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Is sustainable exploitation of coral reefs possible? A view from the standpoint of the marine aquarium trade

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Coral reefs are at the brink of a global, system-wide collapse. Human populations living at the water's edge are a vital key to the long-term survival and maintenance of these global biodiversity hotpots. Global trade combined with high levels of poverty threatens to siphon out biodiversity riches from developing nations to the developed world for short-term gains. The difficult challenge for local governance, conservationists, and resource managers alike is to create and maintain as diverse and well-functioning a Coral Reef Socio-Ecological System (CRSES) as possible. A fundamental shift in the structure of business practices, incentives and values are needed to move the marine aquarium trade to a more sustainable state. Rapid growth in the cultured coral trade and better fishery management in small fisheries are bright spots in the marine aquarium trade, and demonstrate that this trade can be part of a broader solution to reef conservation.

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Marine aquariums at the intersection of sustainability and global trade

As the global human population increases all natural ecosystems are being stressed. This is particularly true in the Coral Triangle [1] a region of great impoverishment and high population density and at the same time, extremely biodiverse [2]. Given the high productivity of coral reefs and their often remote locations, the human communities living adjacent to reefs depend on marine resource extraction as the basis of their economies. Coral reefs are experiencing rapid global degradation and exhibit a stunning loss of coral cover and integrity in recent decades. This is due to large scale (climate change) and local anthropogenic impacts, including the demand for reef-derived natural resources [3]. Recently, conservationists have begun to acknowledge the importance of coupling natural resource protection tightly to economic development [4]. As people are entirely dependent upon ecosystem services, social and ecological systems operate as a functional unit (the socio-ecological system, SES). Local governance, conservationists, and resource managers in coral reef countries face a difficult challenge in the need to maintain as diverse and well-functioning a coral reef socio-ecological system (CRSES) as possible.

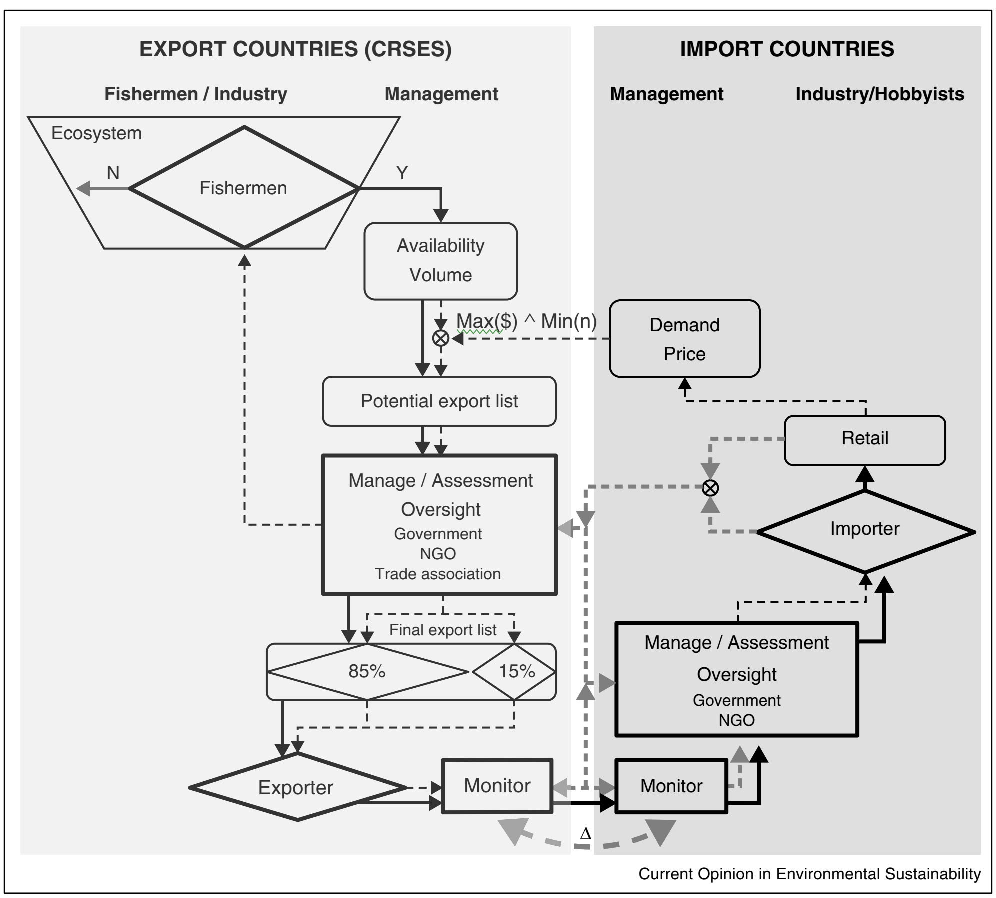
Within a healthy CRSES, the economic and societal needs of the human inhabitants are provided for in the short term while also ensuring the future of these ecosystem services [5]. The primary means of ensuring sustainability is ecosystem-based management, usually involving a spatial plan or zoning scheme that acknowledges the contributions of all the habitats that directly or indirectly support marine resource flows. Two important tools for maintaining a functional CRSES meld no-take areas for biodiversity maintenance and replenishment, and closely monitored extractive activities to imbue the CRSES with accountability and adaptability. One challenge in particular that commands close attention: regulatory and monitoring activities — however essential — are almost always too expensive to be practical. Without a fundamental shift in the structure of business practices of natural resource extraction, science based management and monitoring, and the incentives and values that lead to proper application of the science, are elusive and which makes sustainability unattainable.

The marine aquarium trade (MAT) is sometimes singled out as a threat to coral reef conservation, but it can also be a positive component of a functional CRSES. The MAT involves the wild capture of over 1800 species species of marine fishes from more than 40 countries [6••] and likely another thousand species of invertebrates and corals. This wildlife is collected for the purpose of stocking artificial aquatic habitats in homes, offices, and public institutions (aquariums, museums and zoos) throughout the world. The trade in coral reef biodiversity for private and public aquaria has seen rapid growth and expansion over the past few decades. The trade has brought benefits: a new and badly needed source of income to coastal communities of the Indo-Pacific, inspiration to people in the developed world to care about remote regions of the developing world, improved access to coral reef species for basic research and education, and young children encouraged to practice scientific principles and to ultimately choose science as a career [7,8•,9,10,11]. There are also risks that come with this trade [reviewed in [9]], including wasteful and destructive fishing practices within the Coral Triangle (as elsewhere), impacts on populations of rare and endemic species, and the introduction of non-native species to foreign habitats [12–15]. Can developed nations encourage the trade that provides income to impoverished people without piling new woes on threatened coral reefs and driving species to depletion? In an increasingly globalized world, can enormous poverty, global trade, and coral reef conservation coexist, and if so, can the aquarium trade have a constructive and catalytic role in ameliorating poverty and healing natural habitats? If so, what would this look like? Here we imagine what a sustainable aquarium trade could look like, and suggest a plan to address the oversight necessary to accomplish this. In so doing, we hope to inspire others to follow on, adopt a critical view, and debate the relevant issues in an effort to ensure that global generations after ours can continue to enjoy the wealth of these ecosystems.

How we define sustainability

The broadest definition of sustainability is that current actions enable the combined human and natural ecosystem to maintain its health and productivity for future generations. Since the world is constantly changing, behaviors meant to ensure sustainability must also change and adapt. This can be problematical because user groups and consumers may view sustainability as static attribute, for example, 'x product is sustainable'. In reality we can only move toward being sustainable, constantly improving practices to reflect new knowledge about the changing state of the ecosystem [16]. It is not enough to know that extraction rates are lower than replacement rates for any

Figure 1



Steps to assure the sustainability of live fish trade from coral reef socio-ecological systems. Actions within the CRSES export countries are on the left (lighter box) where those of the importing countries are on the right (darker box). Square text boxes indicate managerial/oversight activity, rounded boxes are data, diamonds are choke points were actions can be optimized. Thin dotted lines indicate decisions and data flow while solid lines indicate product flow. It is important that the oversight in the export country include a trade association or co-op that can collect increased revenue and redistribute it to the fishermen. Gray dashed lines indicate potential for synergistic opportunity in export and import countries, and Δ indicates an opportunity to examine illegal and unreported trade.

particular species. We need as broad and robust a definition as possible. We suggest the following definition for the MAT: 'a relationship between society and reef that continually sustains and improves the net benefit to the CRSES' [17]. This relationship should include the extraction of live organisms, up to a point, as well as other activities, such as aquaculture, that improve human well being without decrementing coral reef health.

Because of the need for continual improvement and adaptation, there must be feedback loops where net benefits are monitored, failures noted, and appropriate corrective measures taken promptly. It will take effective communication between the harvesters, managers in exporting and importing countries, and markets, all of which need to be integrated across the multitude of species being harvested. If you consider the functional unit of MAT being 'species A' exported from 'country B', then in 2005 there were over 6700 AB combinations for marine fishes being imported into the US [6••]. Not all of these species/country combinations are at the same point on the journey to sustainability [18•]. In order for the MAT to be fully sustainable as a whole, each component of the aquarium trade must be sustainable in itself. The key is to not treat every species/country combination equally, but to use adaptive learning and management to assess those situations most in need of oversight [18•]. It is also critical to engage the local communities in collection of their reef resources. If the reef-side community is not engaged, then collection will be conducted by roving bands that have little regard for the long term health of the fish stocks [19••]. General principles of best practice — biological, social and economic — should be discovered and applied everywhere. There must be *in situ* monitoring of reef, village and market to know what is and is not working, and with this knowledge, to modify management adaptively.

The MAT decision loop

In any country that participates in sourcing organisms to the MAT there is a list of potential species that might be exported, based upon the summed intersection of the availability and volume of the potential species, integrated across the demand and price from the importing countries (Figure 1). The removal of each individual organism from the CRSES incurs some kind of systemic cost. A sustainable and adaptive MAT will maximize the total net-benefit by always floating the maximum acceptable price per individual while limiting the number exported (Figure 1 and Box 1). In addition, the ideal MAT will minimize

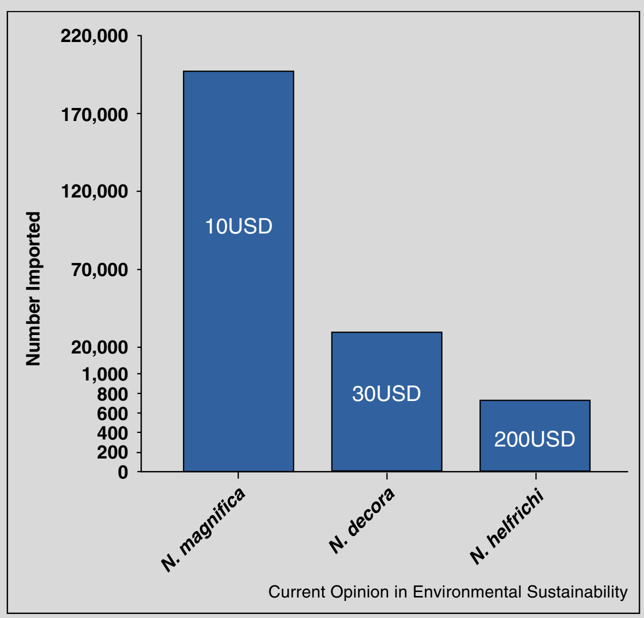
Box 1 Simultaneous maximization of price and minimization of numbers.

Maximization of price and minimization of quantity exported.

A major threat to the sustainability of the MAT is the inverse relationship of export volume and price. The supply demand curve in the aquarium trade is sharp, where species with perceived rarity command extremely high prices and those prices quickly fall as supply is increased [8•]. The reality is that as volume of a species increases, a negative feedback loop quickly takes effect and drives prices down further which in turn increase volume as more people are able to afford a given species. This feedback loop often affects the care of species throughout the supply chain, which increases mortality and feeds back with increases fishing pressure. The relationship of volume of a species imported and retail price is well demonstrated in fishes of similar size, appearance and coloration. For example, the firefishes (*Nemateleotris* spp.) are some of the most highly prized species in the trade, both in terms of rarity and volume. Firefishes exhibit the typical supply demand curve where volume greatly impacts price, with retail prices in 2005 as low as 10USD for the most common species and more than 200USD for the least common (Figure I).

Another example of over supply and its influence over price and quality in the MAT is the flame angelfish (*Centropyge loricula*) and the Pacific island nation of Kiribati. The aquarium trade is the most highly valued export product of Christmas Island and thus represents an important source of income to an extremely remote island community. The key aquarium fish export from Kiribati is the flame angelfish, which developed as a high price, low volume fishery in the 1980s and slowly shifted into a high volume low price fishery by the mid 1990s [10,29]. Until recently price and supply was only controlled by market forces (both air freight availably and the number of exporters). The result was a large increase in production and a sharp decrease in quality of fish that corresponded to a devaluing of the fishery, with fisherman were catching twice as many fish for the same income. More recently an export quota has been put in place to reduce supply and increase the export price and value of the fishery. Perhaps the most important message from these two examples is that small island nations that supply key species to the trade can only maintain a sustainable fishery if they control the volume of fish exported.

Figure I



Number of three firefish species (*Nemateleotris* spp.) imported into the United States in 2005 and retail value (numbers on bars, approximant retail value in USD) (See [6••] for methods of data collection).

system cost by closely tracking emergent indicators of reef health and resilience as well as the population biology of target and non-target species. Given these conditions, there will always be a list of available species that should not be exported (e.g. uneconomical cost–benefit where elevated risk of extirpation or ecological harm are potential costs). The suite of MAT-suitable species should then be integrated into the country's marine spatial plan (as in, there ought to be one!), including performance criteria for no-take and extractive reserves (for example, the abundance of MAT species should increase or remain stable in no-takes and spill over to extractive reserves and open access areas, Figure 1 and Box 2). Effective management of MAT participation is a portion of the overall governance capacity of the country, along with institutional capacity for staffing in the field and at ports. This management ultimately feeds back into the ecosystem level (top left polygon in Figure 1), of which extraction for the aquarium trade is only a single component. It is particularly important to include a trade association or co-operative in the adaptive management. They can gather additional revenue collected as a function of increased valuation of product from sustainable fisheries, and redistribute these funds to the fishermen and their communities. Participation in the MAT makes sense and can be made sustainable only from a whole-system perspective. If aquarium extraction is prevented (N decision within the ecosystem box, Figure 1), there will be consequential impacts on the ecosystem, ecosystem services and the CRSES. If local communities do not derive economic benefit from the harvest of fish for the MAT, they will continue to utilize reef resources, but quite likely in an unsustainable manner. The MAT enterprise is also the recipient of the impacts of other activities. For example, if fishing for reef herbivores or deforestation in the watershed is allowed, coral reef habitat may be lost and along with it the value of MAT exports [20,21]. This provides MAT beneficiaries with an incentive to protect the entire watershed and coastal ocean system.

Box 2 Is the Hawaiian yellow tang moving toward sustainability?

The Hawaiian yellow tang (*Zebrasoma flavescens*) fishery represents the most heavily studied wild-capture ornamental fishery of any marine aquarium species. Managers [30] working with scientists [31,32••,33] have developed a well-understood fishery in terms of both fish biology [34] and fishery socioeconomics [35]. This fishery primarily occurs on the Kona coast of the Island of Hawaii' where it represents the most valuable inshore fishery in the main Hawaiian Islands. Tissot [36] documents numerous user conflict issues and the management methods (e.g. MPA and Fishery Replenishment Areas (FRA)) that have been successful in stabilizing fish abundance. Spillover from FRAs into areas open to fishing has been confirmed by parentage analysis of juveniles born of adults from adults within the FRA [37]. However, the question of the sustainability of this fish from this area requires more than a resilient wild population. Until recently MPA and FRA reserves offered the only management structure, and market forces controlled the supply and price of yellow tang and other Hawaiian aquarium fishes. Recent efforts [38] have put in place a white list of acceptable species, and bag and size limits on key species. Importantly the West Hawaiian fishery is moving to sustainability in meaningful terms with specific license requirements and a limited entry fishery. From field to fishery, the Kona enterprise is a model for management of aquarium species where you have a high level of governmental capacity, fisheries data and MPA networks. However, gaps remain in terms of a system for setting catch limits. In Hawaii, catch limits could be assessed through the monitoring of exports. The Hawaiian Island's isolation affords easy access for chokepoints (international airports) that managers could target to collect important export data. There is currently no inspection process designed to collect data on the aquarium fisheries at the point of export. This represents a major shortcoming in management efforts. In addition collectors and exporters' (wholesalers) fish holding facilities are not required to be licensed and inspected. The licensing of these facilities would assure sufficient welfare of the animals pre-export, where fishery dependant landing data are collected.

Besides implications for ecosystem-based management, the other outcome of the management of the MAT is that a final export list will be created (Figure 1 and Box 2). There are a number of factors that will go into this list. One management tool we have suggested [6••,22•] is to focus on those target species that make up 85% of the export volume. Typically, only a small subset of the total number of species being exported will be handled in large volumes. For example, in 2005, only 477 of the total 1802 species imported into the US consisted of 1000 or more individuals [6••], and would likely need to be monitored. Monitoring the trade is important [18•,23•,24,25,26••] both at export and import as the difference could indicate illegal or unreported trade. *In situ* mariculture production is also a partial solution ([7] Box 3), but sole reliance on mariculture could lower incentive to protect a healthy reef systems [9]. In the schematic presented here (Figure 1), monitoring rests at that important point in the transport chain where shipments cross political boundaries. Its location within the schematic is to point out that ideally trade monitoring would be a cross-political boundary activity that would integrate activities of both export and import, and would feed back into the management of the resources of each country (Boxes 2 and 3). The 15% of the species that make up 85% of the volume of the trade (*sensu lato*, e.g. Florida, USA) are the species for which detailed life history characteristics are required to actively manage the species [22•]. Currently, little monitoring of trade occurs within each country, or none at all, and there is virtually no feedback between countries and into the management of the MAT. Trade monitoring should include assessment (and discouragement) of destructive fishing practices, such as the use of cyanide [27••].

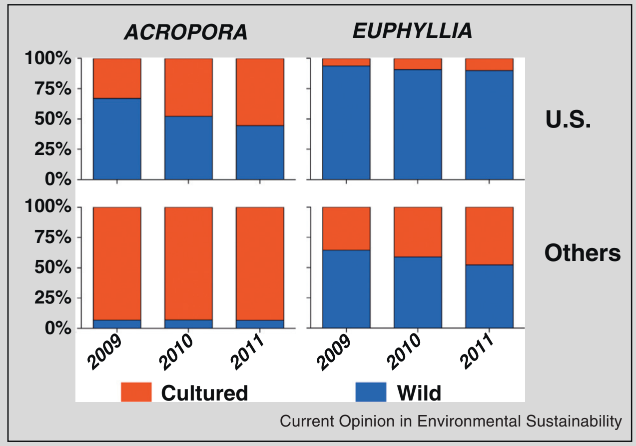
Given the limitations of cross boundary cooperative monitoring, once wildlife products enter the import country they should be inspected for illegally harvested or injurious wildlife that should not be imported into the country. Ideally, there should also be point-of-import-recording of all of the import data as well as a check on

Box 3 Corals; management capacity, international treaties and mariculture.

Stony corals provide a unique window into the sustainability of the MAT. The trade in corals is managed under international treaty (CITES) and was comprised solely of wild harvests for several decades. The larger coral trade including the take for curios and basic minerals, had been considered as a major threat to the health of coral reef ecosystems [39]. However, beginning in the late 1990s a major shift began to emerge. The ability of hobbyists to maintain stony corals in aquariums advanced allowing for the fragmentation of captive stocks. At the same time small island nations began mariculture operations [8•]. The Solomon Islands' village at Marau Sound has been farming corals for nearly 2 decades. This provided an alternative model to wild harvest and by the mid 2000s Indonesia began developing mariculture standards and has now positioned itself to be the global leader in coral mariculture (See [6••]). CITES provides a cap on supply. This makes it more difficult to export and import product, and because of this, despite complaints that some countries are exporting more than published quotas, we argue that, while far from a perfect solution, CITES has been an effective tool in controlling the supply of corals for the MAT. CITES provides trade monitoring and importantly it places a ceiling on the total number of exports of wild corals allowed. These two factors were likely the key drivers in Indonesia's transition from a wild fishery to a maricultured product. Furthermore, under CITES, exporters must possess quota and importers must comply with rigid data collection and inspection standards. In total, this limits the number of exports into the marketplace and provides necessary data for trade oversight. Additionally, EU countries prohibit importation of some genera of wild corals that they view as unsustainable [40]. The pressures of CITES quotas combined with pressure from importing counties through both legislation and dialog have transformed the trade in corals and moved it along the path toward sustainability. Indonesia now exports a majority of its *Acropora* spp. as maricultured and the highly desirable slower growing large polyp corals such as *Euphyllia* spp. are becoming a maricultured product (Figure I). Interestingly Europe is a major consumer of mariculture imports of *Acropora* spp. and *Euphyllia* spp.

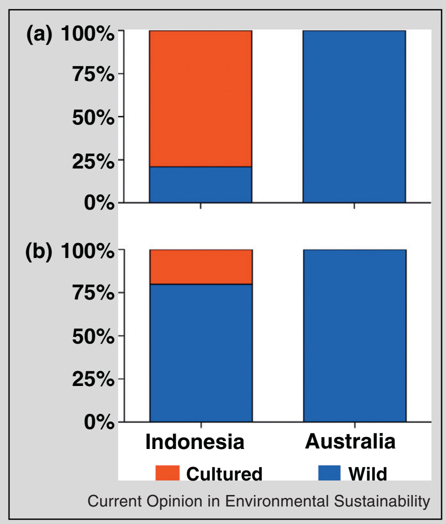
The sustainable trade in coral reef species is tightly coupled with the regional or national governance capacity of the source country or state. Countries with high levels of poverty, low governance capacity, and/or resource management concerns will have difficulties maintaining a sustainable coral fishery and should adopt the mariculture model. Notability, Australia a country with high governance capacity maintains a robust wild harvest coral fishery and has not moved to a mariculture model (Figure II). During three years 2009–2011, Indonesia exported more than 75% of the *Acropora* and nearly 20% of the *Euphyllia* as maricultured while Australia maintains only a wild fishery. Both have the ability to be sustainable. Furthermore it is well documented that Fiji's coral fishery takes a very small amount of biomass that has no measurable impact on the future production of its coral reefs [41] and is a model fishery.

Figure I



Three-year trend of Indonesian aquarium coral exports of two popular genera, *Acropora* spp. (Left) and *Euphyllia* spp. (Right) to the United States (Top) and all other nations (Bottom) (See [8•] for data collection methods).

Figure II



Comparison of three years, 2009–2011, of export data from Australia and Indonesia of two genera of corals, *Acropora* spp. (a) and *Eupyllia* spp. (b) (See [8•] for data collection methods).

its accuracy, with this information being shared with all points in the value chain as feedback for improved management.

Is sustainable exploitation of coral reefs possible?

Coral reef animals can be removed for the MAT in a way that is carefully targeted, low-volume, with little environmental impact, and closely monitored. Done in this way, there are many places that the MAT can provide livelihoods for reef-side communities. For small-scale fishers, often the needs of the community have greater importance than the capitalistic aspirations of individuals [28]. As we have discovered for other fisheries, single species management that is ignorant of the dynamics of the linked ecological and economic system is a bad idea, and in the case of the MAT, with more than 3000 species originating from over 40 countries, the notion is absurd.

There are many opportunities to further the journey of the MAT toward sustainability [7], and we have identified many tools here to move the MAT on this journey. Of course, all of these tools are not going to fall in place simultaneously. It is important to take small deliberate steps toward improvement, and over time, an adaptive program ideal for each country will be created. Overall, we suspect that the benefits of a more sustainable MAT will greatly exceed the risks and costs of ending the trade in marine organisms altogether, or of entirely substituting the *in situ* wild capture or mariculture at reefside for *ex situ* aquaculture production. PetCo, one of the largest retailers of MAT within the North American market, has made a pledge to move toward sourcing 100% aquacultured products over any wild caught marine species (http://www.petco.com/petco_page_PC_aquacultured.aspx). This strategy can reduce the functional CRSES as it removes the in-country biodiversity benefit without recompense. Industry leaders should avoid these simplistic shortsighted policies and instead adopt comprehensive sustainability policies that employ market power [23•] to help drive reforms that benefit CRSES from the consumption side.

The MAT trade also needs to be framed within the larger global situation. MAT can be a means to help create value for reefs, and give them cause for protection. This is needed in today's reality of global processes that are enormously more threatening than the aquarium trade. These include anthropogenic climate change, and its four component stressors: warming, acidification, sea level rise, and volatile, extreme weather, along with a second existential threat to coral being proximity to dense human populations. These are bad for coral reefs in so many ways, that scientists have come to regard these cumulative effects as a unitary process. At the root of these effects for coral reefs, though, are overfishing for food species and bad watershed and wastestream management, aggravated by a shifting baseline phenomenon. For example, people overfish ecological keystone species, such as parrotfishes [20]. It does not take very long for people to forget the quality and value of a healthy coral reef system, and then lose their motivation to be good stewards of it. Without good local stewardship, there is no hope for coral reefs. And without humans seeing value in coral reefs, there is no hope for good local stewardship. The MAT is at a level that it can be a quite important component of how people derive value from coral reefs. If we eliminate it, we lose conservation leverage, and the harm done will not matter anyway because the coral reefs of the world will expire. If we focus the MAT intelligently, then the resulting conservation leverage will be an important contribution to an overall strategy for pulling coral reefs through the inferno of climate change. On this scale, the extraction of animals for the MAT, along with certain other forms of artisanal fishing, are entirely compatible with a full suite of coastal activities that support local livelihoods — ecotourism, agriculture, forestry, and industry — but only if the entire CRSES is envisioned and stewarded in a sustainable manner. The MAT may in fact possess a greater transformative power than these other extractive sectors, and is thus in the position to serve as a catalyst. Rather than destroying the reef, the marine aquarium trade could play a role in saving it, a role totally out of proportion to its size, and even out of proportion to its potential to do harm.

It is time for aquarium hobbyists, sport divers, fishermen, the marine aquarium trade, conservationists, and citizens of coral reef nations to look beyond their own shores and most immediate concerns, toward the relationship between their actions and a global future. With judicious management, pertinent monitoring, well-placed testing, and cooperation by all members of the value chain (collectors, producers, exporters, importers, managers, and the hobbyists) the MAT can be a positive conservation force, and a spark plug in the engine to save every CRSES.

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