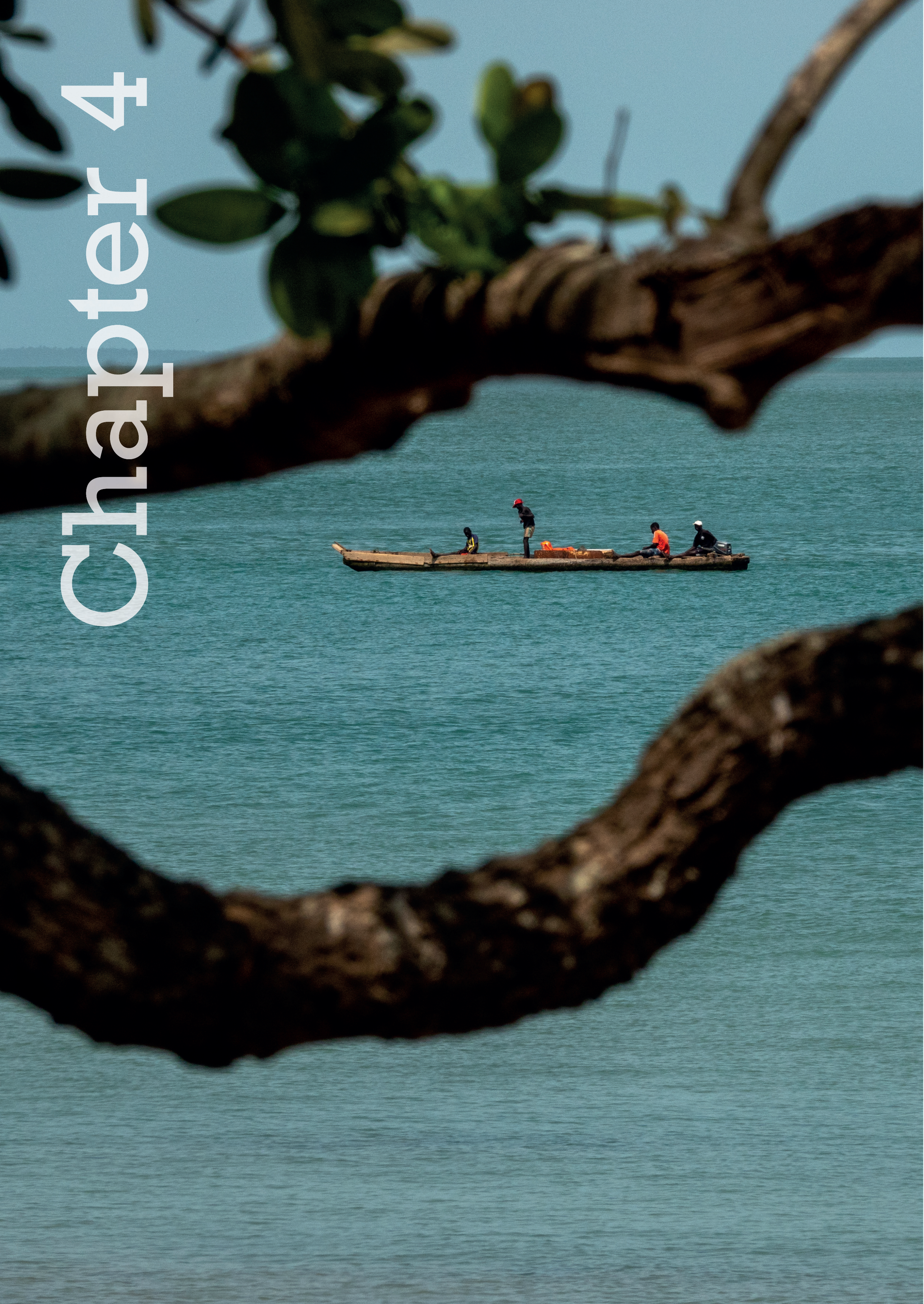
Chapter 4



Reconstructing historical population trends of threatened sharks and rays based on fisher ecological knowledge

Guido Leurs, Rima W. Jabado, Assana Camará, Lilísio Dos Santos, Diosnes Manuel Nonque, Thije J. Zuidewind, Iça Barry, Pierre Campredon, Benja Blaschke, Karin de Boer, Nadia Hijner, Han Olff, Samuel Ledo Pontes, Aissa Regalla, Matthew Bjerregaard Walsh, Laura L. Govers

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Abstract

The lack of historical shark and ray catch information often hampers the management of small-scale fisheries. We reconstructed historical population trends and current fishing pressure by combining local ecological knowledge, satellite-based vessel counts, and a short-term landing site survey. To demonstrate the effectiveness of this methodology, we focused on the Bijagós Archipelago (Guinea-Bissau, West Africa), where historical fisheries data are lacking. We conclude that benthic rays (stingrays/butterfly rays), benthopelagic rays (eagle/cownose rays), guitarfish, requiem sharks, and hammerhead sharks have declined in abundance by 81.5 to 96.7% (species dependent) between 1960–2020. Fishing effort increased annually: fishing trip duration by 42.0 ± 3.4% (1960-2020) and number of vessels by 12.0 ± 1.1% (2007-2022). We estimated that in 2020, fishing vessels collectively captured approximately 340 sharks and up to 2,553 rays per day within the archipelago. However, this likely underestimates the actual catch since vessels from neighboring countries operating in these waters were unaccounted for. We recommend reducing shark and ray catches through the regulation and enforcement of fishing fleet size and reinforcing boundaries of protected areas to safeguard these vulnerable species within the archipelago. Our study demonstrates the value of this innovative three-pronged approach in determining historical trends and fishing pressures in regions lacking such baseline data, which is a common challenge in areas with small-scale fisheries and limited research capacity.

Introduction

The impact of global fisheries on marine ecosystems, marine biodiversity and fish populations is profound (Jackson *et al.* 2001, Lotze *et al.* 2007). These changes have been linked to shifts in ecosystem functioning and a loss of ecosystem services (Jackson *et al.* 2001, Lotze *et al.* 2006, Worm *et al.* 2006). One of the most affected species groups is sharks and rays (i.e., elasmobranchs), highlighted by their deteriorating global conservation status. Indeed, an estimated one-third of all shark and ray species are threatened with extinction (Dulvy *et al.* 2021). The impact of industrial fisheries on shark and ray populations has been documented extensively (e.g., Baum *et al.* 2003, Worm *et al.* 2013, Queiroz *et al.* 2019). Many of these fisheries are managed through regional fisheries bodies (e.g., tuna Regional Fisheries Management Organization) and fishing agreements (e.g., Sustainable Fisheries Partnership Agreements), which include requirements on catch data reporting, and whereby industrial vessel fishing locations can be traced (Kroodsma *et al.* 2018) and potential illegal activities can be predicted (Welch *et al.* 2022). The majority of these industrial fishing fleets are restricted to deep waters (> 200 m depth) or to a certain distance from the shore (e.g., five nautical miles) and operate on the edge of coastal areas and in pelagic realms (Kroodsma *et al.* 2018, Leurs *et al.* 2021). Therefore, these fisheries are mostly expected to impact pelagic shark and ray species (Pacoureau *et al.* 2021) that move over long distances (Queiroz *et al.* 2019) and species moving away from coastal reproductive and feeding areas (Leurs *et al.* 2021).

Within coastal areas, where most shark and ray species occur, the combined effects of fisheries and habitat degradation are disproportionately high (Dulvy *et al.* 2021). Here, sharks and rays are mostly affected by small-scale fisheries (i.e., fisheries using small (coastal) vessels and minimal use of technological gear, Chuenpagdee *et al.* 2006, Guillemot *et al.* 2014), and their interaction with industrial fisheries can be limited. Globally, catches associated with small-scale fisheries make up a large proportion of total fish catches (Teh and Pauly 2018, Palomares and Pauly 2019), especially in regions where these fisheries have a close link with local communities and are important for food security (Palomares and Pauly 2019). Small-scale fisheries have increased steadily over the past decades (Teh and Pauly 2018, Palomares and Pauly 2019) and can have high targeted and incidental catch of sharks and rays (e.g., Temple *et al.* 2019, Karnad *et al.* 2020, Haque *et al.* 2021). Due to the spatially concentrated nature of small-scale fisheries in nearshore areas, their overlap with coastal shark and ray species can be relatively high, likely exerting high localized pressure on their populations. In addition, these fisheries can impact the vulnerable early life stages of shark and ray species using nearshore areas as nursery and feeding areas (Knip *et al.* 2010). Despite the increase of these fisheries and their importance to local communities for income or subsistence (Teh and Pauly 2018, Haque *et al.* 2021), they are often unregulated, with little or no reporting of catches (Belhabib *et al.* 2014, Ekpo and Essien-Ibok 2019, Haque *et al.* 2021). Such limited data availability and low traceability of fishing efforts make the assessment of the impact of these fisheries on sharks and rays challenging.

Here, we attempt to determine the historical and current population trends of sharks and rays in areas where fisheries-dependent data collection is scarce or nonexistent. We focused on one of the largest coastal ecosystems in one of the most data-deficient regions of the world: the Bijagós Archipelago off the coast of Guinea-Bissau in West Africa. In West Africa, both industrial and small-scale fisheries have rapidly expanded over the past decades (Campredon and Cuq 2001, Lemrabott *et al.* 2023, Leurs *et al.* 2021). Sharks and rays are often targeted or retained when incidentally caught for their fins, destined for international markets, and their meat for local or regional markets (Diop and Dossa 2011). Coastal areas in the region are potentially important for the various life-history stages of sharks and rays (Campredon and Cuq 2001, Valadou *et al.* 2006, Knip *et al.* 2010, Leurs *et al.* 2023a, 2023b). However, it is unclear how small-scale fisheries have affected these species, what their current status is, and how high the current fishing pressure is. We used a novel three-pronged approach combining (i) fisher local ecological knowledge (LEK), (ii) satellite-based small-scale fishing vessel counts, and (iii) a short-term landing site survey to determine the historical and current population status of sharks and rays within the Bijagós Archipelago. Specifically, we (1) determined the historical population trends of shark and ray species based on fisher LEK, (2) evaluated changes in fishing effort when considering the number of fishing vessels, fishing trip duration and gear used, and (3) estimated the daily catches of sharks and rays under different levels of small-scale vessel activity scenarios. We show that this combination of methods enables the reconstruction of historical and current fishing pressure on vulnerable taxa, yielding insight into urgently needed management interventions.

Methods

Study area

The Bijagós Archipelago (11°15’N, 16°05’W) is located off the coast of Guinea-Bissau (West Africa) and consists of 88 islands and islets, of which approximately 20 are permanently inhabited (Figure 4.1). The archipelago is situated in the estuary of the Geba River and comprises a complex system of islands fringed by mangrove forests and extensive intertidal flats connected through a system of small tidal creeks and channels. The archipelago is internationally recognized as a wetland of international importance

(Ramsar site; 2014) and as a UNESCO Biosphere Reserve (1996). Within the Bijagós, sharks and rays play an important role in the socio-cultural traditions and beliefs of the archipelago's indigenous communities (Cross 2014) and in the functioning of this large intertidal ecosystem (Leurs *et al.* 2023). Sharks and rays are occasionally targeted for offerings in traditional ceremonies (Cross 2014). However, over the past decades, the international demand for shark and ray products has increased targeted fisheries and retention of incidental catch across the entire West African region (Campredon and Cuq 2001, Diop and Dossa 2011). Within the archipelago, since 1985, small-scale fisheries have developed from a seasonal to a year-round operation that often targets sharks and rays (Campredon and Cuq 2001). Fishers mostly use human-powered dug-out canoes or larger wooden pirogues (Appendix 4.1) powered with one or multiple outboard engines or use beach seine nets deployed on foot. Historical and current catch data on the (artisanal) small-scale fisheries operating within the archipelago waters are nonexistent.

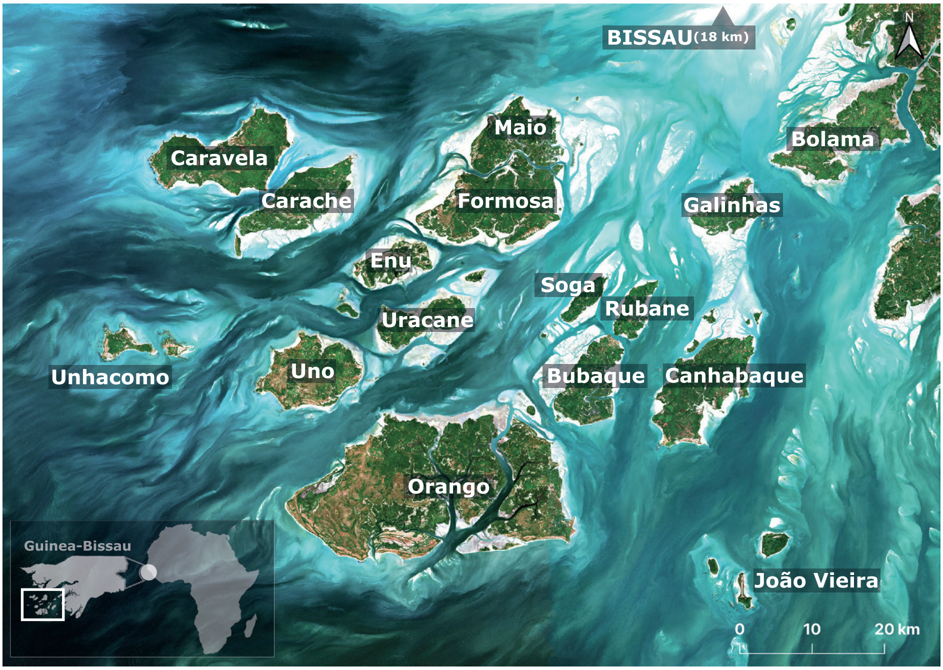

Figure 4.1 The Bijagós Archipelago (11°15'N, 16°05'W) in Guinea-Bissau consists of 88 islands and islets, of which approximately 20 are inhabited year-round.

Elicitation of fishers' ecological knowledge

Two local researchers were trained to conduct in-depth structured interviews with fishers that operate within the Archipelago. Interviews were conducted in Portuguese

Creole from February to June 2021 at the largest small-scale fish market in the country: the Alto Bandim fish market in Bissau (11°50'29" N, 15°35'19" W). To identify participants, snowball sampling was used whereby respondents were asked to recommend other fishers to be included in the study (Goodman 1961), but by considering spread sampling efforts across the entire age range of the fishing community. The central objective of these interviews was to capture perceptions of changes in species abundance, fishing effort, gear use and species utilization over the past decades. Fishers were primarily asked about (1) their demographics, (2) fishing gear use, (3) fishing areas, and (4) species-specific captures. Open-ended discussions focused on the current management of fisheries and any other information fishers wanted to share (Appendix 4.2). To increase the accuracy of data collected from fishers, we recorded change by asking about the moments a fisher could recall best: when the fisher started fishing and the most recent year of fishing (or if a fisher was not active anymore, about the last year of fishing which was subsequently recorded) (e.g., Tesfamichael *et al.* 2014). Although this approach leads to fewer data points per fisher, data points collected are likely the ones a fisher can recall the most accurately (Appendix 4.3). This approach was used in all questions intended to capture change (e.g., changes in catches and gear use). We combined this approach by interviewing fishers of all ages in the fishing communities, which enabled us to reconstruct historical trend lines (Appendix 4.2). Photographic species cards were used throughout the interview to establish a mutual understanding of species identity. As species in Creole are grouped, and fishers were unable to differentiate between species, species were grouped in the following functional species groups: benthic rays (i.e., stingrays *Hypanus* spp., *Dasyatis* spp., *Fontitrygon* spp. and butterfly rays *Gymnura* spp.), benthopelagic rays (i.e., duckbill eagle ray *Aetomylaeus bovinus* and Lusitanian cownose ray *Rhinoptera marginata*), guitarfishes (i.e., common guitarfish *Rhinobatos rhinobatos* and blackchin guitarfish *Glaucostegus cemiculus*), requiem sharks (i.e., *Carcharhinus* spp. and milk shark *Rhizoprionodon acutus*) and hammerhead sharks (i.e., *Sphyrna* spp.) (Appendix 4.4). For each group, specific information such as individuals caught per fishing expedition, average length of captured individuals, processing, and trade were recorded. Fishers were asked to indicate the total lengths of captured individuals on a metric scale for comparison. Interview duration ranged between 1 and 2.5 hours since fishers were encouraged to expand on their experience.

Ethics statement

Before each interview, informed consent was obtained from each participant by explaining the purpose of the interview and the study's objectives. We communicated that the interviewee could terminate the interview at any given time or not answer specific questions. Once the interviewee had a clear understanding of the intentions of the study, the researcher asked permission to make an audio recording of the interview solely for translation and note-taking purposes. To guarantee the interviewee's anonymity, no names or contact information was written down or recorded, and no information was stored that could lead to identifying participants. All files and information collected during the interview were treated as confidential. All research was conducted in accordance with regulations of the national Instituto da Biodiversidade e das Áreas Protegidas and the national Instituto Nacional de Investigação das Pescas e Oceanografia of Guinea-Bissau (permit #06/10/IBAP/2021). All data was collected and stored securely, conforming to the regulations and guidelines of the University of Groningen.

Landing site surveys

From February to November 2021, a landing site survey was initiated in collaboration with INIPO. An enumerator with experience in fisheries research was trained to document shark and ray landings at the Alto Bandim fish market. By interviewing fishers at the point of landing at peak landing times in the morning (6-9 AM, three times a week) and documenting species, the enumerator was able to collect data on the fishing area (i.e., location name, distance from shore, depth), gear specifications (i.e., gear type, length, mesh/hook size, material), and details on the catch (i.e., species, number of individuals, lengths, sex).

Small-scale fishing vessels abundance

To determine the number of small-scale vessels operating within the boundaries of the archipelago and how this has changed over the past decades, we used satellite imagery of the Alto Bandim small-scale fishing port. We used the historical satellite imagery option in Google Earth Pro (v.7.3). The resolution of this imagery between January 2007 and December 2023 was appropriate (~0.5m/pixel; imagery sources: Airbus and Maxar Technology) to count individual small-scale fishing vessels (~8-20 meters in length, see Appendix 4.1). We exported each satellite image (n = 95) and used ImageJ (v. 1.53k) to crop each image to a standardized bounding box around the port. We then annotated each fishing vessel within this bounding box as a proxy for the number of fishing vessels actively fishing in the Bijagós. Images were available for multiple months for most years (Appendix 4.5). This approach only included an estimation of small-scale fishing vessels from Guinea-Bissau, not including any vessels from neighboring countries (e.g., Senegal and Guinea) also known to operate in the waters of the archipelago, but that land their catches in their respective countries and would therefore not have appeared in the imagery.

Data analyses

Data analyses were conducted using R (v.4.3.0). We analyzed changes through time based on interview data using mixing models to account for the variation in responses between fishers. We used generalized linear mixed models with a Poisson distribution to analyze changes in gear type use (e.g., number of sets, gear length, and soak time). Beach seine nets were included as small multifilament nets based on their material, but mostly as small multifilament nets. We used a negative binomial distribution when overdispersion was determined in the Poisson models. We used the same approach to analyze changes in the number of fishing vessels observed by fishers at their fishing sites and in the duration of their fishing trips. For all these models, we used 'year' as a fixed effect and the unique (anonymous) identifier for each fisher (i.e., 'fisher ID') as a random effect. The number of vessels in the primary small-scale fishing port was analyzed by modeling the 90% quantile. We applied a quantile regression model with year as a fixed effect to determine the maximum number of fishing vessels active each year. To determine changes in the abundance of species groups based on fisher experience, we used generalized additive mixed models with a negative binomial distribution to account for overdispersion. In these models, we used the number of individuals of a species group captured per fishing trip as a response variable, year as a fixed variable and fisher ID as a random effect. If fishers provided a range (e.g., two to four individuals captured) during the interviews, we used the midpoint for further data analysis. We used the prediction of fishing trip duration as offset to transform the number of individuals captured per fishing trip to the number of individuals captured per day per vessel. Species composition was determined for each decade between 1960 and 2020 and compared using a permutational analysis of variance (i.e., 'permanova'). Before applying species group models and species composition analysis, we removed the top 5% of the data to minimize the influence of outliers caused by overestimation by interviewees. As data points of a fisher are linked (i.e., one data point when the fisher started fishing and when one stopped or in 2020), both data points were removed when one (or both) were within the top 5% of the data. We used generalized linear mixed models with a gamma distribution to analyze changes in the total length of species groups, with year as a fixed variable and fisher ID as a random effect. We removed values below the reported smallest size-at-birth and above the maximum size for species in each species group to correct for under/overestimation. We extrapolated the number of individuals captured per day by one vessel to the number of individuals captured daily throughout the archipelago by the entire active small-scale fishing fleet. To account for the uncertainty in the species group models and predictions of vessel numbers in the Alto Bandim fish market, we simulated these models for 1,000 Monte Carlo iterations. To determine the influence of fleet activity (i.e., the percentage of vessels counted on satellite imagery that are actively fishing that day), we repeated these simulations for each 10% increment between 10% and 200% fleet activity. We then multiplied each species group's predicted catch-per-unit-effort (i.e., individuals per day) for each species group with the number of vessels for each iteration. We used 10,000 bootstrap iterations to estimate the activity of interviewed fishers by calculating the proportion of weekdays spent fishing in 2020. We then used this estimate to describe daily catches of sharks and rays within the archipelago of the maximum estimated number of fishing vessels at the landing site.

Results

A total of 75 interviews were conducted with fishers operating throughout the Bijagós Archipelago (Figure 4.2, Appendix 4.6). The fishing experience of fishers ranged from 6 to 56 years (29.3 ± 12.4 years; mean ± s.d.), corresponding to a retrospective period from 1964 to 2020 (Figure 4.2AB). As part of the landing site survey, 122 vessels active throughout the archipelago were sampled (Figure 4.2CD). Vessels operating within the archipelago were monitored from February to November 2021. However, the majority of vessels were sampled in March (n = 21, 17.2%), June (n = 17, 13.9%) and July (n = 18, 14.8%; Figure 4.2C). Spatially, the combination of interviews and monitoring of the landing site covered fishers and vessels of the archipelago's main islands (Figure 4.2D).

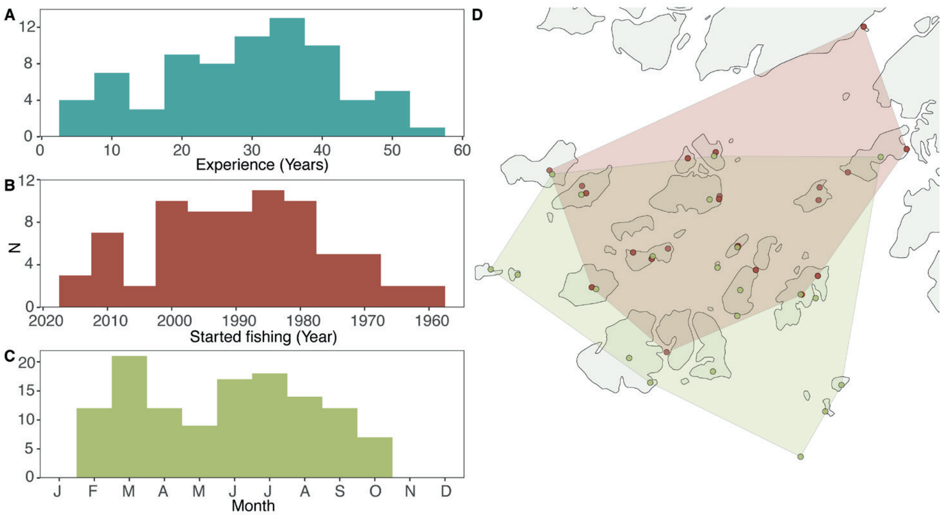

Figure 4.2 Overview of demographics of fishers captured by two different methods in this study: (A) respondent fishing experience in years, (B) the year a fisher started fishing, (C) the number of vessels sampled each month during landing site surveys, and (D) the spatial coverage of the interviews (i.e., the place of residence of fishers; red) and the landing site survey (i.e., base of every fishing vessel; green) indicated by the place of residence of each fisher or fishing vessel.

Species group trends and composition

Based on the interviews with fishers, we determined that the catch-per-unit-effort (in individuals per day) significantly decreased for all ray and shark species groups (Figure 4.3). Decreases over the entire study period ranged from 81.5 ($CI_{95\%}$: 77.8-82.6%) to 96.7% ($CI_{95\%}$: 91.4-97.6%), whereas decreases over the past two decades (2000-2020) ranged from 43.0 ($CI_{95\%}$: 42.4-44.4%) to 71.8% ($CI_{95\%}$: 69.6-72.8%). Although significant declines were noted in catch-per-unit-effort (CPUE; $p < 0.01$, Appendix 4.7), the most frequently captured elasmobranch group throughout the study period remains the benthic rays with an estimated 7.88 ± 1.31 individuals captured per day in 2020 ($p < 0.01$, Appendix 4.7). Overall, the steepest declines (96.7%, $CI_{95\%}$: 91.4-97.6%; $p < 0.001$) between 1960 and 2020 were noted for guitarfish, with on average 20.44 ± 7.45 individuals captured per vessel per day in 1960 and 0.66 ± 0.08 individuals captured per vessel per day in 2020. Other groups experiencing similar rates of declines over the same period were the requiem (93.0%, $CI_{95\%}$: 72.0-95.0%; $p < 0.001$) and hammerhead sharks (89.8%, $CI_{95\%}$: 71.8-92.3%; $p < 0.001$). In terms of individuals captured per day, in 2000, fishers caught an estimated 4.12 ± 0.74 and 1.35 ± 0.24 individuals of requiem and hammerhead sharks per day, whereas in 2020 this was 1.16 ± 0.18 and 0.43 ± 0.07, respectively. This represents a decline of 71.8% ($CI_{95\%}$: 69.6-72.8%) and 67.8% ($CI_{95\%}$: 66.8-68.3%) over the last two decades for requiem and hammerhead sharks, respectively. The average size of captured individuals of benthopelagic rays, guitarfishes, requiem sharks, and hammerhead sharks decreased significantly (Appendix 4.8). The average guitarfish captured in 1962 was 134.1 ± 10.1 cm in total length (TL) and 86.7 ± 3.9 cm TL in 2020 (β = -0.01 ± 0.03, z = -4.9, $p < 0.001$). For requiem sharks, this was 148.8 ± 14.2 cm TL in 1960 and 72.1 ± 4.4 cm TL in 2020 (β = -0.22 ± 0.03, z = -6.7, $p < 0.001$), and for hammerhead sharks 179.0 ± 18.5 cm TL and 90.6 ± 6.2 cm TL (β = 0.21 ± 0.04, z = -5.9, $p < 0.001$). Species composition of catches did not differ significantly across decades (d.f. = 5, F = 1.0, p = 0.3), with rays making up 85.4 ± 1.7% of the catches over the study period and sharks 14.6 ± 1.7% (Appendix 4.9). Based on the landing site survey only encompassing boats that captured elasmobranchs, the highest proportion of elasmobranch catches were the blackchin guitarfish (22.6%, *Glaucostegus cemiculus*), milk shark (27.3%, *Rhizoprionodon acutus*), and scalloped hammerhead shark (7.7%, *Sphyrna lewini*).

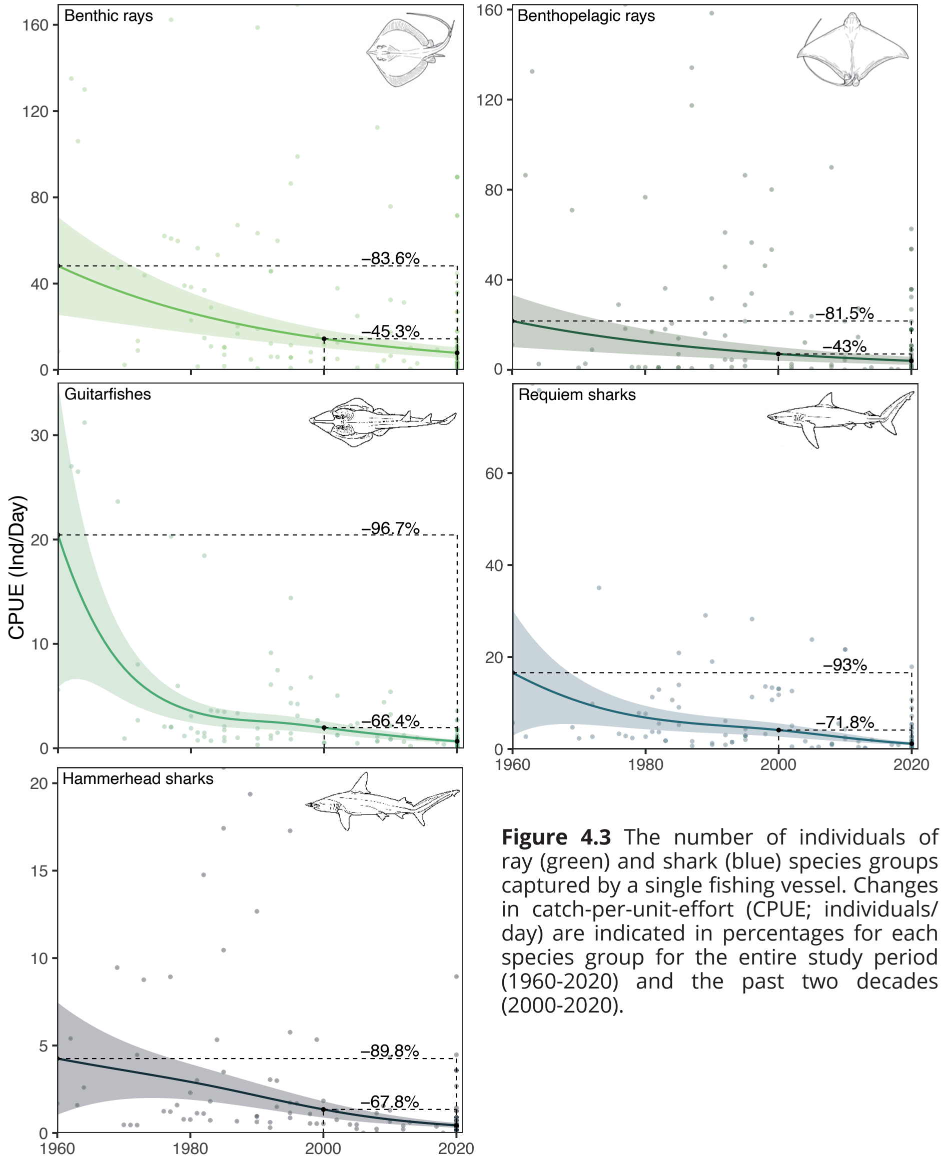

Figure 4.3 The number of individuals of ray (green) and shark (blue) species groups captured by a single fishing vessel. Changes in catch-per-unit-effort (CPUE; individuals/day) are indicated in percentages for each species group for the entire study period (1960-2020) and the past two decades (2000-2020).

Gear use and fishing effort

In terms of gear use, large multifilament (>40mm mesh), small multifilament (≤40mm mesh) and longlines were the most common gear types based on interviews. In contrast, small monofilament nets (≤40mm mesh) are the second-most common gear type based on landing site surveys (Figure 4.4A). Based on the landing site surveys, in terms of overall fishing effort, large multifilament, small monofilament, and longlines were the most prevalent gear types. Target catches predominantly consisted of teleost species groups. However, 29.7% and 26.3% of fishers used large multifilament and small monofilament nets to target elasmobranchs, respectively (Figure 4.4B). Fishers mostly used demersal small monofilament nets to target benthic rays. The realized catch (i.e., fishers stating catches of certain species groups with a gear type) shows that elasmobranchs are captured using all gear types, but mostly with longlines (66.7%), small monofilament (53.6%), large multifilament (57.1%) and small multifilament nets (45.1%; Figure 4.4C). The mean soak time of large multifilament nets significantly increased by 26.8%, from 5.6 ($CI_{95\%}$: 4.1-7.3) hours in 1960 to 7.1 ($CI_{95\%}$: 5.5-9.1) hours per deployment in 2020 ($\beta = 0.07 \pm 0.03$, $z = 2.43$, $p = 0.02$). However, no significant changes in the number of sets, gear length, and soak times were reported for most gear types (Appendix 4.10).

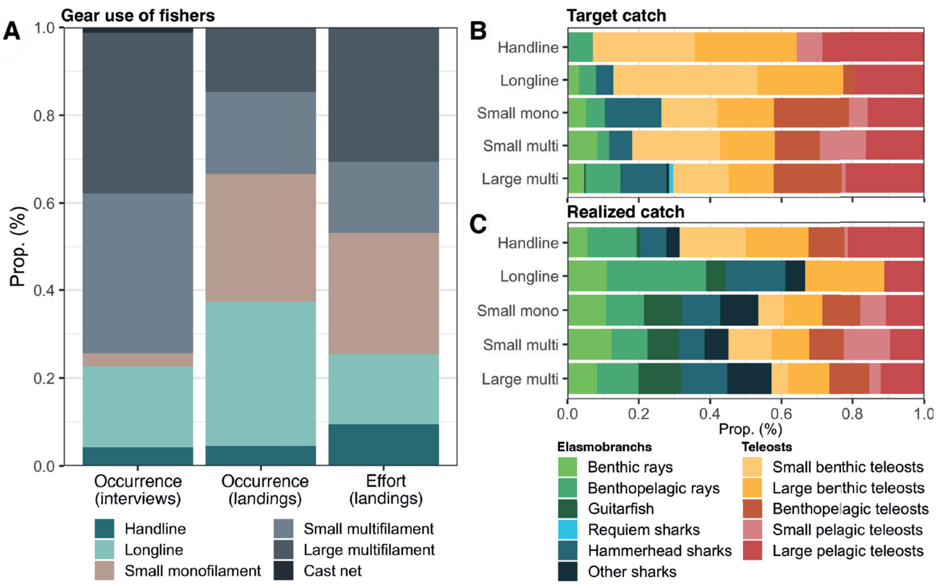

Figure 4.4 The use of different fishing gear in the Bijagós Archipelago small-scale fishery. (A) The prevalence of different gear types as a proportion of interviewed fishers that use this gear, the occurrence of gear on vessels sampled during the landing site survey, and the effort (hours soak time) gear was used during fishing trips. (B) Fishers were asked which species were targeted for each gear type ('target catch') and (C) which species were captured ('realized catch'). Gear type sizes are >40mm mesh for large multifilament nets and ≤40mm for small multifilament and monofilament nets.

Fishers indicated that the number of vessels observed at their fishing locations increased from 4.0 ± 0.4 vessels in 1960 to 11.5 ± 0.6 in 2020 ($\beta = 0.31 \pm 0.03$, $z = 11.07$, $p < 0.001$; Figure 4.5A), representing an increase by 187.5%. In addition, we determined that the total number of small-scale fishing vessels operating within the archipelago increased by 12.0 ± 1.1% (mean ± s.e.) on an annual basis and by a total of 443.7% between 2007 (46.4 ± 5.9) and 2022 (252.5 ± 14.8; $\beta = 0.11 \pm 0.01$, $t = 9.93$, $p < 0.001$)

(Figure 4.5B). Furthermore, fishers indicated that the duration of their fishing trips increased from 1.8 (1.5-2.1) days in 1960 to 5.6 (5.2-6.0) days in 2020 ($\beta = 0.35 \pm 0.03$, $z = 10.38$, $p < 0.001$; Figure 4.5C). Based on the landing site survey, fishing vessels catching sharks and rays were at sea for 7.4 ± 0.5 days in 2021 per fishing trip (Figure 4.5C).

Predicting daily fleet-wide catches

We used the models predicting historical catches of species groups based on fishers' local ecological knowledge and the reconstruction of the increase in small-scale fishing vessels to predict the current number of individuals of each species group captured on a single day in the last study year, 2020 (Figure 4.6). We determined the number of fishing vessels actively fishing on a single day within the archipelago under different activity levels (Figure 4.6A) and determined, based on interviews with fishers, that this activity level was approximately 80% (mean: 80.6%, $CI_{95\%}$: 76.5-84.8%) in 2020 (Figure 4.6B). Under this scenario, we estimate that approximately 191.5 ± 1.5 (mean ± s.e.; interquartile range, IQR: 159.4 - 214.5) fishing vessels were fishing on a single day in 2020 (Figure 4.6A). Together, these vessels captured an estimated 1,595.6 ± 32.6 (IQR: 867.3 - 2,1092) benthic rays, 815.5 ± 18.0 (IQR: 438.3 - 1,036.8**)** benthopelagic rays, 141.2 ± 4.3 (IQR: 50.4 - 194.1) guitarfishes, 241.9 ± 6.6 (IQR: 103.5 - 319.7) requiem sharks, and 97.5 ± 3.2 (IQR: 24.7-141.4) hammerhead sharks on a single day within the archipelago in 2020 (Figure 4.6B). We further show how lower and higher fleet activity levels influence the daily catches of these species groups.

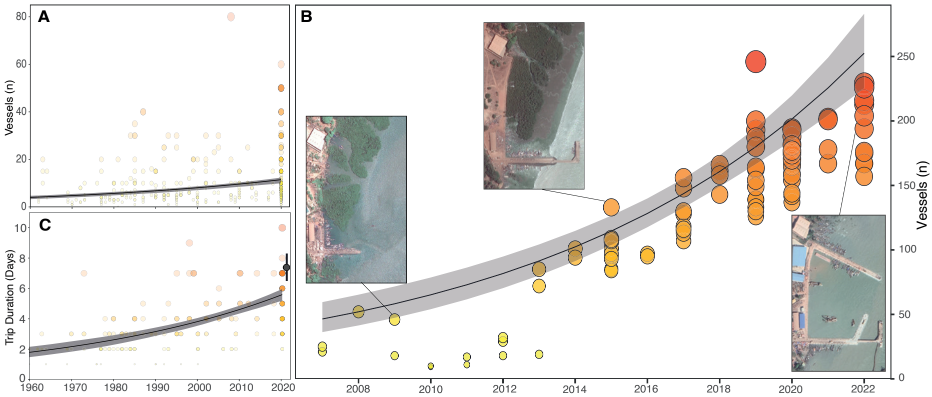

Figure 4.5 The fishing effort of small-scale fishing vessels within the archipelago has increased over the past decades. (A) Fishers were asked to estimate how many vessels they would observe in their fishing area. (B) Satellite imagery provided an overview of the increase of small-scale fishing vessels and the expansion of the primary port of Alto Bandim in Bissau from 2007 to 2022. The curve represents 90% quantile regression with a 95% confidence interval. (C) Based on interviews, the mean duration of a fishing trip significantly increased over time. The trip duration of fishing vessels sampled in the 2021 landing site survey is given with a 95% confidence interval (black point). The number of gear sets, length, and soak times did not significantly increase over time (Appendix 4.10). Satellite imagery taken from Google Earth Pro (downloaded on September 2nd, 2023).

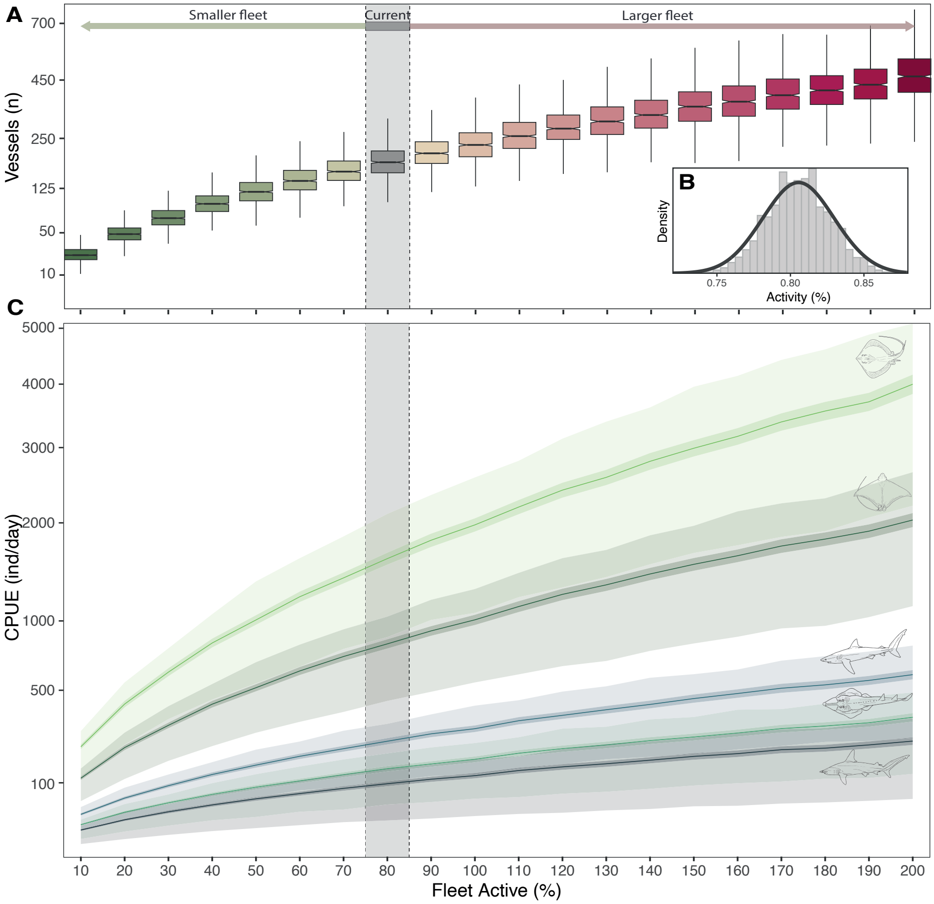

Figure 4.6 (A) The estimated number of small-scale fishing vessels in the Alto Bandim port on a day in 2020 under different fleet activity levels. (B) Based on fisher interviews, bootstrapped estimates of fleet activity in 2020 were between 75% and 85%. Green colors (in A) indicate a lower fleet activity (<80%), and red colors indicate a higher fleet activity (>80%). (C) We then simulated daily catches for the entire small-scale fishing fleet for a day in 2020 for each 10%-increment in fleet activity. Lines indicate the mean 1,000 Monte Carlo simulations, dark-shaded areas represent two times the standard error of the mean, and light-shaded areas indicate the 50% interquartile range. Shark species are indicated in blue, and ray species in green. The gray bar indicates the current situation (i.e., fleet activity 75-85%, B). Note that y-axes have a square-root transformation for visualization purposes.

Discussion

We show that a novel combination of readily available approaches can be successfully used to shed light on small-scale fisheries and historical catches of vulnerable marine species such as sharks and rays. Our findings indicate severe declines in catches and landings of all shark and ray species groups (83–97% depending on the species group) in the Bijagós Archipelago, Guinea-Bissau. At the same time, the size of the fishing fleet continues to increase exponentially. Although current catches and landings are still substantial from a population perspective (daily catches are approximately 340 sharks and up to 2,553 rays), they are now only a fraction of historical catches despite no noteworthy changes in gear use over time that may have influenced changes in shark and ray catches. This is concerning considering the threatened status of most shark and ray species found in Guinea-Bissau and the limited fisheries management measures in place.

Globally, sharks and rays face increasing threats, but overfishing has led to drastic declines in populations of more than a third of species over the past decade (e.g., Dulvy *et al.* 2021). The conservation status of sharks and rays in the West African region has been challenging to assess due to the limited data available. However, the available species level information indicates severe declines (e.g., fisheries independent data from Mauritania for common guitarfish *Rhinobatos rhinobatos* and common smoothhound *Mustelus mustelus*; Jabado *et al.* 2021a, 2021b). Our findings confirm that this is not limited to a few species, and populations of all elasmobranch species are likely to have severely deteriorated. The negative population trends of guitarfishes and hammerhead sharks are especially worrying, as these species groups include some of the most threatened vertebrates globally (Dulvy *et al.* 2021, Kyne *et al.* 2020). Other coastal areas where small-scale fisheries are predominant have also reported declines in historical shark and ray catches and size over the past decades (e.g., Kyalo and Stephen 2013, Humber *et al.* 2017, Vianna *et al.* 2020, Fernando and Stewart 2021, Wambiji *et al.* 2022). However, the declines we report here are amongst the most severe. Declines in catch-per-unit-effort and average size of elasmobranchs are clear signs of overfishing (Froese 2004, Hoggarth *et al.* 2006) and were already reported almost two decades ago in this region (Diop and Dossa 2011). Our estimates show that high catches of sharks and rays continue to date while the fishing effort continues to increase to feed a growing coastal population. Our estimates are likely still an underestimation, as fishers report that many vessels from neighboring countries (especially from Senegal and Guinea) target sharks and rays within the archipelago (Campredon and Cuq 2001, Diop and Dossa 2011). As these vessels land catches in their respective countries, these are unaccounted for in our satellite-based vessel count. Further, our work does not account for industrial vessels often operating legally and illegally in the waters of Guinea-Bissau that likely have large catches of sharks and rays (Leurs *et al.* 2021). Overall, this highlights that current fishing pressure on sharks and rays is likely much higher than we report here and significantly impacts these species.

Declines in shark and ray populations can potentially impact the ecological functioning of coastal areas (e.g., Ferreti *et al.* 2010). Depending on the species and life stage, sharks and rays can have a large variety of food web roles in large coastal ecosystems (Navia *et al.* 2016, Hammerschlag *et al.* 2019, Heithaus *et al.* 2022). We show that the average size of the majority of elasmobranch species groups has declined over time, which could be explained by a within-group shift in species composition (e.g., a shift from larger carcharhinid species (>1 m total length) to generally smaller milk sharks (<1 m total length), as larger individuals are threatened more by fisheries, e.g., Dulvy *et al.* 2021), or by the disappearance of adult individuals of these species groups. Changes in the composition of the elasmobranch community, or even a complete loss of species groups (e.g., guitarfish), could lead to a loss of ecological roles, impairing coastal ecosystem functioning. Fisher's ecological knowledge indicates that species once common, such as sawfishes, have disappeared from most of the coast of West Africa (e.g., Leeney and Poncelet 2015). Additional research in neighboring Mauritania and Senegal also suggests that wedgefishes and some species of guitarfishes are now locally extinct (R.W. Jabado *unpubl. data*). Community elders in the Bijagós also indicated they are worried that 'kasapai' (i.e., guitarfishes) face the same fate (G. Leurs, *unpubl. data*). Species-specific information was possible to collect from LEK surveys because of distinct morphological features that fishers could describe (i.e., rostrum of sawfishes, coloration and large fins of wedgefishes; Jabado *et al.* 2015). However, while declines at the group level were possible to estimate, the lack of species-specific information may have masked larger declines in certain species that fishers could not accurately identify. Further research is needed to accurately determine changes in the species composition of catches in this region.

The disappearance of sharks and rays from these coastal areas may also have socioeconomic repercussions for coastal communities. Our results suggest that fishers go to sea more often or for longer periods but consistently catch less. This aspect of overfishing can have significant implications for local incomes and subsistence (Golden *et al.* 2016). Shark fisheries are often linked to local consumption of shark and ray meat, and (shark) fisheries are a crucial part of local economic systems (Glaus *et al.* 2018, Booth *et al.* 2019, Karnad *et al.* 2020). This is often the case in regions where poverty levels are high and food security is low (Golden *et al.* 2016). Therefore, regulating and managing (shark) fisheries is crucial to contributing to the alleviation of poverty and to strengthening food security in coastal regions. Within the Bijagós archipelago, sharks and rays also have a central role in spiritual ceremonies and traditions (Diop and Dossa 2011, Cross 2014, Leeney and Poncelet

2015). The sawfish features on the regional currency (West African CFA Franc), villages have buildings and ornaments inspired by this species, and sawfish, guitarfish, and hammerhead sharks are often represented in traditional masks and costumes (Cross 2014, Leeney and Poncelet 2015). The loss of the sawfish may also represent a loss of the cultural value of these species. These socioeconomic and ecological considerations render small-scale (shark) fisheries management complex (Booth *et al.* 2019, Haque *et al.* 2021). Finally, while the loss of shark and ray species constitutes an ecological loss in West African coastal communities, it can also constitute a loss of tradition, values, and culture.

We modeled how a reduction (or increase) of small-scale fishing vessel fleet size can affect current catches of sharks and rays within the archipelago. The small-scale fishing fleet has been reduced in other coastal areas to reduce catches of species of concern. However, it can only succeed if alternative incomes and livelihoods are mobilized for fishing communities (Salas *et al.* 2007, Pomeroy 2012). Although marine protected areas are also an effective strategy to conserve some shark and ray species, for larger and mobile elasmobranch species, some protected areas may not be as beneficial (White *et al.* 2017, Mackeracher *et al.* 2019). Our results show that fishing pressure throughout the archipelago remains high, including within the protected areas of Orango and the community-managed national park of Urok. Improving enforcement of existing regulations and limiting fishing capacity by reducing fleet sizes and overall fishing pressure within these areas will likely benefit shark and ray populations. This is particularly important since these large coastal areas are mostly used by early life-stage elasmobranchs with relatively smaller home ranges (Knip *et al.* 2010, Leurs *et al.* 2023a). However, other strategies to minimize the continued exploitation of these vulnerable species should also be further studied and implemented. This may include enforcing and extending the monofilament net ban within and outside the protected areas, a retention ban of highly threatened species like hammerhead sharks, and seasonal closures of fishing areas in key areas (e.g., reproductive areas). The latter should be studied further, as the presence of some elasmobranch species is likely linked to the rainy season (Leurs *et al.* 2023b). In conjunction with improved actions to support the conservation of these species, a monitoring system, including the collection of fishery-dependent data, will be essential to measure impact and effectiveness.

Our reconstructed historical catch trends relied on the local ecological knowledge of the fisher communities in combination with other monitoring approaches (i.e., satellite-based vessel counts and landing site surveys). Local ecological knowledge is considered a key approach to studying the biology of species (e.g., Neis *et al.* 1999, Gilchrist *et al.* 2005, Anadón *et al.* 2009), their distribution (Lopes *et al.* 2019) and temporal changes in abundance (Gilchrist *et al.* 2005, Beaudreau *et al.* 2014). This approach also ensures the inclusion of resource users in decision-making and can lead to a broader understanding of the socio-ecological system at hand (Gilchrist *et al.* 2005, Beaudreau *et al.* 2014, Lopes *et al.* 2019). However, effective species management also requires quantitative information (Gilchrist *et al.* 2005, Tesfamichael *et al.* 2014). Studies capturing local ecological knowledge can be limited to the collection of qualitative (e.g., Gilchrist *et al.* 2005) or low-resolution quantitative information (e.g., high, low abundance; Neis *et al.* 1999, Silvano and Valbo-Jørgensen 2008, Anadón *et al.* 2009). In many cases, quantitative information is also collected at vague temporal scales difficult to recall by the interviewee (e.g., abundance in the year 2000, 2010; Azzurro *et al.* 2011, Beaudreau *et al.* 2014, Colloca *et al.* 2020). The resulting information can be highly variable or lack appropriate resolution, limiting adequate statistical analyses for inclusion in management strategies. For this study, we only focused on the moments a fisher can recall best: when one started fishing and the current situation (e.g., Tesfamichael *et al.* 2014). We show that this methodology can be used to reconstruct temporal change when combined with a sampling scheme that targets fishers across the age range (i.e., experience) of the fishing community. Using this method, we confirm severe declines of all elasmobranch species groups but also that younger fishers are likely used to catching fewer elasmobranchs compared to older generations. This baseline shift (Pauly 1995) is similar to the shift in generational sawfish baselines within the Bijagós Archipelago and other African coastal areas (Leeney and Poncelet 2015, Braulik *et al.* 2020). Two aspects that can increase the sampling error and variability in fisher ecological knowledge data are the willingness of fishers to share information (e.g., when information would indicate non-compliance to regulations or increase competition; Anadón *et al.* 2009) and the fishers' ability to identify the species of concern correctly (Anadón *et al.* 2009). The former was evident as we compared the use of monofilament (forbidden in the archipelago) by interviewed fishers, which was low, to monofilament use on boats sampled by the fisheries observer, which was higher. The latter was addressed by establishing a mutual understanding of the species through visual aids (i.e., species photographic cards). Fishers often have accurate knowledge of species identification, especially species that are easily recognizable or closely linked to communities, as is the case with sharks and rays in the Bijagós (Neis *et al.* 1999, Jabado *et al.* 2015). This suggests that fishers were comfortable with these discussions and that the data collected reflected the current state of shark and ray fisheries in the Bijagós Archipelago.

We showed that a combination of LEK and conventional methods (e.g., landing site surveys and satellite boat counts) can provide important baseline information needed to improve the management of threatened marine species, especially in regions with limited resources and capacity. This information is the basis for future (adaptive) management of these vulnerable species of ecological and socioeconomic importance to coastal communities, such as in the Bijagós Archipelago. Considering the current conservation status of sharks and rays in the region, immediate action needs to be taken to reduce mortality through improved fisheries management measures as well as monitoring and enforcement of established regulations.

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