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Effect of unmanaged harvests for the aquarium trade on the population status and dynamics of redline torpedo barb: A threatened aquatic flagship

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Abstract

1. The freshwater aquarium trade provides economic and livelihood opportunities to the rural poor, but has been implicated in biodiversity loss through population declines and local extirpation of high-value endemic species. Previous observations on population declines are largely based on anecdotal data, however, and there are no studies on the population dynamics or stock assessment of freshwater fish species collected for the aquarium pet trade.
2. To understand how wild collection of endemic and threatened species for the aquarium trade could affect their populations, the sustainability of collecting the endangered redline torpedo barb (*Sahyadria denisonii*), and its evolutionarily distinct lineages (henceforth RLTBs), from the Western Ghats region (part of the Western Ghats–Sri Lanka biodiversity hot spot) for the aquarium trade was studied to provide baseline data to inform conservation action.
3. Local populations of RLTBs at the five commercial collection sites showed high mortality rates, and fish were exploited before they attained sexual maturity. The unmanaged fishery has led to unsustainable levels of exploitation, and populations of RLTBs at three sites are vulnerable to an impending collapse.
4. Endemic and threatened freshwater fish species used in the aquarium pet trade are exposed to local extirpations and global extinctions unless management plans and legislative controls are implemented and strictly enforced. Management plans and conservation actions to help guide the responsible fisheries of RLTBs are suggested, and the wider implications of unmanaged exploitation of endemic aquarium fisheries are discussed.

KEYWORDS

aquarium trade, conservation, endangered, freshwater fish, Western Ghats

1 | INTRODUCTION

The ever-increasing demand for live tropical animals as pets, combined with high levels of poverty, threatens to eliminate biodiversity from developing economies for short-term benefits (Rhyne, Tlusty, & Kaufman, 2014). Tropical aquarium fishes comprise one of the most

valuable of such biodiversity-related commodities, traded from the developing to the developed world with poorly documented, yet significant conservation and livelihood implications (Lunn & Moreau, 2004; Moreau & Coomes, 2007; Tlusty, Dowd, & Raghavan, 2008). Close to 5000 freshwater and 2000 marine fish are traded around the world (Hensen, Ploeg, & Fossa, 2010; Rhyne, Tlusty, Schofield,

Kaufman, & Morris, 2012), many of which have a high risk of extinction (Raghavan et al., 2013; Rowley, Emmet, & Voenn, 2008). Although wild collection of such species for the aquarium trade has been postulated as a major threat, this link is largely unsubstantiated because of a lack of quantitative data (Raghavan et al., 2013). Many of the observations on population declines and extirpations of freshwater aquarium fishes are based on anecdotal data from fishers and key informants, and to the best of our knowledge there have been no quantitative estimates of these aspects.

To understand fully the impacts of wild collection for the aquarium trade, information on the health and status of populations (stock assessments), the number of fish being harvested (exploitation levels and rates), and the link between these two, are required (Raghavan et al., 2013; Sanjeevi et al., 2017). Such information is not available for many of the freshwater fish species harvested for the aquarium trade.

In the Western Ghats region of India (part of the Western Ghats–Sri Lanka biodiversity hot spot), the unmanaged harvest of freshwater fish for the aquarium pet trade is a conservation issue that has received less attention (Raghavan, 2010; Raghavan et al., 2013; Raghavan, Prasad, Ali, & Sujarittanonta, 2007; Raghavan, Prasad, Pereira, Ali, & Sujarittanonta, 2009). Of more than 100 species in the trade, approximately 24 species are regularly exported, including several thousand individuals of endemic and threatened species (Raghavan et al., 2013). One of the regular export items from India is the redline torpedo barb of the genus *Sahyadria*, comprising two valid species – *Sahyadria denisonii* and *Sahyadria chalakkudiensis* – and six evolutionarily distinct lineages (RLTBs) (John et al., 2013; Raghavan et al., 2013). Since its first export in 1996, and subsequent rise to fame (Raghavan et al., 2009), RLTBs have been indiscriminately collected for the aquarium pet trade, with over 300 000 wild-caught RLTBs exported from India between 2005 and 2012 (Raghavan et al., 2013).

RLTBs are found in 14 small westward-flowing river systems draining the Western Ghats region, between 9° and 12°N, where they have an extremely restricted area of occurrence of (<500 km²; Ali, Raghavan, & Dahanukar, 2015; Raghavan & Ali, 2015) and fragmented distribution (John et al., 2013). Owing to peculiar reproductive characters, including extremely low fecundity and a skewed sex ratio, RLTBs have been suggested to be unsuitable species for large-scale aquarium collections (Solomon et al., 2011). Based on their restricted distribution, continuing decline in quality of habitats, indirect effects of destructive fishing, and anecdotal (and unpublished) information on population declines at commercial collection sites, RLTBs have been assessed as 'endangered' (Ali et al., 2015; Raghavan & Ali, 2015) in the International Union for Conservation of Nature (IUCN) Red List of Threatened Species.

Scientific information based on strong empirical evidence is required if conservation-related decisions are to be taken seriously by governments (Jepson & Ladle, 2010). The development of policies and their subsequent implementation and enforcement in biodiversity-rich, developing countries is often delayed by the justification that scientific information is unavailable. Understanding the status and dynamics of populations, levels of exploitation, and sustainability of trade in threatened species, such as the redline torpedo barb, is therefore an immediate priority for informing science and policy.

The study of length-structured population dynamics, based on exploited individuals, can provide important insights on the growth

performance and fishing pressure for the species, which can help in assessing the sustainability of exploitation. Therefore, to understand whether commercial-scale wild collection of RLTBs for the global aquarium trade is sustainable, the annual length-structured population dynamics of RLTBs harvested by collectors was studied in five locations in the Western Ghats of India.

2 | METHODS

2.1 | Study sites

Based on previous studies (John et al., 2013; Raghavan et al., 2009, 2013; Raghavan, Prasad, Ali, & Pereira, 2008) and interactions with local aquarium fish collectors, five commercial collection sites were selected, spread across five river systems in the region (Periyar, Chalakudy, Chaliyar, Valapattanam, and Chandragiri; Figure 1). An integrative taxonomic study (John et al., 2013) documented the presence of eight evolutionarily distinct lineages (EDLs) among the two nominal species of RLTB (*S. denisonii* and *S. chalakkudiensis*). *Sahyadria chalakkudiensis* is restricted to the Chalakudy and Periyar rivers (Figure 1), and care was taken to ensure that only this species, and not its sympatric EDL, was used as samples from these two rivers (the sympatric EDL does not possess a black blotch on the dorsal fin; John et al., 2013). The other three rivers (Chaliyar, Valapattanam, and Chandragiri) harbour populations of the species currently known as *S. denisonii*, but in fact these populations include different EDLs that should be considered as distinct management units (see John et al., 2013). For the sake of the present paper, *S. denisonii*, *S. chalakkudiensis*, and all EDLs of the genus *Sahyadria* are referred to as 'redline torpedo barb' or 'RLTB'.

2.2 | Data collection

Monthly samples ($n = 30$) of RLTBs meant for exports were obtained from collectors operating in each of the five rivers. Individual fish were measured to the nearest 0.1 mm (total length, T_L) after anaesthetization with clove oil. Data on T_L were then arranged in a length–frequency table, with 5 mm as the smallest mid-length and with a 10-mm class interval.

2.3 | Analysis of population dynamics

To address whether commercial-scale wild collection of RLTBs for the global aquarium trade is sustainable, length-structured population dynamics (Pauly, 1984) were modelled to estimate the asymptotic length, growth coefficient, growth performance, total mortality, natural mortality, fishing mortality, length at first capture, and current exploitation of RLTBs from five collection sites. The estimates of parameters related to growth, mortality, and exploitation were then used to assess the sustainability of exploitation.

A contour plot was prepared to understand the distribution of length classes in relation to different months and different collection sites. Growth, mortality parameters, as well as exploitation levels were then estimated from the length–frequency data using ELEFAN I incorporated in FISAT II (Gayanilo & Pauly, 1997). As there was no strong

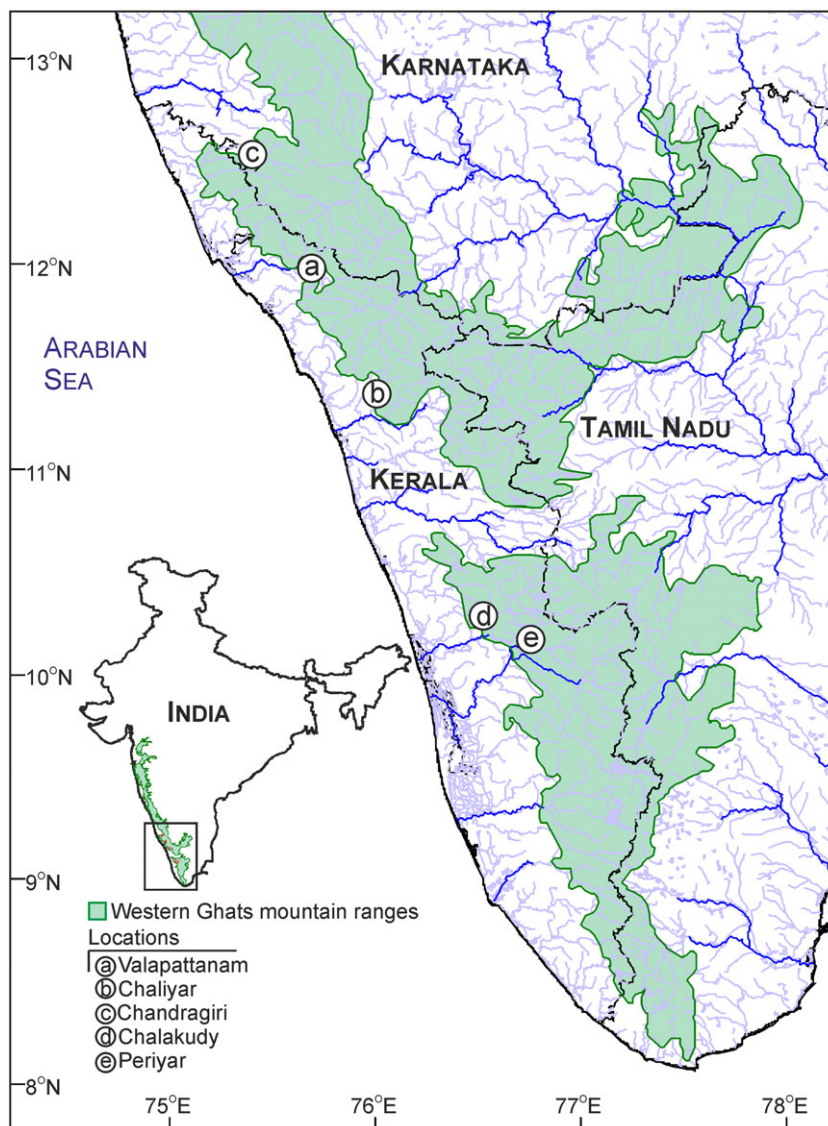


FIGURE 1 Map of southern Western Ghats showing the sampling sites of redline torpedo barbs

influence of season in the study sites, the von Bertalanffy Growth Formula (vBGF) was used, given by the formula, $L_t = L_\infty (1 - e^{-KD(t-t_0)})^{1/D}$, where L_∞ is the asymptotic length, K is the growth constant, t is the time, L_t is the length at time t , t_0 is the hypothetical time when the length is zero, and D is a positive constant (Pauly, 1984). Based on L_∞ and K values, the growth performance index ($\phi' = 2 \log L_\infty + \log K$) of RLTBs was estimated for different rivers (Pauly & Munro, 1984). Total mortality (Z) was estimated using length-converted catch curves (Pauly, 1984), whereas natural mortality (M) was determined using Pauly's M equation, $\ln(M) = -0.0152 - 0.279 \ln(L_c) + 0.6543 \ln(K) + 0.463 \ln(T)$, where T is the average annual temperature of the site. Fishing mortality (F) was calculated as $F = Z - M$, and the exploitation level was calculated as $E = F/Z$ (Gulland, 1970). The length-converted catch curve was used to estimate the length at first capture (L_c). To understand whether the RLTB populations are overexploited, the theoretical E_{50} (exploitation rate where the stock is reduced to half its virgin biomass) and E_{max} (exploitation producing maximum yield) values were calculated using Beverton and Holt's (1966) relative yield per recruit (Y/R) and biomass by recruit (B/R) analysis, with the knife-edge selection method, by inputting the values for L_∞ , L_c , M , and K (Pauly, 1984).

To understand how different growth, mortality, and exploitation-related parameters differed among the various study sites, a principal component analysis (PCA) was performed using the correlation matrix between the variables in PAST 3.12 (Hammer, Harper, & Paul, 2001).

3 | RESULTS

3.1 | Length frequency of exploited populations

The frequency distribution of length classes showed considerable variation in the length range of the RLTBs exploited from various rivers across different months (Figure 2). The minimum and maximum exploited length (T_L) classes of RLTB were between 30 and 190 mm. Small size-class RLTBs (<100 mm T_L) were highly sought after in most of the rivers. Although only 8% of the exploited RLTBs were below 100 mm T_L in the River Chalakudy, in increasing order the proportion was 32% in the River Periyar, 75% in the River Valapattanam, and $> 90\%$ in the rivers Chaliyar and Chandragiri.

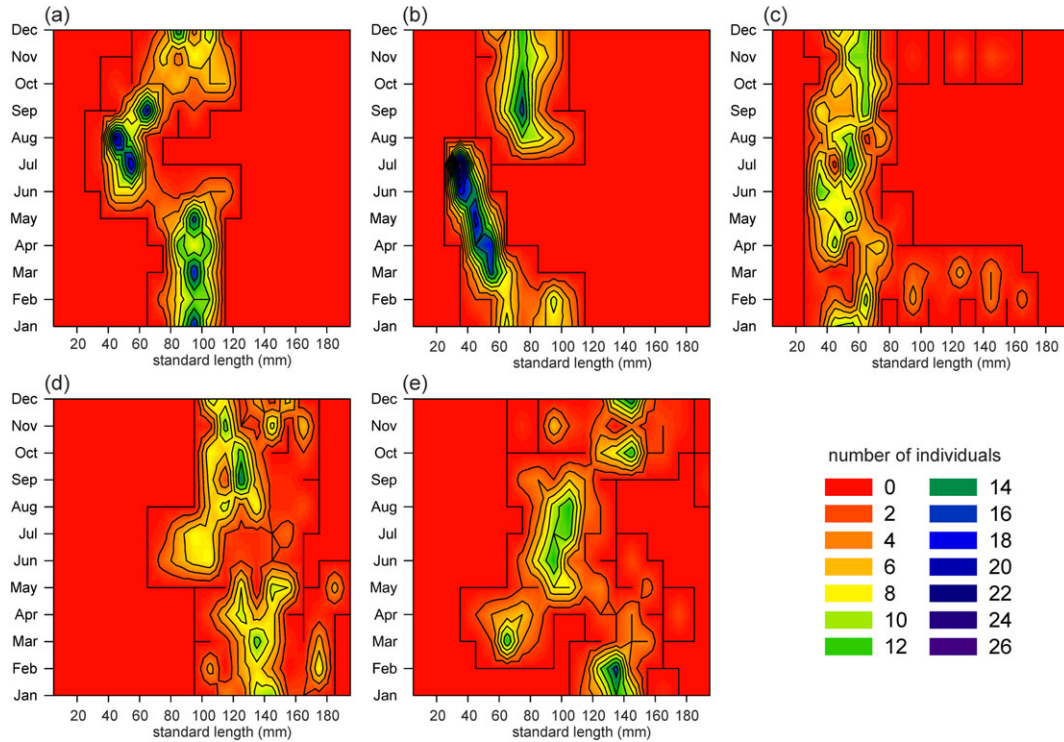


FIGURE 2 Distribution of length frequencies of redline torpedo barbs across five rivers in the Western Ghats: (a) Valapattanam, (b) Chaliyar, (c) Chandragiri, (d) Chalakudy, and (e) Periyar

3.2 | Growth and mortality

The RLTBs occurring in the Chalakudy and Periyar rivers comprise the larger-growing lineage (mean asymptotic length $L_{\infty} = 199.5 \pm 7.4$ mm; range of 194.25–204.75 mm) within the RLTB

species complex (Figures 3, 4). The growth coefficient value (K) also varied considerably between different lineages (Figure 4), with the highest K value observed among RLTBs occurring in the Valapattanam (Table 1), indicating that the growth pattern of these EDLs in RLTBs are different. The fishing mortality rate (F) was higher

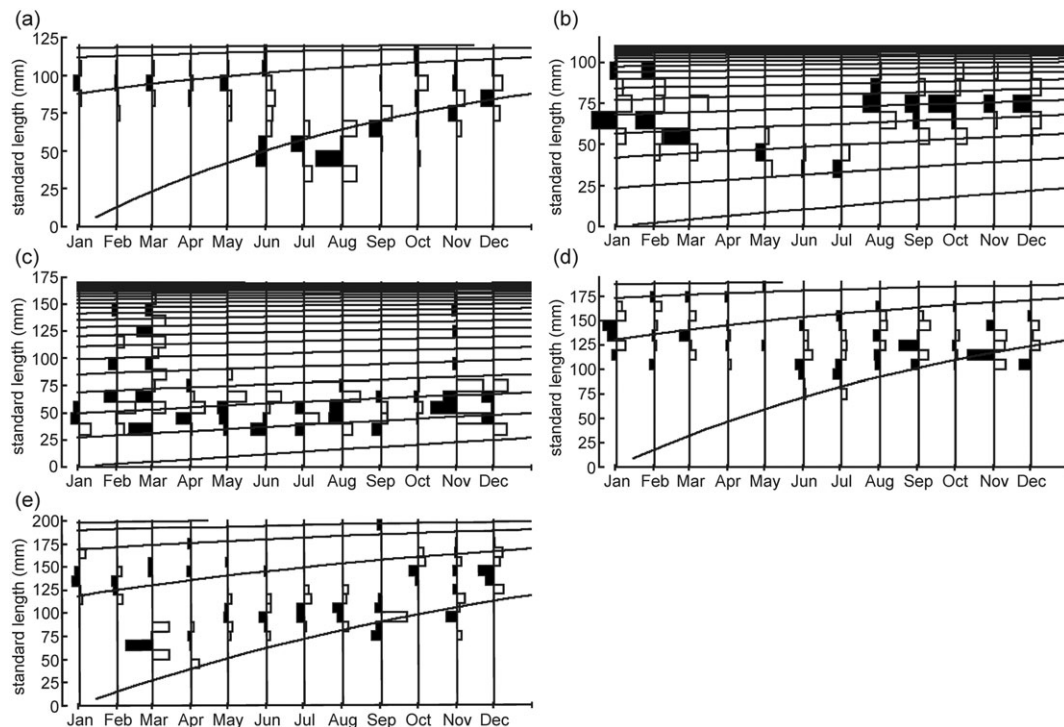


FIGURE 3 von Bertalanffy growth curve of redline torpedo barbs in five rivers in the Western Ghats: (a) Valapattanam, (b) Chaliyar, (c) Chandragiri, (d) Chalakudy, and (e) Periyar

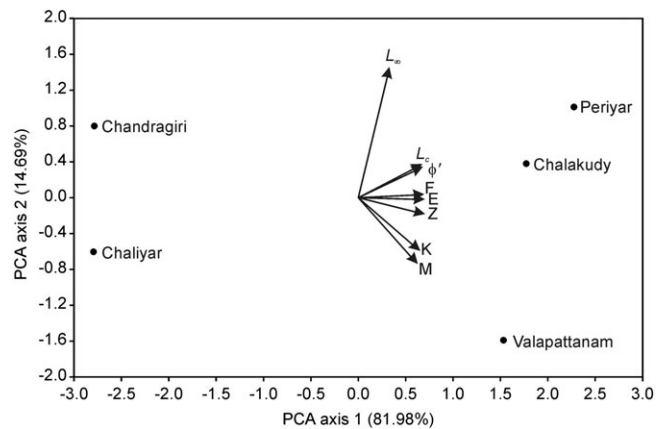


FIGURE 4 Principal component analysis based on parameters related to growth, mortality, and exploitation of the redline torpedo barbs in various rivers of the Western Ghats. Values in parenthesis are the percentages of variation explained by factors. Abbreviations are defined in the legend to Table 1

than the natural mortality rate (M) for RLTBs in the Chalakudy, Periyar, and Valapattanam rivers (Figure 4; Table 1), suggesting that these populations were under high fishing pressure. In comparison, Chaliyar and Chandragiri populations had a lower rate of fishing mortality (0.093 and 0.023 year⁻¹, respectively) than natural mortality (0.436 and 0.306 year⁻¹, respectively).

3.3 | Exploitation

The length at first capture (L_c) obtained from the probability of capture generated from the catch curves was 65.41 – 127.04 mm (Table 1). In the River Chandragiri, L_c was just 38% of L_∞ , whereas it was 57 – 64% of L_∞ in the Chalakudy, Periyar, and Chaliyar rivers. This harvest of small-sized individuals is alarming, as it indicates that specimens may be getting caught even before they become mature and contribute to further recruitments. The exploitation level (E) of RLTBs in the Chalakudy, Periyar, and Valapattanam were higher (0.6 , 0.74 , and 0.59) than the expected optima (E_{50}), indicating that local populations at these sites are overfished (Table 1). The exploitation level (E) in the Periyar River was also very close to the exploitation level at maximum yield per recruit (E_{max} ; Table 1), indicating severe fishing pressure. In general, populations of RLTBs in the Periyar, Chalakudy, and Valapattanam rivers had high exploitation levels and fishing mortality, compared with the Chandragiri and Chaliyar rivers (Figure 4).

4 | DISCUSSION

4.1 | Population dynamics and harvest levels

The intrinsic rate of increase in a population is strongly related to the size at first maturity (Vandermeer & Goldberg, 2003). The size at first maturity for the RLTBs is known to be 85.33 ± 1.52 mm T_L in males, and 95.66 ± 1.15 mm T_L in females (Solomon et al., 2011). Length–frequency analysis suggests that a large share of the RLTBs is collected for trade before attaining sexual maturity. Collecting small fish before they mature and breed leads to a slow recovery of exploited populations (Myers & Mertz, 1998), as well as to a reduction in fisher productivity and profit (Isaac & Ruffino, 1996), and is therefore unsustainable in high-value aquarium fisheries such as that for the redline torpedo barb.

Current observations show that the maximum total length (T_L) for RLTBs is greater than previously observed (John, 2009; Sajeevan, Mercy, & Malika, 2015), and the calculated mean asymptotic length (L_∞) indicates that the fish could grow to larger sizes than have been recorded in the wild.

The growth coefficient (K) of the RLTBs is comparable with cyprinids such as *Hypseleobarbus carnaticus* (0.5 – 0.65 year⁻¹; Manojkumar & Kurup, 2010) and *Dawkinsia filamentosa* (1.19 – 1.20 year⁻¹; Wijeyaratne & Perera, 2003), species that co-occur in their native range. Although the growth performance index (ϕ') of species within the same family is expected to be more or less similar (Moreau, Bambino, & Pauly, 1986), fish populations subjected to overfishing are known to adapt to a higher growth rate (Regier & Loftus, 1972; Spangler et al., 1977). The higher growth rate among populations in three rivers – Chalakudy, Periyar, and Valapattanam – could therefore be because they have been overfished in the recent past (see also Sajeevan et al., 2015), as these sites were the epicentres of RLTB collections throughout the last decade (Raghavan et al., 2009).

A ratio between total mortality and growth coefficient (Z/K) of <1.0 indicates a growth-dominated population, whereas a ratio of >1.0 indicates a mortality-dominated population (Etim, Lebo, & King, 1999). The local populations of RLTBs in all five rivers studied were dominated by mortality ($Z/K = 1.94$ – 4.00). In particular, the fishing mortality in three rivers (i.e. Chalakudy, Periyar, and Valapattanam) was very high, suggesting that 1.7 – 2.6 times as many fish are being caught as were present at the beginning of the fishing season. This is an alarming situation as it indicates that this overfishing could lead to a gradual loss in recruitment, resulting in severe population declines in the near future.

TABLE 1 Growth-, mortality-, and exploitation-related parameters of redline torpedo barbs from different rivers in the Western Ghats

Site	L_∞	K	ϕ'	Z	M	F	E	E_{50}	E_{max}	L_c
Valapattanam	120.75	1.31	4.28	3.32	1.34	1.98	0.60	0.45	1.00	97.71
Chaliyar	110.25	0.24	3.47	0.53	0.44	0.09	0.17	0.41	1.00	70.27
Chandragiri	173.25	0.17	3.71	0.33	0.31	0.02	0.06	0.33	0.60	65.41
Chalakudy	194.25	1.11	4.66	2.82	1.12	1.70	0.60	0.39	0.72	110.54
Periyar	204.75	0.87	4.57	3.48	0.88	2.60	0.75	0.40	0.79	127.04

Abbreviations: L_∞ , asymptotic length (mm); K , growth coefficient (year⁻¹); ϕ' , growth performance index; Z , total mortality (year⁻¹); M , natural mortality (year⁻¹); F , fishing mortality (year⁻¹); E , current exploitation rate; E_{50} , exploitation rate where the stock is reduced to half its virgin biomass; E_{max} , maximum yield per recruit; and L_c , length at first capture (mm).

An open-access, common-pool fisheries management system creates a powerful economic incentive for overfishing (Porter, 2003). This is especially so in aquarium fisheries, because of the prevalent socio-economic forces and lack of a strong enforcement body (Shuman, Hodgson, & Ambrose, 2005). Although no studies on population dynamics and stock assessment of freshwater aquarium fishes are available, there are several documented records of local population extirpations of aquarium species from tropical freshwater ecosystems, based both on catch-per-effort data and on local knowledge (Crampton, 1999; Ng & Tan, 1997). This is in addition to a large number of studies that have implicated aquarium trade in the overfishing of marine species (Kolm & Berglund, 2003; Rhyne, Rotjan, Bruckner, & Tlustý, 2009; Tissot & Hallacher, 2003).

In an optimally exploited stock, fishing mortality (F) should be about equal to natural mortality (M), resulting in an exploitation rate (E) of 0.5 year^{-1} (Gulland, 1970). The exploitation rates (E) of RLTBs in three rivers (Chalakydy, Periyar, and Valapattanam) are higher than 0.5, indicating overfishing, whereas the exploitation level in the Periyar River almost equals the predicted E_{max} , indicating that local populations are under extremely high fishing pressure and are vulnerable to collapse, unless management plans are implemented urgently. Genetic bottlenecks detected for the RLTBs in the rivers Valapattanam and Chalakydy (Lakra, Mohindra, & Lal, 2007) could therefore be attributed to high fishing pressure and exploitation rates. In all but one river, (Periyar), the lengths at first capture (L_c) of the RLTBs were less than their mean sizes at first maturity, suggesting the possible occurrence of growth overfishing. Harvesting of small-sized individuals before they become mature can have drastic effects on wild populations, by decreasing recruitment.

Fecundity, sex ratio, and the rate and frequency of recruitment have a significant impact on the recovery rate of a species after exploitation. The redline torpedo barb is known to have a skewed (male-dominated) sex ratio, as well as an extremely low fecundity (Raghavan et al., 2009; Solomon et al., 2011). A change in sex ratio in response to overfishing has been well documented in marine reef fish (Coleman et al., 2000), but not in freshwater fish species. Whether overfishing is responsible for the changes in sex ratio in RLTBs needs to be investigated in greater detail.

4.2 | Conservation management plans

Developing sound conservation strategies for aquarium species requires the identification of populations warranting management because of potential overexploitation (Weese & Santos, 2009). We have identified three such populations (i.e. lineages/management units) of RLTBs in the rivers Chalakydy, Periyar and Valapattanam, where signs of overfishing are clearly evident. A combination of strategies, including restrictions on gear, enforcement of size limits, implementation of no-take zones, and closed seasons will be key to managing the RLTB fishery in the Western Ghats. Although some populations of RLTBs are protected inside National Parks and Wildlife Sanctuaries, others (e.g. entire populations of *S. chalakkudiensis*) remain outside the protected area network (Raghavan, Das, Nameer, Bujukumar, & Dahanukar, 2016). In order to allow RLTBs to mature before they are collected for trade, a minimum size limit of 110 mm

needs to be set, which is greater than the mean length at first maturity. Setting size limits should also be supplemented with restrictions on the mesh size of the nets used by collectors. If suitable gear restrictions are implemented effectively, there is little chance that the fishery will come in contact with 'yet to be mature' juveniles (Charles, 2001). As RLTBs are known to spawn from October to March (Solomon et al., 2011), a closed season for collection needs to be put in place during these 6 months to protect the spawning stock, and to help in increasing recruitment. The closed season that is currently enforced is mistimed, and extends from June to October (Solomon et al., 2011). There is also an immediate need to declare RLTB collection sites in the three overfished rivers as no-take zones until local populations are given enough time to rebound. Such no-take zones should be specifically located in critical breeding and recruitment habitats (Arthington, Dulvy, Gladstone, & Winfield, 2016). Although both voluntary and mandatory no-take areas/zones have been put into practice to promote responsible aquarium fisheries in marine environments (Dee, Horii, & Thornhill, 2014), their use in freshwater systems is poorly known (but see Rowley et al., 2008). The fact that at present there are very few management and conservation plans for the freshwater ecosystems of the Western Ghats makes it necessary for the implementation of such spatial closures to be mandatory.

Government and non-governmental organizations and agencies should also stop providing further developmental assistance and subsidies for promoting the export of endemic and threatened aquarium fishes in the Western Ghats, until baseline data on the population status of the species become available, and necessary management plans are put in place (Iyer, Raghavan, Dahanukar, Sood, & Molur, 2016). There is also a need for greater government involvement at the national level through the inclusion of RLTBs (as well as other endemic and threatened freshwater fish species) in the Wildlife Protection Act of India, which is the most important legal system for protecting threatened taxa in the country.

4.3 | Implications for global ornamental fisheries

The harvest and trade of threatened species for the aquarium pet market has been suggested as an emerging conservation issue (Raghavan et al., 2013), but the absence of quantitative studies on harvest levels and their implications on wild populations has resulted in a lack of serious global and local attention towards their management. This study on RLTBs provides important insights into the dynamics of exploitation of an endemic and threatened freshwater fish, which can form a baseline for hundreds of other endemic wild-caught species in the global aquarium trade.

It is widely suggested that small-sized, short-lived, early-reproducing, 'r-selected' species (e.g. tetra, *Paracheirodon* spp.) can withstand high levels of exploitation (Junk, 1984), whereas large-sized, late-maturing, 'K-selected' species with low fecundity (e.g. arowanas, *Scleropages* spp., and *Osteoglossum* spp.) are known to be biologically unsuited for ornamental fisheries (Moreau & Coomes, 2006; Raghavan et al., 2013; Rowley et al., 2008). In addition, there are hundreds of species from the rivers of South America and South/Southeast Asia that are poorly known with respect to their biology, ecology, and

demography, but are extensively collected for the pet trade. Many of these species may be unsuited for large-scale harvests, as is evident from their population decline and threatened status on the IUCN Red List (e.g. *Otocinclus cocama*; del Aguila & Chocano, 2016). The development of extractive ornamental fisheries invariably needs to be preceded by gathering data on species-specific biology and populations (Gerstner, Ortega, Sanchez, & Graham, 2006), resulting in selecting species based on biological features that make them robust to exploitation (Tlustý, 2002). It is also unwise to select species for ornamental fisheries solely based on generic assumptions of body size and early reproduction. This may not be appropriate, as demonstrated in the case of RLTBs, which are small in size yet possess peculiar reproductive characters, including extremely low fecundity and a skewed sex ratio (Solomon et al., 2011), making them unsuitable for large-scale collections. There is an urgent need, therefore, to understand in detail the natural history and population status of poorly known tropical freshwater fishes present in the international aquarium pet trade so as to promote sustainability. This case study from an exceptional hot spot of freshwater diversity and endemism has shown that unmanaged collection for the aquarium pet trade can potentially lead to overexploitation and population declines of range-restricted freshwater species. Studies such as these are warranted elsewhere in the tropics, where such fisheries have been in existence for several decades, but have been poorly monitored.

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