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Intense pressure on small and juvenile coral reef fishes threatens fishery production in Madagascar

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Abstract :

Size-based indicators are appropriate for monitoring status and guiding management of multi-species, multi-gear fisheries, such as coral reef fisheries. From May 2018 to April 2019, size distribution and composition of coral reef fish catches were monitored through a participatory landing survey in southwestern Madagascar. Fishers targeted a large diversity of fish taxa (75 families) and range of sizes (1.6–86 cm). Five predominant gears accounted for most of the catch (1360 [±39] t), including mosquito net trawl (27.7%), beach seine (26.8%), speargun (7.2%), gillnet (30.6%), and handline (7.1%). Due to widespread use of gears made from mosquito nets, 75% of fishes smaller than 9 cm and 47% of juvenile fishes were represented in the total catch number. Large-size taxa (Scaridae, Lethrinidae, Siganidae, Acanthuridae, Synodontidae, Mullidae, and Labridae) were mostly harvested as juveniles. Catches varied by 8%–70% throughout the year. Size of coral reef fish, annual catches, and catch rates all declined since the 1990s.

Keywords : bay of Toliara, ImageJ, management, mosquito net trawl, size distribution, small-scale fisheries

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Ethical statement- not applicable.

1. INTRODUCTION

In developing countries of the tropics, small-scale fisheries (SSF) remain poorly assessed despite their importance for national economies and coastal populations. SSF have long been overshadowed by the perceived importance of industrial fishing, yet attention to those fisheries has risen since the 1990s (Smith & Basurto, 2019). Most of SSF suffer from a lack of appropriate management (Costello et al., 2012), which directly impacts and compromises the health of ecosystems and the services and goods they provide to fishing communities (Babcock et al., 2013; van der Elst et al., 2005). Inefficiency of SSF management results in part from data deficiency and lack of institutional and financial resources for characterising and monitoring the state of these fisheries (Dowling et al., 2019). Specifically, historical information about catch and effort is often deficient, although these data are commonly required for conventional stock assessment or for estimating resource indicators (Babcock et al., 2013; van der Elst et al., 2005).

Varying methodologies and stock assessment tools have been developed to characterise data-poor SSF (e.g., Dowling et al., 2016; McDonald et al., 2018; Pons et al., 2020). These methods must be understood and implemented by fishery managers with limited technical and financial capacities. In multi-species and multi-gears SSF, size-based indicators appear particularly appropriate because the impact of fishing can be measured at the level of all exploited species (e.g., Froese et al., 2018; Hordyk et al., 2015; McDonald et al., 2018). For example, abundance of large individuals of target species and average size of catches should decline in response to fishing, while the proportion of small individuals in catches should increase (Graham et al., 2005). Size data can also be used to estimate the proportion of individuals in catches above or below the size at maturity, a key indicator of fishery exploitation (Froese, 2004). Generally, size-based indicators (e.g., mean length, minimum and maximum length (Lmin and Lmax), and length at maturity (L_{50})) have been proposed to characterise impacts of fishing and to assess health and exploitation level of marine populations, which would help to implement ecosystem-based fisheries management (Rochet & Trenkel, 2003).

Among SSF, coral reef fisheries are complex to characterise and regulate, so are particularly threatened by overfishing, due to high diversity of exploited species and the diverse, and often informal, nature of SSF activities (Guillemot et al., 2009; Leenhardt et al., 2016). Multi-annual assessments of the size structure of catches from coral reef fisheries can detect overfishing, monitor changes in resource status over time, and propose resource management measures (Ault et al., 2005; Dulvy et al., 2004; Gough et al., 2020; Hicks & McClanahan, 2012; Humphries et al., 2019; Jennings & Dulvy, 2005). Unfortunately, sampling designs often do not allow for estimating size structure of fish catches and gear selectivity of the whole fishery. Instead, size structure can only be characterised within catch samples, which is not consistent with common recommendations for fishery assessment due to heterogeneity in the use of fishing gears (Gulland & Rosenberg, 1992). Moreover, although catch composition typically varies intra-annually in coral reef fisheries (Kuo et al., 2001), seasonal variation in catch size structure has rarely been evaluated (but see Teh et al., 2007). These limitations reduce the relevance of size-based indicators estimated for most of these fisheries for delivering operational diagnosis and fine-tuned fishery management advice, such as fishing effort restrictions across gear types (Breen et al., 2016).

In Madagascar, coral reef fisheries face severe sustainability issues due to management deficiency, and a growing coastal human population and fishing pressure (Le Manach et al., 2012). We aimed to determine the size structure of coral reef catches across fishing gears operated in southwestern Madagascar. We monitored the size distribution and composition of coral reef fishery catches over a 12-month period through participative landing surveys. Our primary goal was to estimate the catch level and composition ~30 years after the last fishery assessment (Laroche & Ramananarivo 1995; Laroche et al. 1997). Our second goal was to increase effectiveness of monitoring and management of these coral reef fisheries.

2. METHODS

2.1. Study area

This study was conducted in the Bay of Toliara, southwestern Madagascar (Figure 1), one of the largest coral reef fisheries of the country, including fishing grounds in the shallow (<15 m) lagoon, 18 km-long barrier reef, and 272 km² reef slope (Behivoke, 2022). The coastal area is the most densely populated in the Southwest region due to its proximity to the city of Toliara and surrounding villages, which have a human population of about 350,000 inhabitants.

In the study area, SSF play an important role as a livelihood and main source of income due to high urban demand for fish, ongoing migration from inland to coastal areas, and scarce alternative economic opportunities (Davies et al., 2009). Neither locally-based fishing rules nor territorial user rights have been established for the fishery. National fishing regulations on seine use have been weakly enforced, which has resulted in free access to marine resources for 892 traditional, 2.5–7 m long, outriggers sailing fishing boats (~2,000 fishers) in the area in 2017 (Behivoke et al., 2021). These boats make daily fishing trips that typically last only 4-7 hours because ice cooling storage is not available. Five fishing gears are commonly used in the area, including 10-45 mm mesh-size gillnets, handlines, spear guns, mosquito-net trawls, and beach seines with mosquito-net codend (Table 1).

2.2. Data collection

From May 2018 to April 2019, a participatory catch survey was carried out in all fishing villages on the bay of Toliara (Figure 2, Step 1). Participation of fishers and community leaders in the survey aimed to improve local understanding and perceived usefulness in survey results and cost effectiveness of the monitoring program (Brenier et al., 2012). We explained to all 411 participant fishers future information use and provided a small financial incentive (USD 1.2

month^{-1}). The survey was structured in six 2-month periods: May-June 2018, July-August 2018, September-October 2018, November-December 2018, January-February 2019, and March-April 2019.

During each period, 42 to 123 boats were selected using a stratified sampling strategy by gear based on information obtained during a preliminary fisher survey. The sampling rate was roughly proportional to the total number of boats per gear and village. Sampled boats varied across survey periods to account for heterogeneity of fishers' activity. We assumed that data were representative of fishing gear use due to the large sample size and distribution of the sample among gears over the whole study area. Fishers monitored their catch each trip during ~30 consecutive days (Figure 2, Step 3). After each fishing trip, fishers recorded weight of their total catch by taxonomic categories (invertebrates, small pelagic fishes, coral reef fishes) using a scale with a precision of 250 g.

For characterizing catch composition, fishing trips of selected boats were subsampled once per survey period, through a landing survey (Figure 2, Step 3). For each trip, reef fish catches were observed for gillnet, handline, and speargun catches (i.e., the entire catch of the trip was purchased) and sampled for mosquito net trawl and beach seine catches (i.e., a 1-kg random sample of the catch of each trip was purchased) (Figure 2, Step 4). In the laboratory, coral reef fishes were identified to the family level and photographed. Total length of each individual fish was measured using the automatic procedure developed by Andrialovanirina et al. (2020). For each fishing trip of the catch landing survey, information on fishing gear, total weight of the catch, weight per catch category (coral reef fish, small pelagic fish, and invertebrates), sample weight (for mosquito net trawl and beach seine), and size distribution per family was collected and uploaded into a database.

2.3. Data analysis

2.3.1. Catch level and diversity

Catch data were extrapolated to the whole fishery of the Bay of Toliara following conventional methods of fishery monitoring and assessment (Appendix 1). First, catch weight (C = kg) of each category of fish (coral reef and small pelagic fishes) was estimated for each gear and survey period (Figure 2, Step 2). The daily activity rate (A = $trip*day^{-1}*fisher^{-1}$) of sampled fishers (i.e., fishing frequency) was calculated as the ratio of the total number of trips (T) by the survey duration (D = fisher day). The mean daily catch per fisher (Cd,f = $kg*day^{-1}*fisher^{-1}$) was estimated by multiplying the mean catch per trip (Ct = $kg*trip^{-1}$) by A during each survey period. Finally, C was estimated by multiplying Cd,f by the survey period duration (P = days) and the total number of fishers for that gear (Fg). The variance and 95% confidence interval of catch weight estimates of each stratum were calculated following the statistical procedure for two-way stratified sampling using the package 'Rmisc' version 1.5 and the summarySE function (Rayan, 2013) of the R software version 3.5 (R Core Team, 2018).

Catches were summed across statistical strata (i.e., gear x survey period) to estimate the annual catch of the whole fishery. The variance and 95% confidence interval of annual catch weight estimates (total and by gear type) were calculated based on the intra-stratum variance and sample size (Cadima 2005; Appendix 1).

Second, composition of the catch of coral reef fishes was estimated for each fishing trip of the landing survey (Figure 2, Step 3). Reef fish were identified to the family level based on morphospecies. The number of coral reef fish per family was counted in catch (i.e., for gillnet, handline, and speargun) or estimated from samples (i.e., for mosquito net trawl and beach seine) by multiplying the number of individuals per family in each sample by the ratio of the weight of the total catch of that trip to the sample weight. The number of fish of each family in catches (N) was then estimated for each gear and survey period by multiplying the mean daily number of fish harvested per fisher (Nd,f = fish*day^{-1}.fisher^{-1}) by the survey period duration (P = days) and the total number of fishers for that gear (Fg) (Figure 2, Step 4). Catch numbers were finally summed across statistical strata (i.e., gear x survey period) to estimate the total number of fish in annual catches of the whole fishery. The 95% confidence interval of catch number estimates was also calculated as that of the catch weight estimates as described above. Fish families that reached more than one million individuals in total annual catch were designated as primary target families.

2.3.2. Size distribution of coral reef fishes

The size distribution of coral reef fish catches was estimated by using extrapolation method (Figure 2, Step 4). For each fishing trip of the catch landing survey, the number of coral reef fish per family in each 1-cm size class was counted in the catch or estimated from catch samples. The same procedure as was used for estimating total catch number was followed for estimating the size-class distribution of catches of each coral reef fish family for each gear and survey period. Results were summed across fish families to estimate the size-class distribution of total annual catch of the whole fishery.

Taxa identification was limited to the family level, so mean size at maturity was approximated for each family as follows: (i) Fricke et al. (2018)'s checklist in Madagascar was used to establish the list of species of each family in coral reef ecosystems, (ii) the size at maturity of these species was retrieved from FishBase (Froese & Pauly, 2021), and (iii) the mean size at maturity of these species was calculated as the size at maturity for corresponding families (Appendix 2). The latter was used as a threshold for estimating juvenile and adult fish catches at the family level and for the whole fishery using the same procedure that was used for estimating size-class distribution.

To detect seasonal variation in catch size structure, study periods were grouped into a cold season, from May to October 2018, and a warm season, from November 2018 to April 2019

(Clausade et al. (1971). Size structure was summarized by gear, survey period, and season. Changes in median size across those factors was tested using a Generalized Linear Mixed Model (GLMM). A unique identifier was attributed to each fishing trip and set as a random effect because individual fish sizes were nested within fishing trips. Other variables (season, fishing gear, survey period, and interaction terms) were set as fixed effects (Appendix 3). Size data were ln-transformed prior to analysis to approximately conform to normality (as checked by residual plot). We used the lmer and lmerTest functions of the package 'lme4' version 1.1.19 in R (Bates et al., 2015) to run the GLMM. Three size categories were defined according to the observed size range in catches: small (≤9 cm), medium (>9-15 cm), and large (>15 cm).

3. RESULTS

3.1. Annual catches

The 411 boats (46% of all boats) sampled fished 120,807 trips (65% of total fishing effort) (Table 1). Each fisher mostly used one gear during a single fishing trip. The number of trips used for characterizing catch composition and fish size ranged from four to 53 per gear x survey period stratum, due to unpredictable factors on the sampling date (e.g., availability of fishers, number of fishers at sea). The catch from 561 trips (0.46% of trips surveyed) by all fishing gears and survey periods (Table 2) included 23,110 fishes. The number of measured fishes varied among gears according to the weight or number of fish subsampled per gear (Table 2).

Total catch of reef and small pelagic fishes was 1,360 (±39) t*year^{-1}, or an average catch rate of 5.0 (±0.1) t*km^{-2}*year^{-1} (cf Appendix 1). Reef fish catch corresponded to 68.7 (±5.4) million individual fish (with a mean weight of 50 g per fish). Mosquito net trawls (72%; 370 (±50) t) and beach seines (22%; 351 (±73) t) harvested 94% of the total number and 53% of the total weight of reef fishes. Other gears contributed for only 6% and 44% of annual reef fish catch in number and in weight, respectively (Table 3). Total catch of small pelagic fishes was estimated at 50 (±5.7) t*year^{-1} (3.6% of total fish catch). Coral reef fish catches were composed of 75 families (Appendix 2). Overall catch in number was dominated by 13 families (85%), including Labridae (24.4%), Gobiidae (12.6%), Blenniidae (9.1%), Scaridae (7.7%), Siganidae (7.6%), Leiognathidae (3.9%), Apogonidae (3.9%), Mullidae (3.7%), Lethrinidae (3.6%), Syngnathidae (3.4%), Pomacentridae (1.7%), Synodontidae (1.7%), and Acanthuridae (1.6%).

Coral reef fish sizes ranged from 1.7 cm to 86.0 cm (median length = 9.0 cm) and exhibited a unimodal distribution that peaked at 5-6 cm (Figure 3). Fish >30 cm contributed only 2.8% of the catch. Overall, 47% of individual fish were juveniles. Fish length differed significantly among gears (Figure 4). Mosquito net trawls (6.3 cm median length, $P < 2.10^{-16}$, Appendix 3) and beach seines (7.3 cm, $P = 0.023$, Appendix 3) caught significantly smaller fish than gillnets (15.2 cm) and handlines (14.6 cm), while spearguns caught significantly larger fish that both latter gears (18.7 cm, $P = 0.0007$, Appendix 3). Small fish (≤9 cm, 72% of total catch) were mostly harvested by mosquito net trawls (80%) and beach seines (20%). Medium-sized fish (9-15 cm, 16% of total catch) and large fish (>15 cm, 6.5% of total catch) were mainly harvested by other gears.

Juveniles were 54-96% of overall catch numbers of seven predominant, large-sized fish families (Scaridae, Lethrinidae, Siganidae, Acanthuridae, Synodontidae, Mullidae, and Labridae). Juvenile fish were a small proportion (from 0 % to 22.1 %) of the catch of small-sized fish families (Gobiidae, Syngnathidae, Pomacentridae, Apogonidae, Bleniidae, and Leiognathidae, Table 4) that were mainly harvested by mosquito net trawl and beach seine.

3.2 Temporal variations in catches

Most fish were harvested during the warm season (60%), with the annual minimum in July-August 2018 (5.7 million fish) and a gradual increase up to 18.7-million fish in March-April 2019 (Figure 5A). This temporal pattern was mostly attributed to the number of fish ≤9 cm that markedly increased in catches during the warm season. The catch size structure of each survey period was consistently unimodal, with a peak at 5-6 cm, except in July-August 2018, when a second mode was at 2-3 cm (Figure 5A).

Fish size varied through time for all gears (Figure 5B) although not significantly except for speargun and beach seine. Median fish length of speargun catches decreased significantly from 19.2-28.7 cm to 12.2 cm at the end of the warm season (P=0.049, Appendix 3) (Figure 6). Conversely, median fish length of beach seine catches increased significantly from 4.3-10.2 cm to 12.2 cm at the end of the warm season (P=0.038, Appendix 3).

Most families peaked at 0.6-5.8 million fish in two-month periods (Figure 7, Group 1). Peak catches primarily corresponded to small fishes caught during or at the end of the warm season, except for Siganidae and Syngnathidae, which contributed to high fish catches in March-April 2019 (Figure 5A). In contrast, catches of three families (Acanthuridae, Pomacentridae, and Synodontidae) varied slightly through time and remained low (700 to 0.3-million of fish) over the year (Figure 7, Group 2). Within this group, catch numbers increased between July 2018 and February 2019.

4. DISCUSSION

4.1. Fishery indicators suggest severe decline in coral reef fish resources

Our study is one of the first case studies of coral reef fisheries to describe intra-annual change in catch size structure and diversity at the scale of a whole fishery. We found that a large range of coral reef fish taxa and sizes were intensely harvested by this major fishery in Madagascar. Overall annual catch was 35% lower (-640 $t*year^{-1}$) than the estimated catch in the Bay of Toliara in 1990 (Laroche & Ramananarivo 1995). This severe decline corresponded to a 58% decline in the spatial catch rate (12 $t*km^{-2}*year^{-1}$ to 5.0 $t*km^{-2}*year^{-1}$) as fishing grounds expanded from 153 km^2 to 273 km^2 over the ~30-year period. Catches were largely dominated by individuals smaller than 9 cm throughout the year. Most of these small fishes were harvested by mosquito net trawls and beach seines, although these gears were used by only 29% of fishers.

In contrast, 30 years ago, catches were dominated by Lethtinidae, Haemulidae, Siganidae, and Lutjanidae, most of which ranged 15-20 cm and were harvested by gillnets (Laroche et al., 1997; Laroche & Ramananarivo, 1995). Furthermore, we observed that most of the large-sized fish taxa harvested were likely juveniles, which suggests intense exploitation of coral reef fish as in other coastal fisheries in western Madagascar (Gough et al., 2020) and the western Indian Ocean (Hicks & McClanahan, 2012; McClanahan & Mangui, 2004). Decreased catch rates and fish size in the Bay of Toliara coincided with degradation of marine ecological conditions and intensification of fishing activity, including mosquito-net trawling, beach seining, and gillnetting (Brenier et al., 2012; Bruggemann et al., 2012). In East Africa, growing use of mosquito nets in coastal fisheries since the 2000s was attributed to decreased yield, increased competition among fishers, and availability of cheap mosquito nets initially introduced for malaria control (Bush et al., 2017).

Our findings suggest that mosquito-net trawls exacerbated fishing pressure on coral reef fishes, which likely contributed to the dramatic decline in overall catch. Other sources of ecological perturbation could also explain the observed shift in catch diversity. Hand-made mosquito-net trawls target similar-sized fish (≤9cm) as beach seines, so strongly increased (+52%) overall fishing pressure on small fish in the area, including juvenile fish. Moreover, the catch composition of mosquito-net trawls overlapped with other gears (Labridae, Siganidae, Scaridae, and Mullidae) that target these fishes at larger size. Mosquito-net trawls that are used in shallow areas that are generally not exploited by other gears thereby increased the spatial extent of fishing grounds and allowed access to marine ressources that were not previously targeted. For instance, we observed that some families (Gobiidae and Blenniidae) caught by mosquito-net trawls were not, or only lightly, harvested by other gears. Consequently, overall diversity of exploited fish increased from 28 fish families in the 1990s (Laroche et al., 1997) to 75 fish families in our survey, highlighting the high diversity of exploited resources in the study area. Such a diversification in target taxa and fishing areas may have mitigated effects of increased fishing on overall catch (Robinson et al., 2020). However, shallow seagrass beds that were targeted by mosquito-net trawl fishers are nursery habitats for many coral reef fish species (Beck et al., 2001). Mosquito-net trawls harvested most fish species at juvenile stages (Raharinaivo et al., 2020), which would partly extend to beach seines with similar size selectivity and catch composition as mosquito-net trawls. Our results showed that adults of small-sized taxa (e.g., Gobiidae, Blennidae, Labridae) were a significant fraction of mosquito-net trawl catches.

4.2. Management implications

Our results suggest that coral reef fish catches in the Bay of Toliara are dominated by juveniles of large-size fish taxa of high commercial value. Our study was limited to family-level taxonomic identification because species-level identification using DNA barcoding is still being developed. Different species within the same family (particularly large-bodied species) can still differ considerably in size at maturity, so species-specific size at maturity estimates would enable more accurate estimation of juvenile and mature fish in catches.

The estimated high proportion of juvenile fish in catches has major ecological and socioeconomic implications for fishery sustainability. For example, high harvest of juvenile fish jeopardizes spawning biomass and subsequent marine resource renewal (Pauly et al., 2005), which may a driver of the decline in total annual catch in the Bay. In addition, harvest of medium- and large-sized fish may have impacted reef fishery resources. In contrast, such a harvest strategy also generates socioeconomic vulnerability within fishing communities by increasing interannual variation on reproductive success and larval supply, thereby increasing variation in catch levels. In addition, juvenile fish were harvested at a smaller size than what would produce maximum yield per recruit (Froese, 2004), thereby implying growth overfishing by the fishery, a state that further reduces economic performance.

Despite such worrisome fishery patterns, productivity was unexpectedly high. Average spatial catch rate of the fishery declined, but not below the sustainability threshold of coral reef fisheries since the 1990s (~5 t*km^{-2}*year^{-1}; Newton et al. 2007). This threshold may vary among locations, particularly in relation to the mean trophic level of the catch (Newton et al., 2007). High productivity in our study area and seasonal peaks of small fish catch may be partly explained by seasonal supply of larvae and juvenile fish originating from nearby areas where fishing pressure was likely lower (Jaonalison et al., 2020). Such connectivity may have contributed to renewal of exploited ressources in the Bay of Toliara for decades. Alternatively, elective exploitation patterns that approximate a "balanced harvest approach" may have changed the trophic level of the catch and productivity of the coral reef system. A "balanced harvest approach" distributes fishing pressure across all size classes and trophic levels in proportion to (usually unknown) natural productivity (Garcia et al., 2012), which would theoretically allow higher maximum sustainable yield than selective fishing (Jacobsen et al., 2014). In our study, the fishing gear combination allowed harvesting a wide range of fish sizes (1.7 to 86 cm), species (several hundred species in 75 families; Jaonalison, 2019), life stages, and trophic groups in all marine habitats of the bay.

The concept of balanced harvest has not been explored in coral reef ecosystems and its ecological, environmental, and economic foundations, along with its applicability to real-life fishery settings have raised much debate (Froese et al., 2016; Pauly et al., 2016). Approximations to a balanced harvest approach are a fairly common consequence of SSF in tropical regions that suffer from lack or absence of fishing regulation, as in the bay of Toliara. Importantly, the expected theoretical benefit of balanced harvest on fishery productivity would only be perceived if juvenile fish harvest does not exceed a context-dependent productivity threshold, which remains difficult to define in practice in highly diverse fisheries.

Managing fishing gear selectivity across fish sizes would be crucial for managing the fishery in the Bay of Toliara (e.g., Babcock et al.,2018; Humphries et al., 2019). Mosquito-net trawling and beach seining should urgently be reduced in the area, as a precautionary measure. Beach seines and mosquito net trawls have been prohibited in Madagascar since 2015 (Fishing Code Chapter 4 article 17 of law n°2015-053). However, enforcing the national ban on mosquito nets would severely affect many poor fishing and consumer households, which makes that regulation very impopular and a source of conflicts despite support by environmental organizations. An alternative strategy would be to regulate mosquito-net trawling to balance fishery productivity and contribute to socioeconomic and food security (Short et al., 2018). From a socioeconomic point of view, small fish are crucial for subsistence of rural communities in less advanced countries, as a source of protein, micronutrients, and income (Hutubessy et al., 2014; Kolding et al., 2016). In Madagascar, small coral reef fish, marketed fresh or dried, provide low-cost protein for vulnerable social groups as far away as the central highlands. Beach seines and mosquito-net trawls also capture small pelagic fishes (<4% of all fish caught in our study) and invertebrates, thereby generating additional income to mitigate socioeconomic impacts of declining coral reef fish catches on local economies. Mosquito-net trawling and beach seining may be regulated by adopting appropriate community-based measures supported by fishery regulations, such as limiting the number of users in fishing villages (e.g., by directing new fishers to other gears), reducing net size (e.g., setting a maximum headline length), or temporary partial closing of nursery areas. Government health services would also be key in directing mosquito net use to malaria control rather than fishing.

To be ecologically effective and socially acceptable, fishery management must account for resource biology and the livelihoods and socioeconomic opportunities of fishing households while building on existing formal and informal institutional processes (Allison & Ellis, 2001). The capacity of fishing communities to self-implement regulation of juvenile and adult fish exploitation at the scale of the Bay of Toliara through restricted mosquito-net trawling, beach seining, and gillnetting will be a key element in determining sustainability of the fishery. Effective implementation of such regulations would enhance socioeconomic returns to fishers in the next decade, as in other coral reef fisheries. Collaborative research will improve monitoring of the fishery, community awareness, and commitment to regulated fishing practices, and ultimately contribute to improved resource management and socio-economic outcomes for fishing communities.

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TABLES

Table 1: Number of boats, range of boat size, number of fishing trips estimated and surveyed for five fishing gears in the Bay of Toliara, Southwestern Madagascar from May 2018 to April 2019 (from Behivoke, 2022)

	Fishing gears				
	Gillnet	**Handline**	**Speargun**	**Mosquito net trawl**	**Beach seine**
Number of boats (% total number)	358 (40.1%)	142 (15.9%)	133 (14.9%)	131 (14.7%)	128 (14.4%)
Range dimension of total length (m)	75-164	_	_	19-77	84-118
Total number of trips estimated	78,196	29,098	24,981	1,814	2,385
Total number of trip surveyed (% of trips estimated)	49,800 (63.7%)	21,721 (74.6%)	16,341 (65.4%)	16,447 (60.3%)	16,496 (59.3%)

Table 2 : Number of subsampled trips and fish measured for length in a landing survey of five fishing gears in 2-month survey periods in the Bay of Toliara, Southwestern Madagascar from May 2018 to April 2019. *1-kg samples were taken from mosquito net trawl and beach seine catch per trip while the entire gillnet, handline, and speargun catch per trip was observed.

	Fishing gears				
	Gillnet	**Handline**	**Speargun**	**Mosquito net trawl***	**Beach seine***
1.Number of subsampled trips					
May-Jun 2018	12	9	6	12	4
Jul-Aug 2018	30	26	9	18	3
Sept-Oct 2018	41	21	11	11	3
Nov-Dec 2018	52	25	16	21	10
Jan-Feb 2019	39	21	18	16	10
Mar-Apr 2019	53	24	16	14	6
Total (in % of total number)	227 (40.7%)	126 (22.6%)	76 (13.6%)	92 (16.5%)	36 (6.4%)
2.Fish length measurements					
Number of fish (% of all fish measured)	5,014 (23.2%)	2,223 (10.2%)	731 (3.3%)	11,545 (53.4%)	2,089 (9.6%)

Table 3: Estimated annual coral reef fish catch (number and weight ± 95 % confidence intervals) by five fishing gears from main target families in the Bay of Toliara, Southwestern Madagascar from May 2018 to April 2019. Families representing more than 6.5% of catches by any gear are presented.

	Gillnet	**Handline**	**Speargun**	**Mosquito trawl net**	**Beach seine**
1. Annual catch					
Total weight (t)	406 (± 48)	97 (±15)	102 (± 27)	369 (± 50)	382 (± 70)
Total weight of reef fishes (t)	400 (± 48)	93 (±15)	94 (±27)	369 (±50)	350 (±73)
Proportion of total weight of reef fishes (%)	30.6%	7.1%	7.2%	27.7%	26.8%
Total number in million (% of total number)	2.8×10^6 (4.1%)	0.8×10^6 (1.2%)	0.4×10^6 (0.7%)	49.4×10^6 (72.1%)	15×10^6 (21,9%)
2. Catch diversity					
Number of families	51	43	31	48	43
Main target families	Lethrinidae (17.8%), Pomacentridae (9.9%), Scaridae (7.3%), Acanthuridae (7.2%), Labridae (7%), Mullidae (7%), Carangidae (6.3%)	Labridae (15.7%), Lethrinidae (15.3%), Pomacentridae (9.1%), Mullidae (7.5%), Siganidae (6.8%), Lutjanidae (6.7%), Serranidae (6.6%)	Pomacentridae (18.6%), Acanthuridae (15.9%), Labridae (11.3%), Scaridae (7.3%), Scorpaenidae (6.6%), Serranidae (6.6%), Mullidae (6.1%)	Labridae (31%), Gobiidae (14.9%), Blenniidae (12.6%), Scaridae (6.1%)	Siganidae (16.1%), Leiognathidae (15%), Scaridae (13%), Mullidae (8.8%), Gobiidae (8.7%), Apogonidae (7.4%), Labridae (7.4%)

Table 4 : Estimated catch numbers (millions ± 95% confidence intervals) of coral reef fish families in three size categories and maturity stages (from www.fishbase.org) for all fishing gears in the Bay of Toliara, Southwestern Madagascar from May 2018 to April 2019.

1.Fish size categories				**2. Maturity stage**	
Coral reef fish families	**Small ≤9cm**	**Medium >9cm-15cm**	**Large >15cm**	**Mean length at maturity (cm)**	**Proportion juvenile (in %)**
Labridae	13 (±1.6)	2.5 (±0.5)	0.6 (±0.1)	6.7	54.3
Gobiidae	7.2 (±0.9)	1.3 (±0.3)	0.3 (±0.1)	2.5	0
Blenniidae	6.2 (±1.3)	0.01 (±0.008)	0	3.8	16.7
Scaridae	4.0 (±1.3)	1.2 (±0.4)	0.2 (±0.02)	15	95.2
Siganidae	3.7 (±1)	1.5 (±0.6)	0.2 (±0.06)	13.3	93.2
Leiognathidae	2.5 (±0.9)	0.3 (±0.1)	0	5.5	22.1
Apogonidae	2.7 (±0.5)	0.1 (±0.06)	0.003 (±0.001)	3.3	7.6
Mullidae	1.5 (±0.2)	0.9 (±0.2)	0.2 (±0.02)	9.3	59.8
Lethrinidae	1.8 (±0.3)	0.5 (±0.05)	0.4 (±0.1)	20	96
Syngnathidae	0.2 (±0.07)	2.0 (±0.4)	0.2 (±0.05)	4.5	0.7
Pomacentridae	0.7 (±0.1)	0.4 (±0.05)	0.08 (±0.01)	3.7	1.9
Synodontidae	0.6 (±0.1)	0.5 (±0.1)	0.1 (±0.02)	11.4	74.6
Acanthuridae	0.6 (±0.1)	0.2 (±0.03)	0.2 (±0.06)	14.8	78.4
Other families	4.0 (±0.4)	2.3 (±0.3)	0.2 (±0.2)	_	54.8

FIGURES

Figure 1: Fishing grounds within the main geomorphological units of the Bay of Toliara, Southwestern Madagascar surveyed from May 2018 to April 2019. The lagoon (light blue), shallow terrace (green area), coral reef patches (grey area), and outer reef slope (deep-blue area) are shown (adapted from Behivoke, 2022). Numbers correspond to villages (1 = Sarodrano; 2 = Ankilibe; 3 = Ankiembe-haut; 4 = Mahavatse-1; 5 = Ankiembe-bas; 6 = Mahavatse-2; 7 = Besakoa; 8 = Ambohitsabo)

Figure 2 : Catch sampling procedure used for characterizing and estimating catch level, composition, and size structure of the coral reef fishery in the Bay of Toliara, Southwestern Madagascar from May 2018 to April 2019. C = total catch weight (kg), N = total in number caught, A = daily activity rate (trip*day^{-1}*fisher^{-1}), T = total number of trips (trips), D = cumulated survey duration (fisher*day), Cd,f = mean daily catch per fisher (kg*day^{-1}*fisher^{-1}),

Nd,f = mean daily catch per fisher (number of fish*day^{-1}*fisher^{-1}), P = survey period duration (day), Fg = total number of fishers using a specific gear.

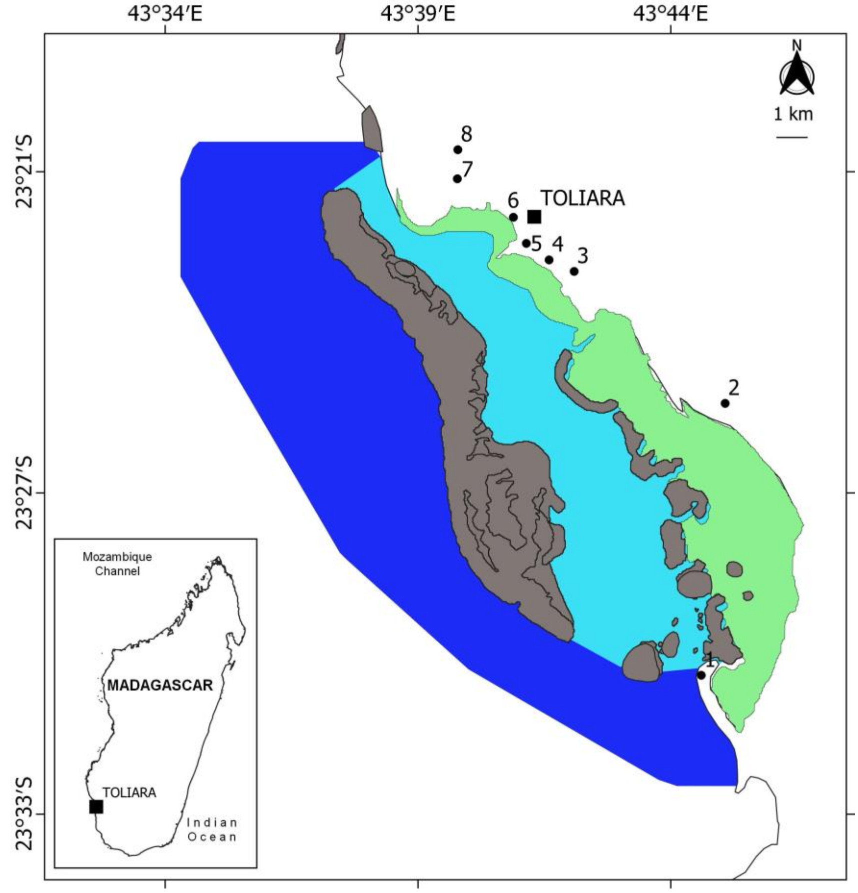
Figure 3: Length frequency of estimated annual coral reef fish caught by all fishing gears in the Bay of Toliara, Southwestern Madagascar from May 2018 to April 2019. The X-axis was truncated at 30 cm for clarity (maximum fish length was 86 cm).

Figure 4: Size distribution of annual coral reef fish caught by five fishing gears in the Bay of Toliara, Southwestern Madagascar from May 2018 to April 2019. Horizontal lines = median lengths, boxes = interquartiles, and blackened circles = outliers.

Figure 5: Length distributions of coral reef fish caught by all fishing gears (A = numbers) and across fishing gears (B = %) at each 2-month period in the Bay of Toliara, Southwestern Madagascar from May 2018 to April 2019. Black lines delineate three size categories (≤9cm, >9-15 cm, and >15cm). N= estimated total number of fish caught. Mosquito net trawl (yellow bars), beach seine (red bars), handline (green bars), gillnet (blue bars), and speargun (purple bars) catches are shown.

Figure 6: Median length of reef fishes caught by all gears and among gears over the 2-month survey periods in the Bay of Toliara, Southwestern Madagascar from May 2018 to April 2019. Horizontal lines represent median length.

Figure 7: Temporal variation in estimated catch numbers of 13 main targeted families and other non-predominant families in three size categories (red line: ≤9cm, green line: >9-15cm, and blue line: >15cm) in the Bay of Toliara, Southwestern Madagascar from May 2018 to April 2019. Scales for y-axis differ for the two groups.



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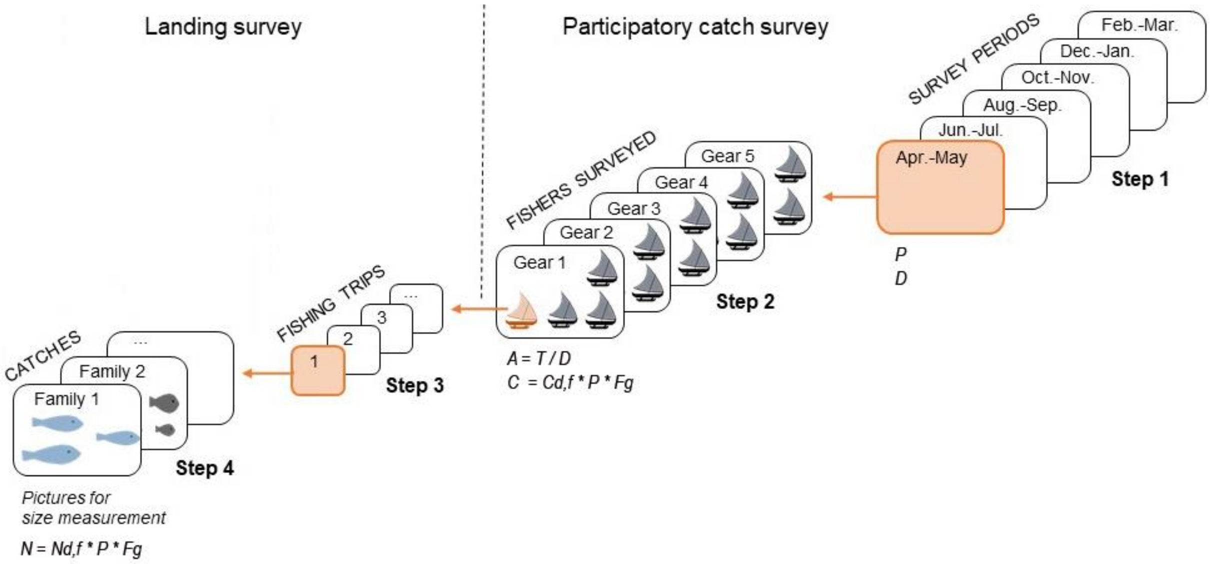

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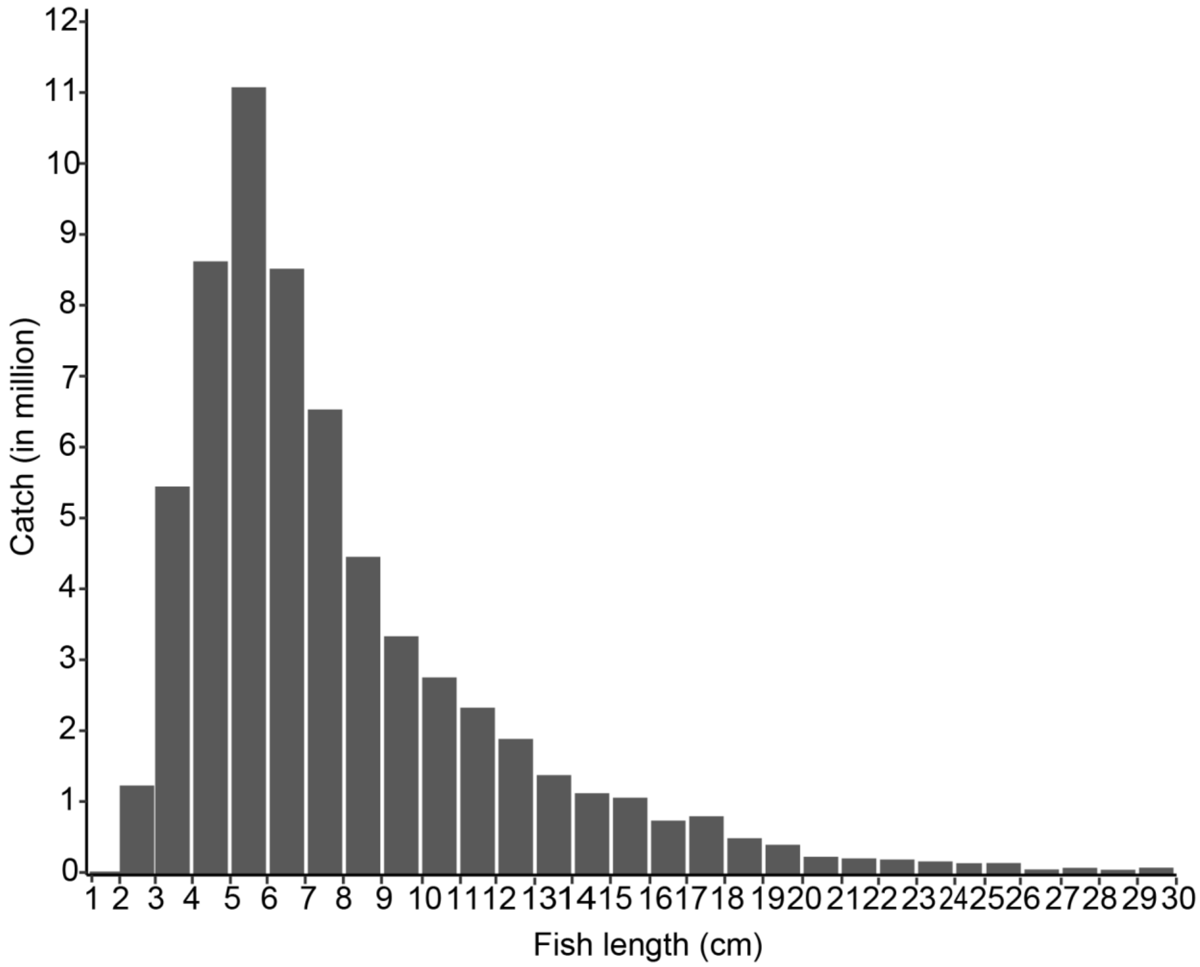

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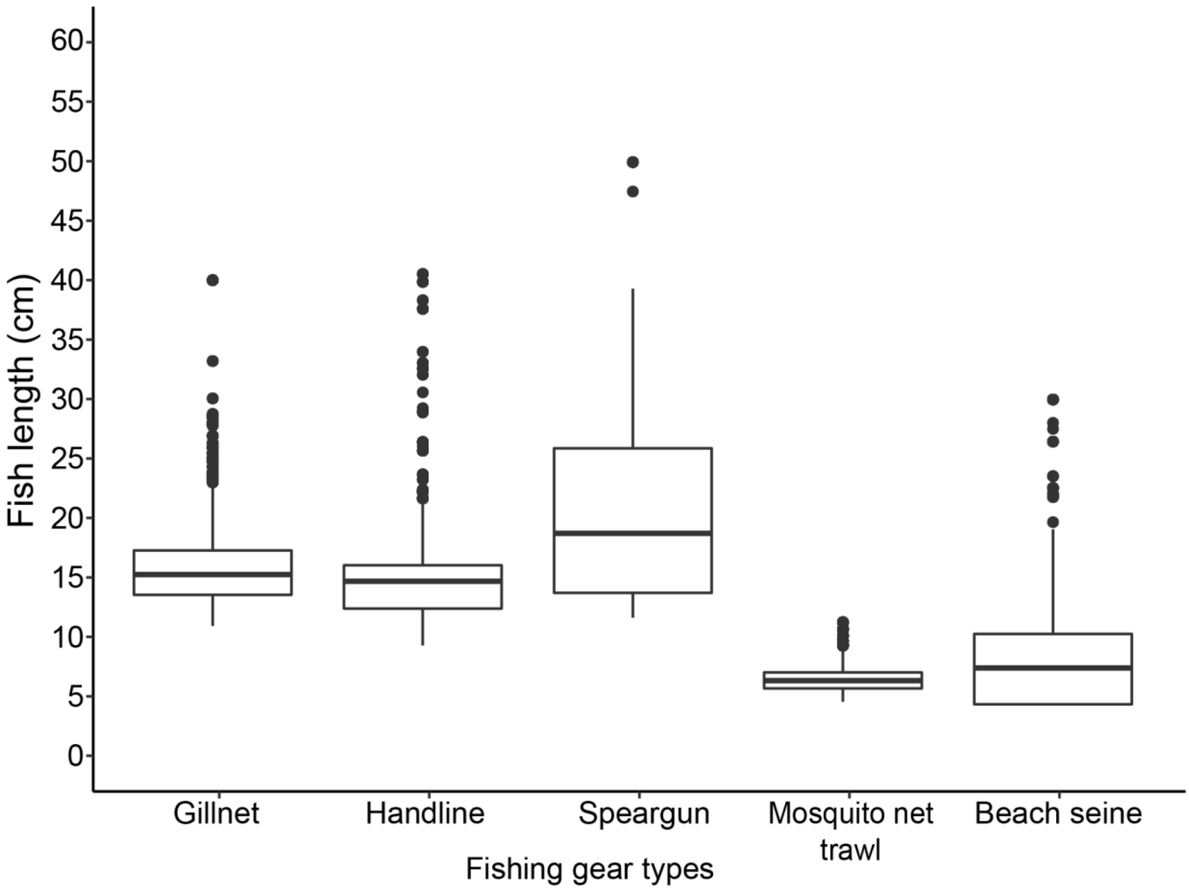

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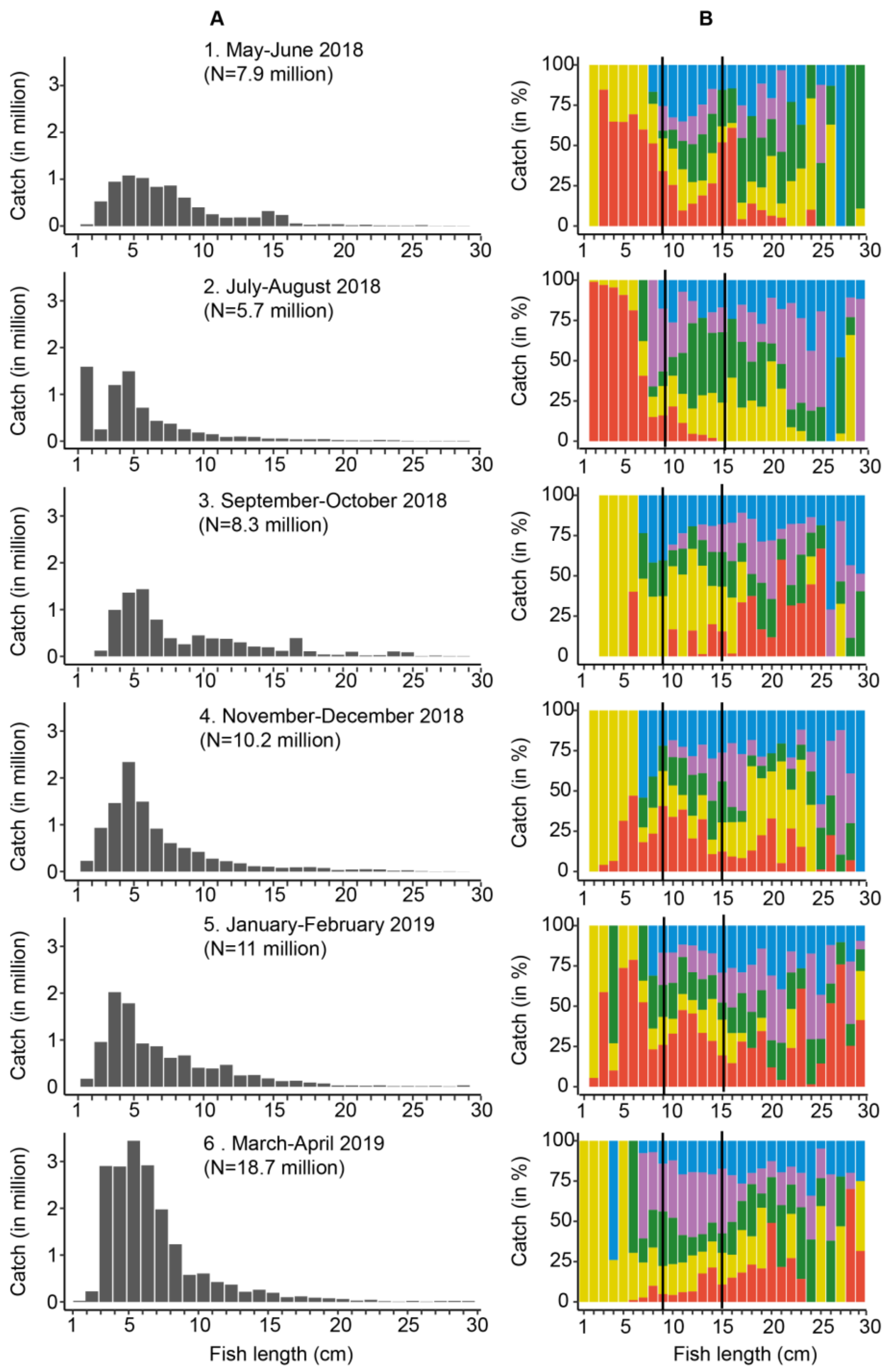


Figure 5: Length-distributions of coral reef fish caught (A = numbers) and across fishing gears (B = %) in each 2-month period in the Bay of Toliara, Southwestern Madagascar from May 2018 to April 2019. Black lines delineate three size categories (≤9cm, >9-15 cm, and >15cm). N = estimated total number of fish caught. Mosquito net trawl (yellow bars), beach seine (red bars), handline (green bars), gillnet (blue bars), and speargun (purple bars) catches are shown.

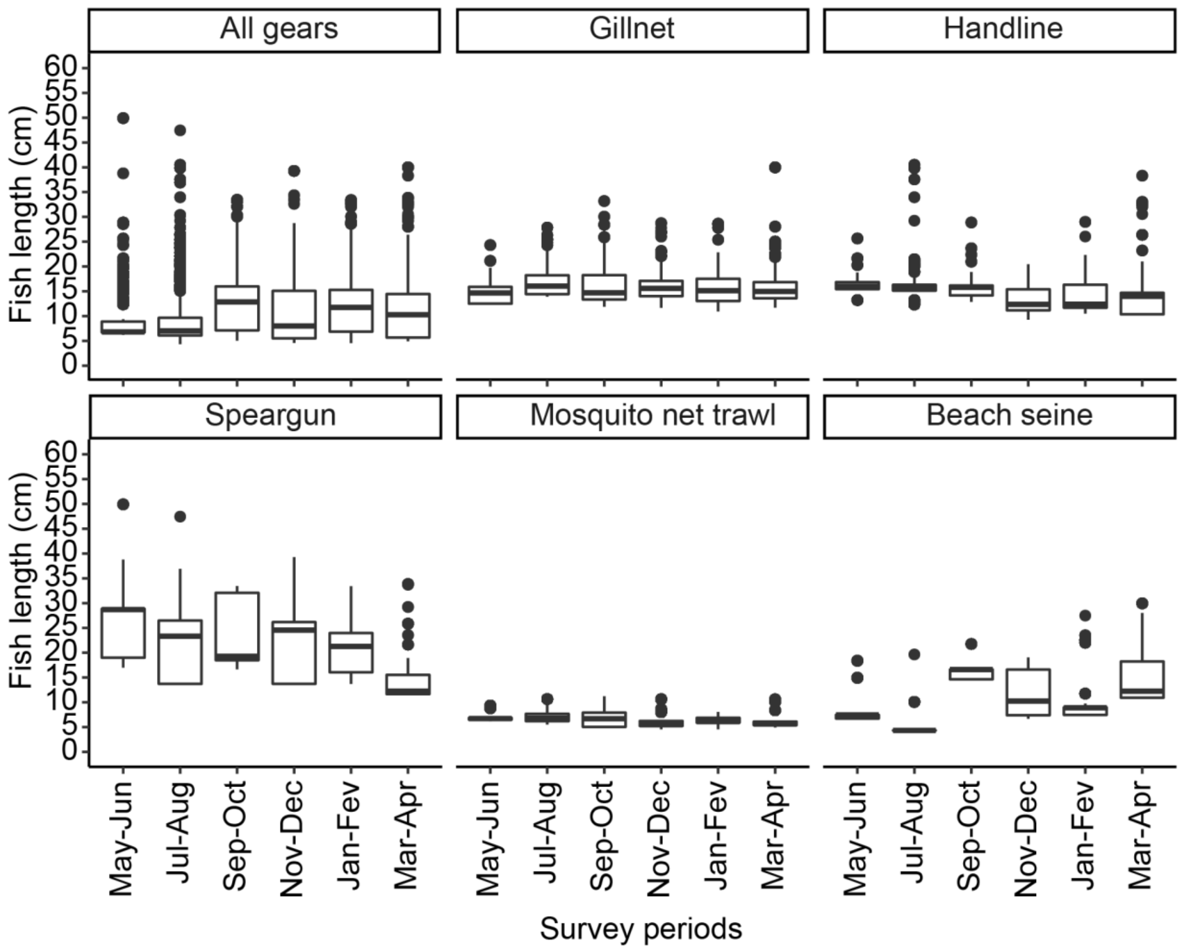


Figure 6: Median length of reef fishes caught by all gears and among gears in 2-month survey periods in the Bay of Toliara, Southwestern Madagascar from May 2018 to April 2019. Horizontal lines represent median lengths.

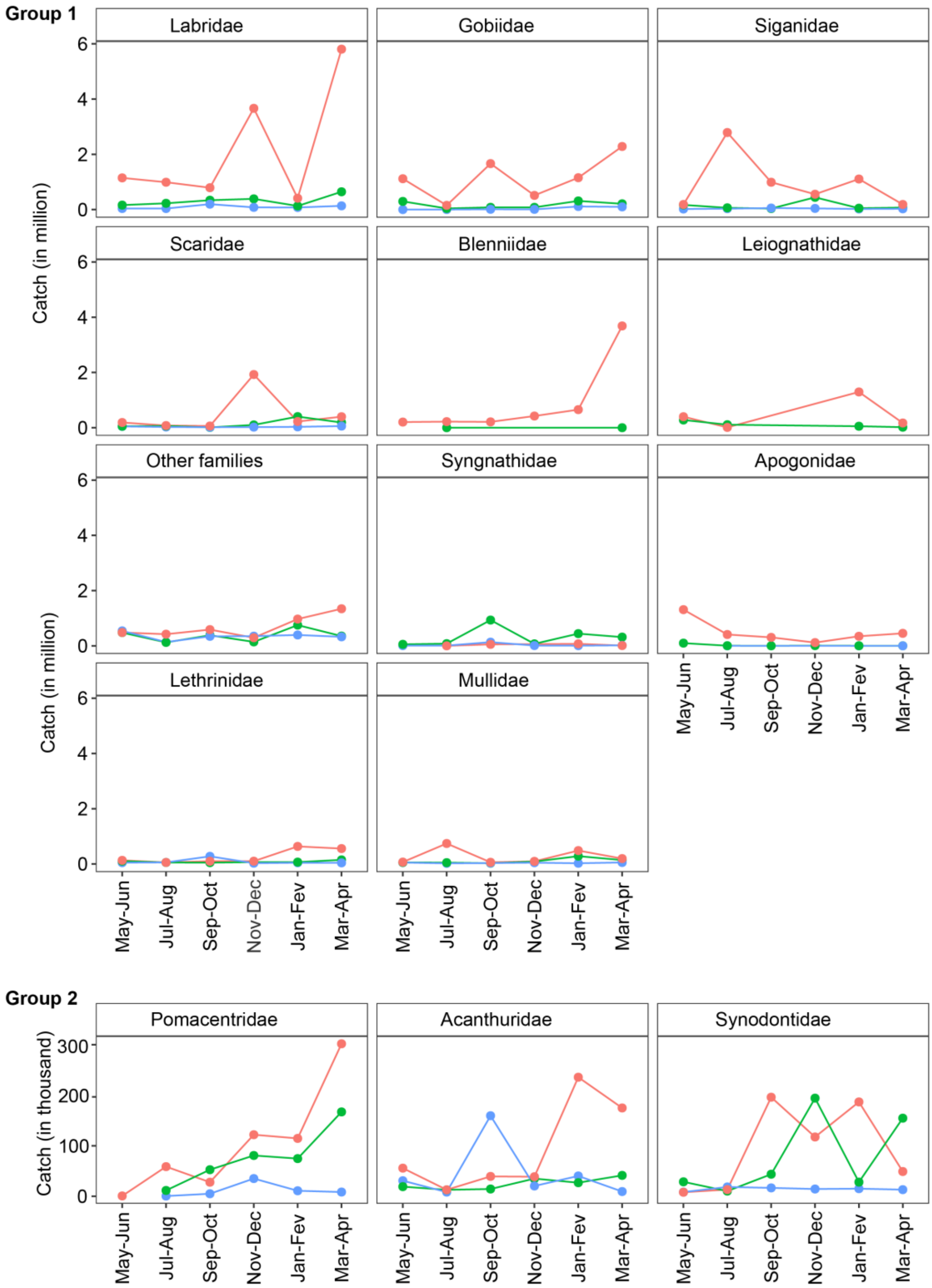


Figure 7: Temporal variation in estimated catch numbers of 13 main targeted families and other non-predominant families in three size categories (red line: ≤9cm, green line: >9-15cm, and blue line: >15cm) in the Bay of Toliara, Southwestern Madagascar from May 2018 to April 2019. Scales for y-axis differ for the two groups.

APPENDICES

Appendix 1: Estimation procedure of the total catch of the fishery. That procedure was used at the different taxonomic levels (reef fish family, fish category, and whole fish catch) within each statistical stratum (i.e. survey period * fishing gear type).

1. Daily activity rate (A) = T / D
2. Mean catch per trip (Ct) = ∑ Cw / Nt, where Cw = Cn
3. Mean daily catch per fisher in weight or in number (Cd,f or Nd,f) = Ct * A
4. Total estimated catch in weight or in number (C or N) = (Cd,f or Nd,f) * D . Fg
5. Variance estimates of annual catch by gear typ: $\mathrm{Var}\ (Y) = 1 - (ni/\sum_{i=1}^{k} ni) * se^2$
6. Variance estimate of total annual catch: $\mathrm{Var}\ (Yt) = \sum(ni/\sum_{i=1}^{k} ni) * \sum(\mathrm{Var}\ (Y))$

With:

- Fg: Total number of fishers
- T: Total number of trips of the sampled fishers during the survey period
- P: Period duration (in days)
- D: Cumulated survey duration among fishers (in days)
- Cw: Catch weight of each category (reef fishes and pelagic fish) per trip (in kg)
- Cn: number of individual reef fish in the catch per trip
- Ws: Weight of catch observed or sampled (in kg)
- n_i: number of the sample unit to be drawn for each stratum
- $\sum_{i=1}^{k} ni$: total number of fishers surveyed
- se: standard error

Appendix 2: Diversity and size structure of fish families caught in the coral reef fishery in the Bay of Toliara in 2018-2019, Southwertern Madagascar

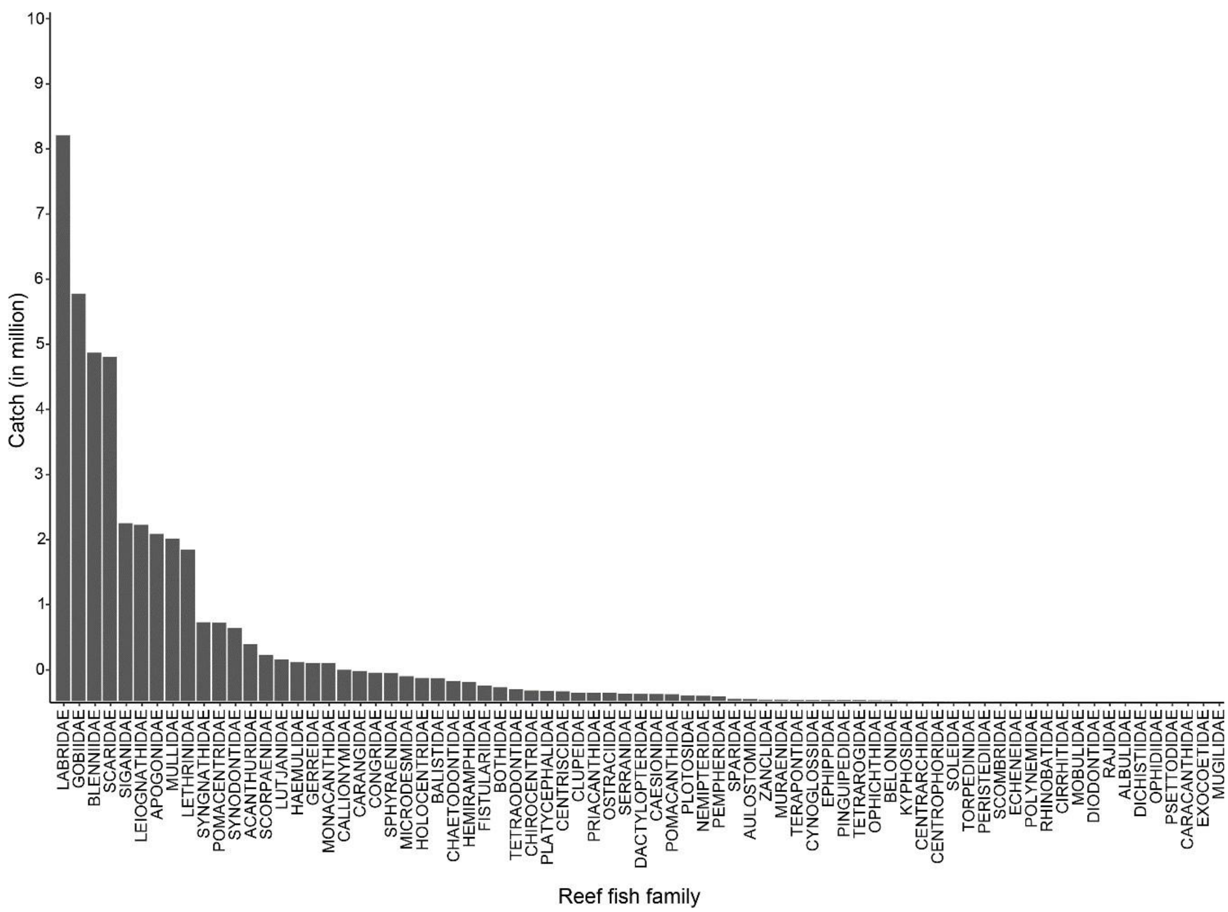
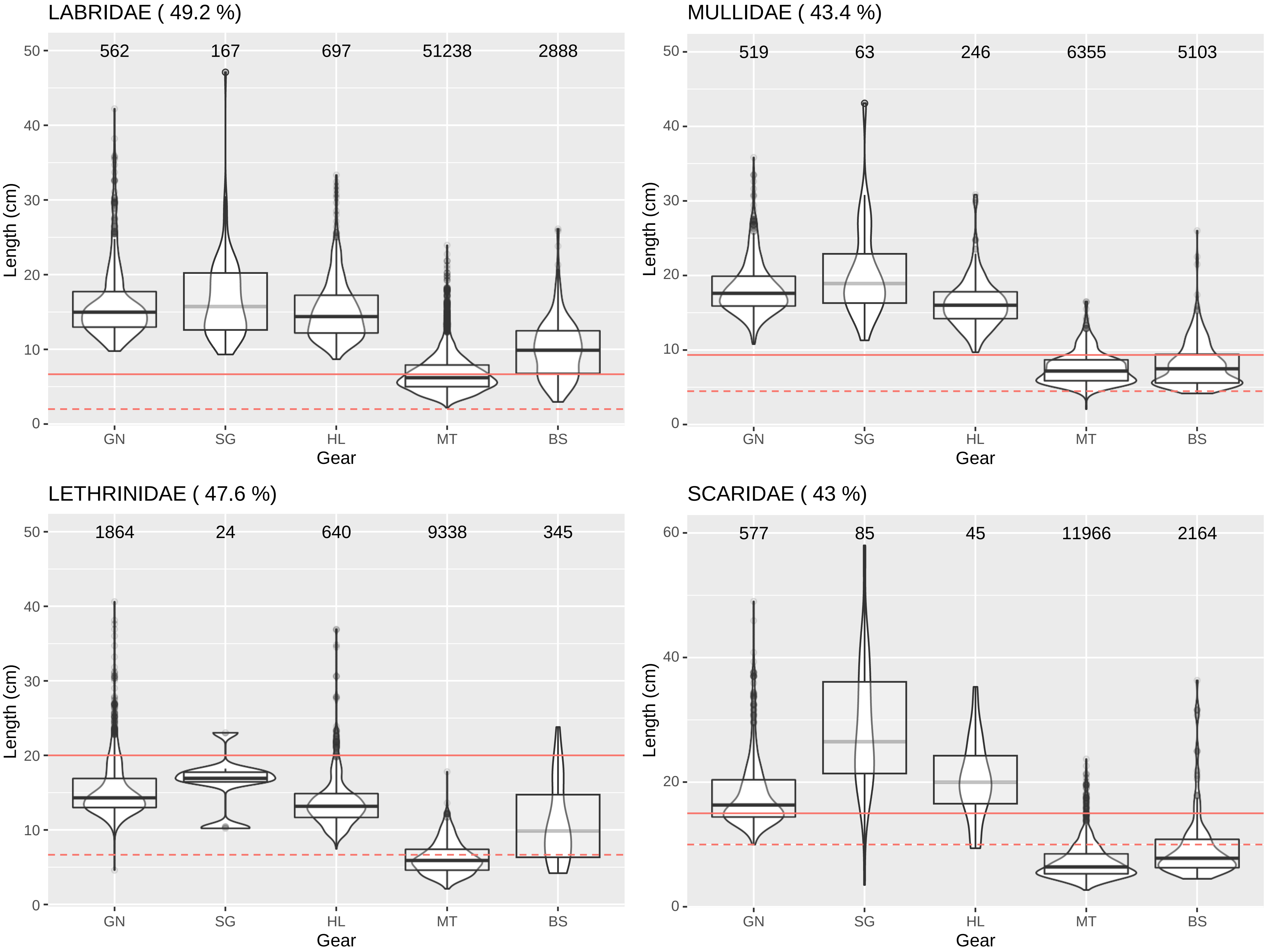
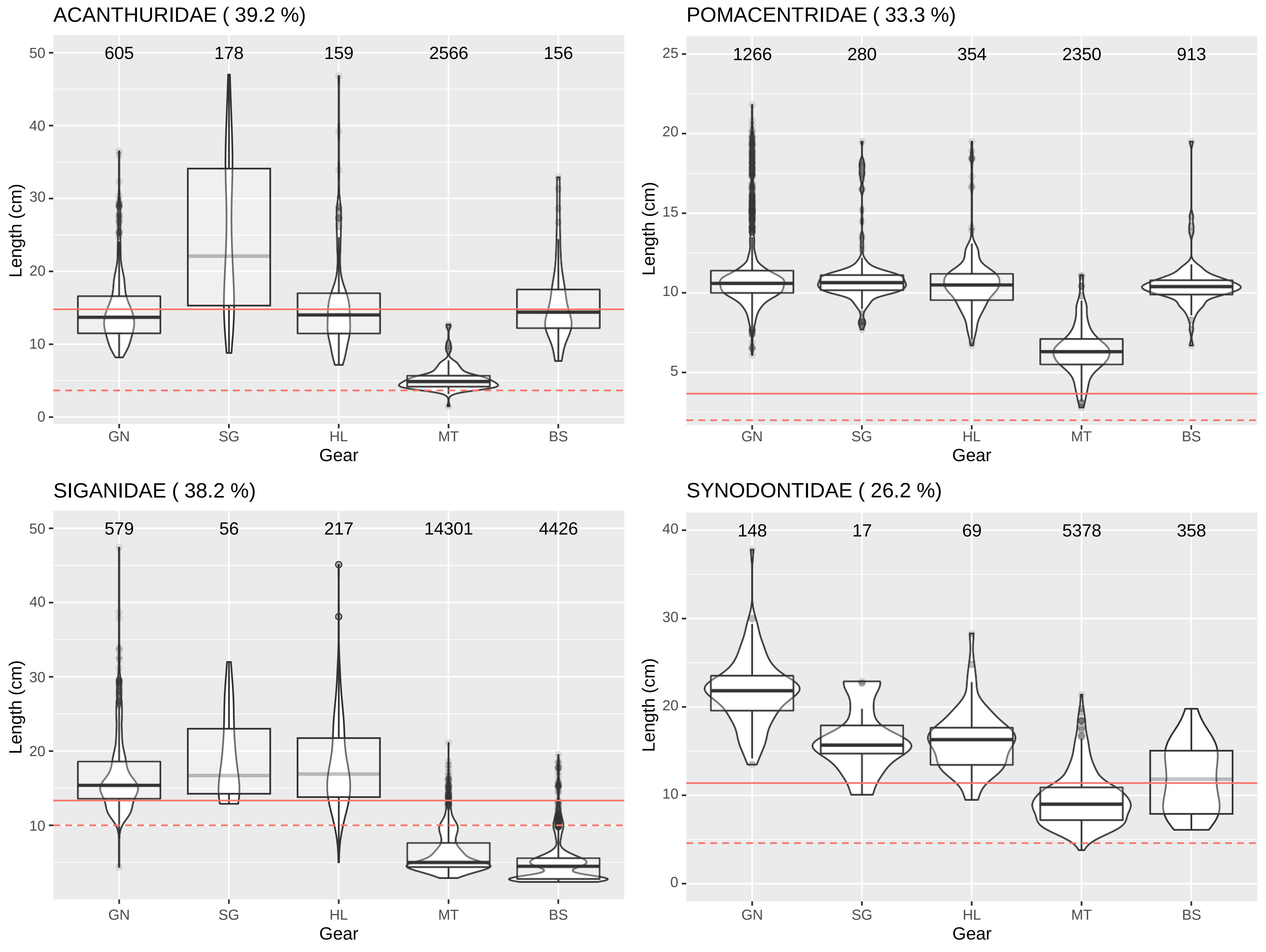


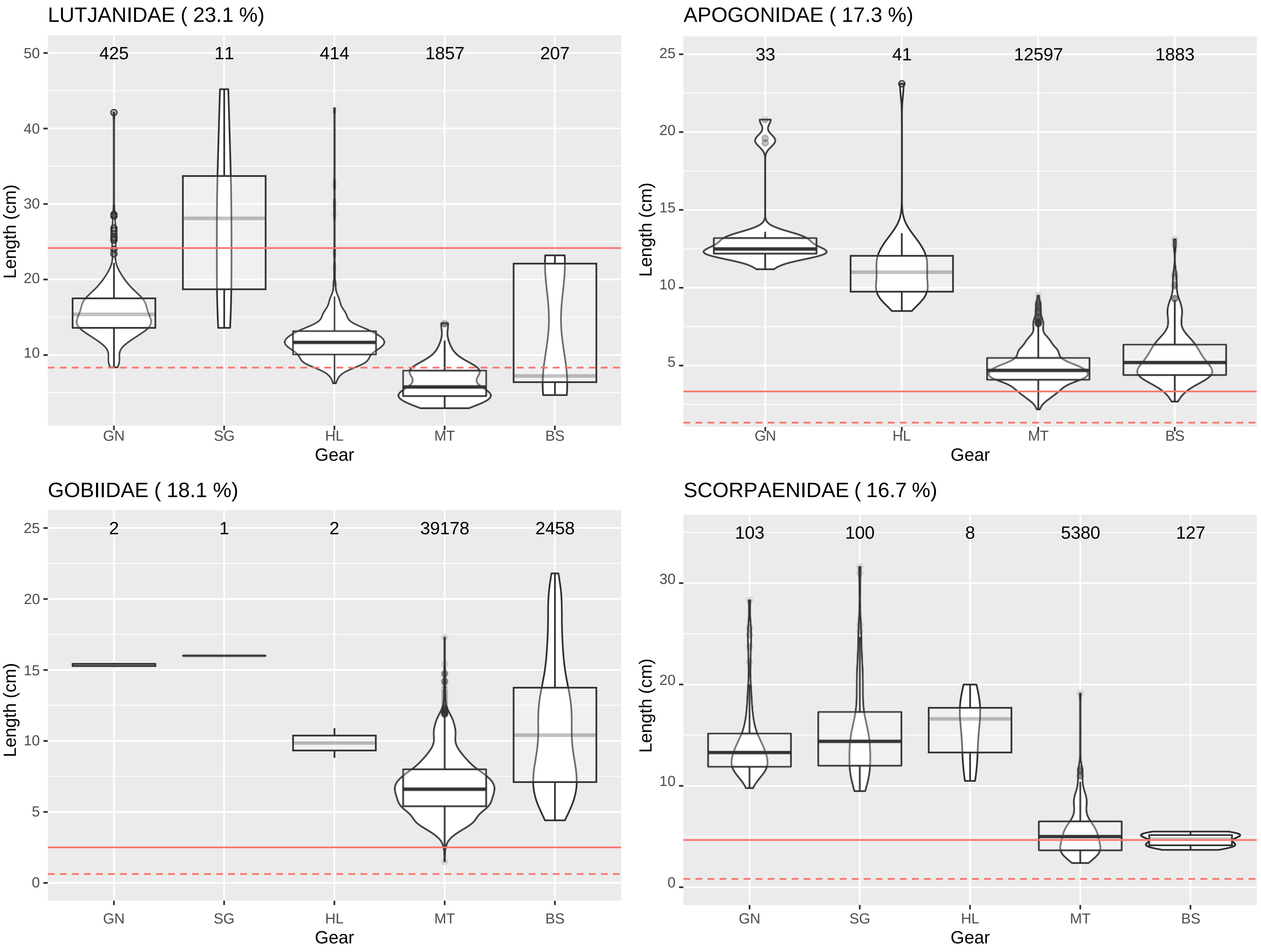
Figure S1. Annual estimated number of fish (68.7 million in total) of families (n=75) in catches ofthe coral reef fishery in the Bay of Toliara in 2018-2019, Southwertern Madagascar

All figures below:

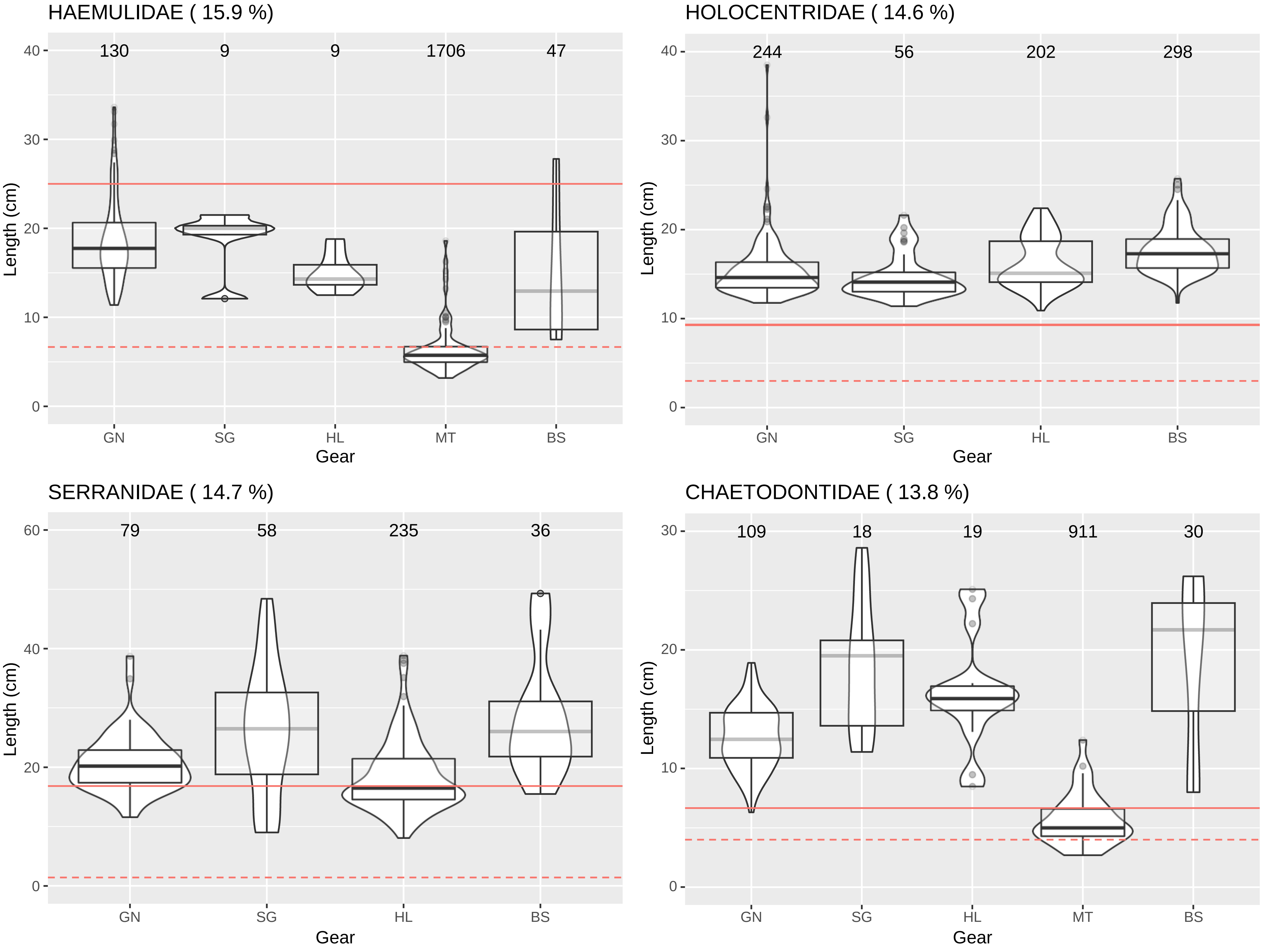
Catch size structure of target reef fish families across fishing gear types (GN: Gillnet; SG: Speargun; HL: Handline; MT: Mosquito net trawl and BS: Beach seine). Solid red line represents the mean size at maturity (at the family level) of those species of Fricke et al. (2018)'s checklist of finfish species in coral reef ecosystems of Madagascar. Dashed red line represents the lowest size at maturity of those species at the family level. The size at maturity of these species was retrieved from FishBase (Froese & Pauly, 2021).


LABRIDAE (49.2 %)
562
167
697
51238
2888
MULLIDAE (43.4 %)
519
63
246
6355
5103
LETHRINIDAE (47.6 %)
1864
24
640
9338
345
SCARIDAE (43 %)
577
85
45
11966
2164
Length (cm)
Gear
GN
SG
HL
MT
BS
0
10
20
30
40
50
60

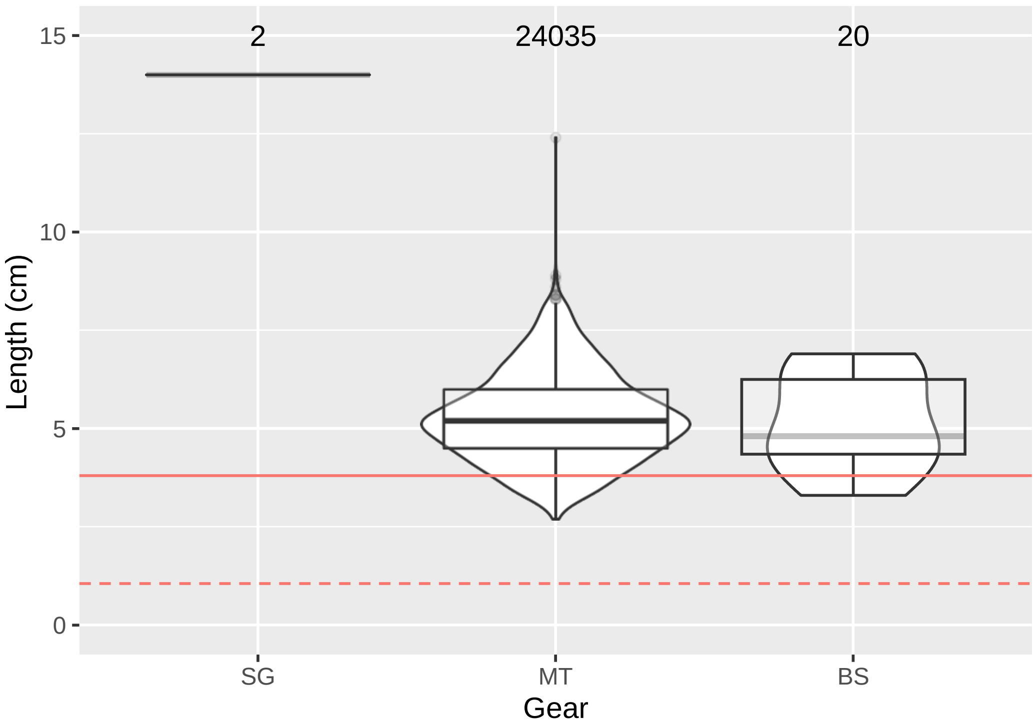

ACANTHURIDAE (39.2 %)
605
178
159
2566
156
Length (cm)
Gear
GN
SG
HL
MT
BS
POMACENTRIDAE (33.3 %)
1266
280
354
2350
913
Length (cm)
Gear
GN
SG
HL
MT
BS
SIGANIDAE (38.2 %)
579
56
217
14301
4426
Length (cm)
Gear
GN
SG
HL
MT
BS
SYNODONTIDAE (26.2 %)
148
17
69
5378
358
Length (cm)
Gear
GN
SG
HL
MT
BS



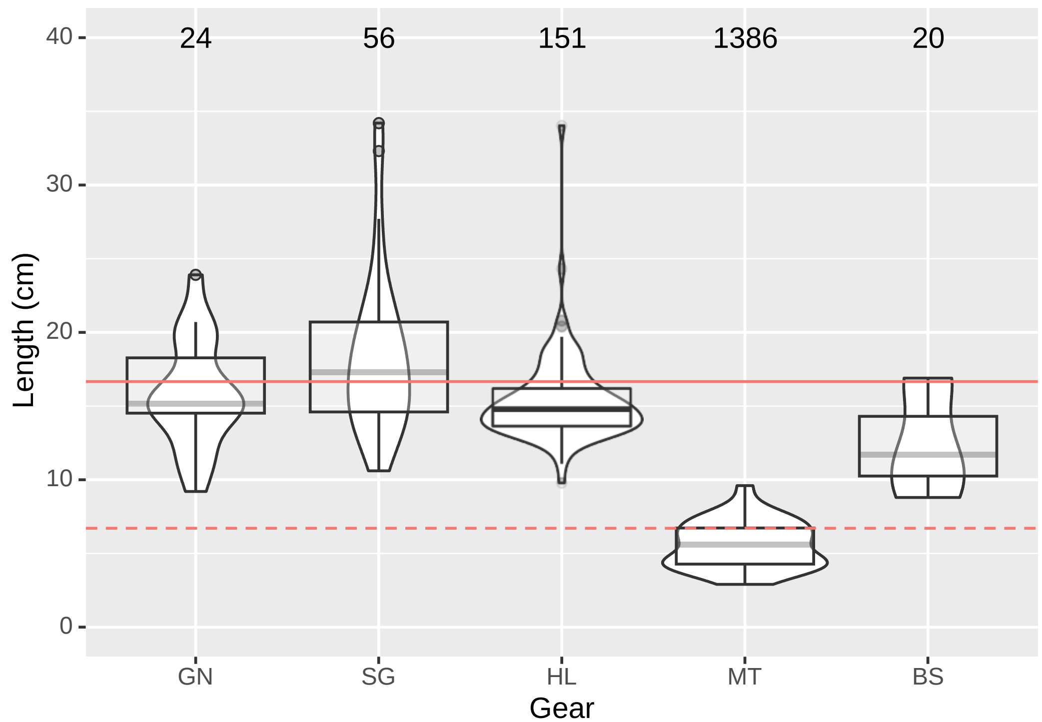
LUTJANIDAE (23.1 %)
425
11
414
1857
207
50
40
30
20
10
Length (cm)
GN
SG
HL
MT
BS
Gear
APOGONIDAE (17.3 %)
33
41
12597
1883
25
20
15
10
5
Length (cm)
GN
HL
MT
BS
Gear
GOBIIDAE (18.1 %)
2
1
2
39178
2458
25
20
15
10
5
0
Length (cm)
GN
SG
HL
MT
BS
Gear
SCORPAENIDAE (16.7 %)
103
100
8
5380
127
30
20
10
0
Length (cm)
GN
SG
HL
MT
BS
Gear


HAEMULIDAE (15.9 %)
130
9
9
1706
47
Length (cm)
Gear
GN
SG
HL
MT
BS
HOLOCENTRIDAE (14.6 %)
244
56
202
298
Length (cm)
Gear
GN
SG
HL
BS
SERRANIDAE (14.7 %)
79
58
235
36
Length (cm)
Gear
GN
SG
HL
BS
CHAETODONTIDAE (13.8 %)
109
18
19
911
30
Length (cm)
Gear
GN
SG
HL
MT
BS

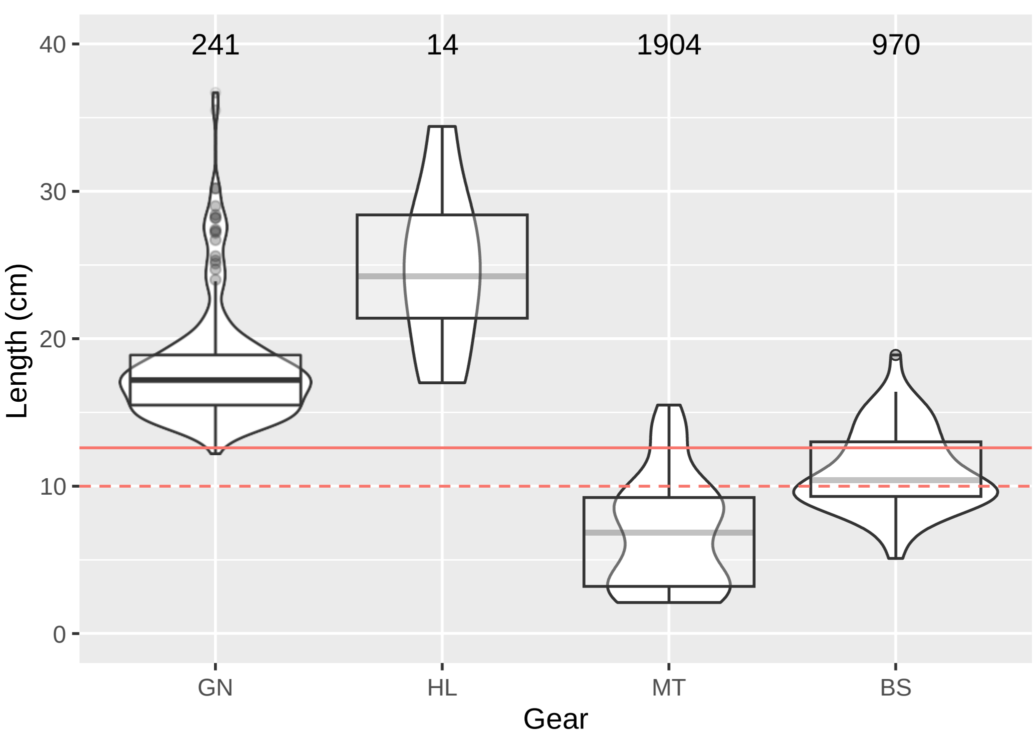
BLENNIIDAE (12.9 %)



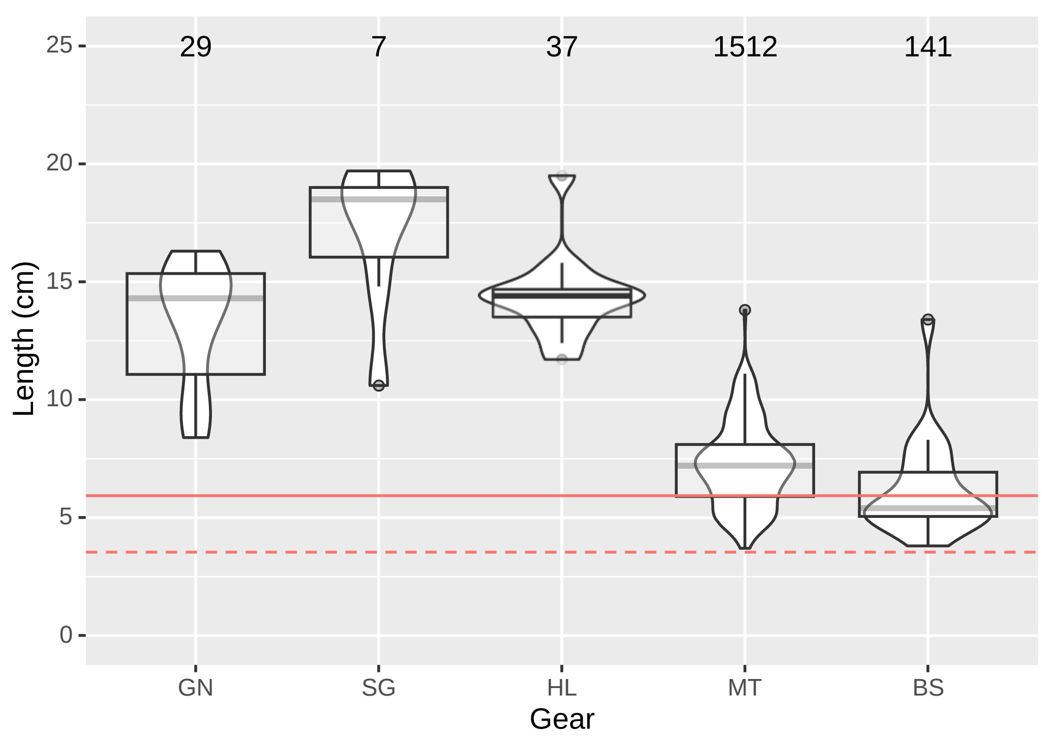
BALISTIDAE (12 %)



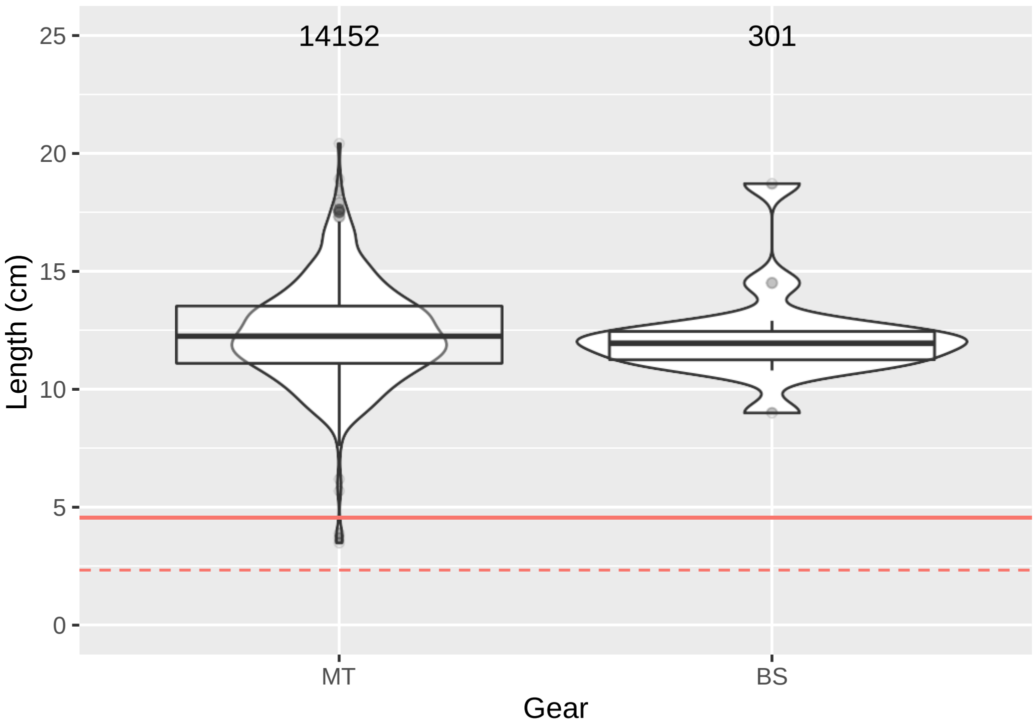
GERREIDAE (12.1 %)



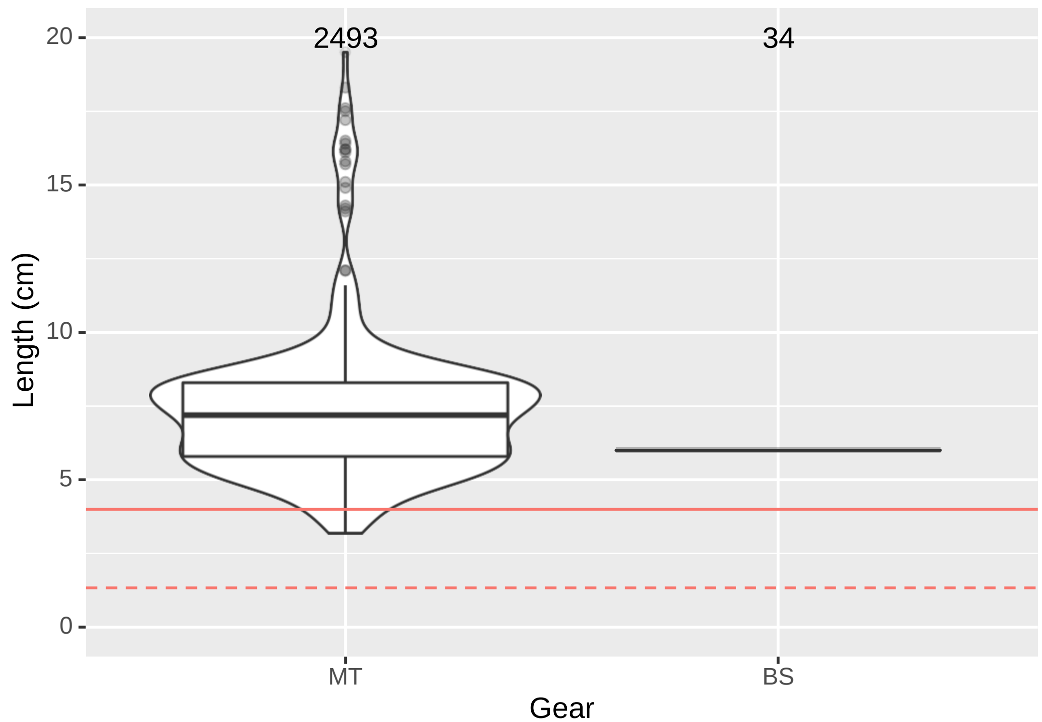
MONACANTHIDAE (12 %)



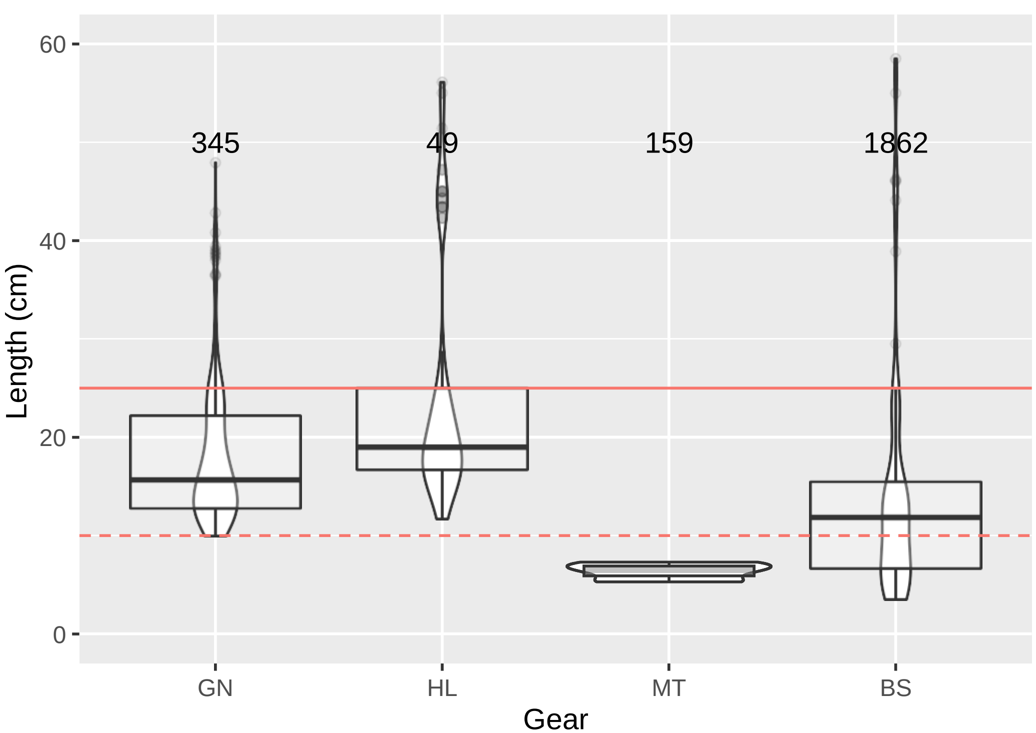
SYNGNATHIDAE (11.5 %)



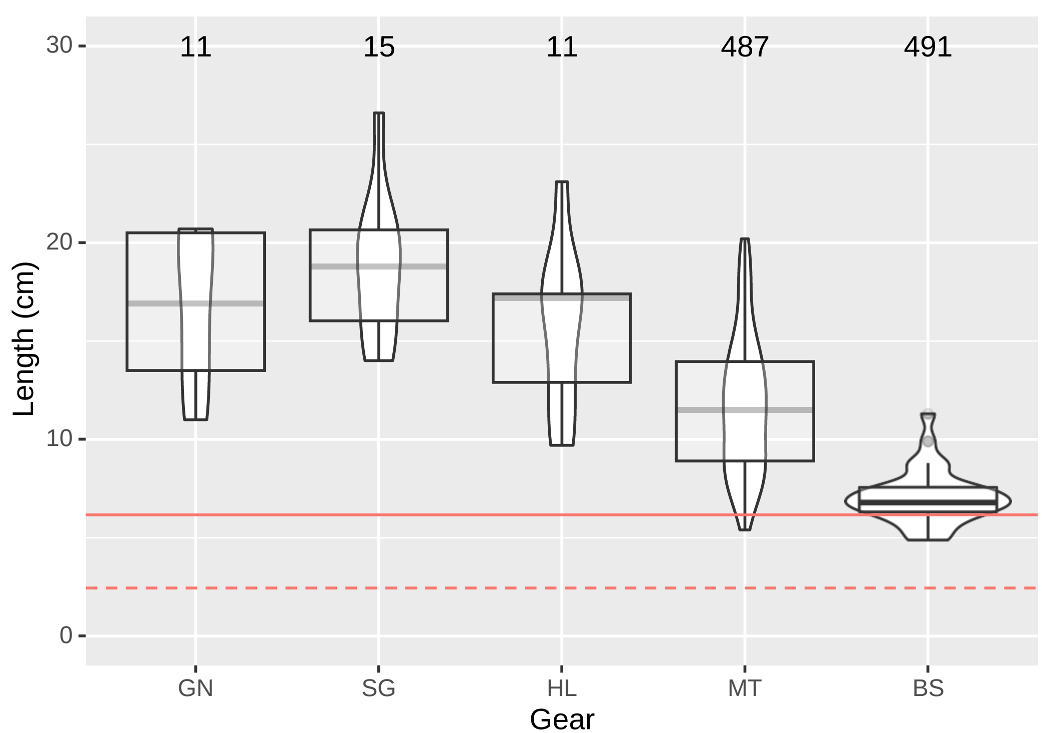
CALLIONYMIDAE (6.6 %)

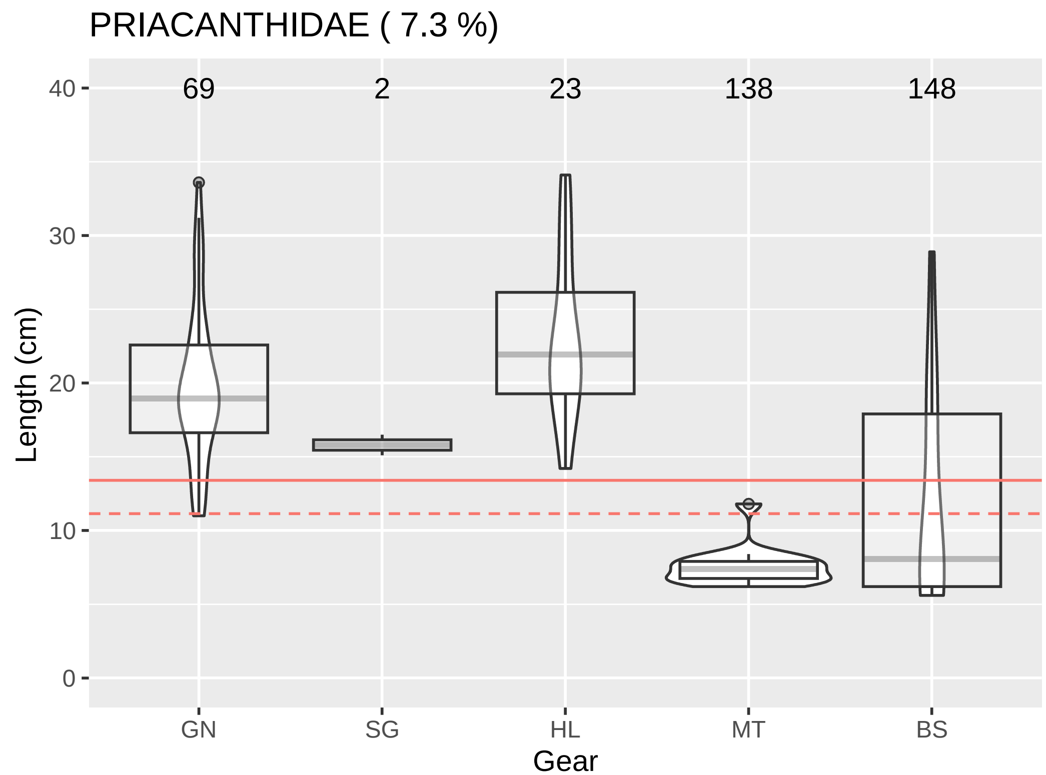


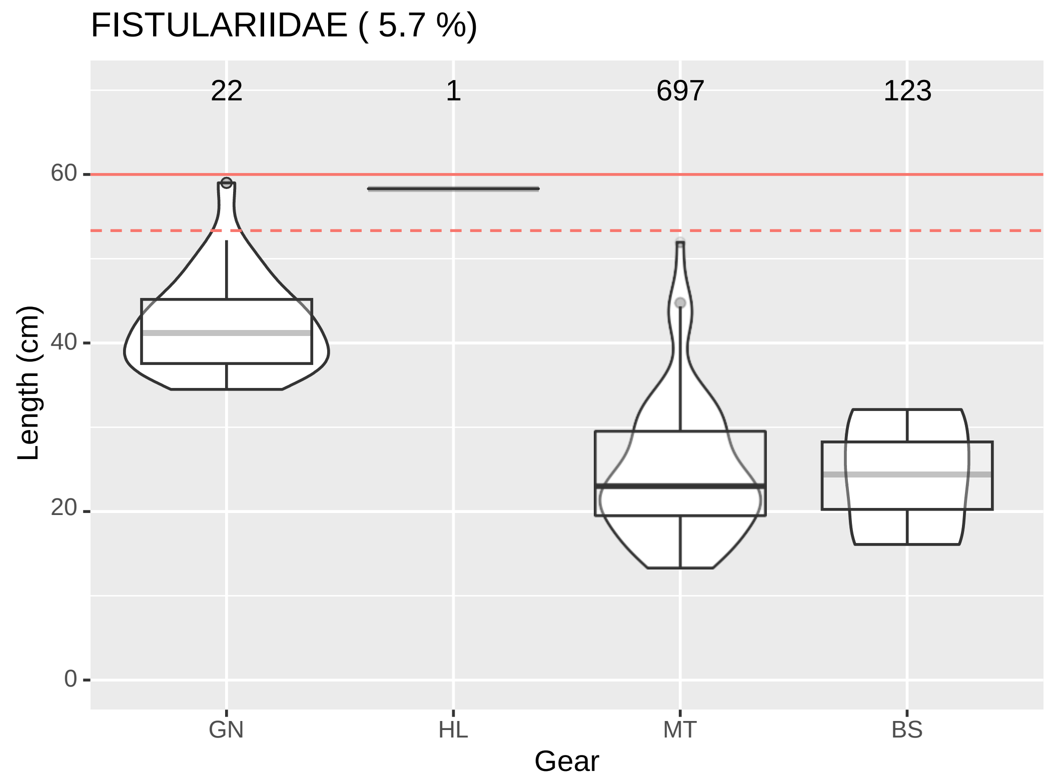
CARANGIDAE (10.8 %)

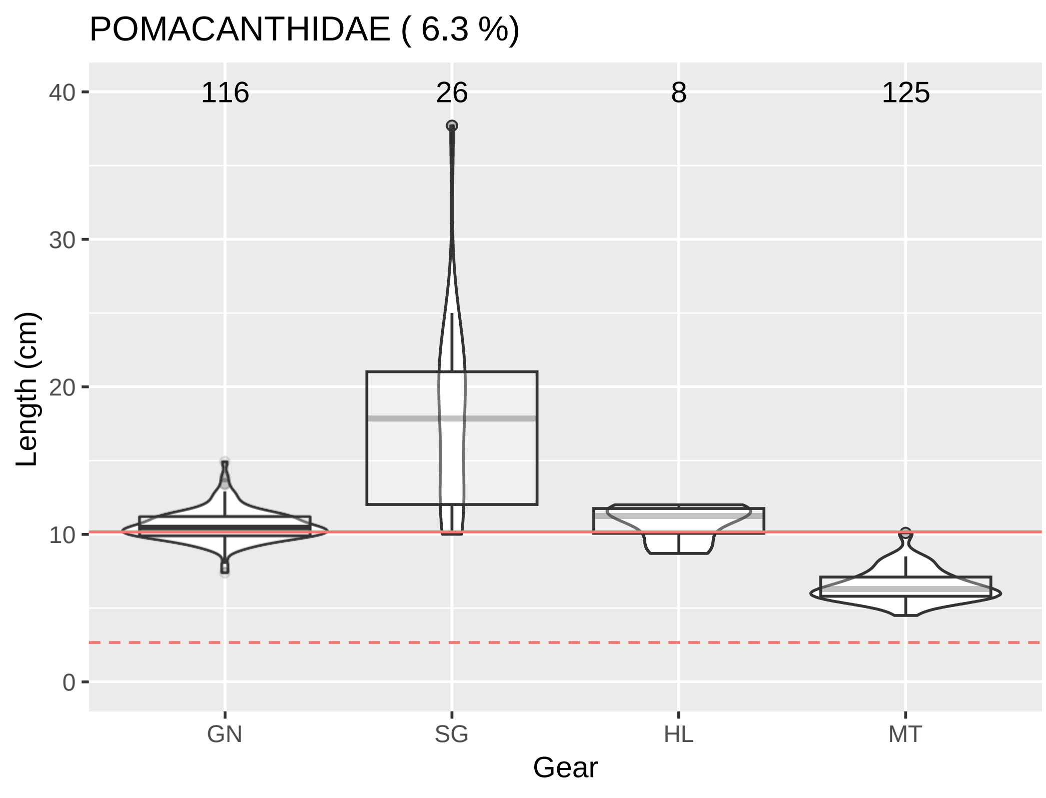


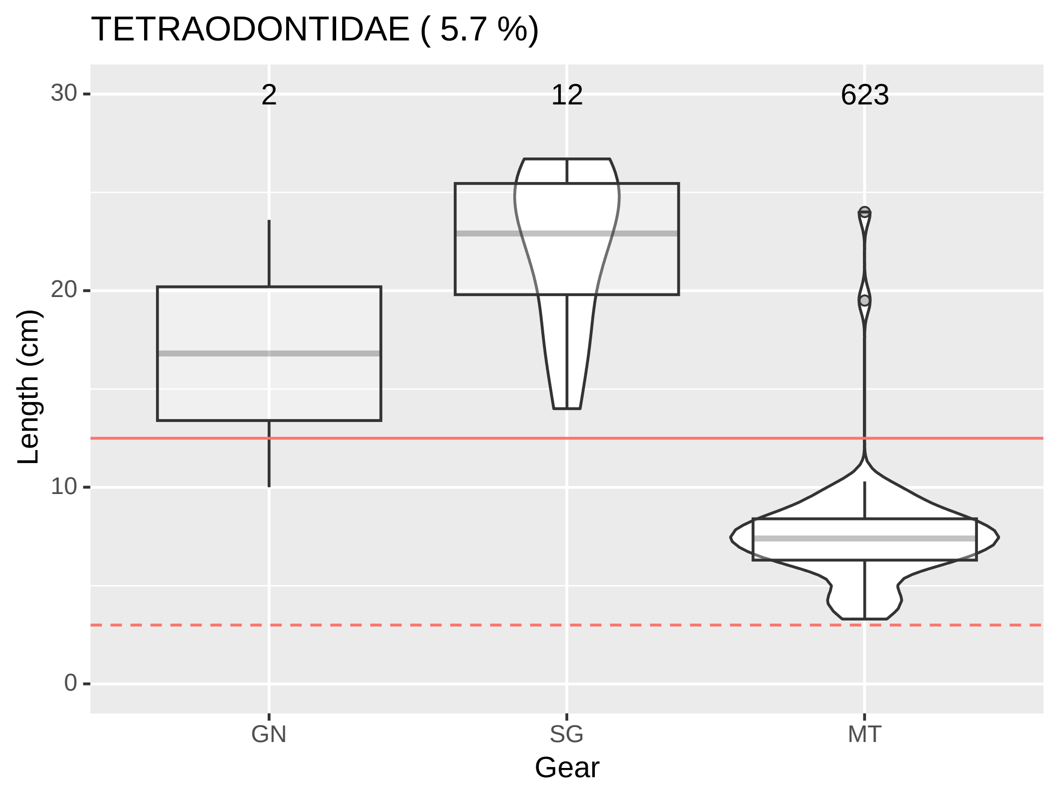
BOTHIDAE (8.6 %)

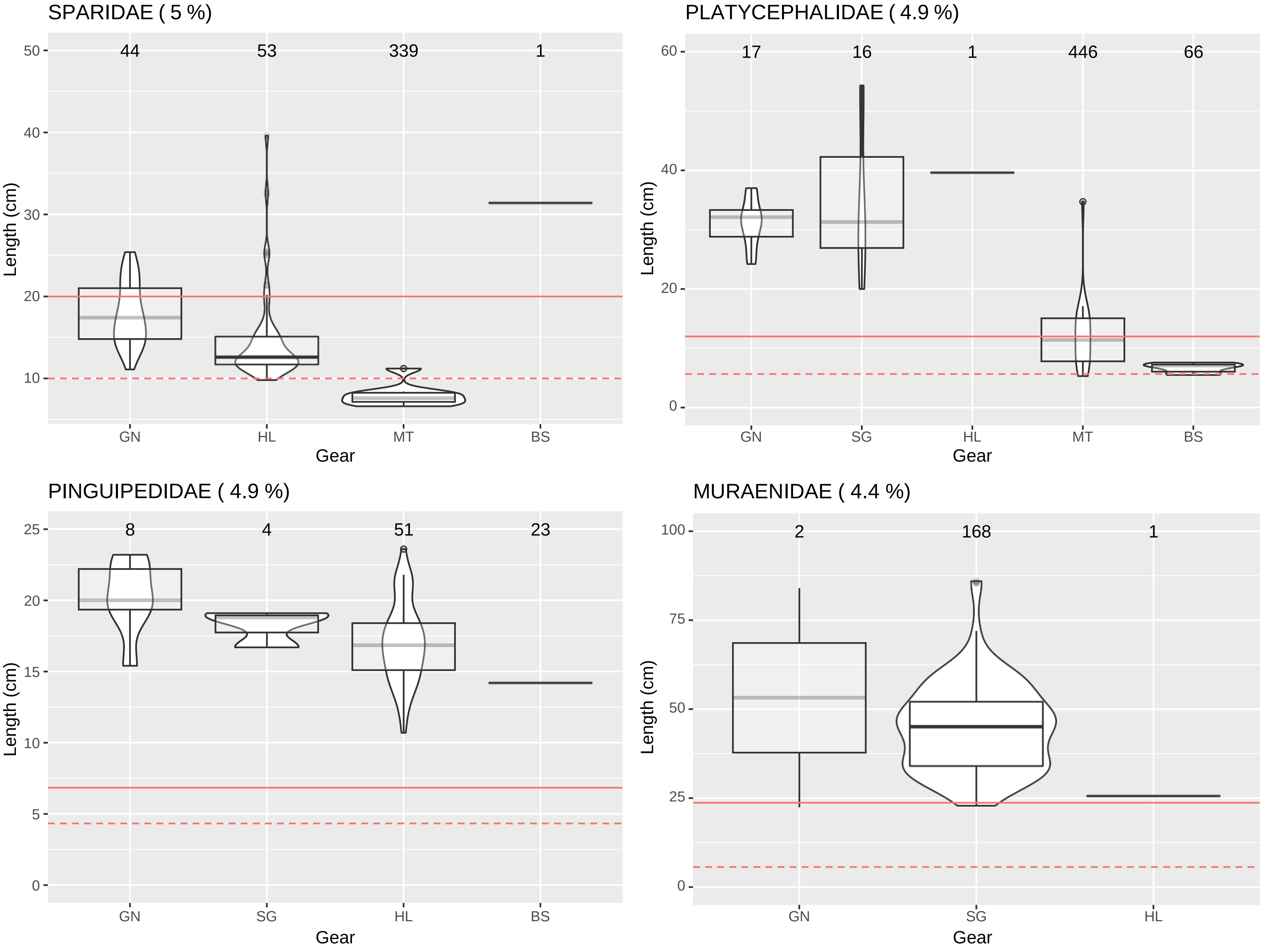



PRIACANTHIDAE (7.3 %)
69
2
23
138
148
Length (cm)
0
10
20
30
40
GN
SG
HL
MT
BS
Gear

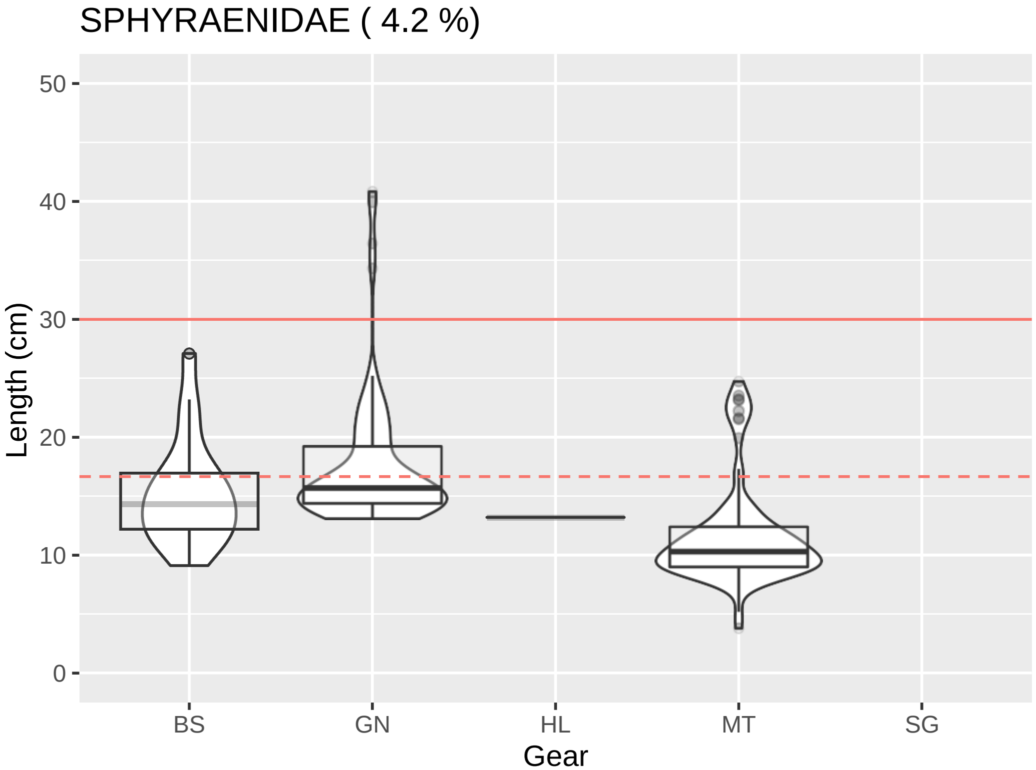

FISTULARIIDAE (5.7 %)
22
1
697
123
Length (cm)
0
20
40
60
GN
HL
MT
BS
Gear

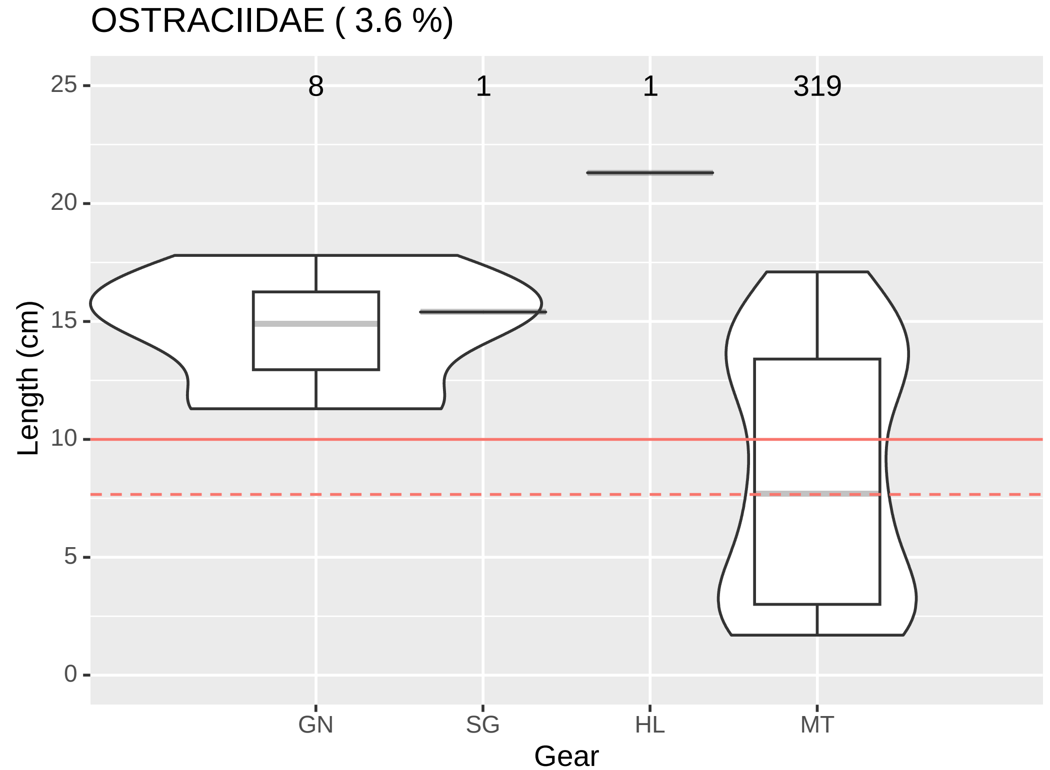

POMACANTHIDAE (6.3 %)
116
26
8
125
Length (cm)
0
10
20
30
40
GN
SG
HL
MT
Gear

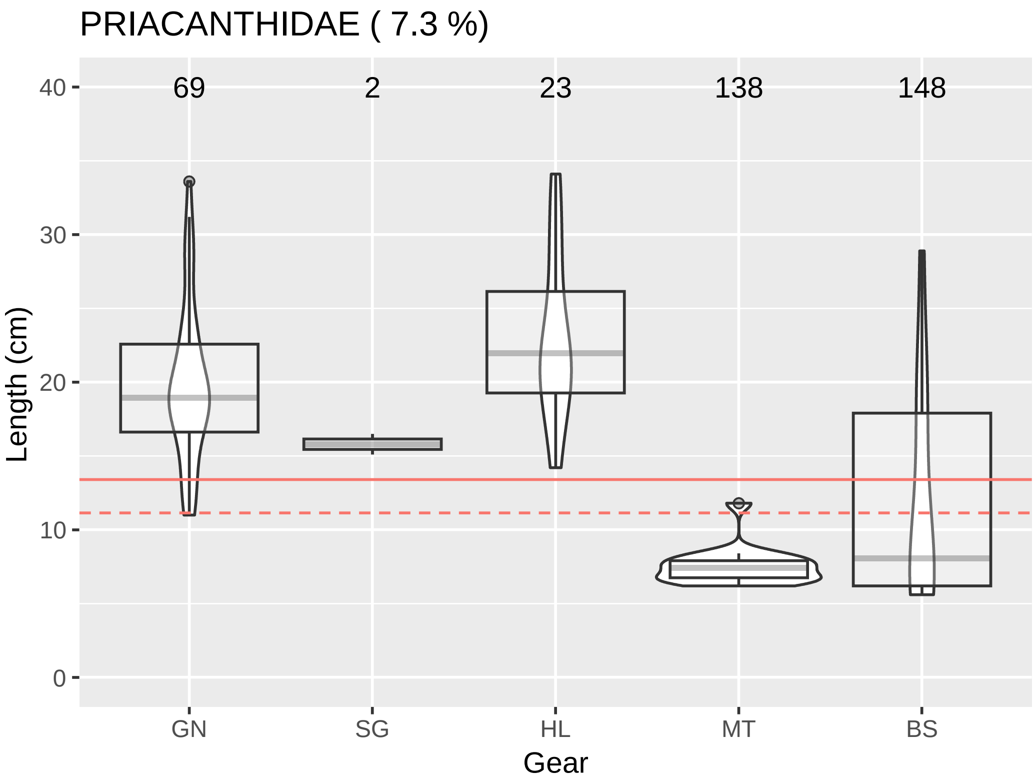

TETRAODONTIDAE (5.7 %)
2
12
623
Length (cm)
0
10
20
30
GN
SG
MT
Gear

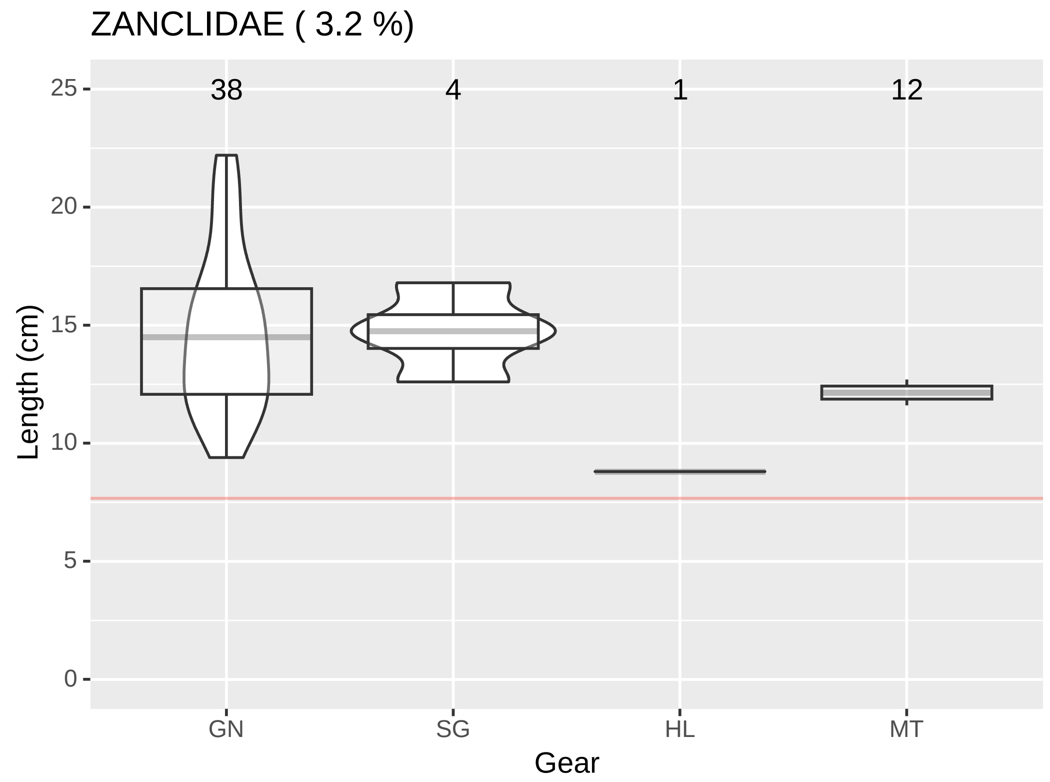


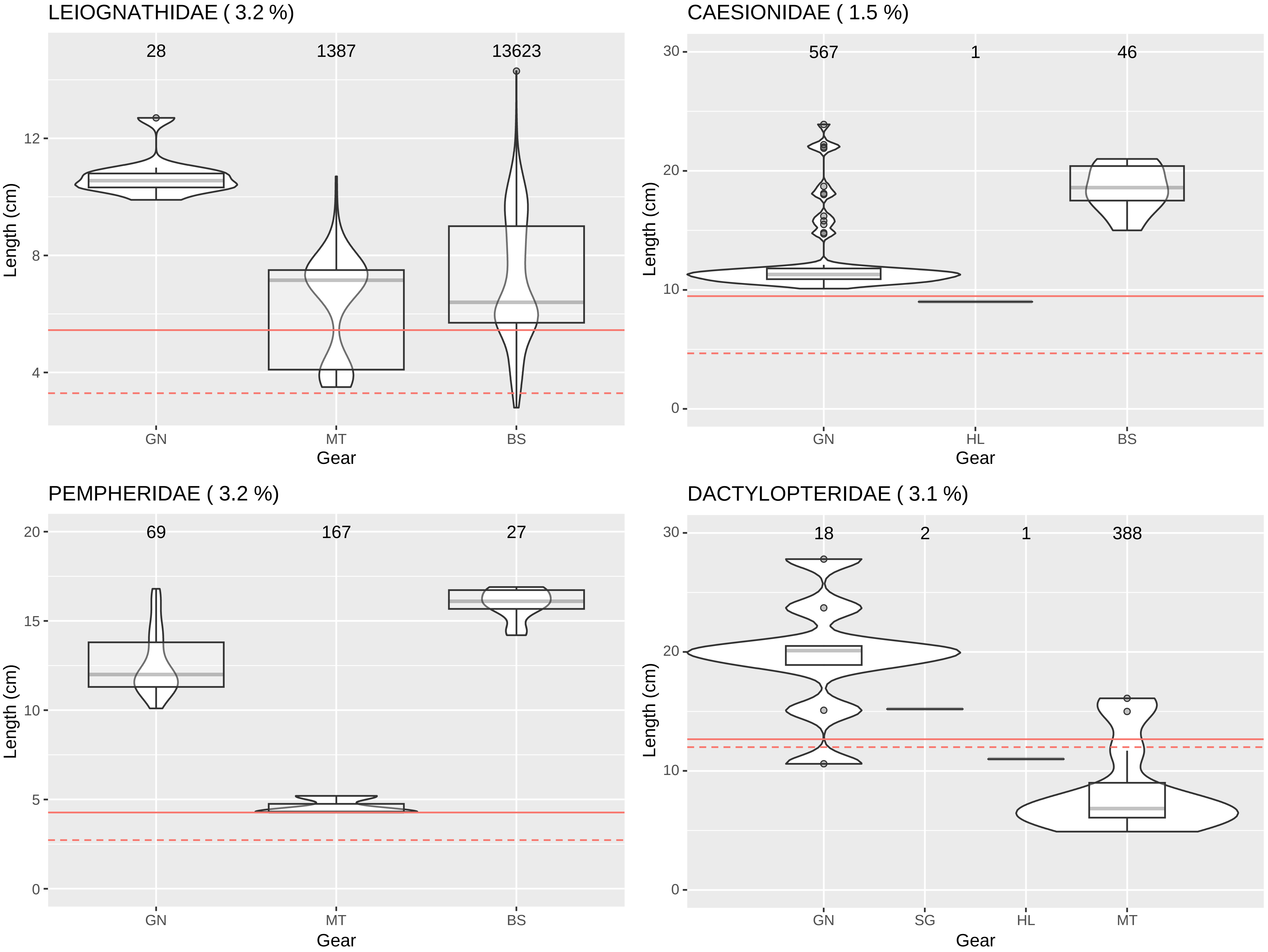
SPARIDAE (5 %)
44
53
339
1
50
40
30
20
10
Length (cm)
GN
HL
MT
BS
Gear
PLATYCEPHALIDAE (4.9 %)
17
16
1
446
66
60
40
20
0
Length (cm)
GN
SG
HL
MT
BS
Gear
PINGUIPEDIDAE (4.9 %)
8
4
51
23
25
20
15
10
5
0
Length (cm)
GN
SG
HL
BS
Gear
MURAENIDAE (4.4 %)
2
168
1
100
75
50
25
0
Length (cm)
GN
SG
HL
Gear


SPHYRAENIDAE (4.2 %)
Length (cm)
0
10
20
30
40
50
BS
GN
HL
MT
SG
Gear


OSTRACIIDAE (3.6 %)
8
1
1
319
Length (cm)
0
5
10
15
20
25
GN
SG
HL
MT
Gear


PRIACANTHIDAE (7.3 %)
69
2
23
138
148
Length (cm)
0
10
20
30
40
GN
SG
HL
MT
BS
Gear


ZANCLIDAE (3.2 %)
38
4
1
12
Length (cm)
0
5
10
15
20
25
GN
SG
HL
MT
Gear


LEIOGNATHIDAE (3.2 %)
28
1387
13623
12
8
4
Length (cm)
GN
MT
BS
Gear
CAESIONIDAE (1.5 %)
567
1
46
30
20
10
0
Length (cm)
GN
HL
BS
Gear
PEMPHERIDAE (3.2 %)
69
167
27
20
15
10
5
0
Length (cm)
GN
MT
BS
Gear
DACTYLOPTERIDAE (3.1 %)
18
2
1
388
30
20
10
0
Length (cm)
GN
SG
HL
MT
Gear

Appendix 3: Generalized linear mixed model (GLMM) and outputs using lmer and lmerTest functions of the package ‘lme4’ version 1.1.19 in R (Bates et al., 2015)

1. Model description

$$\mathbf{ln(Tl+cte) = i_{period} + j_{gear} + l_{periodxgear} + (1 \mid fishing\ trip) + \varepsilon_{residual}}$$

- Tl: total length of fishes in cm
- cte: value of the constant
- i: fixed effect “survey period”
- j: fixed effect “fishing gear”
- l: interaction between fishing gear and survey period
- ε: residual value

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, *67*(1). https://doi.org/10.18637/jss.v067.i01

2. Model outputs

Linear mixed model fit by REML

t-tests use Satterthwaite's method ['lmerModLmerTest']

Formula: `log_Tl ~ period + fishing gear + period * fishing gear + (1 | trip)`

Data: `dt_trip`

REML criterion at convergence: `7188.6`

Scaled residuals:

```
    Min      1Q  Median      3Q     Max
-4.0201 -0.6328 -0.0679  0.5141  9.6320
```

Random effects:

```
 Groups   Name        Variance Std.Dev.
 trip     (Intercept) 0.07542  0.2746
 Residual             0.07567 0.2751
Number of obs: 21602, groups: trip, 525
```

Fixed effects:

```
                              Estimate Std. Error       df   t value Pr(>|t|)
(Intercept)                  2.913e+00  4.554e-02  4.078e+02  63.970  < 2e-16 ***
periodJul-Aug               8.876e-02  6.961e-02  4.199e+02   1.275 0.202991
periodMar-Apr               6.046e-03  5.992e-02  4.062e+02   0.101 0.919679
periodMay-Jun              -4.957e-02  9.343e-02  3.995e+02  -0.531 0.596027
periodNov-Dec               5.049e-02  6.630e-02  4.188e+02   0.762 0.446766
periodSep-Oct               6.336e-02  6.428e-02  4.213e+02   0.986 0.324812
gearSpeargun                2.872e-01  8.393e-02  4.592e+02   3.422 0.000678 ***
gearLine                   -6.458e-02  7.834e-02  4.293e+02  -0.824 0.410229
gearTrawlnet               -9.470e-01  8.324e-02  3.872e+02 -11.377  < 2e-16 ***
gearBeachseine             -2.333e-01  1.024e-01  4.195e+02  -2.278 0.023240 *

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Interaction factors:	Estimate	Std. Error	df	t value	Pr(>|t|)	
Jul-Aug:gearSpeargun	1.035e-02	1.433e-01	4.935e+02	0.072	0.942449	
periodMar-Apr:gearSpeargun	-2.347e-01	1.188e-01	4.563e+02	-1.976	0.048747	*
periodMay-Jun: gearSpeargun	2.762e-01	1.711e-01	4.661e+02	1.614	0.107138	
periodNov-Dec: gearSpeargun	-3.239e-02	1.239e-01	4.643e+02	-0.261	0.793917	
periodSep-Oct:gearSpeargun	-3.699e-02	1.340e-01	4.999e+02	-0.276	0.782672	
periodJul-Aug:gearLine	8.750e-02	1.104e-01	4.328e+02	0.793	0.428368	
periodMar-Apr: gearLine	9.535e-02	1.059e-01	4.288e+02	0.901	0.368318	
periodMay-Jun: gearLine	1.597e-01	1.481e-01	4.156e+02	1.079	0.281231	
periodNov-Dec: gearLine	-1.423e-01	1.169e-01	4.285e+02	-1.218	0.223982	
periodSep-Oct: gearLine	-4.288e-04	1.104e-01	4.323e+02	-0.004	0.996903	
periodJul-Aug: gearLine	5.565e-02	1.180e-01	3.872e+02	0.472	0.637464	
periodMar-Apr: gearLine	3.390e-02	1.179e-01	3.806e+02	0.287	0.773900	
periodMay-Jun:gearTrawlnet	1.941e-01	1.411e-01	3.817e+02	1.376	0.169721	
periodNov-Dec: gearTrawlnet	-4.209e-02	1.249e-01	3.832e+02	-0.337	0.736255	
periodSep-Oct: gearTrawlnet	1.011e-01	1.265e-01	3.864e+02	0.799	0.424697	
periodJul-Aug:gearBeachseine	-3.922e-01	2.089e-01	4.398e+02	-1.878	0.061044	.
periodMar-Apr:gearBeachseine	3.396e-01	1.629e-01	4.320e+02	2.085	0.037699	*
periodMay-Jun:gearBeachseine	-1.449e-01	1.909e-01	3.910e+02	-0.759	0.448473	
periodNov-Dec:gearBeachseine	-3.690e-02	1.376e-01	4.129e+02	-0.268	0.788677	
periodeSep-Oct:gearBeachseine	1.754e-01	1.989e-01	4.149e+02	0.882	0.378326	

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1