# Fifteen years of elasmobranchs trade unveiled by DNA tools: Lessons for enhanced monitoring and conservation actions

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The authors declare no competing interests exist.

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## Highlights

- Meta-Analysis of DNA-based tools for monitoring trade, focusing on Brazil's elasmobranchs.
- Challenges in molecular identification were identified (e.g., limited database resources).
- Brazil comprises 203 elasmobranch species, and 64 were molecularly detected in trade.
- 83% of species detected are threatened (IUCN), including recently updated assessments.
- Ten research gaps were outlined, along with recommended practical solutions for future work.


## Abstract

The trade of elasmobranchs (sharks and rays) in Brazil threatens the country's rich endemic biodiversity. The present study explored the use of DNA-based tools to monitor the Brazilian elasmobranch trade, focusing on their role in identifying processed products and supporting conservation efforts. A systematic search of literature was conducted and included 35 peer-reviewed papers published between 2008 and 2023. A shift from the development of DNA-based tools to direct trade applications has been observed since 2015. Molecular identification challenges, including costly sequencing and limited resources in national databases, were identified along with proposed solutions, such as protocol optimization and exploration of cost-effective alternatives. Biases in trade analysis papers, particularly the lack of research in the Northeast Region of Brazil, and issues with sample sizes were evident. Species identified using DNA-based tools included the critically endangered Scalloped Hammerhead Shark (*Sphyrna lewini*), which appeared in 46% of the evaluated papers, followed by the Blue Shark (*Prionace glauca*), and several others threatened species, such as the critically endangered and endemic Brazilian Guitarfish (*Pseudobatos horkelii*) and the recently categorized as vulnerable Sharpnose Shark (*Rhizoprionodon porosus*). Other species were reassessed by IUCN, including previously non-threatened species that are now at risk, emphasizing the need for fisheries management, trade monitoring and conservation measures. Our findings highlight the importance of continued genetic monitoring to analyze market trends and adjust legislation, encouraging compliance with frequent inspections to enhance wildlife conservation. We also identified gaps in research and recommended strategies for accurate species identification, broader investigation, and effective management.



## Keywords

Brazilian trade; Conservation genetics; DNA-based tools; elasmobranchs (sharks and rays); endemic species; forensics

## 1. Introduction

The capture of elasmobranchs (sharks and rays) has been increasing worldwide due to industrial, artisanal, and recreational fisheries catering to diverse markets (Pacoureau et al. 2021). There has been a rising demand for shark fins in Asia and an expanding market for their meat in Europe and South America (Dent and Clarke 2015; Okes and Sant 2019). Brazil has emerged as the largest importer of shark meat and the eleventh-largest country for shark fishing (Barreto et al. 2017; FAO 2020). High demand for shark meat is often attributed to the regulatory practices surrounding finning worldwide, as a substantial growth in the trade has coincided with the global requirement for landings of both fins and the rest of the body (Dent and Clarke 2015; Rangel et al. 2021).

Some authors have indicated that the Brazilian market responded to the finning regulation by heightening demand for shark meat in the country so they could continue to obtain fins and export them to the international market, which can be referred to as "fin laundering" (Rangel et al. 2021). Moreover, low meat prices and the umbrella label "cação" (extensively used in Brazil for shark meat) lead to a lack of awareness among consumers that this term corresponds to sharks and some ray species. Consequently, Brazil is currently one of the leading consumers of shark meat globally (Bornatowski et al. 2015; FAO 2020). This is noteworthy, especially considering that fish meat is not the preferred protein source for most of the Brazilian population (Hase Ueta et al. 2023). The consumption pattern varies across macro-regions of the country. The North Region exhibiting the highest consumption compared to others, with 41.7% of its population consuming fish twice or more per week, while the non-coastal Central-West Region has the lowest fish consumption, with only 15.5% of fish consumption twice or more per week (Lopes and Freitas 2023).

The global shark trade has undergone significant market shifts recently, with shark meat presenting an increased market value over time, but not reaching the value of fins in market (Niedermüller et al. 2021). Indeed, there is a paradox in the values of shark meat and fins. Even though the overall volume and value of the meat market is higher, the value varies according to the species targeted and regions, and fins always attain higher prices per kg (Niedermüller et al. 2021). The rays trade, although less understood, is also concerning. This is primarily because Brazilian markets consider rays an inexpensive product, and they are caught mainly as bycatch (Dent and Clarke 2015). Nevertheless, Brazil has experienced an increase in ray captures, earning the status of the third-largest exporter of ray meat to South Korea in 2021, the primary consumer of ray meat worldwide (Niedermüller et al. 2021).

Elasmobranchs have limited capacity to withstand anthropogenic pressures due to their life history characteristics, including late sexual maturity, low fecundity and slow growth rates (Cortés 2002; Frisk et al. 2005; Stevens et al. 2000). Unreported and unregulated catches have led to substantial extinction risk for elasmobranchs (Mozumder et al. 2023; Sherman et al. 2023a; Worm et al. 2013), making them the primary lineage of marine fish with elevated threats, with over a third of chondrichthyan fish species currently categorized as threatened (Dulvy et al. 2021). The Brazilian Guitarfish (*Pseudobatos horkelii*, Pollom et al. 2020a), Largetooth Sawfish (*Pristis pristis*, Espinoza et al. 2022) and Daggernose Shark (*Isogomphodon oxyrhynchus*, Pollom et al. 2020c) are among the Brazilian elasmobranchs facing increased risk of extinction. Decreases in biological diversity of elasmobranchs has led to changes in the whole marine community, including ecosystemic imbalance, shifting in trophic cascades, and decline in seafood catches (Bornatowski et al. 2014; Pimiento and Pyenson 2021; Sherman et al. 2023b).

Brazilian legislative measures have been established with the intention of reducing the mislabeling and the commercialization of species categorized as Vulnerable (VU), Endangered (EN), or Critically Endangered (CR) according to the Brazilian Ordinance 445/2014 of the Brazilian Ministry of Environment (updated in 2022 and 2023, as ordinances 148/2022 and 354/2023). However, mislabeling and the sale of threatened species continue to occur, and monitoring to curb these practices is still an outstanding challenge (Almeron-Souza et al. 2018; Alvarenga et al. 2023; El Bizri et al. 2020; Feitosa et al. 2018; Souza et al. 2021; Wosnick et al. 2023). Consumers continue to buy elasmobranch meat inadvertently due the practice of removing heads and fins before selling the processed meat as "cação" filets or steaks (FAO 2020; Rodrigues-Filho et al. 2012). Important diagnostic features of the species are lost in these processes, hampering the morphological identification of the products at landing and commercial sites (Domingues et al. 2021).

Molecular techniques have played a fundamental role addressing the illegal commerce of shark and ray products when identification by morphological diagnostic features used for is restricted. These techniques enable the accurate identification of species composition at landings sites, the tracking of finning practices, and the identification of processed meat (Clarke et al. 2006; Domingues et al. 2021). Nevertheless, there is still a need to: a) compile the information available on the use of DNA-based tools to track the Brazilian elasmobranch trade, b) expand the use of molecular techniques to efficiently understand the traded species composition, and c) assist enforcement inspections by using genetic tools and increasing inspection frequency, which can help decelerate the current alarming extinction risk of elasmobranch species.

In this context, this study aimed to provide a historical assessment of the contribution of molecular tools in analyzing the Brazilian market of shark and ray products by reviewing all peer-reviewed journals published until June 31st 2023. Our overarching objectives included a comprehensive overview of the research on Brazilian elasmobranch trade and identifying potential areas for further research, which can improve law enforcement, fisheries management, and conservation efforts. To achieve this, five specific goals were established: (i) examine the existing scientific literature in all Brazilian regions, identifying the sampling strategy applied in the context of the papers analyzed and their geographic range, (ii) evaluate the contribution of genetic tools in analyzing the trade of elasmobranchs in Brazil, including an analysis of the most commonly used techniques and the status of genetic databases for Brazilian species, (iii) identify the species composition in Brazilian markets that has been detected with molecular techniques, with a particular focus on the commercialization of threatened and endemic species over time, (iv) assess the extent to which legislation has contributed to monitoring the fishing and trade of elasmobranchs in Brazil, and (v) evaluate mislabeling activities. Furthermore, recommendations are provided to contribute to improving conservation efforts.

## 2. Material and methods

### *Data collection and categorization*

We performed our literature search following the protocol from the RepOrting Standards for Systematic Evidence Syntheses (ROSES; Haddaway et al. 2018) to ensure methodological rigor. First, an extensive Boolean search (AND, OR, NOT) on Web of Science and Scopus was carried out to collect peer-reviewed papers that applied molecular tools for the analyses of elasmobranchs catch and trade in Brazil. Our literature collection strategy included keywords, titles, and abstract content related to mislabeling and molecular identification. We included papers that met the following criteria: (i) research carried out in Brazil, (ii) published until June 31st 2023, and (iii) research articles. To consolidate data from both databases and remove potential duplicates, we used the R package Bibliometrix (Aria and Cuccurullo 2017), obtaining a matrix with 67 papers. Second, a Boolean search on Google Scholar was performed, adding the first 50 papers in our matrix (Haddaway et al. 2018).

To ensure relevancy to our analysis and remove duplicates from the Google Scholar search, we manually inspected the papers matrix for inclusion into our final database. The inspection was performed by three authors, using *strict consensus* criteria, meaning that all the authors that curated the papers agreed to the addition of a paper, resulting in 32 total papers. We computed the inter-rater agreement to infer the consistency and reliability of our assessments by measuring agreement among independent raters evaluating the same set of items (Gisev et al. 2013). Finally, to detect and recover any potentially missed papers, the Snowball Method was applied, which involves a search for papers in the list of citations (forward snowballing) and in their cited references (backward snowballing) (Wohlin 2014), retaining 3 additional papers. For a comprehensive overview of our search process, see Figure 1 and Appendix A.

To provide a historical assessment on the use of molecular tools to analyze the Brazilian market, we categorized the 35 selected peer-reviewed papers into two groups: "Trade Analysis" (papers focusing mainly on the analysis of elasmobranch trade) and “Methods” (papers that developed DNA-based tools for species identification). These two categories were non-exclusive, which means that there could be papers fitting in both categories and therefore assigned to "Methods/Trade Analysis" (papers combining the development of a DNA-based technique with its applications for trade analysis within the same paper). Initial metadata construction depicts each sample from the respective papers in specific categories to characterize the use of genetics to analyze trade activity in Brazil. For a comprehensive understanding of the metadata and detailed information on the individual categories, see Appendix B. We used the metadata information to conduct a routine exploratory data analysis (data cleaning, summarization, visualization) in R (Luque and Donlan 2019). For a detailed description of the analyzes performed and R packages applied, see Appendix D. We investigated DNA-based tool applications for analyzing the elasmobranch trade in Brazil, assessing papers and samples at national and state levels. In particular, examining the development of genetic tools, the composition of species on trade, threats trends, and mislabeled products.

Two additional datasets were generated based on the species composition found to obtain information on their genetic availability, extinction risk status and legislation (Fig. 1). The first dataset focused on genetic information for each of the identified species, specifically the number of sequences available in the National Center for Biotechnology Information (NCBI) GenBank and in the Barcode of Life Data System (BOLD) database. NCBI GenBank sequences were obtained using the *esearch* command in Entrez Direct (EDirect; Kans 2013) while BOLD sequences were accessed through the *bold* package (Chamberlain 2021) in the statistical software R v.2022.02.3 (R Core Team 2021). Both sets of additional data can be found in Appendix C.

The second dataset focused on the extinction risk for each species according to the Brazilian Red Book of Threatened Fauna (ICMBio 2018), SALVE System (Portuguese for "Biodiversity Extinction Risk Assessment System", available online at: https://salve.icmbio.gov.br/) and the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (hereinafter IUCN Red List, available at: https://www.iucnRed List.org/). Whenever available in the online IUCN Red List assessments, additional specific observations on species populations status for the Southwestern Atlantic Ocean (SWA) were also included. In the same dataset, we depicted key legislations for biodiversity conservation and labeling regulations over time.

*Data Analysis*

In order to achieve the five specific objectives of this work, we divided our analysis into five stages:

***2.1 Research Trends***

We evaluated research trends using DNA tools to analyze the elasmobranch trade focusing on the main metadata, specifically examining information on publication year, sample size, and market characteristics (Fig. 1).

### *2.2 Molecular Species Identification*

The analysis centered on how molecular methods were used to identify species composition in the elasmobranch trade using the main metadata, specifically the information on molecular identification (Fig. 1). It also considered the accuracy of the identification (i.e. sample identified at species level). Moreover, we evaluated whether sequences of all species molecularly detected in the papers retrieved were available in the main databases (i.e. GenBank and BOLD System) using the first additional dataset (genetic information metadata).

### *2.3 Species Composition in Trade*

We assessed all species that were detected in landing sites and in trade using molecular tools, specifically the information on species composition (Fig. 1 - Main metadata). We also evaluated the extinction risk status and assessments updates of each species molecularly detected in the papers retrieved over time based on the main metadata (Fig. 1).

### *2.4 Brazilian Legislation*

We explored historical trends in Brazilian legislation related to wildlife conservation and fish labeling over time, comparing the legislation metadata with the national extinction risk status only for the species molecularly detected in the papers retrieved (Fig. 1).

### *2.5 Mislabeling Activities*

We assessed mislabeling activities by comparing the declared market label and the species detected with molecular tools in the main metadata (Fig. 1; Appendix B), checking if the detected species complied with the Brazilian labeling regulation (MAPA 570/2023).

For detailed information on statistical and visualization analyses conducted, please see the R Markdown script provided in Appendix D and the GitHub repository available at (link available upon acceptance).

## 3. Results

### *3.1 Research Trends*

A total of 35 peer-reviewed publications (referred here as papers) published between January 2008 and June 2023 were assessed (Fig. 2a). Of these, 24 (69%) were categorized as “Trade Analysis”, eight (23%) as “Methods”, and three (9%) fitting in both categories as "Methods/Trade Analysis" (Fig. 2b). The focus of research has shifted towards trade analysis since 2012, noted by an increase of “Trade Analysis” compared to “Methods” ones (Fig. 2a).

Among the 11 “Methods” papers, a variety of DNA-based tools were developed: Multiplex PCR in five papers, PCR-RFLP in four papers, tandem repeats in one paper, and Sanger sequencing in one paper (Table 1; Table S2, in Appendix B). The most frequently employed molecular marker was COI (n = 6), whereas 16S was the least utilized (n = 1).

The 27 "Trade Analysis" papers collectively involved 3,784 samples collected for molecular detection (mean = 192; min = 7; max = 747; SD = 194) from 15 Brazilian states, which represent 55% of the total country's federative units, and 88% of those on the coast (Fig. 1c). The sampling sizes and strategies for market screening (e.g., market type, labeling, sample location) varied greatly among the papers (Fig. 1d,e). Out of the total samples, 85% (n = 3,235) were assigned to specific Brazilian states while the remaining samples were labeled "Unidentified Location" due to incomplete information provided in the papers regarding each sample individually (Table S1, in Appendix B). The State of Pará had the highest number of papers and samples (n = 10 and 1,022), followed by São Paulo (n = 8 and 998), and Santa Catarina (n = 6 and 194). Notably, there was a scarcity of research from the Northeast Region of Brazil, with only four papers across seven of the nine states in this region and 311 samples collected (Fig. 2c-e).

Shark meat was the main target in the Trade Analysis, accounting for 81% of the papers (n = 22) and 1,419 samples, while ray meat was analyzed in 22% of the papers and comprised 335 samples (Table S1, in Appendix B). We observed papers that collected specific groups of elasmobranchs such as guitarfishes (Alvarenga et al. 2021 - 75 samples; De Franco et al. 2012 - 267 samples), angel sharks (Bunholi et al. 2018 - 85 samples), and whiptail stingrays (Schmidt et al. 2015 - 97 samples). Three papers assessed elasmobranch captured as bycatch (Domingues, 2013 - 317 samples; Ferrette, 2019 - 228 samples, Guimaraes-Costa, 2020 - 73 samples), one assessed the fin trade (Ferrette et al. 2019b - 747 samples), and one assessed sawfish rostra (Faria et al. 2013 - 77 samples). In education institutions' dinning services, such as school and universities cafeterias, 23 shark samples were served as a fish protein option, and in commercial restaurants, four out of 14 samples were found to be mislabeled (Alvarenga et al. 2021). A total of nine papers evaluated the mislabeling in elasmobranch trade, including sharks being sold as salmon or croaker (Staffen et al. 2017) (Table 1 and Table S1, in Appendix B).

### *3.2 Molecular Species Identification*

Among the molecular tools applied in "Trade Analysis" papers, PCR-RFLP (n =1) was the least applied, followed by Multiplex PCR (n = 5). Sanger sequencing (n = 24) was the most applied, and the only technique observed in all papers published since 2018, with the exception of one study in 2019 that used Multiplex PCR (Fig. 3a). The COI was the most applied molecular marker for both shark and ray identification, and the most represented in current databases (Fig. 3b). Among the 26 papers that used COI, the primer set developed by Ward et al. (2005) was applied in 23 papers. Ninety seven percent of the samples (n = 2345) were identified to species level by the authors of the assessed papers using the COI marker, while the remaining 3% of the samples (n = 69) were identified at the family level (Rajiformes, n = 1), genus level (*Dasyatis* sp., n = 39; *Gymnura* sp., n = 5; *Hypanus* sp., n = 1; *Mustelus* sp., n = 5; *Narcine* sp.), or as a species complex, in which case it was not possible to assign the sample to a single species (*Carcharhinus obscurus*/*C. galapagensis*, n = 4). Other species complexes were identified through NADH-ubiquinone oxidoreductase chain 2 (ND2) (*Squalus brevirostris/S. megalops*, *n = 1*), and 12S/16S (*C. plumbeus/C. altimus*, n = 4). The region comprising 12S/16S also failed to identify samples at species level (*Rhizoprionodon* sp., n = 35; *Sphyrna* sp., n = 2). Overall, 11 misidentifications were reported (Table S1, in Appendix B).

By examining the availability of genetic resources in the public sequence databases, we detected a clear bias toward sharks compared to ray species (Fig. 3b). Furthermore, it is worth noting that public sequence databases still have gaps. For example, the 27 papers assessed here represent 64 species deposited in the NCBI database, but not for all markers (Fig. 3b). Moreover, from the approximately 203 species of sharks and rays known for Brazilian waters (Kotas et al. 2023), only 144 are present in the NCBI database, representing 71% of the overall Brazilian diversity. Gaps in genetic databases are particularly present for species with restricted distribution, such as endemic species of Brazil (Fig. 3c). The availability of complete mitochondrial genomes was higher for species with a wide distribution range, whereas the use of shorter mitochondrial markers showed consistent representation across species with both wide and restricted distributions (Fig. 3c).

### *3.3 Species Composition in Trade*

A total of 73 species (44 genera and 28 families) were reported in all "Trade Analysis" papers (Table S3 in Appendix A). Among these species, 36 shark species belong to 16 genera and 28 rays belong to 20 genera (18 marine and two freshwater). Additionally, we detected nine species of bony fish mislabeled as elasmobranch meat (Fig. 4). Within the identified families, Carcharhinidae was the most abundant, with three genera leading the ranking: *Carcharhinus* (886 samples in 17 papers), *Prionace* (464 samples in 10 papers), and *Rhizoprionodon* (375 samples in 15 papers) (Fig. 4). The top position within paper count was led by the genus *Sphyrna* (345 samples) and *Carcharhinus* (886 samples), both detected in 17 papers (Fig. 4). For rays, guitarfishes (genus *Pseudobatos)* were detected in 298 samples across 8 papers, in which 187 samples belonged to the CR *Pseudobatos horkelii* (Fig. S2 in Appendix A), whereas 111 samples belonged to the recently categorized as EN *P. percellens.* The most threatened ray genus, *Pristis*, was also detected in high numbers (113 samples in 3 papers), as well as other genera of commercially explored and threatened sharks and rays (Fig. 4).

In the trade analyses, we observed threatened species being detected in high (Table 2) and increasing numbers (Fig. S2, in Appendix A). Currently, 83% (n = 54) of the elasmobranch species detected were categorized as threatened (VU, EN or CR) and 12% as Near Threatened (NT) by the IUCN Red List, with only three species categorized as Least Concern (LC) (Table 2). A total of 81% of the valid elasmobranch samples (n = 2,877) detected here belong to threatened categories (Fig. S1, Table S3).

The IUCN Red List extinction risk assessments changed over time (Fig. 5, Fig. S2 in Appendix A), with only one species experiencing a decrease in extinction risk (*Rhinoptera brasiliensis,* from EN to VU). Contrastingly, we detected 33 cases where the extinction risk has increased, including 17 species not previously considered threatened, and seven species whose extinction risk worsened by more than one category (Fig. 4a). In particular, frequently traded species have become more threatened, such as *Carcharhinus acronotus* (NT to EN), *Rhizoprionodon porosus* (LC to VU), *Sphyrna lewini*, and *S. mokarran* (EN to CR). Additionally, among the 16 species previously categorized as Data Deficient (DD), 14 have had their extinction risk assessed with nine currently considered threatened (Fig. 4b), including two of the most commercially traded species: *R. lalandii* (DD to VU), and *C. porosus* (DD to CR). Overall, eight of the species detected are now CR.

Among the reviewed papers, only 55% referenced to the Brazilian Red Book, while 89% relied only on the IUCN Red List. No paper referenced the SALVE System, since it was made available in 2023. There were discrepancies in species assessment between the extinction risk in the lists analyzed here (Fig. 6), mainly regarding the number of species assessed. All the 64 species found in this study were assessed in the IUCN Red List, while there were Not Evaluated (NE) species in the other two lists: 51% in the Brazilian Red Book, and 8% in the SALVE System. Also, 11% of the species did not have an observation for their IUCN SWA populations. Among the categorized species, we noted some differences in the IUCN Red List assessments of risk of extinction when comparing global and SWA population status. For example, 18% of species present in Brazilian waters were globally assessed as CR, while specific consideration of the SWA populations increased this percentage to 31%.

Overall, species assessed at a regional level (Brazil or SWA) tended to have higher extinction risk categories, with 25% of them listed as CR in the Brazilian Red Book and 31%

in the SALVE System (Fig. 6a). In contrast, species categorized as EN or CR in the IUCN Red List presented lower risk of extinction categories in the published version of the Brazilian Red Book (e.g., *Carcharhinus perezi* - VU) and SALVE System (e.g., *Pseudobatos percellens* and *Zapteryx brevirostris* - VU) (Table S1, in Appendix C).

### *3.4. Brazilian Legislation*

We examined the historical evolution of Brazilian legislation and species extinction risk assessments. First, we analyzed the extinction risk lists (Fig. 6a), including the newly released SALVE System, and the most pertinent regulatory measures based on these assessments (Fig. 6b). We identified a discrepancy in the categorization of threatened species (VU, EN, CR) and their protection under Brazilian ordinances. Significant progress was noted from the initial legislation (IN 05/2009), which protected species in Appendices I and II, to subsequent regulations (MMA 445/2014, MMA 148/2022 and MMA 354/2023), which protect VU, EN and CR species. However, the latest regulation (MMA 354/2023) still categorizes a lower percentage (47%) of species as threatened compared to the most recent Brazilian extinction list in the SALVE System (63%). Second, we analyzed labeling regulations, which revealed limited taxonomic classifications and a prevalent use of umbrella labels over time (Table S1, in Appendix C). Only one regulatory measure mandates species-specific labels, and it applies exclusively to one Brazilian state (Paraná) rather than to the entire country.

### *3.5. Mislabeling*

According to the current national fish labeling (MAPA 570/2023), our study identified mislabeling in 237 samples. This included instances where bony fishes were sold as elasmobranchs in 33 samples, with the swordfish *Xiphias gladius* being the most frequently mislabeled species (n = 13). Furthermore, there were 85 cases where rays were sold as sharks and 22 cases where sharks were sold as rays. Specific instances of mislabeling were also recorded, such as sharks, skates, and stingrays being labeled as guitarfishes (n = 65). Also, a common change in labels was noted among angel sharks and guitarfishes, where angel sharks were labeled as guitarfishes (n = 5), and guitarfishes as angel sharks (n = 16). For other mislabeling cases, please refer to Table S2, in Appendix B. Half of the papers analyzing the meat trade included a description on the market label, but only 40% of them aimed to evaluate mislabeling activity (Table 1).

## 4. Discussion

The present study examined the effectiveness of genetic tools in identifying processed products. Furthermore, it explored their relevance in law enforcement based on market trends detection to inform legislative adjustments as well as continuing genetic monitoring. Since Brazil holds the second-largest number of endemic elasmobranch species globally (IUCN 2023), frequent inspections can encourage compliance, thereby improving conservation actions both in Brazil and potentially worldwide. There has been a rise in papers addressing the capture and commercialization of elasmobranchs using genetic tools over the past decade, with a clear temporal trend regarding the type of research ranging from papers developing molecular tools to ones applying them to inspect the trade (Fig. 2). This shift can be attributed to the rapid decrease in supplies prices and an increase in applicability of molecular techniques, including the use of DNA barcoding for elasmobranchs (Ward et al. 2005).

### **4.1.** ***Current State of the Art***

The DNA-based tools applied in Trade Analysis papers experienced a temporal switch, with Sanger sequencing emerging as the predominant technique (n = 24), and the only one applied since 2018, except for a single study in 2019 (Fig. 3b). While Sanger sequencing is highly effective for accurate species identification, its continued high-cost for large sample sizes poses challenges, particularly in resource-limited regions like Latin America, which can restrict frequent market inspections. Several approaches can be pursued to address this, including optimizing DNA sequencing protocols, using high-throughput sequencing (HTS) methods like amplicon sequencing, and exploring modern cost-effective methods, like real-time PCR and closed-tube DNA barcoding (Ballard et al. 2020; Cardenosa et al. 2018; Prasetyo et al. 2023; Yeo et al. 2023).

In the economic context of the Global South, it is important to recognize the value of traditional cost-effective techniques, such as PCR-RFLP and Multiplex PCR, which can identify a large set of samples at lower prices (Böhme et al. 2019). Despite Brazil's high elasmobranch biodiversity (n = 203, Kotas et al. 2023), it is noteworthy that we found that the 10 species most sold in the Brazilian trade (Fig. S1) contributed to 56% of the trade (sample count). Considering this, focusing on a small subset of the most commonly traded species could be effective for analyzing trade in Brazil. Exceptions to the usual traded species (detected as a negative in cost-effective approaches) could then be analyzed with Sanger sequencing, reducing costs by limiting sequencing to fewer samples. Although these techniques require initial costs for development, some sets that comprise the most traded species in the Brazilian market are already available (Albercrombie et al. 2002; Caballero et al. 2012; Ferrito et al. 2019; Shivji et al. 2002), including those developed nationally (Table S2, in Appendix B). Among the techniques developed in Brazil, only the Multiplex PCR Method developed by De-Franco et al. (2010) was fully implemented in a Trade Analysis paper (De-Franco et al. 2012). Although the others full Multiplex PCR sets were not used, single primers have been used to obtain additional genetic information on shark species (Table S1, in Appendix A). For instance, primers from Pinhal et al. (2012) were used by Davis et al. (2019) to assess population genetics of *Rhizoprionodon* in the Northwest Atlantic Ocean.

Fisheries research often relies on opportunistic sampling (Pardo et al. 2016), which can be a result of the constrained availability of research funding in environmental sciences and limited access to the required field and laboratory equipment. This strategy and sample sizes obtained through it can impact forensic analysis. The lack of a statistically calculated sampling campaign may conflate particular aspects of the trade, such as a seasonality, rather than comprehensively covering the entire trade dynamics. This also compromises the accuracy of comparisons across studies (Luque and Donlan 2019; Pardo et al. 2016). Sample sizes varied among the reviewed papers because they were discrete studies, however, it was clear that some regions tended to concentrate more studies and samples than others.

A geographical bias was detected along the Brazilian coast, with a high number of research papers conducted in the State of Pará (n = 11, samples = 1,022) in the Northern Region of Brazil, followed by São Paulo (n = 8, samples = 998) in the Southeast and Santa Catarina (n = 6, samples = 194) in the South, while fewer papers were published in the Northeastern Region (n = 5, samples = 260) (Fig. 2). This bias is concerning because certain elasmobranch species endemic to the Northeast, such as *Squalus bahiensis* (DD; R Pollom et al. 2020d), *Hypanus marianae* (EN; R Pollom et al. 2020b), and *Squatina varii* (LC; Rincon et al. 2019) may be subject to unacknowledged overexploitation. Overall, bias in biodiversity research can impact or hinder the implementation of conservation efforts, and strategies to avoid it should be implemented (Hickisch et al. 2019). The observed pattern of papers published in the North and South/Southeast regions highlights another issue of national funding distribution, which affects infrastructure and human resources.

Another important point is that states with higher tax revenues (e.g., Santa Catarina and São Paulo) usually provide more funding support for research, when compared to states with a lower tax income (e.g., Piauí and Amapá). This could result in different degrees of commitment in monitoring and combating the illegal trade of elasmobranchs and fin exports to foreign markets. Strategic allocation of efforts and resources might reflect in improved inspection; for example, one of the largest seizures of illegal shark fin export in the world took place in São Paulo, with approximately 28.7 tons of illegally obtained fins that would be taken to Asia (Frontini and Mano 2023).

Despite having a greater number of endemic and threatened species (IUCN 2023), the number of papers analyzing rays is disproportionately low, considering that the diversity of rays (n = 104) is reported as higher than the sharks (n = 99) in Brazilian waters (Kotas et al. 2023), highlighting a preference for sharks in genetic elasmobranch research (Dudgeon et al. 2012; Soares and Petean 2023). Rays are usually captured as bycatch in trawling and gillnet fisheries, and their meat has been undervalued in most Brazilian markets, being sold at low prices, exported, or mislabeled (Dulvy et al. 2014; Ferrette et al. 2019a). Nevertheless, rays have internationally become a valuable fishery resource with well-documented international trade (Sherman et al. 2023a). Currently, Brazil stands as a major exporter of ray meat to South Korea, the largest consumer of ray meat globally (Niedermüller et al. 2021). However, there is a scarcity of peer-reviewed publications evaluating the impacts and products derived from rays captured as bycatch and in industrial fisheries.

In general, there is a need to better understand the effects of elasmobranch bycatch and finning, and how these activities drive or are being driven by domestic and international trade. In this sense, molecular tools could be applied, such as the use of environmental DNA (eDNA) to assess bycatch activities using vessel water samples (Albonetti et al. 2023) and regular species identification on landing sites (Ferrette et al. 2019a). Moreover, molecular tools can also be aid in geographical tracking to determine whether Brazilian species are present in international fin markets (Domingues et al. 2021).

### *4.2. Unraveling Trade with Molecular Tools: Challenges and Future Directions*

DNA barcoding, the primary tool for species identification, faces challenges that can affect its accuracy. Incomplete species representation in databases and insufficient curation can lead to misidentification issues, such as the "Rajiformes" case noted here, a label that encompassed 297 species. Additionally, some markers applied to DNA barcoding showed lower discriminatory delimitation for closely related species (Alvarenga et al. 2023). This can impact conservation efforts, especially when differentiating threatened and non-threatened species in the same species-complex (e.g., *Squalus brevirostris* - EN and *S. megalops* - LC). Integrating phylogenetic analysis can enhance identification reliability by considering factors like branch length and unusual relationship patterns (Felsenstein 2004). The most applied molecular marker, COI, has shown limitations in identifying elasmobranchs to species level, possibly due to recent divergences (Marino et al. 2017; Naylor et al. 2012). Alternatively, the fast-evolving ND2 and the mitochondrial encoded 12S gene (Fernandes et al. 2021; Naylor et al. 2012; Valsecchi et al. 2020) have been considered more effective molecular markers for species identification but still remain scarce and underrepresented in current databases (Fig. 2b) (Böhme et al. 2019; Shokralla et al. 2012).

Furthermore, mitochondrial signal admixture due to historic hybridization occurred between *C. galapagensis* and *C. obscurus* (Corrigan et al. 2017), highlighting the limitations of mitochondrial markers for some species. Broader marker utilization is needed to improve accuracy and expand database entries, including nuclear markers like ITS2, and multiloci approaches that combine slow and fast evolving markers (Domingues et al. 2021). In addition, the adoption of HTS techniques has been very effective in identifying species in food mixtures (DNA metabarcoding) and in detecting bycatch composition via sampling water from trawl fishing nets (eDNA metabarcoding) (Carvalho et al. 2017b; Albonetti et al. 2023; Cermakova et al. 2023). Nonetheless, false positive detections due to failures of primer specificity, eDNA transport in the environment, and database limitations need to be accounted for when applying eDNA for tracking elasmobranch trade (Albonetti et al. 2023). A reduction of such effects could be achieved through the inclusion of a multi-marker approach and occupancy models (Ficetola et al. 2016).

A significant challenge in analyzing the fin trade is the level of genetic diversity among global populations. Genetic analysis of shark products derived from worldwide industrial fisheries also shares this challenge. The development of a genetic diversity atlas was considered as essential to trace product origins accurately (Domingues et al. 2021). Thus, incorporating fine-scale information and population-level genetic data in sequence databases can offer significant potential for improving the tracking of wildlife products. This applies not only to the fin market but also to the meat market, allowing for monitoring to trace the origin of both imported and exported products in Brazil. This approach would allow the assessment of local versus international elasmobranch production and provide insights on how the trade impacts Brazilian sharks and rays populations or its effects on the Brazilian trade with foreign populations. Unfortunately, such a comprehensive analysis is currently not feasible with the information available to date. Despite their potential (Albonetti et al. 2023; Mottola et al. 2022) HTS techniques are neglected in elasmobranch detection globally, particularly in Brazil, where no papers have been published yet. Increased research funding for Brazilian research is essential to stay abreast of recent international advancements, and to identify shark and ray presence in processed products [e.g., crab dishes, pet food, and cosmetics (Alvarenga 2020; Cardeñosa 2019)] and in the international trade (Cardeñosa et al. 2020)].

In reflection of this, establishing a comprehensive national genetic database with accurate molecular markers, complete with both Brazilian species and populations, and with regular curation is crucial. Such an initiative can also serve as a model for other countries in the future, contributing to conservation efforts, trade regulations, and species management. We strongly recommend conducting thorough examinations of other significant elasmobranch trade locations globally to understand and address their specific requirements.

### *4.3. Species Composition and Threatened Elasmobranchs in Brazilian Trade*

The genetic findings highlight the urgent need for conservation measures to protect Brazil's diverse elasmobranch species, especially those threatened with extinction. Molecular methods detected 64 elasmobranch species traded in Brazil, despite the country´s reported diversity of approximately 203 species (Kotas et al. 2023). Around 70% of all Brazilian elasmobranchs have never been molecularly detected as traded, raising questions about factors contributing to ir. Such detection pattern could be related to commercial interest, fisheries characteristics, capture challenges, species rarity and non-detections caused by the molecular methods applied. This suggests the need for further research to explore elasmobranch trade composition and implications.

Another point we observed was that hammerhead sharks and guitarfishes continue to be sold in alarming numbers, despite their high extinction risk (Alvarenga et al. 2021; Bernardo et al. 2020). Seven out of eight hammerhead sharks and all guitarfishes occurring in Brazil were categorized as threatened (IUCN 2023). This situation emphasizes the significant impact and threat that coastal fisheries represent, especially for endemic [e.g., guitarfishes and angel sharks (Bunholi et al. 2018)] and highly threatened species [e.g., sawfishes (Faria et al. 2013)], but also for other threatened and extensively traded elasmobranchs [e.g., Blue Shark (Alvarenga et al. 2021) and Mako Shark (Ferrette et al. 2019b)]. Intense fishing pressure on sharpnose sharks (*Rhizoprionodon* spp.) is another conservation concern. Despite their relatively high productivity, high levels of fishing have driven the populations of two sharpnose sharks (*R. porosus* and *R. lalandii*) found in the Brazilian coast to declines, as previously cautioned by Lessa et al. (2006), and hence be recently assessed as VU (Carlson et al. 2021; R. Pollom et al. 2020). The frequent catch of Carcharhinidae species overall is of concern, and the highly traded Blue Shark may face a similar fate as the sharpnose sharks. Other carcharhinid sharks are intensively marketed in Brazil, also experiencing high fishing mortality rates (Bond et al. 2012; Dulvy et al. 2014).

The high rates of threatened species found in this study emphasizes the concern for increasing numbers of threatened species. We illustrated a developing trend in extinction risk status, where a growing number of species, especially those frequently traded in Brazil, are becoming increasingly threatened. Overall, 32 out of the 64 species found in this study were reassessed recently in the IUCN Red List, with 18 experiencing an increase in their extinction risk, including seven species receiving multiple uplistings in their assessments. These findings emphasize the detrimental impact of fisheries and trade on elasmobranch populations (Dulvy et al., 2014; Barreto, 2017), adding further pressure to their declines. A single species, *Rhinoptera brasiliensis*, previously categorized as EN showed a slight downlisting, but still remained as VU (Fig. S2). Nonetheless, this positive change is overshadowed by the overall worsening extinction risk status of many other species. The remaining 16 species, previously assessed as DD, were updated and had: 56% assigned to threatened categories (e.g. *Rhizoprionodon lalandii* DD – VU and *Carcharhinus porosus* DD – CR) and 31% assigned to not threatened categories (e.g. *Squalus cubensis* DD – LC, which was one of the least detected species in trade). The remaining 13% corresponded to two Neotropical freshwater stingray species detected in the papers analyzed that remained as DD, emphasizing the need for more research on freshwater elasmobranchs. It is important to note that many DD elasmobranch species have low levels of genetic diversity, which makes them even more vulnerable to stochastic events see (Domingues et al. 2018).

Comprehensive conservation strategies are necessary to safeguard and restore genetic diversity among elasmobranch populations in Brazil, mainly given the country’s extensive coastline, high levels of endemism, and significant role in conservation efforts, substantially impacting elasmobranch preservation worldwide (Becerril-García et al. 2022). Conservation strategies are crucial for preventing further population declines and genetic erosion in Brazil. The country should prioritize habitat protection, promote sustainable fishing practices, establish marine protected areas, regulate trade, minimize bycatch, and sustainably manage fisheries. Collaboration among researchers, Brazilian government, stakeholders, and international organizations is essential to ensure the success of these conservation efforts.

### 4.4. Legislative Measures in Brazil: Towards Effective Elasmobranchs Protection?

Fish conservation regulations in Brazil have evolved over the years, reflecting the country's political landscape. Past initiatives, like anti-finning regulations, showcased Brazil's commitment to elasmobranch conservation. The incorporation of the Brazilian Red Book of Threatened Fauna (ICMBio 2018) assessments into legislation have addressed the trade and exploitation of threatened elasmobranchs. Nevertheless, challenges emerged with the substitution or repristination of previous regulations and with the introduction of new regulation actions by ordinances MMA No. 148/2022 and No. 354/2023, raising concerns on the possibility of the interests of fisheries industries being prioritized over conservation strategies. It is expected that the new national database known as SALVE System will contribute to improve conservation initiatives and provide advances, since it contains assessments that are available online, regularly updated, and easily accessible. These assessments hopefully will be considered in future regulations and thereby improve species management and conservation. Even though the recent release of the SALVE System increased the quantity of species assessed and updated previous extinction risk status, discrepancies between the IUCN Red List still occur, with a high rate of species still to be evaluated. We also found differences in the extinction rate between the international and national lists analyzed (Fig. 5a), including in endemic species, which indicates inconsistent categorizations for geographically restricted species. The discrepancies between national and international lists can be attributed to outdated assessments, limited updates in the Brazilian threatened species lists, and factors like data availability, assessment methodologies, political considerations, and regional conservation priorities. To enhance consistency and effectiveness, it is crucial to invest on regular updates, improved integration of data and assessment methodologies, and accurately assess extinction risks and conservation needs. It is important to highlight that while the IUCN Red List is a comprehensive source on the global extinction risk status of animal, fungus and plant species at a global scale, the SALVE System focuses at regional (or national) level by assessing species that are part of the Brazilian biodiversity, being used to delineate legislative measures. Given this, it is important that future studies on trade consider and analyze jointly the current Brazilian regulations and the IUCN Red List assessments when discussing threatened species.

Even though the labeling regulations were also updated over time, there have been no significant changes for elasmobranch species, which can still be traded under umbrella-labels nationwide. The lack of species-specific labeling and updated scientific names for sharks and rays in fish labeling regulations poses significant challenges for trade monitoring and conservation efforts (Bornatowski et al. 2013). It reduces commercialization transparency, impeding proper species identification, sustainable fishing practices, and conservation effectiveness. Without accurate identification, tracking and regulating the trade of threatened shark species becomes difficult, potentially hiding and escalating their decline. To address this, the labeling regulations need to be aligned with conservation regulations. This can be achieved by appropriately distinguishing labels for threatened species. Alternatively, by outright prohibiting the trade of "cação", as seen for all sharks in the Bahamas, Palau and the Marshall Islands and for a specific umbrella-term that encompass all elasmobranch species in the Maldives, New Caledonia and the Federated States of Micronesia (Ward-Paige 2017).

### ***4.5. The Mislabeling Risk: Deceptive Practices Beyond Label Swaps***

Generic labeling is also a concerning reality for elasmobranchs in Brazil. Besides the use of umbrella labels at markets and restaurants, we also observed generic labeling of fish in education institution dining services, where elasmobranchs are served without proper species identification, leading unaware customers to consume shark meat (Alvarenga et al. 2021). Further investigations are essential to evaluate these cases, as there are also concerns about the presence of shark meat in hospitals, posing risks to both conservation efforts and public health due to high metalloid levels in shark meat (Hauser-Davis et al. 2021; Willmer et al. 2022). Identifying and exposing such activities is crucial to raise awareness, strengthen regulations, and potentially prohibit these practices. Recently, shark meat purchased by the municipality of São Paulo for distribution in schools was recalled due to public pressure, highlighting the effectiveness of raising awareness and taking action against such practices (Bonin 2021).

Shark and ray products have also been distributed under mislabeled names such as salmon and croaker (Staffen et al. 2017), while conversely, bony fishes have been frequently sold as elasmobranchs (Almeron-Souza et al. 2018; Calegari et al. 2019; Cruz et al. 2021). Elasmobranchs have been mislabeled not only as bony fish but also as other elasmobranch species (Almeron-Souza et al. 2018; Alvarenga et al. 2021; Bernardo et al. 2020; Bunholi et al. 2018; Palmeira et al. 2013). This deceptive practice not only undermines consumer trust but also poses an especially significant conservation challenge to threatened rays, which are sold at low cost (Niedermüller et al. 2021).

We also noted instances of incorrect labeling and incomplete information in the papers analyzed. The misidentifications noted comprised: 1) Failure to differentiate between information related to individual samples, making it impossible to verify the sampling location and label associated with each sample (Table S1, in Appendix B); 2) Variation in the availability of information on sampling date, market sector, price, and origin of capture among the papers (some papers provided comprehensive information on all these aspects, while others had missing or incomplete data) (Table S2, Appendix A); and 3) Non-standard labeling information, often representing only the regional names rather than the regulated name under legislative measures (Table S1, in Appendix B). While documenting diverse regional terminology for traded sharks and rays offers valuable insights into market and cultural distinctions within Brazil, it remains important to also incorporate the label of the marketed product. In cases where such designations are absent, explicit acknowledgment should be indicated in the published papers, as the absence could hinder effective identification of mislabeling patterns. Avoiding such inaccuracies in future papers will be essential to assess the magnitude and dynamics of the Brazilian trade and develop a more precise national-scale analysis of market activity.

## 5. Current Research Gaps and Required Actions

In conclusion, the present study emphasizes the need to address general research gaps and suggests actions to enhance trade assessments at a national scale (Table 3). By doing so, we can develop effective management and conservation measures to improve shark and ray species protection in Brazil. It is crucial to address these limitations to advance our understanding and take necessary actions to safeguard these vulnerable species.

The identification of key governmental gaps that warrant attention is also required, and here we highlight two primary points. First, there is a pressing need for more robust legislation, including protecting threatened species to ensure environmental-based risk status assessment, and proper labeling of products torestrain mislabeling activities. Synchronizing legislative measures for both labeling and conservation is also required to promote best market practices that simultaneously safeguard biodiversity and consumers rights. Second, the need for efficient monitoring mechanisms and frequent inspections can help to restrict the trade of protected species and mitigate mislabeling practices.

The Brazilian government is urged to invest in keeping extinction risk assessments updated, enhancing legislative measures and conducting frequent inspections. Additionally, fostering collaborations with research institutions and stakeholders is recommended, such as leveraging on technical expertise and HTS techniques for extensive sampling campaigns and apprehensions utilizing large-scale and cost-effective analysis (e.g., large-scale amplicon sequencing). The proposed actions extend beyond governmental responsibilities, as researchers and citizens are not exempt from contributing to species conservation. It is recommended that these two groups communicate and advocate for new and more effective legislative measures. This can enhance transparency and accuracy in elasmobranch trade and better protect species. A multifaceted approach involving government, researchers, citizens, stakeholders, and international organizations is essential for the comprehensive and effective management of elasmobranch species.

## 6. Appendix

Additional information can be found in the online version of the article at the publisher's website.
Appendix A includes detailed information on data acquisition and supplementary results supporting our findings.
Appendix B provides the main metadata built to analyze the data from all peer-reviewed papers collected, alongside a detailed explanation of each category.
Appendix C offers additional metadata to support our analysis on the availability of genetic resources for Brazilian species and the evolution of Brazilian legislative measures, as well as national and international conservation lists.

Appendix D provides detailed R scripts for the analyses performed in this paper and presented in the main text. The data used with the R scripts are available at GitHub (link available upon acceptance) to ensure reproducibility.

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## 8. Figures and Tables

**Table 1**. Summary of 35 research papers using DNA tools to investigate elasmobranch trade in Brazil from 2008 to 2023, including paper categories, sample sizes, the number of elasmobranchs and endangered species identified (based on the IUCN Red List at publication and current status), dominant species per paper, Brazilian regions studied, type of DNA-based tool and molecular marker applied, and if the paper aimed to detect mislabeling activity.

| Authors | Paper category | Sample size | Elasmo branch species | IUCN Listed (paper) | IUCN Listed (current) | Brazilian Regions | Molecular marker | DNA-based tool | Most frequent species | Mislabel ‡ |
|---|---|---|---|---|---|---|---|---|---|---|
| Pinhal et al. (2008) | Methods | NA | 8 | NA | 7 | All coastal regions | 5S rDNA | Tandem Repeats | NA | NO |
| Mariguela et al. (2009) | Methods | 145 | 3 | NA | 3 | Southeast and South | 16S/COI | PCR-RFLP | *Pseudobatos percellens* | NO |
| Mendonca et al. (2009) | Methods | 86 | 2 | NA | 2 | Northeast and Southeast | COI | Multiplex PCR | *Rhizoprionodon porosus* | NO |
| Pinhal et al. (2009) | Methods | 36 | 2 | NA | 2 | Brazilian | 5s rDNA | PCR-RFLP | NA | NO |
| Rodrigues-Filho et al. (2009) | Trade Analysis | 122 | 11 | 1 | 10 | North | 12S-16S | DNA sequencing | *Carcharhinus porosus* | YES |
| De-Franco et al. (2010) | Methods | 145 | 3 | NA | 3 | Southeast and South | COI | Multiplex PCR | *Pseudobatos percellens* | NO |
| Mendonca et al. (2010) | Methods | 443 | 25 | NA | 20 | All coastal regions | COI | Multiplex PCR | NA | NO |
| Pinhal et al. (2012) | Methods/ Trade Analysis | 62/90* | 7 | NA | 4 | All coastal regions | ITS2 | Multiplex PCR | *Rhizoprionodon terranovae* | NO |
| De-Franco et al. (2012) | Trade Analysis | 267 | 3 | NA | 3 | Northeast, Southeast and Southern | COI | Multiplex PCR | *Pseudobatos horkelii* | NO |
| Palmeira et al. (2013) | Trade Analysis | 44 | 8 | NA | 7 | Northern | 16S/CytB | DNA sequencing | *Pristis perottepeerti* | YES |
| Ribeiro et al. (2012) | Trade Analysis | 41 | 13 | NA | 10 | Southeast | COI | DNA sequencing | *Atlantoraja castelnaui* | NO |
| Domingues et al. (2013) | Trade Analysis | 317 | 4 | 2 | 4 | Southeast | ITS2/COI | Multiplex PCR | *Carcharhinus falciformis* | YES |
| Faria et al. (2013) | Trade Analysis | 77 | 1 | 1 | 1 | Northern | CytB | DNA sequencing | NA | NO |
| Falcão et al. (2016) | Methods | 9 | 3 | NA | 3 | Southern | CytB | PCR-RFLP | NA | NO |
| Schmidt et al. (2015) | Methods/ Trade Analysis | 97 | 4 | 0 | 2 | Southeast | COI | PCR-RFLP | *Dasyatis hypostigma* | NO |
| Schmidt et al. (2015) | Trade Analysis | 1 | 1 | 1 | 1 | Southern | COI | DNA sequencing | NA | NO |
| Nachtigall et al. (2017) | Methods/ Trade Analysis | 67/51** | 8 | 1 | 7 | Northern | ITS2 | Multiplex PCR | *Rhizoprionodon porosus* | YES |
| Carvalho et al. (2017a) | Trade Analysis | 8 | 1 | NA | 0 | | COI | DNA sequencing | NA | NO |
| Staffen et al. (2017) | Trade Analysis | 14 | 5 | 2 | 3 | Southern | COI | DNA sequencing | *Prionace glauca* | YES |
| Almeron-Souza et al. (2018) | Trade Analysis | 63 | 18 | 8 | 14 | Southern | COI | DNA sequencing | *Prionace glauca* | NO |
| Bunholi et al. (2018) | Trade Analysis | 85 | 3 | 3 | 3 | Southern | COI | DNA sequencing | *Squatina guggenheim* | YES |
| Feitosa et al. (2018) | Trade Analysis | 427 | 17 | 4 | 15 | Northern | COI | DNA sequencing | *Sphyrna mokarran* | NO |
| Marques et al. (2020) | Methods | 279 | 10 | 5 | 8 | Southeast | COI/CytB | Morphome trics/DNA sequencing | *Gymnura altavela* | NO |
| Calegari et al. (2019) | Trade Analysis | 7 | 0 | NA | NA | Southeast | COI | DNA sequencing | NA | NO |
| Ferrette et al. (2019a) | Trade Analysis | 228 | 17 | 5 | 12 | Southeast | COI | DNA sequencing | *Dasyatis sp.* | NO |
| Ferrette et al. (2019b) | Trade Analysis | 747 | 20 | 9 | 18 | Northern, Northeast and Southeast | COI | Multiplex PCR and DNA sequencing | *Prionace glauca* | NO |
| Bernardo et al. (2020) | Trade Analysis | 231 | 16 | 7 | 12 | Southern | COI | DNA sequencing | *Prionace glauca* | NO |
| Camacho-Oliveira et al. (2020) | Trade Analysis | 52 | 4 | 1 | 2 | Southeast | COI | DNA sequencing | *Paratrygon ajereba* | NO |
| Guimaraes-Costa et al. (2020) | Trade Analysis | 73 | 20 | 4 | 13 | Northern | COI | DNA sequencing | NA | NO |
| Rodrigues et al. (2020) | Trade Analysis | 118 | 9 | 2 | 5 | Northern | COI | DNA sequencing | *Hypanus guttatus* | NO |
| Alvarenga et al. (2021) | Trade Analysis | 220 | 17 | 13 | 15 | Southeast | COI | DNA sequencing | *Prionace glauca* | YES |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Cruz et al. (2021) | Trade Analysis | 56 | 9 | 6 | 8 | Southern | COI | DNA sequencing | *Prionace glauca* | YES |
| Martins et al. (2021) | Trade Analysis | 127 | 20 | 12 | 17 | Northern | COI | DNA sequencing | *Sphyrna mokarran* | YES |
| Merten-Cruz et al. (2021) | Trade Analysis | 57 | 17 | 7 | 13 | All coastal regions | COI | DNA sequencing | *Prionace glauca* | NO |
| Souza-Araujo et al. (2021) | Trade Analysis | 91 | 13 | 4 | 12 | Northern | COI | DNA sequencing | *Mustelus higmani* | NO |

‡ Mislabel = the paper analyzed used the results provided by DNA analysis to infer if the fish sold was mislabeled. * This paper used 166 samples to design the DNA rapid assay, only 62 of which were collected in Brazil. Also, they applied the technique to 90 other samples collected in Brazilian markets. ** This paper used 67 samples to design the DNA rapid assay, 10 of which were newly collected and 57 from other papers. Also, they applied the technique to 51 other samples collected in Brazilian markets.

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**Table 2**. Summary of the current risk of extinction status and number of shark and ray species found in the papers analyzed. The table includes species categorized CR, EN, VU, NT, LC, DD by the International Union for Conservation of Nature (IUCN) Red List of Threatened Species, and a detailed list of all species found.

| Status | Number of Species | Species |
|---|---|---|
| Critically Endangered | 12 | *Atlantoraja castelnaui, Carcharhinus porosus, Carcharias taurus, Fontitrygon geijskesi, Galeorhinus galeus, Isogomphodon oxyrhynchus, Pristis pristis, Pseudobatos horkelii, Sphyrna lewini, Sphyrna mokarran, Sphyrna tudes, Squatina occulta* |
| Endangered | 20 | *Aetobatus narinari, Atlantoraja cyclophora, Carcharhinus acronotus, Carcharhinus obscurus, Carcharhinus perezi, Carcharhinus plumbeus, Carcharhinus signatus, Centrophorus squamosus, Dasyatis hypostigma, Gymnura altavela, Isurus oxyrinchus, Isurus paucus, Mobula thurstoni, Mustelus higmani, Pseudobatos percellens, Sphyrna tiburo, Squalus mitsukurii, Squatina guggenheim, Styracura schmardae, Zapteryx brevirostris* |
| Vulnerable | 20 | *Alopias superciliosus, Bathytoshia centroura, Benthobatis kreffti, Carcharhinus brachyurus, Carcharhinus brevipinna, Carcharhinus falciformis, Carcharhinus leucas, Carcharhinus limbatus, Carcharodon carcharias, Ginglymostoma cirratum, Hypanus berthalutzae, Hypanus dipterurus, Myliobatis freminvillei, Myliobatis goodei, Rhinoptera bonasus, Rhinoptera brasiliensis, Rhizoprionodon lalandii, Rhizoprionodon porosus, Rioraja agassizii, Sphyrna zygaena* |
| Near Threatened | 8 | *Carcharhinus altimus, Galeocerdo cuvier, Gymnura micrura, Hypanus americanus, Hypanus guttatus, Mustelus canis, Narcine brasiliensis, Prionace glauca* |
| Least Concern | 3 | *Carcharhinus galapagensis, Rhizoprionodon terraenovae, Squalus cubensis* |
| Data Deficient | 2 | *Paratrygon aiereba, Potamotrygon motoro* |

**Table 3**. General research gaps and suggestions of required actions to enhance ability to assess the trade at a national scale.

| Goal | | Research Gap | Required Action |
|---|---|---|---|
| i | 1 | Lack of a strategic monitoring plan, often relying only on opportunistic sampling, and standardized or minimal documentation (e.g., location, date, price, and market origin). | Formulate a comprehensive and basic sampling protocol, considering regional characteristics and the periodicity of data collection, and establish best practices guidelines to ensure detailed documentation for accurate and comparable data. |
| | 2 | Limited number of studies and sampling coverage on the Northeast Region of Brazil. | Expand research efforts in the Northeast Region of Brazil to address regional disparities. |
| | 3 | Concentration of studies primarily focused on analyzing the shark trade. | Expand research to embrace more elasmobranch species in trade (e.g., ray trade, bycatch and finning). |
| | 4 | Insufficient application of cost-effective genetic techniques previously developed for elasmobranchs (such as Multiplex PCR and PCR-RFLP) in trade studies. | Promote the utilization of cost-effective DNA-based tools, such as Multiplex PCR and PCR-RFLP, mainly adopting available tools to improve accessibility and frequency of species identification. |
| ii | 5 | Underutilization of HTS techniques for species identification in Brazil, with a lack of research using metabarcoding (e.g., detect elasmobranch products in food mixtures), eDNA (e.g., fins dust on markets, water of fishing vessels), large-scale amplicon sequencing (e.g., reduce costs and analyze a higher volume of market samples), among others. | Increase the development and implementation of high-throughput sequencing in cases where it applies (e.g., food mixtures, vessel water analysis, large seizures or sampling campaigns). |
| | 6 | Scarcity of DNA sequences from important Brazilian elasmobranch species and populations in genetic databases, particularly ray species | Establish a regularly curated national database with precise species identification and molecular markers, including haplotype differentiation, to effectively support geographical assessments. Foster collaborative initiatives to generate genetic data of Brazilian elasmobranch species, especially rays, and contribute to the expansion of molecular markers in the national genetic database. |
| | 7 | Lack of population genetics and phylogeographic studies for elasmobranch species targeting their whole geographic distribution, impeding a proper geographic tracking of both meat and fins trade. | |
| iii | 8 | Risk of extinction status (e.g., IUCN, SALVE) is not addressed in certain papers. | Incorporate both IUCN Red List, current Brazilian legislation and national risk of extinction status into papers to evaluate compliance with legislation. |
| iv | 9 | Compliance to the regulations to protect threatened species, such as the MMA 354/2023, are not evaluated in most of the papers analysed. | |
| v | 10 | Non-standardized or absent labeling notes when sampling, hindering the assessment of mislabeling activity. | Implement standardized labeling notes when sampling elasmobranch products to enable a comprehensive assessment of mislabeling activity and enhance understanding of the dynamics of the shark trade. |

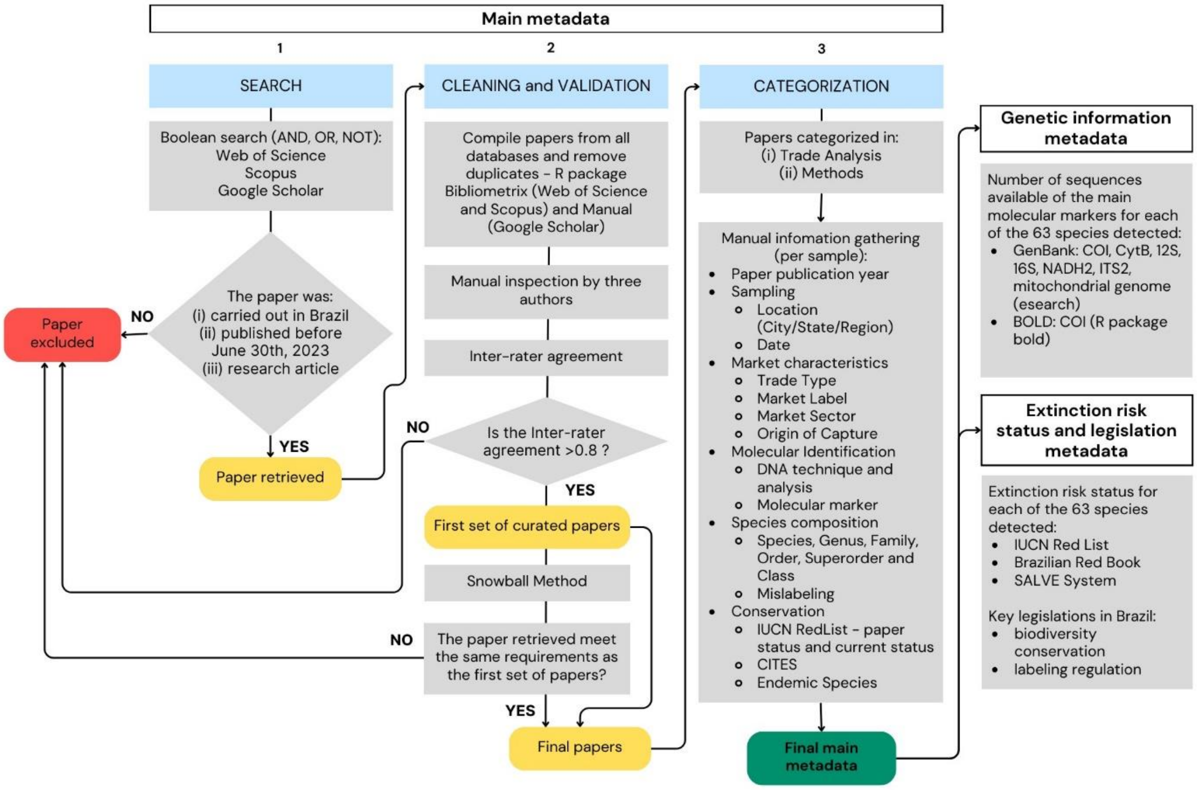


**Fig. 1**. General workflow of the approach used to the assessment of research trends, molecular species identification, species composition in trade and the Brazilian legislation consulted.

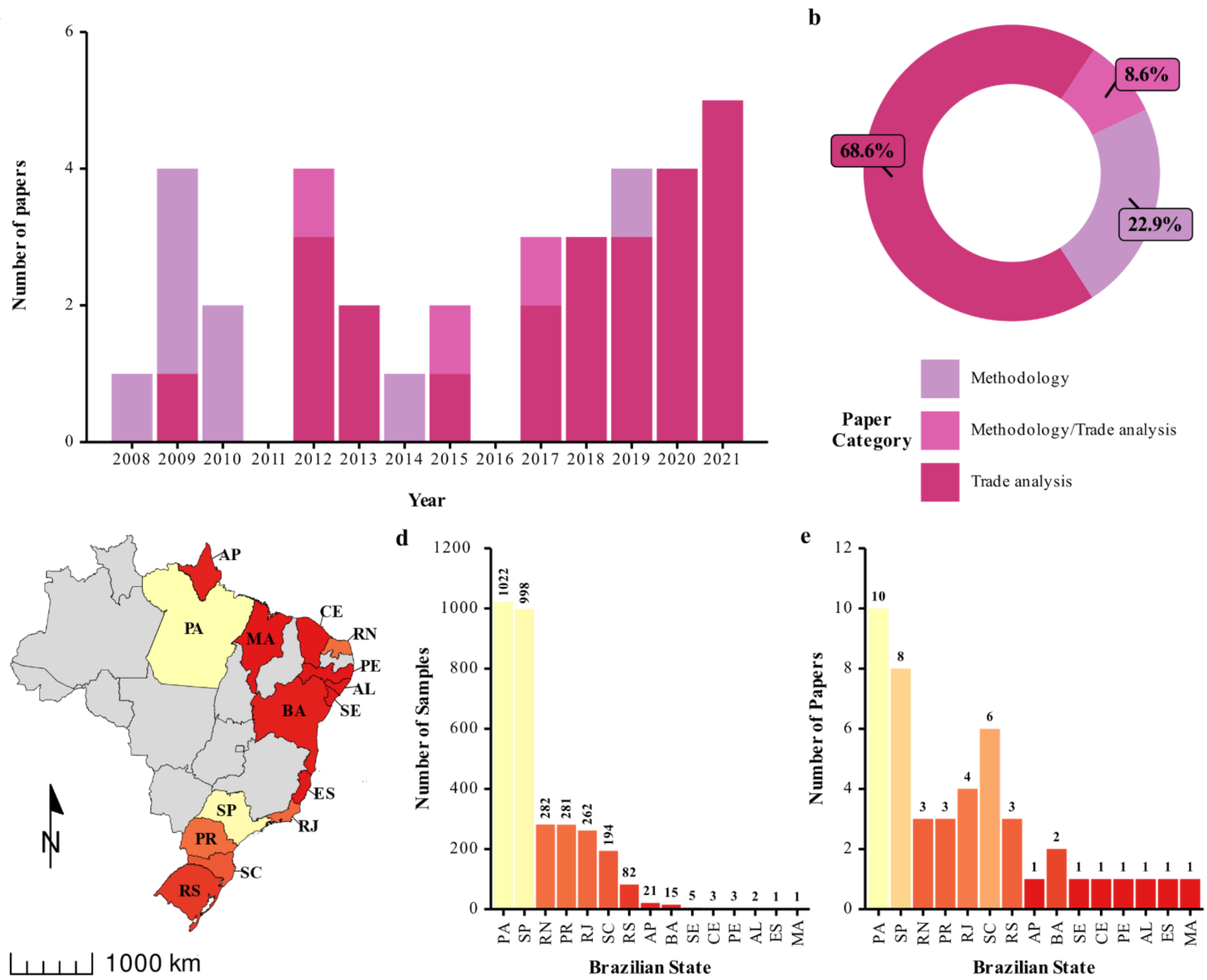


**Fig. 2**. Overview of the papers published on the topic of DNA tools to analyze elasmobranchs trade in Brazil between 2008 and 2023, including (A) year of publication, (B) type of research in each paper, and number of samples per (C) Brazilian regions, (D) samples and (E) papers. Quantity of paper is inversely proportional to the darkness in shade of colors (i.e., in C the regions in dark shades are the ones with less papers published, in D the dark shades mean less samples available, and in E less papers published), and gray color refers to no paper found in the state. The abbreviations refer to Brazilian states, as follows: PA - Pará, AP - Amapá (North Region), MA - Maranhão, CE - Ceará, RN - Rio Grande do Norte, PE - Pernambuco, AL - Alagoas, SE - Sergipe, BA - Bahia (Northeast Region), ES - Espírito Santo, RJ - Rio de Janeiro, SP - São Paulo (Southeast Region), PR - Paraná, SC - Santa Catarina, RS - Rio Grande do Sul (South Region).

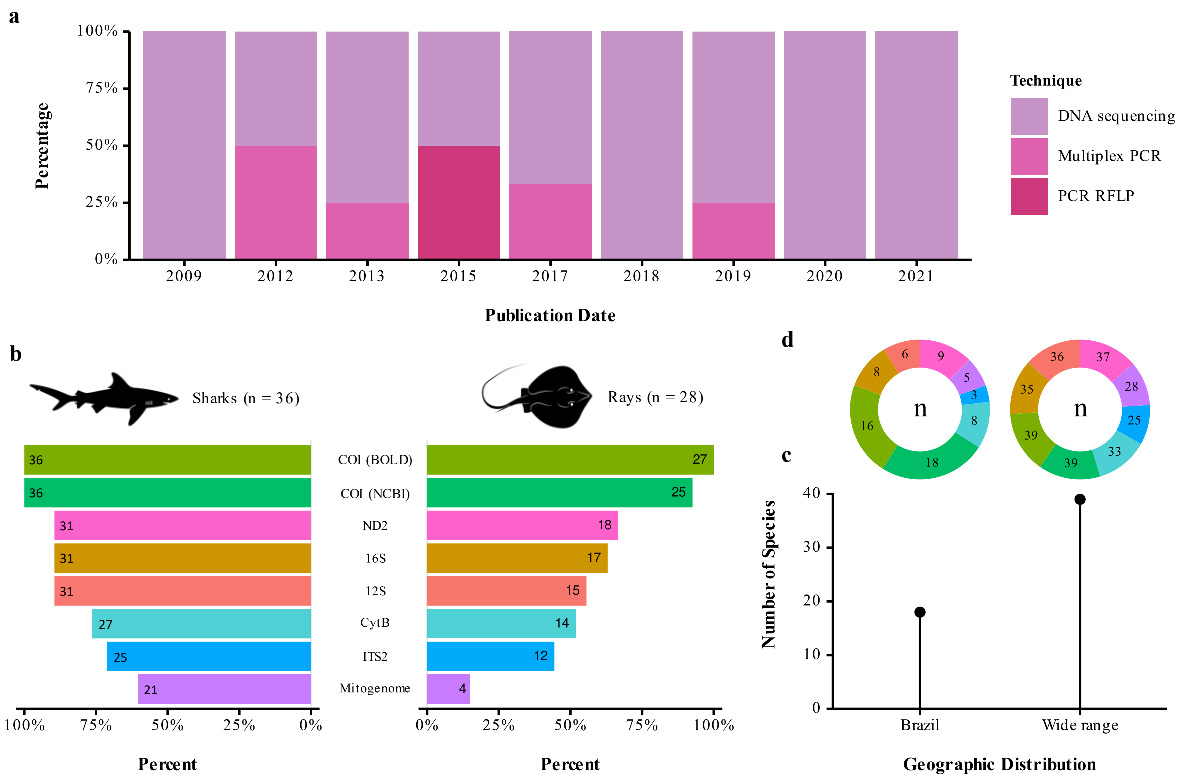


**Fig. 3**. DNA tools in elasmobranch trade analysis. (a) Evolution of the DNA techniques applied through time, (b) number of shark and ray species found in all papers depicted alongside the animals silhouettes, with the percentage of sequences in GenBank and BOLD databases per molecular marker for shark and ray species (absolute numbers depicted inside the bar), and (c) number of species with sequences available in both databases for endemic species of Brazil versus wide-range species, (d) with the number of species per specific molecular marker depicted, using the same color code as in B.

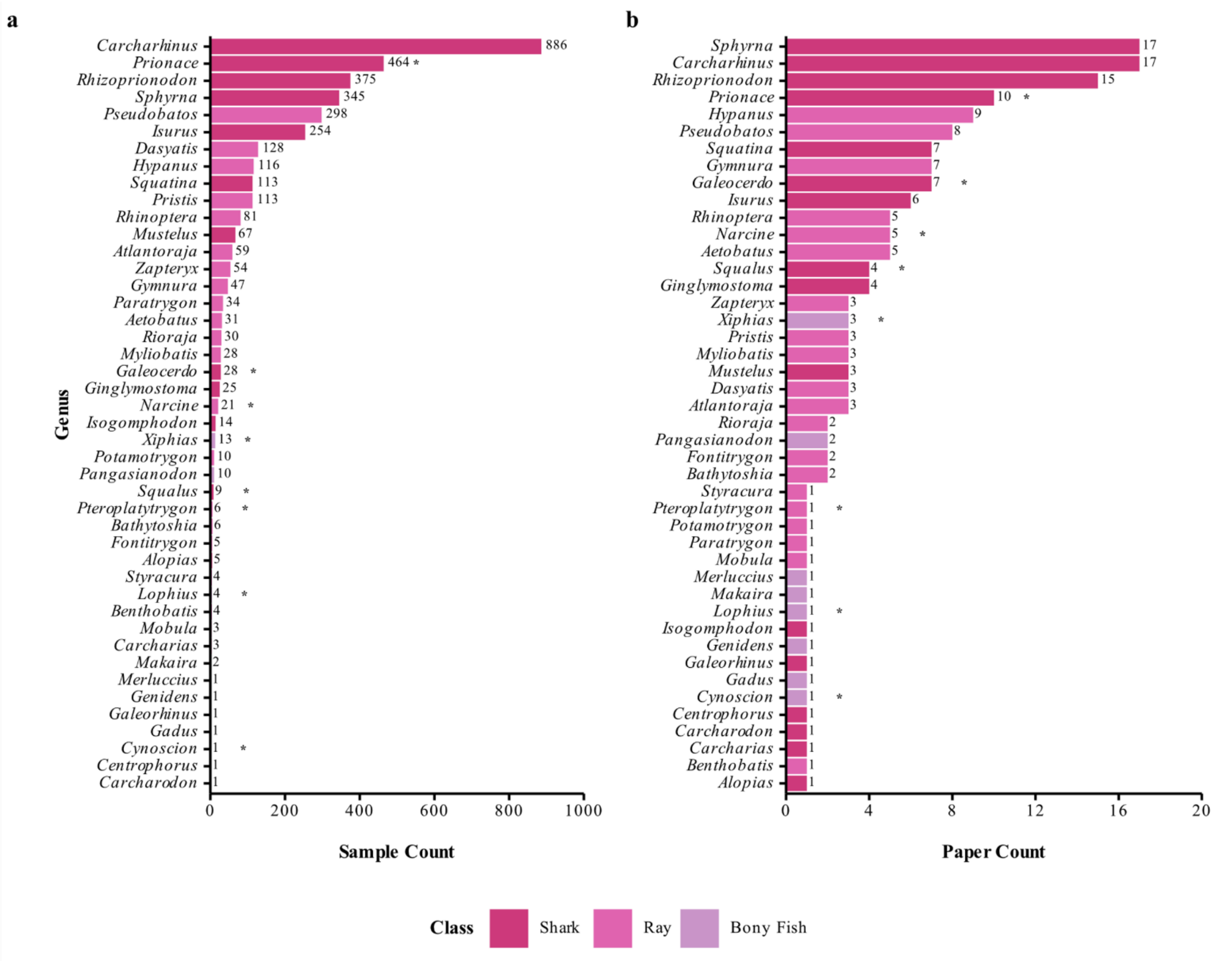


**Fig. 4.** The (a) sample count and (b) paper count of genera found in all papers analyzing the elasmobranch trade in Brazil between 2008 and 2023. The class of each genus (shark, ray or bony fish) is defined by the color in the caption. The genera that did not contain endangered species are marked with *. For a complete list of sample count and paper count of the species found in this study, please refer to table S3 in appendix A.

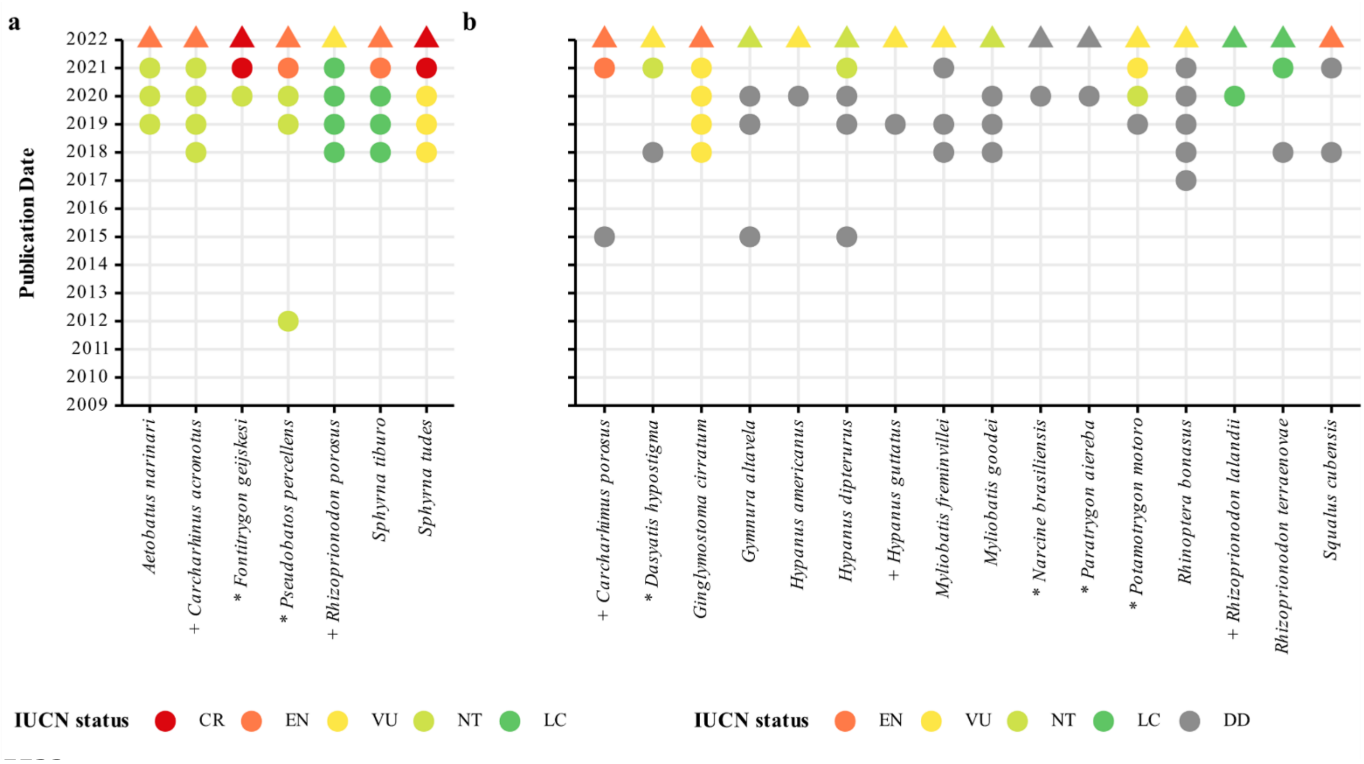


**Fig. 5**. Evolution of extinction risk assessment over time for species found in the present study (a) that increased by two categories and (b) that was previously categorized as data deficient. The category assigned at the time the analyzed paper was published is represented by a circle, while the current category is represented by a triangle. The assessments for all elasmobranch species found in the present study can be found in Figure S3.

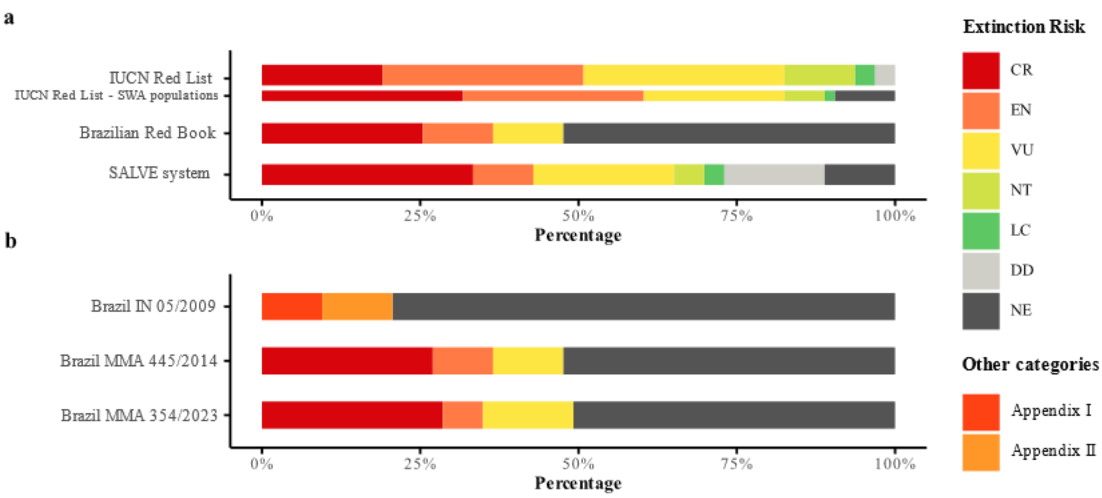


**Fig. 6**. Categorization of all elasmobranch species identified in the present study according to (a) international (IUCN Red List considering global assessment and SWA population details) and national assessments of risk of extinction (Brazilian Red Book of Threatened Fauna and SALVE System), and (b) the three main Brazilian ordinances. The Brazilian Ordinance IN05/2004 was the only one that did not follow the standard extinction risk categories (DD, LC, NT, VU, EN, CR), adopting instead two categories: Appendix I (Threatened) and Appendix II (Overexploited).