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Catching Dory: selling aquarium fish supports coastal livelihoods in Indonesia

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The global marine aquarium trade has created new local markets across the planet, including in Indonesia, now the second-largest exporting country of marine aquarium fish in the world. Participating in the global aquarium trade has been touted as a potentially sustainable addition to fisher livelihoods, but scant data exist showing the numbers of fish coming off the reef and how those fish contribute to income. To determine how participants in the trade incorporate aquarium species in their livelihoods, we examine source-level aquarium fish collecting and trading data in the Banggai Archipelago, a region in Central Sulawesi that has become a significant source for popular aquarium, also known as ornamental, fish species. Using a sustainable livelihoods lens, we examine this data to understand how participants in the aquarium trade both contribute to as well as benefit from the trade and consider how their participation relates to emerging Blue Justice principles. From one year of buying and selling data at the fisher, intermediary buyer, and regional trader levels, we show that catching and selling fish for the aquarium trade represents an average of nearly 20% of their gross annual income and provides added diversity and flexibility to fisher and trader livelihoods in the region, especially during seasons of rough weather. We suggest that managers of an impending marine protected area in the region would do well to consider how to sustain these livelihood benefits.

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INTRODUCTION

Keeping aquarium fish, one of the world's most popular hobbies, is supported by a global trade that moves more live animals across the planet per year than any other industry[1,2]. The trade involves more than 2 million people, from collectors at source sites in export countries, to public aquaria and hobbyists with home tanks in import countries[1,3]. Generating an estimated $15–20 billion in revenue per year[1], this industry has created a constellation of local markets across the globe, often in remote rural, coastal, and island communities.

Due to the dispersed nature of the aquarium trade that often creates opaque supply chains, it is not well-quantified or regulated[4]. This is especially true in the marine aquarium trade (MAT), which involves over 2300 different marine species[5]. Although freshwater aquarium species are mostly captive-reared, marine fish have complex breeding cycles and larval development, which make them difficult to culture, and so are primarily wild-caught[6–9].

Catching fish from tropical coral reefs around the globe[6,10–12], small-scale fishers have been the primary procurers of marine aquarium, or ornamental, species[6,13], this is especially true in the Indo-Western Pacific[4,13,14]. These individuals who participate in the sourcing side of the trade, are an oft-overlooked part of a larger global population working in small-scale fisheries, which employ over 100 million people[15]—more than the other largest ocean sectors combined[16–18].

Over the past two decades, the importance of small-scale fisheries has been increasingly acknowledged through growing attention from researchers[15,16,19] as well as national and international non-governmental organizations (NGOs) and government agencies[20]. With this increased attention, a "Blue Justice" focus has emerged that calls for formally recognizing the rights and economic contributions of small-scale fishers[21,22]. This focus is evidenced at the international level by Sustainable Development Goal 14, which addresses ocean conservation and includes language describing the need to protect the rights and livelihoods of fishers and fishworkers[20].

However, relatively little is known about small-scale fisher livelihoods generally[23], and especially those involved in the MAT[6,24], making it difficult to document their economic contributions and distinct lifeways to help realize Blue Justice principles. This lack of knowledge regarding small-scale fisher livelihoods occurs in part because small-scale fisheries are diverse and decentralized[16,25,26]. Moreover, they often operate in informal spaces beyond the reach of government monitoring and oversight[27]. This opacity increases when small-scale fishers employ illegal fishing methods that require discretion, like using cyanide to stun and catch aquarium fish for the MAT.

These factors, among others, have led to the current state of the MAT in which, although some comprehensive data sets are available at the export/import level (see Rhyne et al.[5]), few data are available quantifying the "ground zero" harvesting level[4]. These source-level data are critical to better managing the MAT[4] in two ways: 1) to better understand the number of fish taken off reefs, as export numbers do not include domestic trade or mortality prior to leaving the source country; and 2) to understand the trade's contribution to small-scale fisher and buyer livelihoods and well-being.

We address this knowledge gap by examining source-level catch and trade data from the Republic of Indonesia. In addition to being the second largest exporter of marine aquarium fish[5], Indonesia is part of Asia where, despite being home to the largest

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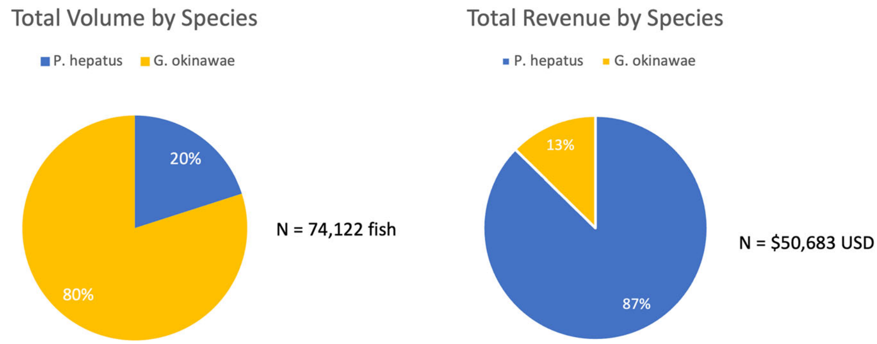

Fig. 1 Comparing total volume and revenue of fish sold by species. The two charts compare total volume of fish traded by species on left versus total revenue by species on right. While the yellow goby (*G. okinawae*) constitutes the majority of the fish traded, the blue tang (*P. hepatus*) constitutes the majority of the revenue.

number of small-scale fishers in the world, the human dimensions as well as community and ecosystem ecology of small-scale fisheries are understudied[28]. Indonesia also has the fourth-largest population in the world, including numerous under-resourced communities that target marine aquarium species[6,29]. Within Indonesia, we examine the MAT in the Banggai Archipelago, in the province of Central Sulawesi. This archipelago is one of several groups of small islands in the seas around Sulawesi, the fourth largest island in Indonesia[30]. Even some of the most comprehensive and recent data on the MAT in Indonesia lack data from Central Sulawesi (cf., Akmal et al.[8]). This paucity of MAT information exists though the Banggai archipelago is at the heart of the Wallacea and Coral Triangle biodiversity hotspots[31] and is a known source for the MAT[32].

The data we present are timely, as a newly legislated marine protected area (MPA) in the region may affect the livelihoods of fishers who target marine aquarium fish once the MPA becomes operational. This impending MPA may infringe on the rights of fishers and fish workers participating in the MAT in this region, as outlined by specific formulations of "Blue Justice" that focus on aspects of spatial justice[33] like dispossession and displacement[34], as well as lost access to marine resources needed to support well-being[34].

We examine the data using a social-ecological systems framework[35,36] and applying a sustainable livelihoods lens[37,38] that seeks to understand ways in which fishers build resilience to the uncertain ecological, economic, and political disturbances they often face[39]. Drawing on this theory and relating it to the emergent concept of Blue Justice, we ask whether and how fishers and fishworkers in the Banggai Archipelago contribute to the global MAT, as well as the inverse: whether and how does the trade contribute to their livelihoods and broader well-being?

RESULTS

Size and structure of the fishery

Fish species traded and fishing methods. A total of 74,122 individual fish were caught and traded across 1042 distinct transactions during the period of data collection spanning October 2018 to October 2019. Considering that total marine aquarium fish exports from Indonesia in 2018 were estimated at 2.61 million individuals[40], our findings represent nearly 3% (~2.84%) of total Indonesian exports. The aquarium fish species primarily traded included blue tang (*Paracanthurus hepatus*), comprising 20% of the fish traded (14,852 individuals) and yellow goby (*Gobiodon okinawae*), comprising 80% of the fish traded (59,270 individuals). Nine Napoleon wrasse (*Cheilinus undulatus*) were also traded but we exclude them from the totals due to their small numbers. Because blue tangs have a higher value, fish of that species comprised 87% of total revenue, whereas the yellow goby (higher in overall number in this sample) only comprised 13% of total revenue (see Fig. 1). Prior to the collection of the data used in this study, researchers and conservationists working in the region were unaware that the lower value, but more abundant and easily caught, yellow goby was being sold from the area[41]. Respondents recorded all blue tang as being caught by a small net, although participant observation and interviews revealed that the use of cyanide, referred to locally as "potas," or another neurotoxin, referred to as "bius," was frequently used to stun the fish to make them easier to catch. Whereas respondents reported that yellow goby were caught using a scoop net with a handle called a "serok" without the aid of neurotoxins. Additionally, spearfishers, who had hookah and compressor diving equipment, would often collect blue tang incidentally, when they spotted them while out fishing for other target species (e.g., octopus, squid, snapper, grouper), only occasionally making trips to target them; whereas, fishers nearly always made trips specifically to collect yellow goby.

Fisher-buyer-trader network. We identified a network of fishers, buyers, and traders that included 111 people (see Figs. 2 and 3 below), of whom 108 resided in the source village. These people involved in the aquarium trade represent 5.8% of the source village population, which was 1855 individuals according to official statistics[42] and an estimated 29% of households using an average of five people per household[43]. The network includes a total of 98 individual fishers who caught and sold fish; 9 intermediary buyers, who purchased fish from individual fishers and then sold the fish to regional traders; and four regional traders who bought both directly from fishers and from intermediary buyers. This network underestimates the number of total fishers involved in the trade, as presumably the buyers who sell to Trader 2 whose data we did not collect, are purchasing fish from individual fishers, and we were unable to collect data from Traders 3 and 4.

In addition to showing the general structure of the aquarium trade network (see explanation of Figs. 2 and 3 in captions below), our Social Network Analysis (SNA) also revealed a wide range of catching, buying, and selling frequency across fishery participants. The four respondents bought and sold fish frequently, with Trader 1 and Trader 2 buying or selling fish an average of every 2.6 days, Buyer 1 every 1.8 days, and Buyer 2 every 1.5 days. Numerous fishers also participated frequently, as denoted by the thicker ties in the SNA figures, with F02 having the most transactions at 70, and 37 of 98 fishers only catching and selling once. However, it could be that those fishers were regularly harvesting and selling to Traders 3 and 4, whose data we were unable to collect, but to whom author S.S.S observed fishers selling aquarium fish. On average, fishers caught and sold aquarium fish ten times during the year of data. The variety in node size shows a wide range of gross income earned, discussed further below. We conducted

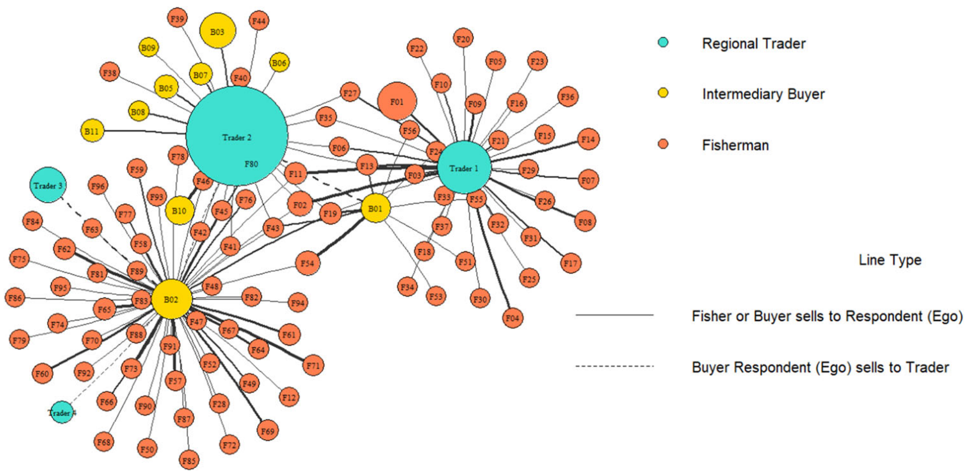

Fig. 2 Social Network Analaysis (SNA) showing trade structure, relative revenue share, & frequency of transactions in the fisher-buyer-trader network in Banggai. The "egos," or central nodes in the network, are the respondents: B01, B02, Trader 1, and Trader 2. The ties or "edges" between the individuals in the network are weighted by the number of times each alter interacted with an ego. Thus, the more transactions between two nodes, the thicker the tie. All solid lines represent transactions incoming to the ego (i.e., buying), and the few dotted lines represent transactions outgoing from the ego (i.e., when buyer ego B01 or B02 sold to a trader). The size of each node visually represents how much total revenue each participant earned compared to others in the network. This figure uses the same scale for all nodes in the network.

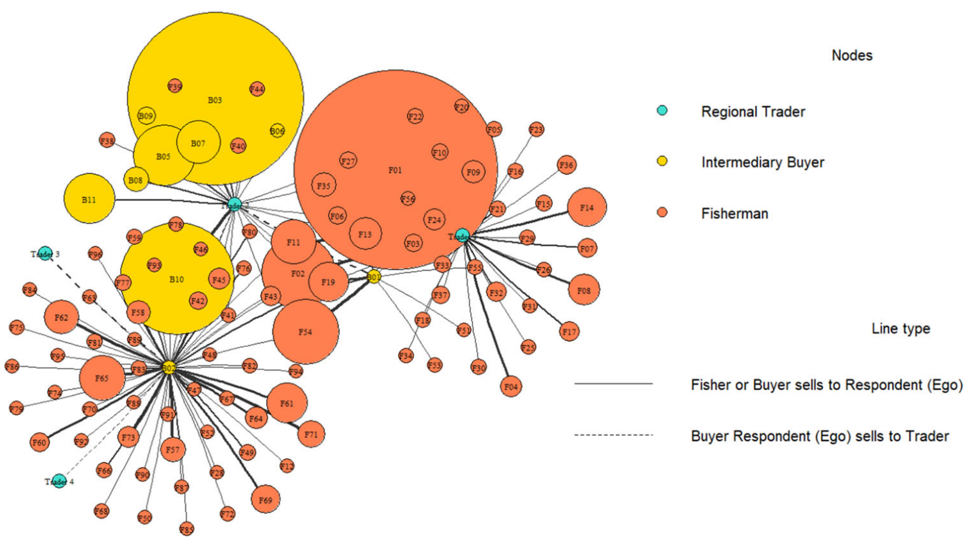

Fig. 3 Social Network Analaysis (SNA) showing trade structure, relative revenue share, & frequency of transactions in the fisher-buyer-trader network in Banggai with static ego nodes. SNA parameters are the same as in Fig. 3. However, this figure holds the ego (respondent) nodes (B01, B02, Trader 1, and Trader 2) static to better see the difference in size of the alter (non-respondent) nodes and compare revenue between each.

deeper analyses of the SNAs that are beyond the scope of this paper, but we present the figures here to provide a visual aid for understanding the network structure.

Revenue from the aquarium trade

The total gross sales figure for the year of data (accounting for purchasing cost but no other costs) was USD $50,683.45, based on the gross sales of the four respondents. This breaks down as follows: Trader 1 with USD $11,731.90 in sales, Trader 2 with USD $28,141.94 in sales, Buyer 01 with USD $3465.95 in sales, and Buyer 02 with USD $7343.66 in sales. The respondents earned the most gross income from buying and selling blue tang, except for Trader 1, who earned over half of his gross income from buying and selling yellow goby (USD $5943.39).

When looking at fishers and buyers together (excluding B01 and B02, who, as respondents, are inclined to have more revenue accounted for than other buyers and fishers in the network), the highest earner was F01 earning USD $6450.42 for the year (see both Fig. 3 above and Fig. 4 below), and the lowest were four fishers (F96, F46, F47, F88) who only sold fish once for a total of USD $1.74. The average gross individual income was USD $288.44 per fisher/buyer for the year. More important was understanding the proportion of the fishers' and buyers' average gross income this represented. Using IDR 1,750,000 as a baseline average gross monthly income in the source village as explained in the methods, which approximates to USD $1470 per year per individual, and comparing this to the average aquarium fish revenue of the fishers and buyers included in our data, which rounds to USD $288 per year, an average fisher/buyer earns nearly 1/5th (19.6%) of his/her annual gross income from selling aquarium fish. When looking at an individual level, we see that the top 15 earning fishers and buyers capture 43% of the total revenue and that five of the top 15 earners are buyers (orange), while the other nine are fishers (green), and one acts as both (yellow) (see Fig. 4). These results show that while buyers are generally thought to have more capital[44–46], some fishers also earn significant gross income from the trade. Again, these results only account for the cost of purchasing fish for traders and buyers. If we estimate fuel costs, the primary cost incurred for fishers, using 9000 IDR/l of fuel (which ranged between ~8000 and 10,000 during data collection) for an average of 7 l per trip (see EC PREP[43]) and our finding of an average of ten transactions per fishers/buyers during the year of data collection, we find an average cost of 630,000 IDR or $44 USD per year for fuel. This leaves a net annual profit of $244 USD, or 16.6% of their gross annual income derived from selling aquarium fish. Buyers have few costs besides purchasing the fish, which is accounted in our calculations, thus we assume their costs are the same or less than that of fishers, which would cover the initial cost of building a net pen to hold the fish until they sell them, and the miniscule cost of fish food. For both fishers and buyers, these are generous cost estimates considering that fishers often catch blue tang when they are already out fishing for other target species and catch yellow goby in areas close to home, requiring little fuel.

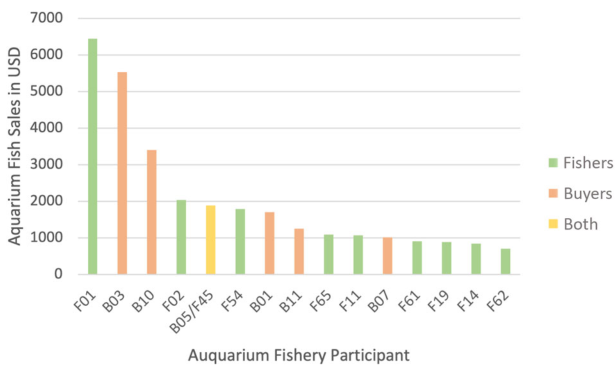

Fig. 4 Top 15 income earners from selling aquarium fish in the Banggai Region between October 2018 and September 2019. These top earners captured 43% of total revenue from the trade. The graph shows that both fishers (green) and buyers (orange) were among the top 15 earners, indicating that although buyers are thought to have more capital, fishers were also able to earn significant gross income from the trade. The yellow data point signifies an individual that acted as both a fisher and a buyer.

Strategy and seasonality

We also developed a linear regression model (see Eq. 3) that was helpful for understanding the relationship between the total number of aquarium fish sold and the type of seller (fisher or buyer), the season (north season, south season, or calm season), and the fish species (blue tang or yellow goby). We found that, on average, fishers sell 81% less individual aquarium fish than buyers, which is logical given that buyers source fish from numerous fishers and sell them forward in the supply chain (see Fig. 5). More counterintuitively, we also found that all participants sell 26% more aquarium fish during the north season, which typically has rougher weather, as compared to the calm season. We examine this finding further in the discussion as it relates to adding diversity and flexibility to participants' livelihood portfolios. Lastly, we found that all participants sell 98% less blue tang than goby across all seasons, which again is logical, as the yellow goby were caught and sold in large numbers as compared to the blue tang. Each of these findings is statistically significant at the $\alpha = 0.001\%$ level.

Finally, we ran an interaction effect model (see Eq. 4) to determine if there were any interactions between the species caught and the seasons which might affect the number of aquarium fish sold by fishers and buyers. We found that the only statistically significant interaction effect (at the 0.05% level) was between the south season and the blue tang, with 36% less blue tang selling on average than goby during this season (see Fig. 6). Or stated inversely, 64% more yellow goby selling on average than blue tang during this season. Additionally, the north season variable, which was significant in our original regression, is insignificant in this interaction effect model, suggesting that the main variation we see across seasons is due to the species type. In other words, the model suggests each target species for the aquarium fishery contributes uniquely to participants' gross income. Author SSS observed that buying and selling aquarium fish supplemented fisher income that was also supplemented by

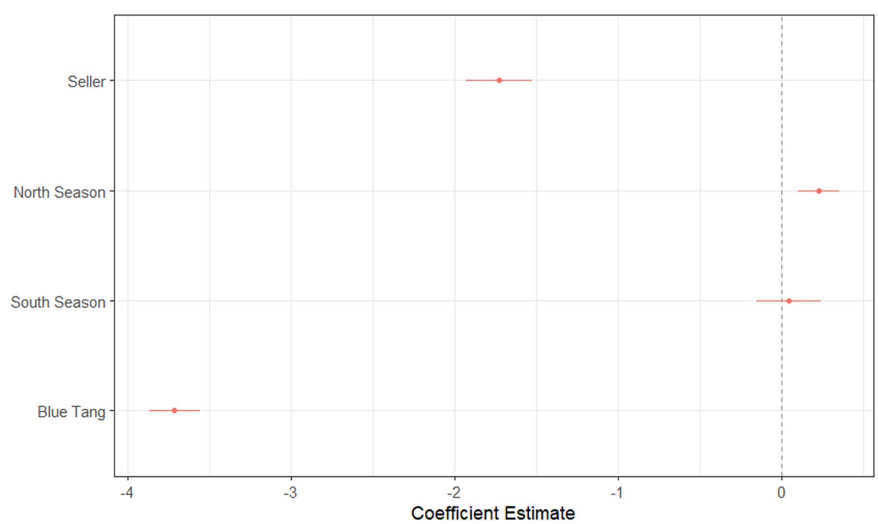

Fig. 5 Factors influencing total fish sold. Regression results show factors that may be influencing total fish sold (see Eq. 3). Each dot represents the coefficient of the respective independent variable and the horizontal lines are 95% confidence intervals. For the weather seasons variable, we grouped the sales data by the months of each season identified by fishers in the source village as follows: "musim utara" or north season = December, January, February; "musim selatan" or south season = May, June, and July; and the two calm weather, or inter-monsoon seasons = March, April, August, September, October, and November. The sample size is 1038 observations of sales transactions.

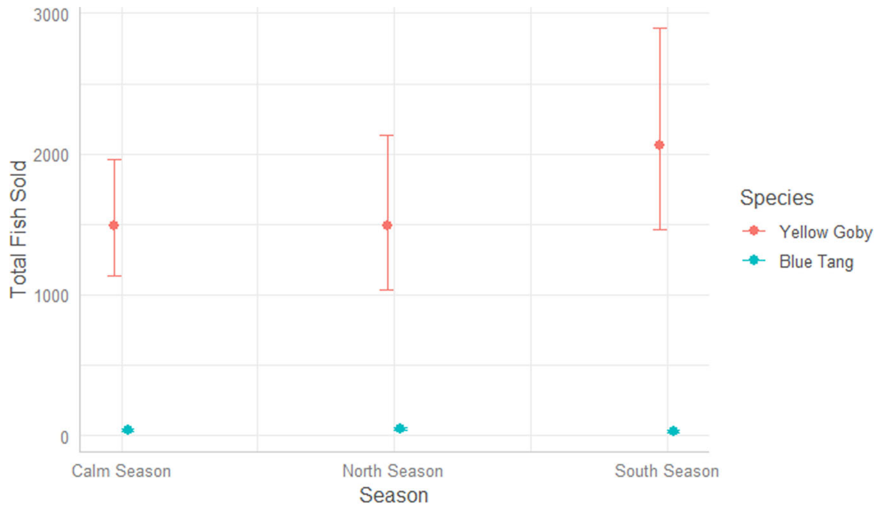

Fig. 6 Weather season interaction with fish species. Regression results show interaction effects between the weather seasons and species type that may be influencing total fish sold (see Eq. 4). The vertical lines are 95% confidence intervals. Each dot represents the predicted value of fish sold in a given season. The interaction term in Eq. 4 (β_2*WeatherSeason x FishSpecies*) allows us to test the difference in the value of fish sold across species and weather season. The individual data points (*n*) for this regression were 1038 observations of sales transactions.

non-fishing income generating activities of both men and women in the household, including boat building; selling local fruits, baked goods, or handicrafts; growing commercially valuable seaweed known locally as "agar agar;" and harvesting tall bamboo poles to build and sell ladders used to harvest cloves during clove season or "musim cinkeh."

The counterintuitive findings from our regression results show two things: 1) on average, fishers continue catching and even catch more aquarium fish in the north season, which typically has strong wind and large swells making it difficult to catch other target species like octopus; and 2) during the similarly rough weather of the south season many fishers pivot to catching the yellow goby specifically. We now examine these findings further to show that the aquarium fish trade not only contributes to gross participant income but also provides added diversity and flexibility to their livelihood options.

DISCUSSION

New contributions

Our results show that fishers, buyers, and traders in the region both supply a substantial amount of Indonesia's MAT exports and earn a substantial amount of their gross income from the aquarium trade, with the blue tang providing the greatest amount of revenue. We show that most participants catch and/or trade aquarium fish with high frequency and regularity across all weather seasons, with both the blue tang and yellow goby providing supplemental sources of income specifically during rough weather seasons. Our data provide evidence that fishers target specific aquarium species at particular times of year to build their resilience to natural stressors. Taken together, we provide evidence that the MAT helps buffer from seasonal weather disturbances by adding options to fisher, buyer, and trader livelihood portfolios throughout the year. We now further examine these results and their management implications.

Fisher, buyer, and trader contribution to the global MAT. Based on our data, nearly 3% of aquarium fish exported from Indonesia originated from the Banggai region, which is conservative considering we do not present a complete trading network in this paper. Supplying this portion of the country's marine aquarium fish export is quite remarkable considering that Indonesia is comprised of over 13,000 islands[47]. The total number of other aquarium fish source regions supplying the trade is currently undocumented. The occurrence of hubs such as the Banggai Region is likely linked to several factors including logistics, such as being near key points on trade routes, presence of species that are in demand by hobbyists, and, relatedly, overall biodiversity. With 18 of Indonesia's 38 provinces exporting some amount of marine aquarium fish[6], future studies could focus on these provinces to identify other top source regions. This information would allow the Indonesian government to prioritize monitoring reef health and aquarium species populations in these areas, as well as work with MAT fishers to ensure they have access to and training in harvesting methods that are both efficient and sustainable. We also discovered that fishers, buyers, and traders were highly focused in terms of the species they caught, bought, and sold, principally targeting the high-value blue tang, while also, more recently, targeting the lower-value yellow goby, which was not previously known to be sourced from the region[41]. This specialization is dictated by market demand, which in turn determines which species traders and buyers will purchase from fishers. Returning to the concerns of the Blue Justice movement and the language of SDG 14, these findings also highlight the economic contributions that MAT participants provide to the broader Indonesian economy.

MAT contribution to fisher, buyer, and trader livelihood by species. By identifying that, on average, the MAT contributed 20% of gross income for individuals participating in the trade and nearly 17% after accounting for fuel costs, we show that the supplemental income derived from aquarium fish is substantial. Our data show that the blue tang was the primary species traded, providing 87% of total revenue. While a few studies have estimated numbers of fish caught for the MAT (see refs. [48,49]), limited direct source-level data exist: to our knowledge, this is the first study to quantify both volume and income for the blue tang. This species is of particular interest as it was popularized by the Disney movies *Finding Nemo* (2003) and *Finding Dory* (2016). With the release of *Finding Dory*, conservationists were concerned that the film would increase demand for the blue tang, but subsequent studies did not find evidence[50] of this so-called "Nemo effect"[51]. Nevertheless, the blue tang has long been one of the most popular aquarium species and is regularly among the top 20 species by volume imported to the United States[5,14,52]. The blue tang is widely, but patchily, distributed across the Indian and Pacific Oceans and is listed as a species of Least Concern by the IUCN[50,53]. In theory, this means that blue tang collection does not pose an immediate threat to the species as would targeting protected or endemic species, such as the Banggai cardinalfish[54,55].

Nonetheless, catching the blue tang does pose unique challenges. For example, the blue tang is a relatively difficult aquarium species to catch[57]. The fish exhibit shy behavior, hiding in coral crevices when approached, and prefer areas with strong currents and deeper water than the Banggai cardinalfish and the yellow goby, which are typically found in sheltered coastal areas 1–5 m deep[41,56], clustered around their preferred microhabitats[57]. Thus, fishers targeting blue tang often use compressed air disbursed underwater by hoses known as "hookah" lines when diving to catch blue tang, a practice which can pose serious health risks to the diver[27,58]. Additionally, fishers often employ neurotoxins such as potassium cyanide (known locally as "potas") to stun the fish, making them easier to retrieve, as author S.S.S observed in this region. These toxic substances are widely considered to pose sustainability issues[59], including damaging coral reefs and causing elevated mortality levels of captured fish[60,61].

By contrast, targeting the yellow goby avoids several of the challenges presented by the blue tang, including the need to use neurotoxins to stun the fish, and provides another opportunity for fishers with less specialized equipment to earn money catching aquarium fish[41], especially during the relatively strong winds and big swells of the south season, as evidenced by our regression results. Fishers with less capital can catch these fish in shallow coral reef areas protected by mangroves near the source village with a simple, human-powered "sampan" (small wooden canoe), and they do not need a boat engine or a hookah-diving compressor as they do to target blue tang. The yellow goby was also recently found to be the most sustainable aquarium species to catch out of the 72 reef species evaluated by a Productivity Susceptibility Analysis that considers ten life history attributes and "12 catchability, management, and fishing practice attributes that are location-specific" (Dee et al.[59], at p. 2). However, one concern with catching this species in the Banggai Archipelago is the observed behavior of fishers pulling up entire coral heads on which the goby congregate to deposit them more easily into the "serok" net they use to catch the individuals, which is likely to result in the mortality of the coral colony, leading to a decline in live coral cover and habitat niches for coral-associated fish[41]. Additionally, while targeting yellow goby may appeal to fishers lacking access to the equipment needed to catch blue tang, other fishers may prefer to focus on blue tang, due to its higher value as well as the adventure and bravado associated with catching species via compressor diving[27].

Diversification and resilience. Because small-scale fishers can be particularly vulnerable to unpredictable ecological disturbances and economic change[39], scholars have argued for an approach to fisheries management that fosters resilience in the face of uncertainty[25,62–67]. Our linear regression models revealed that both the blue tang and yellow goby help build fisher resiliency in the region by providing added flexibility in seasons of typically bad weather with strong wind and large swells that create choppy sea conditions. While these bad weather conditions can vary from island to island[68], fishers in Banggai noted two distinct rough weather seasons, "musim utara" or north season, and "musim selatan," or south season[48]. During these two seasons, strong wind and large swells can make it difficult for fishers to target their primary catch, which varied among fishers but was observed to include octopus, squid, and popular food fish species, like snapper and grouper. However, despite these challenges, the regression reveals that, on average, fishers and buyers sell a higher number of blue tang and goby during the north season. We hypothesize that this difference is because the locations fishers most often frequent to catch blue tang are largely protected from the north season wind and swell direction, while their locations for other target species (including octopus and squid) are not; thus, they focus energy on catching blue tang. However, during the south season, these blue tang locations are more exposed to the wind and swell, while locations for the yellow goby remain protected. Without both species being accessible during the south season, the statistical relationship is non-significant. However, our interaction model showed that blue tang sales decreased in the south season relative to goby sales, suggesting that the yellow goby can continue to provide additional income during this season of rough weather due to its preference for shallow protected habitat.

Taken together, the findings show that each aquarium species contributes uniquely to fisher, buyer, and trader income, especially during poor weather. Thus, the aquarium trade allows fishers and traders to have flexibility to move from specializing during favorable conditions to diversifying during unfavorable conditions[25]. These findings also contribute to understanding how weather influences fisher behavior, a critical and understudied aspect of marine resource management[69]. Additionally, participant observation showed that fishers with less capital can still access the yellow goby, providing alternative income options for less-resourced individuals participating in the trade[41]. Thus, the aquarium trade represents another option for livelihood diversification, which fishers and their families can add to their "livelihood constellations," defined as "several activities that individuals and households combine for income, health, and well-being" (Griffith[70] at p. 82). Families could add selling aquarium fish to their constellation, often without adding significant additional costs, which could supplement the other non-fishing income-generating activities author S.S.S observed.

According to the livelihood resilience strategies identified by Marschke and Berkes[37], livelihood diversification efforts need to build the capacity of a household's flexibility to earn income to be considered a resilience-building measure. We argue that fishing families in our study use the opportunity to earn additional income from aquarium fishing as a resilience-building measure that supports their capacity to manage future change[71] and sustain well-being[72]. Such resilience-building measures or strategies will become increasingly important as climate change continues to affect the region[58]. Indeed, fishers noted that the year the lead author collected the data reported here, the north season was lasting longer than it had historically[73], which supports findings from past studies in the BOKEP region (see EC PREP[43]). Additionally, longitudinal weather studies support these first-hand reports of changing weather patterns in the region[74,75]. If the rough weather seasons continue to extend, both the blue tang and yellow goby can potentially continue providing alternate sources of income due to the more protected areas they inhabit compared to other target species, depending of course upon how climate change affects each species population size and distribution. In addition to potentially providing a buffer to climatic changes, targeting a wider variety of species via the aquarium trade may also be important for ecological sustainability, by placing less pressure on any one species. Again, more studies need to be conducted to understand the ecological effects of species diversification, as in other small-scale fisheries[25].

One caveat to the added flexibility and diversity provided by the fishery is that greater overall community resilience does not necessarily mean an equitable distribution of and/or access to resources across individuals[76]. This is evidenced by our data; while, on average, fishers and buyers earned about 20% of their income from the aquarium trade, when considering individual earnings, the top 15 earners captured nearly half of the revenue. Additionally, though catching aquarium fish may be a resilience-building strategy, according to the Sustainable Livelihoods Approach and Framework[77], which helps to determine the sustainability of a particular livelihood constellation, such strategies will be enabled or hindered by institutions and social processes among other factors[78]. In the BOKEP Region, as in many parts of Indonesia, the patron–client relationship is one such institution, in which the client (fisher) is indebted to the patron (buyer/trader). This ongoing debt and credit relationship can both provide added stability for clients, who can obtain loans and other support from patrons during challenging times[79], while also creating dependency and further entrenching power imbalances[45]. Thus, while fishers may collect aquarium fish as part of a resilience-building strategy, these efforts exist within this complex debt and credit system, complicating the net costs and benefits.

Management implications. Our results demonstrate that weather patterns impact aquarium fish buying and selling; while the blue tang and yellow goby appear to provide a source of income during the rough weather seasons, it could be worth considering how local institutions, both governmental and non-governmental, might provide additional support during these challenging months. One such possibility would be to develop a program disbursing starter kits for eucheumatoid seaweed farming. This activity is a profitable endeavor in which both women and men can participate in the shallow waters directly adjacent to the source village. However, not all residents have access to the "seed" to begin farming, so providing a starter kit could help more residents get involved. Establishing seaweed nurseries in suitable locations and providing seaweed starter kits is just one example of support that government agencies and NGOs could potentially provide during bad weather seasons, and any efforts should be context-specific, and equity-focused.

Most importantly, this study can also help to inform management of the newly formed Banggai MPA which, while legally formalized, has yet to be enforced in practice. Managers would do well to be cognizant of how the MPA could fuel inequity through exclusionary and non-consultative practices as seen in numerous other cases across the globe (e.g., Nayak[80]) that would threaten fishers spatial autonomy[33] as well as limit access to important marine resources[34]. Infringing on these dimensions of Blue Justice is of particular concern as some locations where the fishers target the blue tang (intentionally not disclosed in this paper), as well as the other food fish, octopus, and squid they target, fall within the MPA boundaries. To uphold Blue Justice principles, a participatory process should be undertaken that engages fishers in the management process in order to develop ownership and agency over the MPA, perhaps in a co-management structure, incorporating lessons learned from MPAs in other parts of Indonesia (e.g., Clifton[81]; Campbell et al.[82]).

Finally, the comprehensive data we present on fish species, number bought and sold, and contribution to income is critical for developing better modeling of species collection to understand the trade's impact on wild populations[4]. Our data can serve as a baseline for the Indonesian government to begin implementing annual population surveys for the blue tang, as are already conducted for the Banggai cardinalfish[83,84], to ensure that the coral reef ecosystems remain in balance and income from the MAT remains dependable.

Limitations and future research

Although these findings draw from the most comprehensive set of data on blue tang and yellow goby catching and trading to date, they are not complete. We were unable to obtain complete data from one of the main trading pairs in the region (T03 and T04), though we have partial data from participant B02 frequently selling to these traders. Additionally, the lead author has confirmed that fishers also catch and sell fish to this trading pair from two further out islands, Kasuari and Sonit; those interactions are not captured in this data set. Thus, the numbers presented are a conservative estimate of the total number of fish being sourced from the region.

Additionally, author S.S.S collected data from buyers and traders, because intermediary buyers and traders typically keep a record of their sales; whereas, most fishers do not. However, collecting data directly from fishers could improve understanding of metrics, including a more complete accounting of mortality at this initial step of the supply chain. Also, the lead author was unable to count each recorded instance of buying and selling to check for accuracy in the numbers reported. She was also unable to ensure that every item was completed for each instance of buying and selling, which resulted in some incomplete data. Thus, data were lacking for locations where fish were caught for intermediary buyer B02, as well as for mortality across the respondents' data, except for Trader 2. In the future, spot checking the numbers of fish recorded could help improve accuracy.

Moving forward, it would be interesting to conduct similar analyses in other known aquarium fish source regions across Indonesia to scale up the quantification of the country's trade. Such efforts could be modeled after a participatory data collection program run in the Banggai Region from 2008 to 2012, which was supported by local government agencies[85]. Further quantifying numbers of aquarium fish caught in Indonesia, the world's second-largest aquarium-fish export country, as well as how they contribute to fisher livelihoods, could help improve international management of this important, yet little understood, trade. Additionally, further investigating the ways that weather influences fisher behavior and livelihoods is critical for developing policies that support fishing families during times of the year when earning income is difficult. Building from the findings of this paper can help ensure that those involved at the earliest stages of the aquarium fish supply chain continue to benefit from the trade in a sustainable manner over the longer-term, moving towards lasting Blue Justice for these fishers, buyers, and traders.

MATERIALS AND METHODS

Site selection

Lying at the heart of the Coral Triangle, the Banggai Archipelago comprises hundreds of small inhabited and uninhabited islands, providing habitat for a high diversity of fish[86], including numerous popular aquarium species. One such species, the endemic and distinctly patterned Banggai cardinalfish, *Pterapogon kauderni*[87], primarily found in the Banggai Laut District[88], first brought international attention to the region as a source for the MAT.

Since initially targeting the Banggai cardinalfish (traded as BCF) in the 1990s and early 2000s, a few dozen small-scale fishers from several villages in the Banggai Archipelago engaged in the MAT as part of their livelihood strategy[43,48]. The Banggai cardinalfish was the sole species caught and traded at any volume by local fishers. Other species, including the blue tang *Paracanthurus hepatus*, were collected by roving fishers, mainly from Bali, East Java, or North Sulawesi, who would sometimes employ local fishers[43]. Locally, fishers and traders refer to the blue tang as "leter six," because of the shape of a black number six on its side, which was partially lost in translation as the letter six rather than number six. The blue tang is the only representative of the genus *Paracanthurus*[14], and it is a strictly coastal species in coral reef ecosystems[89].

Harvesting the Banggai cardinalfish for the MAT pushed the wild population to the edge of extinction[86] in less than 5 years[56]. This population decline prompted conservation actions to protect the Banggai cardinalfish at the international, national, provincial, and district levels, including the creation of the Banggai MPA. These actions effectively eliminated the local Banggai cardinalfish trade; they were not being targeted while the lead author was present between 2016 and 2019. Traders supplying the MAT

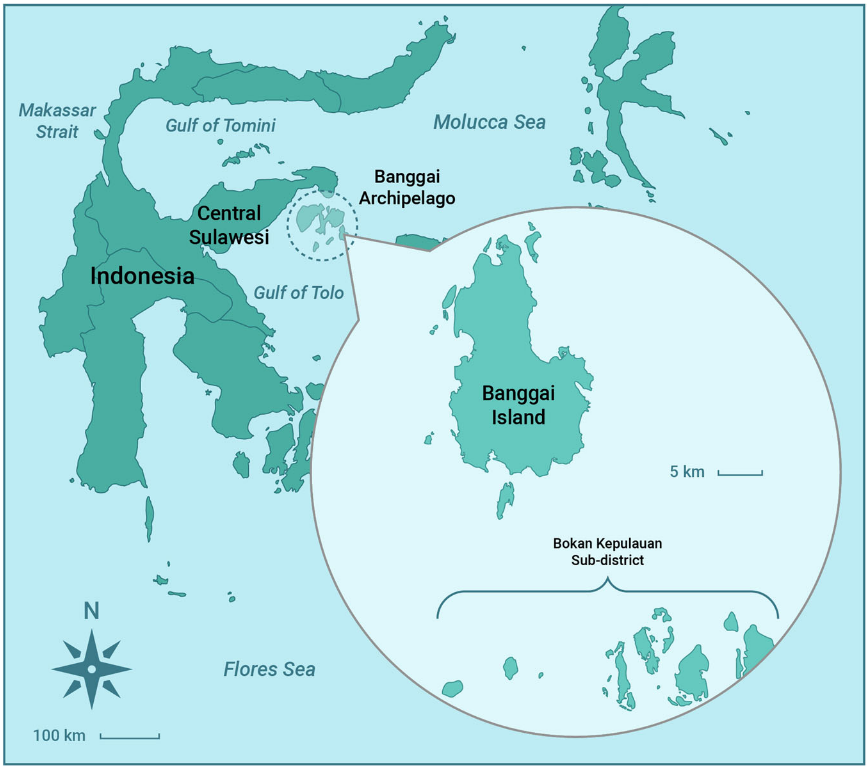

Fig. 7 Map of study site. Location of study site in the Banggai Archipelago, Central Sulawesi, Indonesia.

continued to operate in the region, pivoting to other species[41]. While illegal sea-based trading routes exist[54,88], since 2018 traders in the Banggai region typically send their fish legally by ferry to the port city of Luwuk in mainland Central Sulawesi, from where they are shipped by plane to Bali or Jakarta[54,55].

We will refer to the village that is the focus of our study as the "source village" to maintain anonymity. The source village is in the Banggai Laut District and the Bokan Kepulauan Sub-district (BOKEP) (see Fig. 7). In addition to supplying the MAT, the village is the primary fish-trading hub in the region for other national and international fisheries, including (but not limited to) lobster, snapper, grouper, squid, and octopus. It is uniquely positioned as a midway point between the outer islands bordering the Maluku Province and the main island of Banggai from which large ferries ship cargo to mainland Central Sulawesi via the port city of Luwuk. Thus, the village is ideally situated for studying the aquarium trade. Prior to data collection, our methods were approved under Stanford University's IRB e-protocol 37735.

Data collection

For this paper, we drew on a year of buying and selling data from four individuals involved in the trade operating in the Banggai Laut District. Author S.S.S used purposive sampling, inviting individuals who she knew bought and sold aquarium fish from the source village to record their data. Three of the four individuals lived in the source village in the BOKEP Sub-District, with the fourth buying fish in this village, though he was based in a village on the larger island of Banggai, in the Banggai Utara Sub-District. Author S.S.S was able to directly observe the practices of the four respondents while living for periods of time in both villages as outlined below.

The observational data of author S.S.S, on which we drew, included accompanying a regional trader on his purchasing routes during July 2016 and August 2017, as well as living in the two villages mentioned above—the source village and the village on Banggai Island—from October 2018 through September 2019 for several months at a time. During this latter time period, author S.S.S spent over 450 h at sea with fishers in the region traveling throughout the numerous islands in BOKEP as they targeted multiple species, including the aquarium fish species recorded in the buying and selling data. All data are reported anonymously to protect participant identity. Additionally, while respondents recorded catch locations for each trading transaction, these are not reported here, except to note that many fall within the Banggai MPA.

Throughout this paper we will refer to 1) the individuals catching the fish as *fishers (F)*, 2) the individuals to whom the fishers sell, who also live in the source village and sell their fish onward to higher-level individuals, as *intermediary buyers (B)*, and 3) the individuals who buy both directly from fishers as well as from intermediary buyers and sell to higher level individuals typically based in other provinces, as *regional traders (T)*. The latter two classifications broadly equate to "small punggawas" and "big punggawas," respectively, in the "punggawa-sawi" system, as outlined by Ferse et al.[24] in the coral trading market of South Sulawesi, though these terms were not commonly used in the Banggai Region.

As mentioned above, author S.S.S. collected trade data from four individuals: two intermediary buyers and two regional traders. To the lead author's knowledge, there was only one other regional trader in the Banggai Archipelago supplying the MAT at the time of data collection, though he and his brother, who often work together, declined to record and share their data. However, one of the intermediary buyers (B02), from whom we collected data, sold to these regional traders, thus we partially account for their contribution.

To collect the buying and selling data from the four respondents, author S.S.S. distributed physical notebooks for respondents to record their aquarium fish transactions and explained the data recording process, including the meaning of each item in the datasheet (see Table 1 for items recorded). Author S.S.S. compensated the respondents for this work according to an appropriate and already established amount that aligned with the scale used by a local non-governmental organization (NGO), The

Table 1. Aquarium fish data items recorded by respondents.

Data Entry Items	
English	Indonesian
Date	Tanggal
Name of Fisher	Nelayan
Tool Used	Alat Tangkap
Location	Lokasi
Fish Species (local name)	Jenis Ikan
Total Number of Fish Bought	Jumlah Beli
Number of Small, Medium, Large Fish Bought[a]	Ukuran (T, S, M)
Purchase Price/fish (IDR)	Harga Beli/ikan (IDR)
Amount Died	Jumlah mati
Total Number of Fish Sold	Jumlah jual
Number of Small, Medium, Large Fish Sold[a]	Ukuran (T, S, M)
Sale Price/fish (IDR)	Harga Jual (IDR)

[a]Denotes items only relevant to blue tang because they are priced by size.

Indonesian Nature Foundation (LINI) working with octopus traders in a nearby village. This amount was 150,000 IDR per month (or using 0.00007 exchange rate, $10.50 USD). Because author S.S.S. lived in the source village several months at a time over the course of the year-long data collection, she was able to take pictures of the data sheets as respondents completed them, allowing the original books to remain intact. She was also able to spot-check that the traders were recording the data in a timely fashion, rather than by memory, to help ensure accuracy.

Data analysis

For this paper, we analyzed the quantitative buying and selling data described above as well as the observational data to add context and nuance to the quantitative data.

Data organization. For the quantitative trading data, we transferred the raw data into an Excel workbook where we created spreadsheets for each of the four respondents using the items from the physical data sheets, noting the page number of each data entry. (See Supplementary Tables for complete data set). To maintain anonymity, we assigned each individual in the data set an ID letter and number (denoting F for fisher, B for intermediary buyer, and T for regional trader). In one instance a trader transacted with an individual as both a fisher and a buyer, so that individual is represented as both F45 and B05 in the dataset.

Next, we identified and corrected inconsistencies in the respondents' reported data. This included several instances where fishers or buyers were listed under two different names, which we condensed into the same fisher or buyer ID. Similarly, we condensed locations with multiple names to one name. Additionally, because each research participant began recording on a different date, we collapsed the months into one calendar year, even though, for example, the year of data for Trader 1 (T01) began in October 2018 and ended in September 2019, while Trader 2 (T02) began in November 2018 and ended in October 2019. Furthermore, occasionally, the weekday recorded by the research participant did not match the date written on the physical datasheet. In those instances, we used the date recorded rather than the day. Finally, in the case of the blue tang, which were recorded by size (small, medium, and large), we checked research participant arithmetic for every entry by adding the values reported for each blue tang size and comparing those to the values reported as total individuals caught. We noted when the values did not match and modified the data sheet using the totals that we calculated by adding the totals of each size recorded by the research participant.

To calculate revenue data, we converted the total price sold (i.e., income) from Indonesian Rupiahs (IDR) to US dollars (USD) using the monthly average exchange rates from x-rates.com for the month the data were reported. To avoid double counting incomes when calculating total revenue generated by the trade, we modified the buying and selling data so that each time Buyer 01 (B01) or Buyer 02 (B02) sold to the regional traders, those transactions were only counted one time. We created a new spreadsheet for this modified dataset and used this spreadsheet to tabulate the overall totals for the year of data.

Descriptive statistics. We used the raw data provided by the four respondents (B01, B02, Trader 1, and Trader 2), modified as explained above, to calculate the descriptive statistics in Excel. These calculations included the number of fish traded and revenue, both per month and over the year of data, as well as the proportional amount of each species and proportional revenue by species over the year of data.

Next, we calculated statistics regarding the fishers, intermediary buyers, and regional traders represented in the data set. Those statistics included fisher selling frequency, buyer/trader purchasing and selling frequency, as well as fisher income and buyer/trader income. To calculate the trader purchasing frequency we used reported dates of sales to determine the total days between each sale. We then averaged this metric for individual species and for all fish (Eq. 1). Similarly, we used the reported dates of sales to calculate fisher selling frequency by determining the total days between each sale. We averaged this metric to find the average fisher selling frequency (Eq. 2).

$$(Date\,Sold\,B - Date\,Sold\,A) - 1 = Frequency; \bar{x}Frequency = Trader\,Average\,Purchasing\,Frequency \quad (1)$$

$$(DateSold\,B - Date\,Sold\,A) - 1 = Frequency; \bar{x}Frequency = Fisher\,Average\,Selling\,Frequency \quad (2)$$

Lastly, we calculated intermediary buyer and regional trader revenue using reported sale price (IDR). Sale price in IDR was then converted into USD using exchange rates as noted above. Thus, for fishers and buyers listed in the recorded data, we calculated revenue per transaction in USD using *(Total Sale Value) * (Exchange Rate)*. This metric was applied to all fish sold in each transaction by each individual fisher or buyer and summed across the year of data to find fisher or buyer total revenue. For the four respondents (two buyers and two traders) who recorded the data, we calculated their revenue in USD per transaction using: *(Total Sale Value IDR – Total Price Bought IDR) * Exchange Rate*. We then summed the revenue per transaction calculations to find total revenue for the year of data for each research participant. We conducted these calculations for all fish sold by each buyer or trader as well as for each species sold. The only cost we accounted for when calculating revenue was the cost of purchasing the fish for the buyers and traders. We were unable to account for additional costs such as diesel, food, engine or boat repair, and shipping costs for traders, nor the complex credit systems that exist in the region. Thus, when discussing revenue, we refer to the total revenue before costs (with exception of the cost of purchasing the fish in the case of buyers and traders), and when discussing fisher household income, we refer to gross income before costs and make the assumption that net income is proportional to gross income once accounting for all costs.

To estimate the proportion of gross income fishers earned from catching, buying, and selling aquarium fish, we first calculated the average reported gross household income per month from all revenue sources from a sample of 21 fishers, buyers, and traders the lead author interviewed as part of a photovoice effort in the source village. This average reported gross monthly income was approximately IDR 1,000,000 per month, which, using a 0.00007 exchange rate, is USD $70.00 per month, or USD $840 per year. However, we note that Trader 1 was included in this sample, and the revenue calculated from his reported sales was USD $11,731.90 with a USD $3588.31 profit for the year or USD $299/month (not counting costs of shipping, etc.). This total also does not include income from other species he trades, including lobsters, sea cucumbers, and trevallies, among others. However, his self-reported average total monthly income was only USD $140 (IDR 2,000,000/month). This supports the noted phenomenon that interview/survey respondents' self-reported gross income data may be unreliable[90]. Additionally, another interview participant in our sample asserted that fishers whom author S.S.S. interviewed were underreporting their gross annual income, and that, for most fishers, their gross monthly income had to be closer to IDR 2,000,000–3,000,000 (USD $140–$210) to make the fishing effort worthwhile, considering all associated costs. This underreporting of income has been documented in other small-scale fisheries studies, e.g., in Kenya[91]. Thus, to avoid overcalculating the proportion of gross income earned from the aquarium fish, we took the median value (2,500,000 IDR), added it to the average reported gross monthly income of 1,000,000 IDR, and divided by two to obtain the estimated average: IDR 1,750,000. We used this value as the baseline average gross monthly household income in the source village, which approximates to USD $122.5 monthly and USD $1470 annually.

Social network analysis. We used the same trade data to conduct a SNA using RStudio 1.2.5033 and visually represent the fisher-trader-buyer network. This network shows what is often broadly referred to as patron–client relationships[79], with each node representing a trader, an intermediary buyer, or a fisher, and the node size proportionally representing each individual's total income. Because we were not able to identify network boundaries *ex-ante* but drew on the data reported by respondents to determine who would be included in the network, we used an ego-centric approach[92,93]. Thus, the resulting network shows all buying and selling relationships between the respondents (egos) and the fishers, buyers, and traders with whom they transacted (alters). To visually represent the difference in node size accurately, we created two models, one that used the same scale for all node types and one that held the ego nodes at a fixed size to better visually represent the size difference between the alter nodes.

Linear regressions. We also present results from two linear regression models conducted in RStudio 1.2.5033 (see equations below). The first model, represented by Eq. (3), assessed the relationship between the dependent variable of number of fish sold (log(*sold*)), and the following independent variables: respondents ($\beta_1 TypeSeller$), the weather seasons ($\beta_2 WeatherSeason$), and the species of fish ($\beta_3 FishSpecies$). For the second variable, we grouped the sales data by the months of each season identified by fishers in the source village as follows: "musim utara" or north season, which included December, January, February; "musim selatan" or south season, which included May, June, and July; and the two calm-weather, or inter-monsoon seasons, which included March, April, August, September, October, and November. Historically, the south season did not typically begin until June[48]; however, May 2019 exhibited strong winds and large swells typical of the south season, thus we included May in the south season grouping. For both outcomes, we normalized the data first using log transformations. The following model represents the first linear regression we conducted for fish sold:

$$\log(sold) = \beta_0 + \beta_1 TypeSeller + \beta_2 WeatherSeason + \beta_3 FishSpecies + \epsilon \quad (3)$$

We then ran an interaction model to see if the relationship between fish species and number of aquarium fish sold was moderated by the weather season variable using the following model:

$$\log(sold) = \beta_0 + \beta_1 TypeSeller + \beta_2 WeatherSeason\ x\ FishSpecies + \epsilon \quad (4)$$

DATA AVAILABILITY

The authors declare that the data supporting the findings of this study are available within the paper and its supplementary information files.

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COMPETING INTERESTS

The authors declare no competing interests.

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