the most natural sunlight in order to minimize electrical consumption. The initial design for the PCR in the new building was to utilize a combination of 1 and 2 kilowatt (kW) fixtures to be mounted over the water's surface, with a narrow beam spread in order to penetrate the depth of the tank. Floor-to-ceiling glass provides natural lighting throughout the building in general, with circular skylights overhead providing focal sunlight for shallower parts of the PCR up to 16.5 feet (5 m).

2.2. Veterinary Considerations

As with any other animal at Steinhart Aquarium, veterinary care is provided to the residents of the PCR as needed. Compared to companion animal medicine, aquatic animal medicine—specifically that of invertebrates and fish—is in its infancy. Medical resources for these types of animals are limited, and although therapeutic options are available, knowledge of drug pharmacokinetics, mechanisms of action, and dosing are still not well established [1,6].

The veterinary team at Steinhart Aquarium is notified of abnormalities as they are noticed during routine PCR dives or from any of the habitat's viewing windows. If affected animals can be removed, they are taken in for examination and treatment. The aquarium's medical ward was designed with an assortment of tanks of varying sizes that can be filled with the appropriate type of water and fitted with lighting, flow, and filtration to support patients of varying sizes and life histories. Animals that cannot be removed for hospitalization are monitored closely by both biologists and veterinary staff in-habitat, with weekly or biweekly updates regarding their status. Sequential photographs of ailing PCR fish and invertebrates are invaluable tools for both veterinarians and the biologists monitoring medical cases. For example, repeated photographs of areas of pallor on coral colonies, along with measurements of the widths of these lesions, allow the Steinhart team to determine whether the therapeutics they have used have been effective (Figure 2).



(**a**) (**b**)

Figure 2. Photo documentation can capture the recovery and growth of corals, such as this orange *Montipora foliosa* stony coral from the PCR in (**a**) November 2021 and (**b**) February 2023. The return of natural coloration and signs of growth are best seen through photo documentation, as recovery/growth can span several months/years.

2.3. Welfare Considerations

In general, animal welfare refers to animals' collective physical, mental, and emotional states over a period of time, and it is measured on a continuum ranging from good to poor [7]. As an Association of Zoos and Aquariums (AZA) member institution, Steinhart Aquarium works hard to ensure high levels of animal welfare for all of the animals under its roof. The welfare program at the aquarium is structured in accordance with the AZA Animal Welfare Committee definition of welfare [7]. Steinhart Aquarium has a "cradle to grave" care philosophy for resident animals and acquires animals that are to be cared for throughout the entirety of the animal's life. Therefore, the focus is to provide all animals with appropriate nutrition, a safe environment, and choice and control so that they can be healthy, well nourished, and develop and express species-specific behaviors while at the aquarium.

The welfare of the PCR is assessed both on a case-by-case basis and as a whole. All exhibit inhabitants undergo standardized animal welfare assessments that are overseen by a team of biologists, curators, and veterinarians at the aquarium. Assessments range from daily updates with the biologist caregivers to scheduled formal evaluations conducted by the entire care team. In general, welfare assessments for the teleosts and invertebrates are similar, with a focus on their overall appearance, behaviors, appetite, and any potential underlying medical conditions. Some of the parameters evaluated for the invertebrates are adjusted for taxon of interest. For example, a decreasing body condition score is not a useful descriptor for an ailing coral, while an increasing surface area of bleaching is. Other coral-specific measures of welfare include presence or absence of sufficient light levels for zooxanthellate coral, evidence of target tissue growth or tissue loss, evidence of a typical diurnal pattern of polyp extension, evidence of polyp predation, and presence or absence of aggression in the form of extended sweeping tentacles stinging other corals as a result of them being placed too close together.

2.4. Behavior Considerations

Coral reefs are extremely biodiverse. While this biodiversity varies globally, it has been estimated that coral reefs support more species per unit area than any other marine environment [2]. Successfully replicating such a habitat in human care necessitates accounting for the physical needs of the species involved, not only for their health but also so that they have the opportunity to carry out their natural behaviors. As with mixed-species terrestrial habitats in zoos, the major consideration when planning a mixed-species exhibit such as the PCR is the compatibility of the species [8]. When working with the PCR, the Steinhart team assesses the tank both as a display and in terms of whether it is a healthy mesocosm. Collection planning goes beyond the visibility of the fish to the public to the compatibility both between fish and also between fish and invertebrates. For example, many butterflyfish (Family: Chaetodontidae) are beautiful and favorites among the public, but given their tendency to predate corals, most species are not compatible, and the aquarium limits these in the habitat. Other fish species are chosen for their specific niches within reef systems. For example, the PCR houses 22 species of surgeonfish (Family: Acanthuridae), which were chosen specifically for the functional trophic groups they fall into, each of which make critical contributions to the ecosystem processes through macroalgal removal, affecting sediment dynamics, and other functions [9]. A similar approach has been taken in selecting the wrasse species in the PCR for pest control, such as the sixline wrasse (*Pseudocheilinus hexataenia*), which feeds on Pyramidellidae snails that are pests of Tridacnidae clams, and tail spot wrasse (*Halichoeres melanurus*) that feed on acoel flatworms [2]. The PCR also houses several species of eye-catching schooling fish (e.g., blue and gold fusiliers, *Caesio caerulaurea*), which have been chosen not only for their beauty or to further mimic a living reef ecosystem but also because they are of appropriate size and number to perform this schooling behavior in this particular size tank.

3. Results and Discussion

Interplay between husbandry, veterinary, behavioral, and welfare considerations occurs daily for the PCR.

Maintaining water husbandry for a tank this size is an ongoing task. The production of seawater and maintaining the appropriate parameters has presented unique challenges. The City and County of San Francisco makes seasonal changes to the sources for their primary water supply, with seasonal shifts in alkalinity from as low as 0.25–0.3 mEq/L in the summer to as high as 1.0–1.2 mEq/L in the winter. Incoming water has to be regularly tested, and the salt formulation is adjusted frequently in order to account for these changes. The contamination of salt bags with calcium phosphate, a non-clumping agent for table salt, presented as spikes in the saltwater PO_4^{3-} as high as 1.0 mg/L. Now, the aquarium implements a rigorous protocol of analyzing every bag of salt that arrives, with unacceptable bags being returned to the manufacturer for exchange.

Within the first year of operation, it quickly became evident that the climate of San Francisco was not ideal for natural light-based coral growth. Light intensity should be between 150 and 1000 $\mu E \cdot m^{-2} \cdot s^{-1}$ for optimum coral health and growth [2]; measurements in both light intensity and photosynthetically active radiation (PAR) using sensors and data loggers (LI-193SA spherical quantum sensor and Li-1400 datalogger, both from Li-Cor Inc., Lincoln, NE, USA) found inconsistencies throughout the PCR due to wide variation in light intensity throughout the day and year, as the number of sunny days and angle of the sun changed. Signs of ailment such as bleaching (the expulsion of the symbiotic algae) was seen in corals throughout the tank, and focal death of corals occurred in areas of the PCR where the sun entered the circular skylights. Despite the original building design, a reliance on artificial light of a suitable intensity and color spectrum would be needed. A team of coral reef biologists, light designers, exhibit designers, architects, and outside consultants were therefore tasked with designing the PCR lighting to ensure that it both appropriately adhered to the needs of the reef while staying true to the design aesthetics of the building. A systematic assessment of light penetration by different light fixtures and at various depths was conducted in downtown San Francisco in the temporary coral reef tank that had been built for interim CAS use while the new academy was being built. Using these data and given the design and aesthetic requirements, a compromise design was settled upon: a lighting catwalk to mount the lamps needed closer to the water surface, allowing for ease of maintenance but also to meet the animals' needs and maintain their welfare. Ultimately, seventy-six 1 kW metal halide fixtures would be needed to provide the appropriate spectrum and intensity that the PCR corals would need to thrive but with minimal energy expenditure (Figure 3). In order to provide the habitat with a more natural light spectrum and promote photosynthesis in zooxanthellate corals, anemones, and clams, an emphasis on the shorter blue wavelengths indicative of natural coral reef waters was achieved via the distribution of both 10,000 K and 14,000 K lamps. Lastly, a translucent light film was applied to cover the building skylights that directly impacted the PCR, cutting out 80% of the light. Improvement in coral appearance was seen shortly thereafter, and over the next few years, the vertical glass walls on the west side of the habitat were also covered with this material.

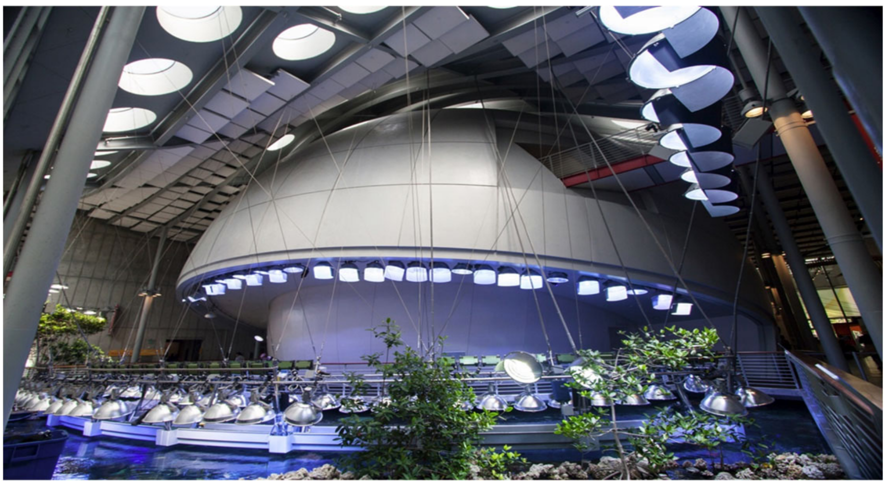
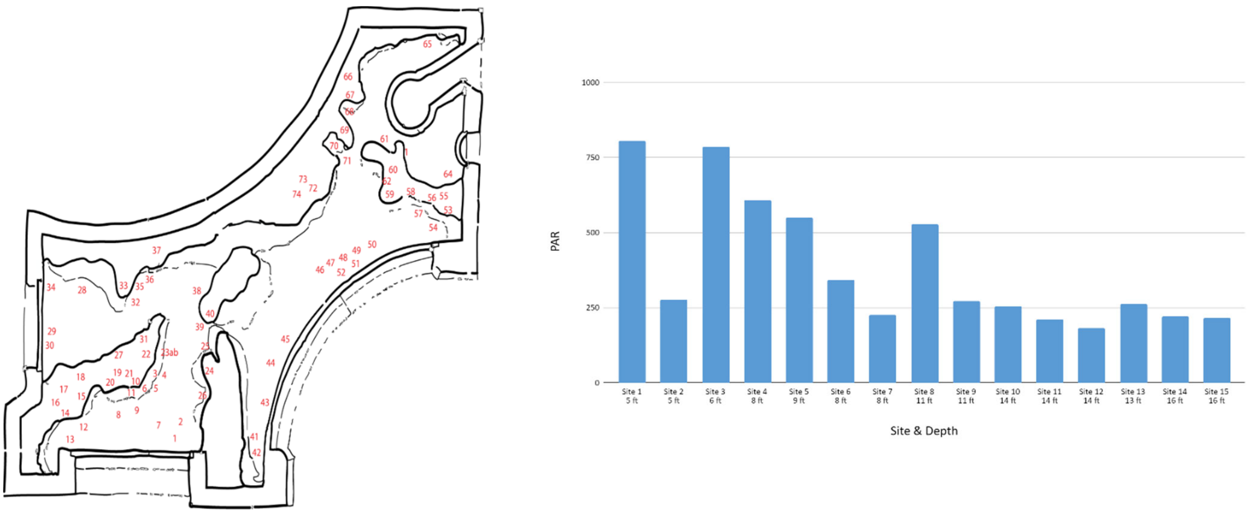


Figure 3. A photograph of the initial HQI lighting plan over the Philippine Coral Reef habitat at Steinhart Aquarium, California Academy of Sciences in San Francisco, CA, USA.

As with water quality, maintaining the lighting for this tank is an ongoing task. Light-emitting diode (LED) lights are more energy-efficient than the metal halide fixtures that have been used over the PCR. Currently, Steinhart Aquarium is replacing the metal halide fixtures with greener LED-based options. As these changes are made, husbandry teams continue to track PAR throughout the PCR tank to ensure that they meet the corals' light requirements (Figure 4). Sites and depths are pre-assigned throughout the tank for consistency. Coral presence at each site is recorded. PAR is measured at varying intervals throughout the year, with the frequency of measurement being increased if major husbandry changes, such as lighting alterations, are made or poor animal health is noted. Meticulous spreadsheets detail dates, weather conditions, and if any lights are broken for each site. In general, PAR is taken during times of peak sun exposure, usually between 11:00 and 15:00. Steinhart Aquarium aims to keep PAR at the PCR sites at 200–1000 $\mu E \cdot m^{-2} \cdot s^{-1}$ for optimum coral health and growth. However, the spectrum varies based on location and depth in the tank, and some coral colonies have been seen to thrive at the extremes of measurements.



(**a**) (**b**)

Figure 4. Photosynthetically active radiation (PAR) tracking of the Philippine Coral Reef. (**a**) Sites of PAR measurement for the habitat. (**b**) PAR measurements for Sites 1–15 taken on a single day during a single dive (1130–1230).

As the aquarium adds fauna to the collection in the PCR, the veterinary team has become even more involved in the health management of this habitat. Often, husbandry parameters alone can facilitate improvement in sick corals. For example, colonies with visible bleaching have been relocated to other parts of the PCR and have improved with no further interference. The ultimate cause of malaise may never be known, but husbandry factors are assumed because the animals' statuses improved with only this change. Although there are currently limited resources for veterinarians working with corals, standard medical philosophies and approaches may be utilized. For the individuals that can be isolated, active diagnostics and treatment are pursued as they would be for domestic dogs and cats. For fish, physical examination, radiography, ultrasonography, and tissue sampling are performed under anesthesia [6]. Animals can be kept in a hospital tank, where they undergo immersive, injectable, or oral therapy depending on the condition being treated, stress of handling, and the efficacy of the administration of medication. Invertebrates such as corals, anemones, urchins, or clams are either hospitalized or isolated in floating baskets that are still submerged within the PCR (Figure 5). If a treatment is indicated, animals are removed and placed into medicated baths. Steinhart Aquarium has had success treating its aquatic invertebrates both with aggressive therapy, such as via daily antibiotic baths, but also with simple nutraceutical approaches, such as Revive Coral Cleaner (Two Little Fishies

Inc., Miami Gardens, FL, USA) or Reef Primer (Polylab, Montreal, QC, Canada) dips for 10 min. In-depth descriptions of veterinary examinations and diagnostic methods are beyond the scope of this paper and can be found in the references [1,6]. However, especially for invertebrates, the value of microscopic analysis as a diagnostic tool cannot be overstated. Bacterial, fungal, or ciliate overgrowth as a cause of coral illness can be diagnosed via a simple skin scrape of tissue and microscopic analysis [1,10]. Corals have a rich endolithic community, and together, they are known as the coral holobiont [1,10,11]. Veterinarians that work frequently with coral colonies may benefit from submitting tissues of healthy colonies for histopathology in order to understand this endolithic community of their animals, which may differ significantly from those of other aquariums, between coral species at the same facility, or even among healthy versus sick colonies of the same species [10]. This would provide baseline information similar to that of "healthy animal" physical examinations, imaging, and blood values. Ill-animal biopsies can identify pathogens causing malaise, while shifts from the normal endolithic makeup can be indicative of the health of the colony, sometimes irrespective of gross appearance [10]. For example, although initially thought to be an overgrowth of microorganisms and a possible cause of malaise in colonies from the PCR, a layer of specific algal hyphae has now been accepted as an appropriate finding for corals from this habitat, as it is seen repeatedly in animals with no evidence of gross nor histopathological abnormalities [10]. Veterinarians working with systems such as the PCR are encouraged to communicate with colleagues regarding the successful or unsuccessful therapeutics used for corals at an individual or population level in an ongoing expansion of the medical body of knowledge available for these animals.

(**a**) (**b**)

Figure 5. Examples of medical interventions for corals at Steinhart Aquarium. (**a**) A Steinhart Aquarium biologist applies a medicated paste to a *Hydnophora exesa* suffering from BJS. (**b**) An ailing *Goniopora* coral with tissue loss and skeletal exposure that has been removed from its habitat and moved to a medical tank. This animal underwent a week of antibiotic therapy and was returned to public display, where it continued to do well.

One of the most frustrating disease syndromes seen with captive coral care is Brown Jelly Syndrome (BJS). The underlying pathogenic trigger of BJS is still unknown, but a multifactorial cause, such as weakening immunity secondary to water stressors, has been considered, and the presence of the *Philaster* ciliate has been associated with the condition [1,2]. Multifocal outbreaks of BJS have been noted in the PCR. With each outbreak, different factors were explored in an effort to understand why they were happening. Fish displaying coral-aberrant behaviors or targeted coral were removed from the tank. Particularly affected colonies were treated medically with Revive or Reef Primer dips or medicated paste [12]. The PCR tank has a history of pycnogonid sea spider presence, and colonies noted to be harboring heavy populations of these arthropods (primarily *Pocillopora damicornis*) were removed to prevent an overflow of sea spiders damaging the other corals [10]. Underwater photographic monitoring of segments of the habitat was utilized to track outbreaks, and although resolution would spontaneously occur in some areas, new outbreaks of BJS continued. Water quality is closely monitored in all of Steinhart Aquarium's aquatic habitats, but in late 2022, with a new BJS outbreak in the PCR and previous methods of interference proving unsuccessful, focus again shifted to environmental parameters as an underlying cause. Orthophosphate levels have historically been high in the PCR, sometimes reaching 0.8 mg/L $PO_4{}^{3-}$. In late 2022, the aquarium modified its water parameter testing procedures, shifting from manual to automated method-based technology, and discovered that phosphate values in the PCR were much higher than previously reported, sometimes up to ten times higher. With ongoing outbreaks in the corals, the aquarium increased the rate of $PO_4{}^{3-}$ removal to bring levels to 0.2 mg/L, targeting < 0.15 mg/L. After this change was made, the incidence of disease declined significantly. One species of coral—*Echinopora*—was almost extirpated from the habitat due to BJS during a 2020 outbreak, but this species has since been reestablished. Currently, testing for phosphate levels (as well as other water quality parameters) in the PCR is performed weekly on a Gallery Discrete Analyzer spectrophotometer (Thermo Fisher Scientific Inc., Waltham, MA, USA).

It is not always possible to hospitalize ailing PCR fish or invertebrates—some fish cannot be caught, some coral colonies are too large, some anemones are too established to move, etc. For these animals, medical interference is limited but on-exhibit treatment can still be pursued. For example, coral colonies diagnosed via skin scrape with Brown Jelly Syndrome (BJS) have benefited from a treatment regimen involving a coral-safe paste (CoralCure Ointment Base2B, Ocean Alchemists LLC, Largo, FL, USA) mixed with amoxicillin (Sandoz Inc., Princeton, NJ, USA), which is applied to affected tissues 1–3 times a week during dives (Figure 5a) [12]. Successful biological control methods have also been employed. Intermittent outbreaks of acoel flatworms, such as the recently described species *Amakusaplana acroporae*, are addressed with freshwater flushes during dives [13]. The control of *Phestilla subodiosus*, nudibranchs that feed exclusively on *Montipora folliosa* coral, was achieved via the addition of their predator, yellow-brown wrasse (*Thalassoma lutescens*). Canary wrasse (*Halichoeres chrysus*) are utilized to depopulate dwarf brittlestars (*Amphipholis* spp.).

When welfare assessments indicate criteria that need improvement, processes are in place to address these. Examples of such criteria include exhibit conditions, diet presentation, collection planning, or providing more opportunities for animals to express agency. In cases of worsening welfare scores, often due to geriatric status or chronic medical conditions, animals are assessed more frequently via a separate Quality of Life Assessment. This assessment, completed by the biologists, curators, and veterinarians at the aquarium, aims to determine if improvements in welfare and quality of life can be achieved for the individual via husbandry, nutrition, or medical care changes. Underwater photography has been an immensely helpful tool for the welfare management of the PCR and the animals within it. Repeated photographs of sectors of the exhibit or particular animals allow for more consistent monitoring of the progression or improvement of subjects (Figure 2). Objective quantification of concerns is performed using rulers and underwater photography during regularly scheduled tank dives. The PCR, in its entirety, is also photographed in set sections so that macro changes to the habitat can be appreciated and compared. Light measurements with handheld PAR meters and inductively coupled plasma-mass spectrometry (ICP-MS) analysis of water from systems with ailing colonies have not only shed light on potential causes of malaise but also helped in identifying changes in certain water quality parameters by which the animals begin to improve. If all courses of action have been exhausted, veterinarians determine if euthanasia is appropriate. If so, euthanasia is performed following the American Veterinary Medical Association (AVMA) and American Association of Zoo Veterinarians (AAZV) guidelines for the euthanasia of vertebrate and invertebrate animals [14,15].

It is important to point out that the causes of many coral ailments in closed systems are still very much a "black box" despite husbandry or medical interference. Often, several changes must be instituted to arrest a suspected disease process. Abiotic factors such as lighting, water flow, and water chemistry can act synergistically, and changes to more than one need to be made in order to cause positive change. The willingness to reevaluate "what works" and adjust it for the benefit of the exhibit and its animals is a key approach for a captive habitat such as the PCR. Ultimately, the interplay of husbandry factors, animal behaviors, and health management contributes to a positive welfare experience and the vibrant growth of all tank animals, leading to the aquarium's excellent, aesthetically pleasing appearance (Figure 6).

(**a**)

(**b**)

Figure 6. A view of the Philippine Coral Reef as a public display aquarium habitat from the same viewing window: (**a**) photograph from the exhibit's opening in June 2008; (**b**) a more recent photograph from February 2023.

A major negative aspect of a mixed-species exhibit is that, despite everyone's best efforts, some species-specific behaviors may be detrimental to the other animals in the habitat [8]. Abrupt changes in animal behavior can occur. For example, the naturally planktivorous pyramid butterflyfish (*Hemitaurichthys polylepis*) in the PCR suddenly began to eat soft corals after 8 years in the system. Steinhart Aquarium addresses such potentially detrimental behaviors by redirecting them to more appropriate outlets. Heads of lettuce or broccoli are lowered into the PCR twice a week in order to provide for herbivorous fish that might otherwise resort to picking at corals for food, redirecting this behavior away from affecting the invertebrates. Fish that continue aberrant behaviors despite husbandry alterations are moved to other habitats within the aquarium or transferred to other aquariums. Similarly, invertebrates that are repeatedly targeted are also either moved or temporarily shielded within a plastic mesh cage to protect them from predation until the fish in question can be removed or the behavior ceases (Figure 7). Failing this, the coral can be relocated to areas of the habitat that can be shielded from the fish species in question.

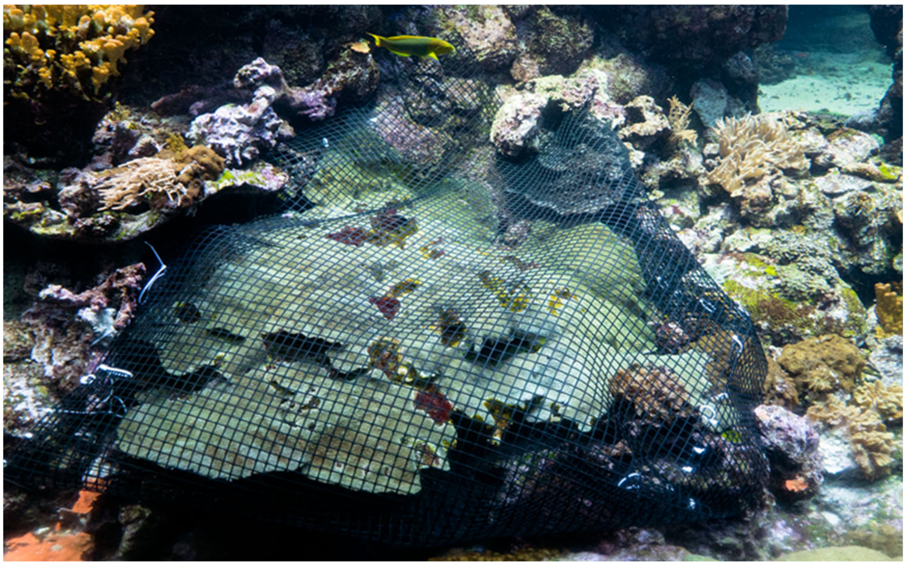


Figure 7. This *Hydnophora exesa* was being targeted by several fish, as can be seen from the necrotic areas of the colony. A sheet of plastic mesh affixed with cable ties was placed over the colony to exclude fish until signs of recovery were observed.

Many aquariums offer the public an opportunity to experience fish feeding behaviors up close via scheduled dive shows and feeds involving in-water divers feeding the fish. Steinhart Aquarium has not allowed diver feedings during scheduled dive shows since the PCR was debuted in 2008. It is important to note that such opportunities would not occur in the wild and that there is potential for negative behaviors to develop from animals when these types of feeds occur, as fish will quickly associate divers with food and swarm them as soon as they enter the water [16]. In addition, some of the fish (e.g., Niger triggerfish, *Odonus niger*) have substantial dentition that can cause damage to fingers, and there has been a history of this in aquaria, including in the old Steinhart Aquarium facility (B. Shepherd, pers. comm.). Therefore, in keeping with the goal of presenting the most natural coral reef system possible, Steinhart Aquarium has chosen not to have divers feed the fish by hand during PCR dives. Instead, food is added from the surface by top-side staff at the tail end of the show to allow for interpretation by a dry-side presenter.

4. Conclusions

The ultimate goal of modern public zoos and aquariums is to educate the public about the natural world while providing an excellent, unique entertainment experience. Current recommendations for zoo and aquarium practices are shifting toward an emphasis on animal welfare and well-being, key parts of excellent captive animal care. Interpretations of these for different species are ever-shifting. Despite the complicated husbandry and species considerations for aquatic animals, these recommendations and standards can be incorporated by public aquariums.

This report details the husbandry, veterinary, welfare, and behavior considerations concerning a habitat containing living coral and a diverse assemblage of other tropical marine animals. However, because of the interplay between the living and nonliving parts of a captive aquarium system, it is important to assess these parameters for aquariums of any size. Detailed recordkeeping of both husbandry parameters and animal appearance or behavior is recommended in order to identify positive or negative shifts within the system. Data-driven changes are made to improve conditions when poor animal or overall tank welfare are warranted. Aquarium teams should consider that not all positive outcomes can be linked to any one particular change and that, sometimes, several simultaneous alterations are required before improvement is noted. Changes to displays and husbandry may be required to improve animal well-being, and a flexible attitude regarding intended tank design and aquarium protocols is recommended if it ultimately improves animal welfare. Finally, the delicate interconnectedness of the flora and fauna in coral reef systems in particular should be noted. Aquariums are encouraged to utilize the current high-standard animal welfare, behavior, veterinary, and husbandry recommendations for coral reef habitats of all sizes.

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