ECOLOGY

Can the global marine aquarium trade (MAT) be a model for sustainable coral reef fisheries?

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Globally, 6 million coral reef fishers provide ~25% of emergent countries' catch, but species have low value. The marine aquarium trade (MAT) targets high-value biodiversity, but missing data amplify draconian governance and demand for international prohibition. To stimulate sustainability and reef conservation investment, we generate a fiscal baseline using the first global analysis of numbers, diversity, and biomass of MAT-traded organisms. Each year, ~55 million organisms worth US$2.15 billion at retail are traded comparable with major fisheries, e.g., tuna. A sustainable MAT also requires overexploitation assessments. We identify 25 species/genera with "Extremely High" risk ratios and place the Indonesian and Sulu-Celebes Seas in the highest exploitation category. Despite predicted hobbyist number increases, unabated reef degradation and low governance will transform the MAT into an aquaculture-dominated industry decoupled from communities (i.e., culture located in importing countries). A "MAT-positive" future requires evidence-based management/governance, consumer education, and sustainable practice incentivization but can address the biodiversity and social and economic inequality crises.

INTRODUCTION

Fishing is the primary driver of diminished coral reef functions (*1*, *2*), compromising ecosystem services for millions of people. With an estimated 6 million coral reef fishers globally (*3*), reefs provide ~25% of the total fish catch in emergent nations (*4*), but as the target organisms are usually low value (*5*), the financial leverage of blue food fisheries to support reef conservation and enhance community livelihoods is limited. In contrast, the marine aquarium trade (MAT) targets biodiversity that can retail for hundreds of U.S. dollars per organism (*6*). The MAT depends on small-scale fisheries from numerous countries generating convoluted global chains of custody (*7*), but is a data-poor exemplar (*6*, *8*–*11*). While a substantial economic value could promote conservation and support sustainable coastal livelihoods, the outdated, myopic MAT estimates (*12*) that still circulate (*13*) have contributed to a narrative of overexploitation, leading to draconian governance (*14*) and international prohibition. Our primary objective is to generate the first global analysis of numbers, diversity, and biomass of MAT-traded organisms and then to calculate point-of-first-sale (PoFS) and retail values. However, as it is critical to include all organisms collected, we also incorporate those rejected/dying within the chain of custody. Because of publicly unavailable commercial data, our approach was to survey retailers to generate average monthly sales combined with retailer numbers from dominant importing developed countries. To generate global estimates, countries with a high human development index (HDI) score (*15*) were selected as "equivalent" for scaleup. Together, and compared to other global fisheries, these data generate a fiscal baseline to stimulate sustainability investment and governance, which may lead to stronger community-reef connections, i.e., benefits flow to the reef-dependent communities.

Although relative vulnerability for a minority of MAT fish species has been estimated using productivity susceptibility analysis (*16*), a species' vulnerability score does not reliably predict overexploitation risk (*17*). To obviate these issues and to include data-absent fish and all invertebrates, we used extent of species occurrence as a population size proxy. We correlate numbers traded with geographic range, generating risk ratios to inform stock assessments. Critically, as the MAT targets biodiversity from areas within multiple countries' (*6*) jurisdictions, we then generate the first exploitation levels for source large marine ecosystems (LMEs)/ecoregions to inform governance.

Just as aquaculture has been suggested to mitigate the global capture fisheries decline (*18*), expanding the cultured organism supply has been postulated to be the MAT's future (*19*). However, ex situ culture, and concomitant capture fisheries disinvestment, may have substantial consequences for MAT-reliant coastal communities and severely limit reef protection support. We calculate future "technology transfer" projections (applying similar aquaculture techniques to closely related species to bring to market). We then generate the first global hobbyist number estimates incorporating key time point predictions in the context of increasing demand due to country-specific population increases and economic growth. These are combined with reef health estimates under future climate scenarios to distill (i) a high-emission "business-as-usual" scenario and (ii) an alternate strong mitigation "MAT-positive" future. Their juxtaposition provides the industry, fisheries/conservation practitioners, and policy makers with a "road map" for governance, maximizing sustainable capture fisheries and aquaculture and preventing decoupling of the MAT, coastal communities, and reefs they both depend on.

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RESULTS

Global numbers, biomass, and value

Survey responses generated mean annual retailer sales of 143 ± 127 SD fish and 378 ± 422 SD invertebrates, confirming that approximately 2.6× more invertebrates are sold as fish. Invertebrates dominate the top five groups sold [snails and slugs, large polyp stony (LPS) corals, hermit crabs, shrimps], with only damselfish (3rd) and gobies (10th) in the top 10 (table S3). As the top 30 species represent 43% of the global numbers traded, our data (table S3) also confirm the MAT is dominated by relatively few species, with our list reinforcing the invertebrate dominance with just three fish in the top 30. Using the global scale-up approach, we estimate that there are 8792 MAT retailers in the 66 developed countries (HDI ≥ 0.8). Combining with mean sales data, we estimate global MAT annual sales of 5.54×10^7 organisms; however, including cumulative chain-of-custody losses (a 1.86 collection to retailer factor) generates a traded number of 1.03×10^8 (Fig. 1). This is only ~50% fewer than the number of yellowfin tuna (*Thunnus albacares*) captured globally, but >7× albacore (*Thunnus alalonga*) tuna numbers.

Given that hobbyist tanks can be just 10 liters, the 1.33×10^4 tons traded is, unsurprisingly, small (Fig. 1). For example, it is ~100× less than yellowfin tuna (*T. albacares*) biomass and 6× less than 6.43×10^4 tons of blood cockles (*Tegillarca granosa*). This low biomass belies the high value of the trade as the mean MAT value at PoFS (US\$$9.68 \times 10^7$) is only ~7× less than albacore (*T. alalonga*), but 44× greater than the green mussel (*Perna viridis*). The combined fish/invertebrate PoFS confirms an important value (equivalent to US \$148 kg^{-1}) to coastal communities, but most striking is the inflation through the chain of custody to retail as the value increases 41× to US\$$2.15 \times 10^9$, higher than the global value of the albacore (*T. alalonga*) fishery and both example invertebrates.

Identifying priority species and regions

The number of individuals traded varies dramatically by species (table S3), for example, excluding chain-of-custody losses, only 528 semicircle angel fish (*Pomacanthus semicirculatus*) are sold per annum compared to 3.6×10^6 Astrea snails (*Astraea tectum*). This diversity is also observed in the geographic ranges: compare the porcupine puffer (*Diodon holocanthus*: 3.9×10^7 km^2) with the Armitage angelfish (*Apolemichthys armitagei*: 8.5×10^3 km^2) (table S3). Our analysis (see fig. S1) does not confirm a significant relationship between MAT popularity and geographic range (viz. abundance); yet, the high variability highlights a species/genus-specific analysis to be essential. Mean $\log_{10}$ risk ratios organized by common name groups (with ±1 SD) and species/genus risk ratios (gray circles) overlaying colored risk levels are presented in Fig. 2. Most of the MAT-specific thematic groups have mean Medium risk ratios (yellow) or lower, with only 13 in the High priority and one (hermit crabs) in the Extremely High (>95 percentile). MAT species/genera risk ratios show considerable diversity, but 25 [fish

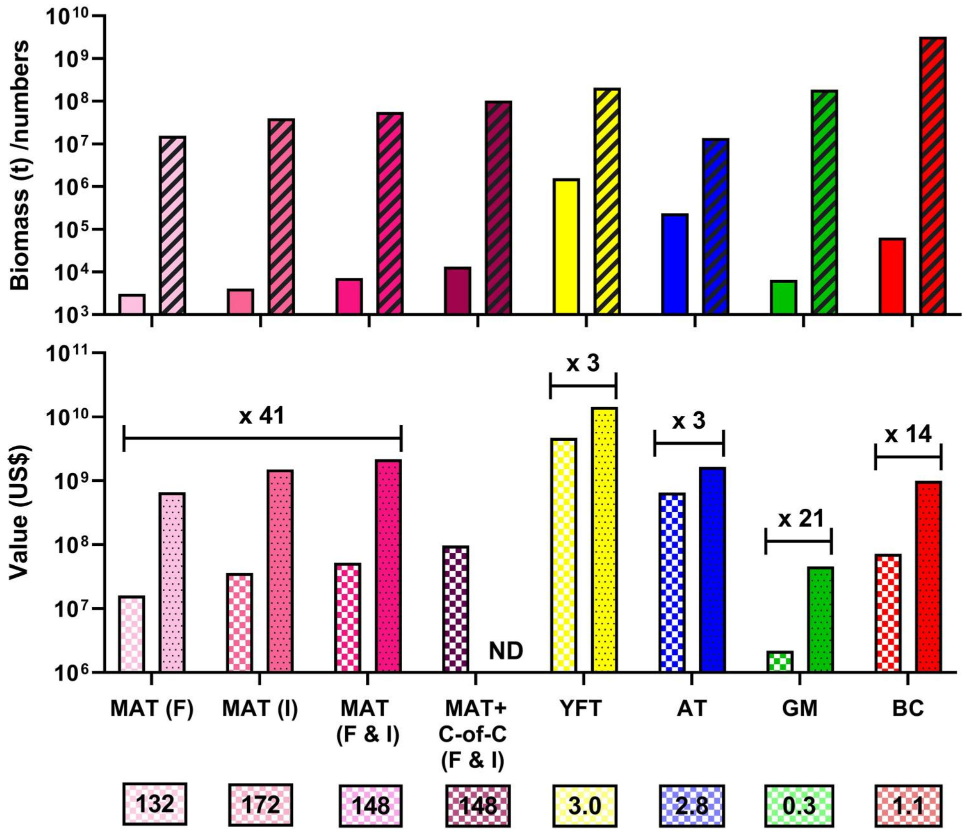

Fig. 1. A comparison of the global MAT with other fisheries. Biomass (solid), number of organisms (striped), PoFS (checkerboard), and retail (stippled) values are organized by fish (F) and invertebrates (I) and also include chain-of-custody losses (C-of-C). YFT, yellow fin tuna (*T. albacares*); AT, albacore tuna (*T. alalonga*); GM, green mussel (*P. viridis*); BC, blood cockle (*T. granosa*). MAT values are means, and markup is the increase from PoFS to retail (lines above bars) per organism. Retail value including chain-of-custody losses was not calculated (ND) as losses occur at multiple nodes before retail. Boxes are the mean price per kilogram at PoFS.

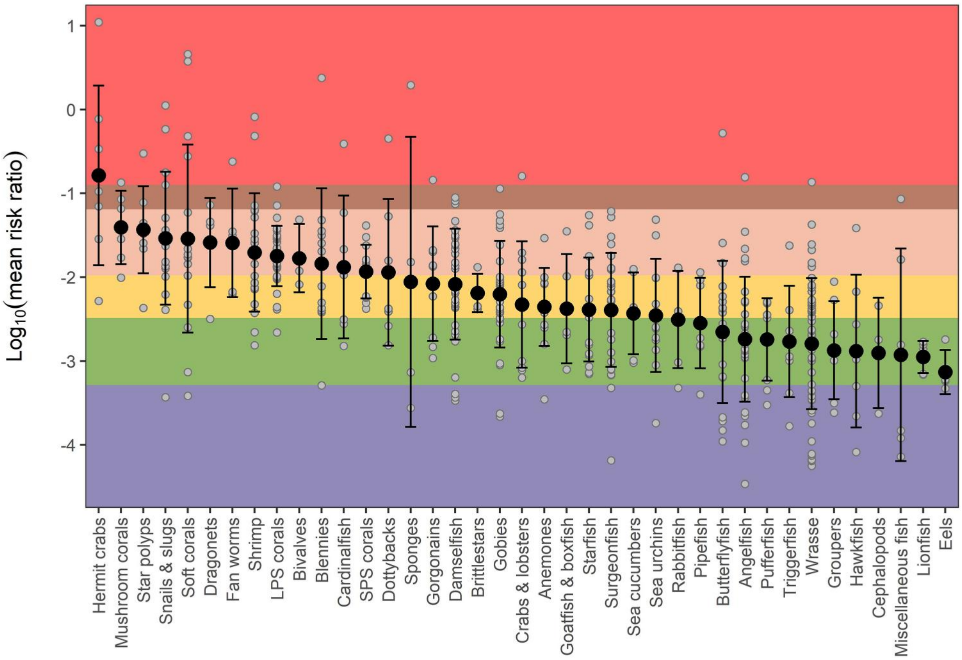

Fig. 2. Relative exploitation risk for species and common name groups for the MAT. Mean $\log_{10}$ risk ratios (±1 SD) per MAT group are plotted with individual species/genera (gray circles) overlaying the six risk levels: blue: Very Low (<1st quartile mean); green: Low (>1st, <2nd quartile means); yellow: Medium (>2nd, <3rd quartile means); light orange: High (>3rd, <4th quartile means); dark orange: Very High (>4th quartile mean); red: Extremely High (>95th percentile). LPS, large polyped stony; SPS, small polyped stony.

(6), soft corals (4), snails and slugs (4), hermit crabs (3), shrimp (2), crabs and lobsters (1), star polyps (1), mushroom corals (1), sponges (1), fan worms (1), and gorgonians (1)] have risk ratios defined as Extremely High (table S3).

Although 39 species/genera emerged with Very High risk ratios or above, management investment limitations in exporting countries necessitate greater prioritization, e.g., those in the Extremely High risk ratio. Of the fish species, the Armitage angelfish (*A. armitagei*) and Yellowband wrasse (*Cirrhilabrus luteovittatus*) are of very low popularity, but with severely restricted ranges (8.5×10^3 km^2 and 3.5×10^4 km^2, respectively). The canary blenny (*Meiacanthus oualanensis*), pearlscale butterflyfish (*Chaetodon xanthurus*), and orchid dottyback (*Pseudochromis fridmani*) have larger ranges but are also much more popular generating risk ratios of 0.376, −0.282, and −0.347, respectively. Finally, even with a larger calculated geographic range (3.3×10^6 km^2), the Banggai cardinalfish's (*Pterapogon kauderni*) high popularity (1.28×10^6 traded per annum, excluding chain-of-custody losses) generates a high risk ratio (−0.410).

Records of MAT species were spread across 24 LMEs and 50 ecoregions (Fig. 3). While the highest exploitation level scores for LMEs and ecoregions align closely with the global tropical coral reef distribution (gray shading), traded species' distributions still extend into areas without this habitat, e.g., a low exploitation level for the west coast of Africa (28, 29) LMEs (table S5).

For those LMEs containing coral reefs, the Sulu-Celebes (37) and Indonesian (38) seas are placed in the Very High exploitation level, while Fiji (147), the Seychelles (96), New Caledonia (149), The Mascerne Islands (98), and The Eastern Galapagos (173) are the five Very High exploitation level ecoregions. Figure 3 also shows (for LMEs only) that higher exploitation levels generally align with higher integrated local threat index (ILTI) threat scores (e.g., within the coral triangle), supported by a positive, though not statistically significant, correlation between total number of organisms traded per km^2 and ILTI scores ($R = 0.292$, $P = 0.2$).

DISCUSSION

Numbers, biomass, and value

Our study has generated the first global estimate of the number of MAT-traded organisms, positioning the MAT firmly alongside (or above) globally important fisheries, e.g., tuna. This estimate is substantially higher than previous studies reflecting chain-of-custody loss omission (all studies), old data [e.g., (*12*)], and analysis of only a proportion of the trade [e.g., (*6*, *8*, *12*)]. However, our assessment is likely to be conservative as, although we have accounted for country-specific variability in hobby popularity (*20*), the calculations exclude countries with an HDI score of <0.8 but have increasing disposable income levels (e.g., China).

Including cumulative chain-of-custody losses is controversial, yet the ratio is based on the only recent, scientifically robust data available. Mortality and rejection levels are species-specific and modulated by country/business, but that 86 organisms could die for 100 to be displayed in a retailer is highly concerning. Transparent and unbiased data collection is, therefore, urgently needed to generate accurate species/group data. Industry training (e.g., the vast majority of the recorded rejection/mortality occurs at the point of collection and in the exporter's holding facility; see table S4) and shorter supply chains will also be critical for increasing sustainability.

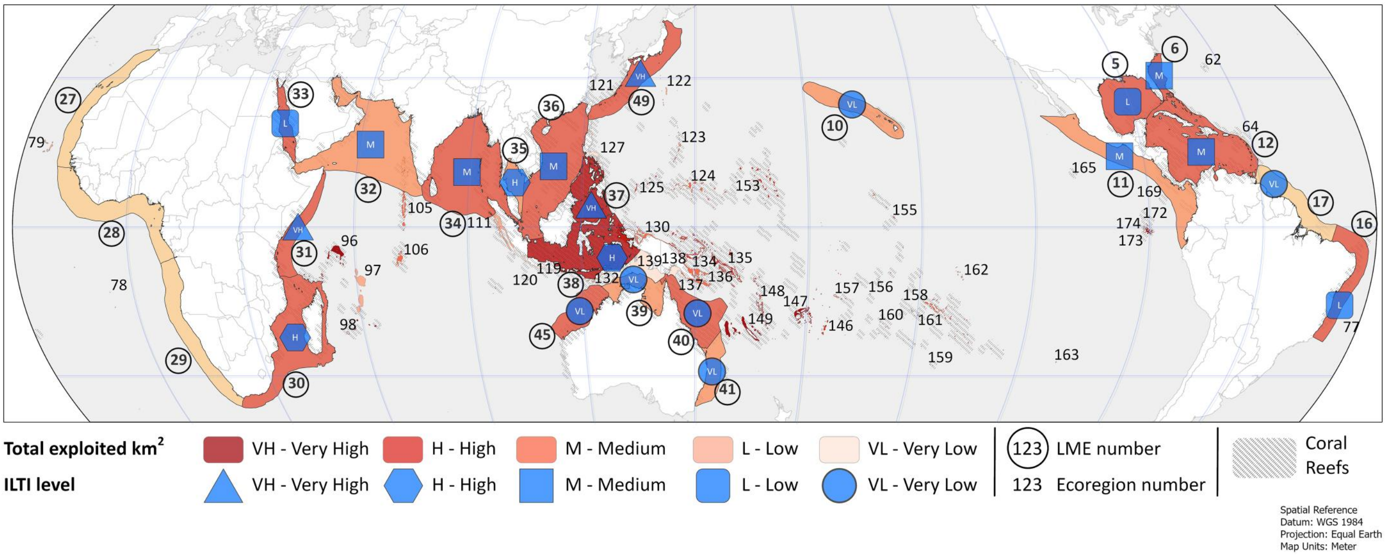

Fig. 3. Relative exploitation of LMEs and ecoregions by the MAT. Total number of organisms traded per km^2 per ecoregion and LME (red shading) organized as a relative five-stage exploitation scale of tropical and majority-tropical LMEs and ecoregions (numbers are as denoted in sources). Very low: <1st quartile mean; low: >1st, <2nd quartile means; medium: >2nd, <3rd quartile means; high: >3rd, <4th quartile means; very high: >4th quartile mean. Tropical coral reef distribution (gray hatched) and integrated local threat index (ILTI) scores (blue shapes) for LMEs that contain coral reefs from (*51*) are overlaid on base data and layers for reef distributions, ecoregions, and LMEs (*60*–*62*).

The MAT's broad focus on diversity (210 invertebrates, 296 fish) is unique among global fisheries; however, 506 different species/genera are substantially fewer than other assessments [e.g., (*9*)], which warrants further consideration. Some species in the list of Rhyne *et al.* (*9*) would not be a MAT target unless for special circumstances, e.g., public aquariums. We only recorded the genus name for invertebrates, whereas Rhyne *et al.* (*9*) listed all species within a genus. The detailed species analysis also confirms the MAT is dominated by relatively few species of invertebrates, although the exact ranking varies [see (*9*–*11*, *20*)] due to country-specific demand and supply chains. Finally, as our study confirms the dominance of invertebrates by number traded and value, fish-only assessments will severely underestimate the MAT (*21*).

The 13,300 tons extracted each year is only a fraction of the global marine biomass removed by capture (*18*) and much lower than those food species compared here. Nevertheless, it may be an even lower value as most fish observed in aquarium retailers by Pinnegar and Murray (*11*) were sub-adult sizes. Regardless of the low biomass, the combined fish and invertebrate PoFS confirms a high value to coastal communities, substantially greater than many "blue-food" coral reef fisheries (*22*). Most striking is the inflation to retail, distancing the MAT from many major global marine fisheries [Fig. 1 and (*18*)]. For example, the MAT (excluding chain-of-custody losses) is only ~7× less valuable than the world's yellowfin tuna (*T. albacares*) catch. The marked increase from PoFS to retail value (41×) reflects freight and life support costs across an extended global chain of custody. Nevertheless, the large MAT value at local, regional, and national scales can provide the financial leverage for future governance to protect coastal community livelihoods.

At a time of unprecedented coral reef decline, it is vital to evaluate the MAT's contribution, with overfishing the most obvious barrier to sustainability. Our data show that traded numbers vary dramatically by species, with no clear relationship between MAT popularity and geographic range. Although limited by distribution data in GBIF, a premium on diversity (*6*, *9*) could risk overexploitation. Our quantile analysis identified 39 species/genera with Very High risk ratios or above, although we recommend Extremely High risk ratio prioritization. That most are invertebrates reaffirms the need to include all MAT-targeted species, while the presence of lower trophic species reflects high demand for cheap "clean-up crew," i.e., those that perform ecological functions (*8*). Of the six fish species, only the Banggai cardinalfish (*P. kauderni*) has been assessed previously at the global level (*16*, *23*). This species' high risk ratio reaffirms it as a clear priority for MAT management (*16*), aligning with its endangered IUCN red list status (table S3). Distribution surveys (*24*), the next step in data-limited management frameworks (*25*), confirmed only a 34-km^2 area of occupancy, which if incorporated here would generate an even higher risk ratio, reinforcing the need for management already implemented/planned.

Our approach is a first critical step in holistic data-limited fisheries management, confirming key species vulnerable to collection requiring precautionary controls and/or stock analyses. Extremely High risk ratio species highlight the need for stronger internationally coordinated management, long recognized for tuna (e.g., via Regional Fisheries Management Organisations). Nevertheless, over 300 MAT species are at Medium or lower risk and a number of the Extremely High risk ratio species are aquacultured (*26*), which would need to be incorporated into any management assessment (*13*).

Identifying priority reefs

As MAT exploitation is organized (and governed) at regional/national scales (*9*), spatial exploitation risk comparisons are essential to allocate limited resources. Records of collected MAT species covering 4.26×10^7 km^2 (~12% of the world's sea surface) confirm an industry that is truly global. Unsurprisingly, the highest exploitation level scores for LMEs and ecoregions align closely with the tropical coral reef distribution, yet traded species' distributions still extend into other areas. This is partially explained by the inclusion of all species within a genus in the distribution calculations. However, MAT management should not discount nonreef areas due to the high trade numbers of species from other habitats (*27*), the targeting of nontropical species (*28*), and tropical reef species invading warm temperate systems (*29*).

The Indonesian and Sulu-Celebes Seas LMEs in the Very High exploitation level are linked to dominant exports by the Philippines and Indonesia (*9*). Of the five Very High exploitation level ecoregions, only Fiji has notable MAT exports, while the Seychelles, New Caledonia, The Mascerne Islands, and The Eastern Galapagos would not be routinely thought of as having important MAT fisheries (*9*). This will be an artifact of allocating the numbers traded for a cosmopolitan species/genus equally across all LMEs and ecoregions. However, our data should also stimulate industry-led discussions to ascertain local fidelity especially as the data of Rhyne *et al.* (*9*) are outdated.

LMEs and ecoregions with the highest exploitation levels (Fig. 3 and table S5) are clear priorities for international and national jurisdictional MAT management. Figure 3 and the weak positive correlation also show (for LMEs only) that higher exploitation levels generally align with higher ILTI scores, confirming that the MAT is just one of many local pressures on reefs. Robust mitigation must be implemented to reduce local threats; however, we posit that the MAT's financial leverage can, with appropriate management, generate rapid positive feedback loops to support these broader interventions.

The future

The MAT finds itself at a critical crossroads with near-future governance decisions having profound implications for the most vulnerable coastal communities, industry, hobbyists, and, ultimately, the MAT's ability to become a global exemplar of sustainable reef fisheries. Two future MAT trajectories are presented in Fig. 4: a business-as-usual and alternate MAT-positive scenario incorporating divergent projections for proportions of cultured organisms, climate change–induced reef degradation, and, crucially, MAT-coastal community connections.

The absence of hobbyist data has resulted in a widely held view of a niche hobby. However, based on the U.S. pet industry's consumer surveys (*30*) of households keeping saltwater and/or freshwater fish and the summed human population of HDI $\geq$0.8 countries, we estimate that there are currently 6.7×10^6 hobbyists, reducing to 4.1×10^6 using the $\geq$0.9 HDI threshold (table S6). Aquacultured species dominate the freshwater sector (*31*), but the proportion of cultured MAT-traded organisms is currently unknown. Our data identify that 139 species/genera have been cultured (table S3), but it would be a great overestimation to assume that all traded individuals for these species are currently cultured. We, therefore, used the "industry standard" (*32*) 90% baseline of MAT organisms being captured. Despite the fact that 30% of coral reefs are now at risk of long-term degradation (*33*), the MAT's present-day reliance on coral reefs generates a strong connection (Fig. 4: Venn diagram overlap) via coastal communities, with considerable value (Fig. 1) flowing from the reef. By 2030, we predict hobbyist numbers of 1.7×10^7 driven by human population growth and 92 countries achieving an HDI of $\geq$0.8. Yet, in both scenarios, 68 to 72% of reefs will be at risk from long-term degradation. Aquaculture production expansion is predicated on technology transfer across species (*34*). If all species with some culture records become fully commercialized, then 60% of organisms would be cultured worth 73% of the PoFS and retail value. For both scenarios, the move to aquaculture production (assuming that most culture is ex situ, i.e., occurs away from exporting country coastal areas) and the increase in coral reef degradation will weaken the MAT-community-reef connection. The year 2050 sees scenario divergence despite continued hobbyist number increases (3.1×10^7). Under the business-as-usual scenario, 98% of coral reefs are subject to long-term degradation (100% if ocean acidification/aragonite interactions are included). A 4% increase in the proportion of cultured MAT organisms leads to a further decline in the capture income/value (to 23%) and erosion of the MAT-community-reef connection. By 2100, all reefs are predicted to suffer long-term degradation. The projected increased demand (4.5×10^7 hobbyists) will be supported by culture (78% of organisms) worth >90% of the PoFS and retail value. Consequently, within approximately one generation, business as usual will almost decouple the MAT (and coastal communities) from the supporting reefs. We forecast that this will lead to considerable reductions in the species diversity available as culture focuses on the most popular (*19*). In this future, the MAT will mirror the freshwater trade (*31*), resulting in little involvement from coastal communities, thus preventing MAT-driven positive feedback loops, stifling economic uplift, and ultimately reducing the hobby's popularity. It may even enhance the degradation of reefs as the coastal communities involved in the MAT move to other activities that affect the reef (e.g., destructive food fishing).

The MAT-positive scenario is fundamentally predicated on society meeting emission targets. Constraining the mean global temperature increase to 1.5°C will lead to a small stabilization of reef loss/degradation, but recovery requires coral thermal adaptation. While capacity may exist for rapid acclimatization, it is unclear how many species could adapt (*35*). Reef systems dominated by thermally tolerant species will bolster the connection, but are still likely to reduce available diversity.

Currently, low international MAT governance capacity is widely accepted and this will continue under the business-as-usual scenario without systemic change. If society moves to net zero, reef recovery via thermal adaption will enable coastal communities to reverse the weakening connection by rapidly increasing the proportion of sustainably managed MAT fisheries and investing in local aquaculture, estimated to be ~20% of targeted species/genera by 2050 (Fig. 4). This integration underpinned by increasing MAT governance will maximize conservation and sustainable exploitation benefits, for example, linking the MAT to nature-based solution programs.

In addition, unlike more nascent approaches purported to drive habitat restoration such as blue carbon initiatives (*36*) or innovative insurance of natural assets, benefits could be rapidly realized as the MAT's global infrastructure and market are fully mature. Some, such as Militz *et al.* (*37*), also now suggest reviving a sustainable certification system. Certification will require solving traceability and fidelity issues (*38*), active governance (e.g., an internationally focused management organization), evidence-based management for those at-risk species highlighted here, industry buy-in, consumer education, and the incentivization of sustainable practices [see

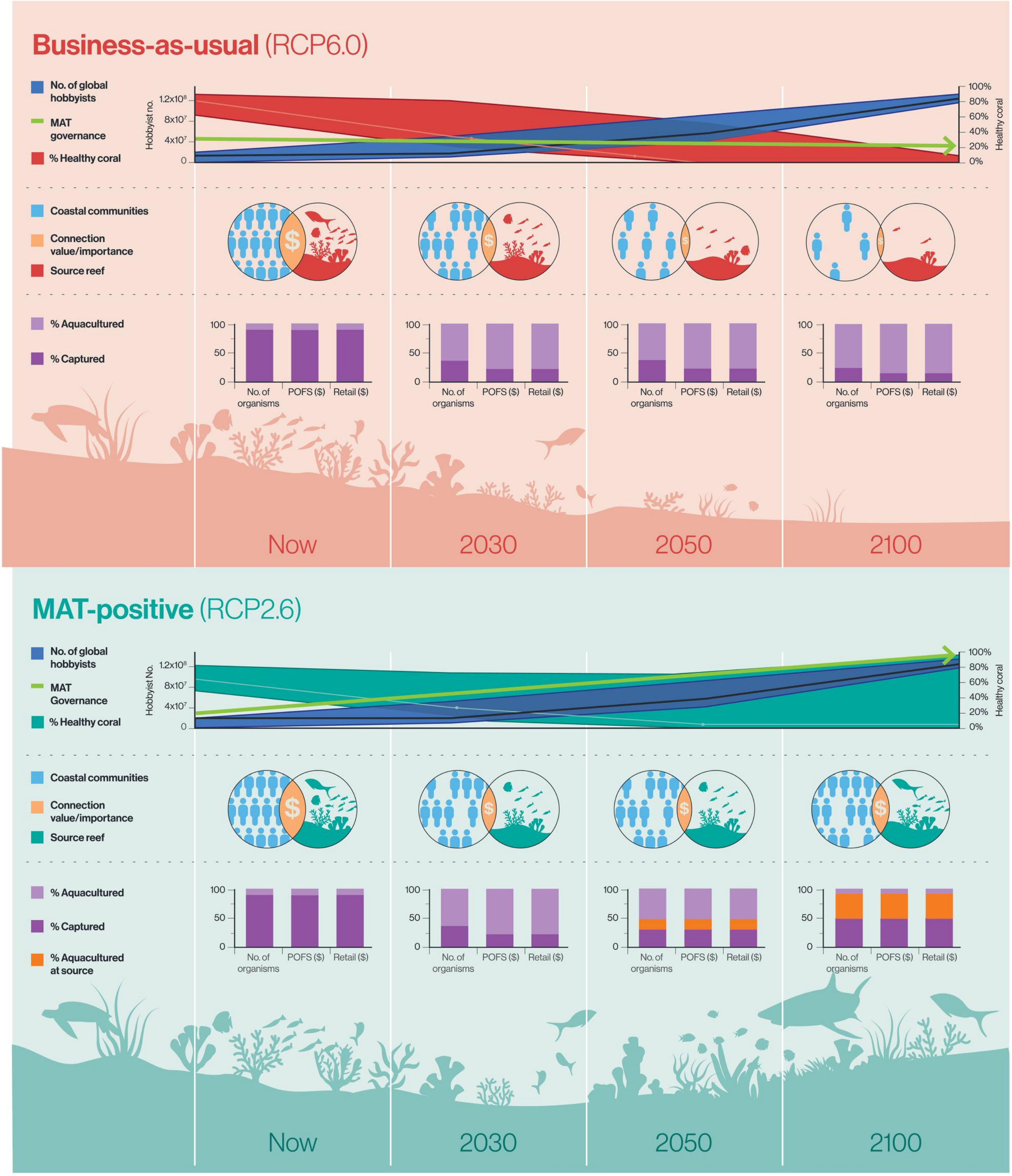

Fig. 4. Alternate futures for the global MAT. Business-as-usual and MAT-positive futures. Healthy (%) coral reef predictions (white line (mean) bounded by red/green) are from (*33*) with upper (coral thermal adaptation) and lower (ocean acidification/aragonite interactions) boundaries. Global hobbyist numbers (blue) for summed countries achieving HDI of ≥0.8 (upper boundary), ≥0.9 (mid-line), and ≥0.95 (lower boundary) incorporating human population increases. Proportions of cultured/captured MAT organisms are based on technology transfer for each time point using the current 90% (*32*) capture estimate and used to calculate value (PoFS and retail). Culture at source of collection by coastal communities is estimated to be 20% in 2050 and 40% by 2100. Strength (i.e., $ value) of connection between coral reef and coastal community of Venn diagram is indicated by size of overlap. Reef health and coastal community prosperity/MAT involvement are depicted within each circle's area. Increasing MAT governance (green line) in the MAT-positive scenario will support sustainable fishery transitions.

(*21*) for possible approaches]. Nevertheless, unlike many other blue-food coral fisheries (*5*), we have shown that the MAT's global value provides considerable fiscal leverage for protecting those communities already most at risk from a business-as-usual future. A MAT-positive future is imaginable, but requires substantial investment from all actors to ensure that the MAT becomes a "force-for-good" and paradigm of sustainable coral reef fisheries.

MATERIALS AND METHODS

Numbers, biomass, and value

Commercially sensitive industry data combined with the complexities of a multi-stage chain of custody required a "top-down" approach using retailer surveys (17 for fish and 20 for invertebrates) to generate monthly livestock (excludes live rock) sales for global scaling (University of Portsmouth Science Faculty Ethical Review Committee, SFEC 2018-019). Informed consent was obtained from all participants before survey initiation. To account for country-specific variability in hobby popularity (*20*), we collected retailer data from three dominant importing countries. Google searches (2020–2022) identified national retailer numbers for the United Kingdom (560) and Italy (528), which were multiplied by the proportion (0.77: United Kingdom, 0.72: Italy) selling marine livestock. These countries were ranked first and fourth in Europe for the number of imported fish (*20*). However, we also included the 272 saltwater retailers identified by Morcom *et al.* (*39*) from a survey of 12 northeast American states (21% of the U.S. population; the largest MAT market) (*9*). Retailer numbers were then divided by the country's human population to generate a mean "retailer/person" ratio (5.63×10^{-6}) for scaling. Despite technological advances, aquarium life-support costs are still substantial, with Rhyne and Tlusty (*40*) even giving the marine aquarium hobby "luxury" status. Therefore, people with a relatively high disposable income are expected to be most able to afford aquariums and, by extension, developed countries will have more hobbyists. A strong and highly significant correlation ($R = 0.88$, $P < 0.001$) between a country's human population and MAT import value from (*20*) further supports the global scale up for the number of retailers: applying the retailer/person ratio to all countries with a high (≥0.8) HDI score equating to "developed" status (*15*).

To enable direct comparisons (MAT organisms are sold as individuals, while food fisheries trade by weight), numbers were converted to biomass using individual weights collated from multiple sources (see table S1). Mean PoFS and retail price per species (US$, 2018–2021) were obtained from Philippine fishermen (*41*) and retailer stock lists (table S2), respectively, with ratios per species/group generated from the two prices to fill gaps. PoFS values can be globally scaled, as Rhyne *et al.* (*9*) states that the Philippines exports >50% of the fish to the United States (the largest MAT importer) and is, therefore, the largest exporting country, and the Philippines' HDI score is similar to many other major exporters so that fisher costs and profits will be equivalent. Mean prices per species/genus were then multiplied by the mean retailer sales at the global scale (table S3). To compare to blue foods (e.g., selected tuna and tropical invertebrate fisheries; table S3), the numbers of organisms captured per annum were calculated by multiplying extracted biomass by mean fished weight (*18*) with prices (PoFS and retail) retrieved from the literature and adjusted for 2018–2021 as required (table S2).

Although many studies have evaluated MAT chain-of-custody mortality, data quality is highly variable. We, therefore, only selected recent, scientifically rigorous/relevant assessments leaving Turner (*42*) and Militz *et al.* (*43*, *44*). These generated cumulative rejection (we assume that organisms are not returned to the reef) and mortality losses from collection, transport from collection to aquarium holding facility in exporting country, holding in aquarium exporting country wholesaler, international transport, and holding in importing country wholesaler aquariums (assuming that organisms are kept for 1 week before being sold to retailers).

Geographical range

Wherever taxonomic groups' data were presented at the genus level, the genus was inputted into World Register of Marine Species (WoRMS; https://www.marinespecies.org/) and filters were applied to include only extant, accepted species names. Each species' geographical range (km^2) (table S3) was estimated using the Global Biodiversity Information Facility (GBIF; https://www.gbif.org) map overview, which presents georeferenced species records. A species/genus' presence or absence (all species combined for a genus) within the 66 LMEs was recorded. The total range (km^2) was calculated by summing LME areas (https://iwlearn.net/marine) with a positive presence record. As species' geographical data points did not always correspond to an LME (e.g., Pacific islands have most of their area outside an LME), the ecoregion was recorded using Spalding *et al.* (*45*) and ecoregion dimensions were extracted. Ranges for blood cockle (*T. granosa*) and green mussel (*Perna virdis*) were calculated as above; however, as the four tuna species records extended beyond the LMEs and ecoregions, these additional areas were delineated in ArcGIS, converted to km^2, and then added to positive records for LMEs and ecoregions (data in table S3).

Identifying priority species and regions

Among closely related/ecologically similar species, spatial distribution is positively correlated with average abundance (local density) (*46*), holding true for many exploited species [see Fisher and Frank (*47*)] and influencing a species' susceptibility to extinction (*48*). Using extent of species occurrence, see Gaston (*49*) for definition, as a proxy for population size, we correlated geographic distributions generated for each genus/species with numbers traded. Risk ratios (numbers traded divided by distribution) for each species/genus were $\log_{10}$-transformed before using the modified quantile method (*50*) to calculate a six-point priority risk level (table S3).

Fisheries catch data are routinely organized by geographic area [e.g., Food and Agriculture Organization of the United Nations (FAO) major fishing areas and International Council for the Exploitation of the Sea (ICES) ecoregions] to assess stock exploitation. However, missing MAT data required a different approach to identify priority areas for future regional governance interventions. Presence/absence records per species/genera for each tropical ecoregion and LME, including LMEs that have a majority overlap with a tropical realm (*45*), were computed and summed, generating a measure of total range (km^2). This was then divided by the total number of organisms traded generating the value X, and replicated in every LME and ecoregion where that species/genus was recorded. To account for diverse numbers of species targeted per LME/ecoregion, we then summed X for all species in each LME/ecoregion to generate the value Y, the total number of organisms traded per km^2

per ecoregion or LME (table S5). A five-stage exploitation scale (*50*) for *Y* was then calculated. To relate MAT exploitation risk to local threats, we overlaid the ILTI developed by McOwen *et al.* (*51*) for LMEs containing coral reefs. Briefly, for each local threat, sources of stress that could be mapped were combined into a proxy indicator that reflects the degree of threat. Distance-based rules were then developed, with threat declining as distance from stressor increases. Thresholds for "Low," "Medium," "High," and "Highest" threats were developed using information on observed impacts of threats to coral reefs. Four calculated local threats—coastal development, watershed-based pollution, marine-based pollution and damage, and overfishing and destructive fishing—were combined to obtain a single broad measure of threat and represent the cumulative impact of these threats on coral reefs. For each LME, the percentage of coral reef area under each of the four Reefs at Risk threat categories (Low, Medium, High, and Highest) was calculated (threat percent). This percentage was then multiplied by a weighting factor, depending on the threat level (Low = threat percent ×1; Medium = threat percent ×2; High = threat percent ×3; Highest = threat percent ×4). The overall ILTI score was then calculated by summing the values for each threat score.

Aquaculture potential and MAT futures

Using Murray and Watson (*26*), The Marine Breeders Initiative (*52*) and the wider literature all species/genera were assigned to one of three categories: (i) no record of culture; (ii) some culture records, but not commercially produced; or (iii) cultured specimens frequently available (table S3). Future technology transfer scenarios were aligned with three time points for becoming commercially available: 2030, species with some culture records (ii) become (iii); 2050, all species in a cultured species' genus become (iii); 2100, all species in a cultured species' family become (iii) (table S3). Technology transfer assumes that similar aquaculture techniques/experience can be applied to closely related species to more quickly overcome bottlenecks and bring a species to market. This is based on that (i) broad reproductive strategies of reef fish tend to be evolutionarily conserved at the family level (*53*) and (ii) marine invertebrate life histories covary strongly with temperature and latitude (*54*); thus, tropical species are more likely to share similar life histories. To calculate the aquaculture-generated proportion of (i) organisms traded, (ii) PoFS value, and (iii) retail value, we assumed that, if commercially available, 100% of the traded individuals would be cultured. The future proportion of species/genera that could be cultured at collection source by coastal communities was based on Murray and Watson (*26*). Each species/genus was assessed for simple culture (e.g., asexual reproduction) method potential, thus aligning with cheap and scalable technologies in local communities.

Country-specific human population data (*55*) were paired with HDI scores (*56*), with 188 countries remaining after excluding unmatched countries (table S6). Future projections (2030, 2050, 2100) of a country's population were then extracted directly from the yearly data. As HDI scores are only available between 1990 and 2019, we fitted linear trend models (Minitab V17) to generate an HDI score per future time point for each country. Predicted human populations for countries with HDIs of ≥0.8, (i.e., developed) per time point were then summed. However, including countries at ≥0.9 and ≥0.95 HDI thresholds accounted for a more limited understanding of the link between hobbyist numbers and a country's HDI.

Despite the decades of research on the MAT, global hobbyist numbers (the key trade driver) have never been estimated. Using biennial (1990–2016) plus 2021 pet ownership data from the American Pet Products survey (*30*) combined with (*57*), we calculate that 0.91% of U.S. households keep saltwater fish. Dividing the U.S. 2019 population (3.29×10^8) by 2.11 (mean number of people per household for the United States and 15 European countries) (*58*) before multiplying it by 0.91% generates an equivalent of 0.43% of the U.S. population that are marine hobbyists. This was then applied to every country, achieving ≥0.8, ≥0.9, and ≥0.95 HDI per time point with the country populations for each HDI group summed to give a high, mid, and low hobbyist population estimate, respectively (table S6).

To align coral reef degradation with the future time points, we used predictions from Frieler *et al.* (*33*) of coral reef cells at risk from bleaching under different representative concentration scenarios (RCPs) (*59*). For a MAT-positive future, we used RCP2.6, a strong mitigation scenario with a global mean temperature increasing by 1° to 2°C by 2050 and 490 ppm (parts per million) peak CO_2 concentrations, while RCP6.0 (high-emission rate scenario, but where total radiative forcing stabilizes after 2100 plus 850 ppm CO_2) represented business as usual. An optimistic coral thermal adaptation projection and a more severe degradation projection (decreasing aragonite-saturation levels driven by ocean acidification) provided upper/lower boundaries. (These projections do not account for impacts caused by local reef stressors.)

Supplementary Materials

This PDF file includes:
Fig. S1
Table S4
Legends for tables S1 to S3 and tables S5 and S6
References

Other Supplementary Material for this manuscript includes the following:
Tables S1 to S3, tables S5 and S6

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Acknowledgments: We thank M. Hill, M. Anfield, J. MacKeller, M. Martin, D. McMannus, R. Thayre, and S. Williams for their help with data collection, especially C. Seid (Scripps Institution of Oceanography) for biomass support and L. Carbone (American Pet Products Association) for supplying survey data. The project would not have been possible without the survey responders. We also thank the Creative Alliance team for help with Fig. 4 and L. Peck and S. Cragg for insightful comments on the manuscript. **Funding:** The authors acknowledge that they received no funding in support of this research. **Author contributions:** G.J.W.: Conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualization, writing—original draft, and writing—review and editing. S.K.: Data curation, formal analysis, investigation, methodology, and validation. J.-J.C.: Data curation, formal analysis, and investigation. J.R.: Formal analysis and visualization. D.A.: Data curation and investigation. C.C.: Data curation and investigation. M.S.: Visualization. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials.

Submitted 7 March 2023
Accepted 7 November 2023
Published 6 December 2023
10.1126/sciadv.adh4942

Science Advances

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Sci. Adv. **9** (49), eadh4942. DOI: 10.1126/sciadv.adh4942