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High levels of mislabelling of shark flesh in Australian fish markets and seafood shops

Teagan J. Parker Kielniacz[A,B], Adam J. Stow[A,B,*] and Nicolette C. Armansin[A,B]

For full list of author affiliations and declarations see end of paper

*Correspondence to:
Adam J. Stow
School of Natural Sciences, Macquarie University, Sydney, NSW 2109, Australia
Email: adam.stow@mq.edu.au

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ABSTRACT

Context. Overfishing is a major cause of decline for many shark species globally, which can be largely offset by shifting consumer demand to sustainable harvests. The inherent difficulty identifying shark species after processing makes informative labelling fundamental to achieving a sustainable market. **Aims.** We evaluated the level of mislabelling in Australia from shark flesh samples obtained from seafood suppliers across the country. **Methods.** We used sequence data from the cytochrome oxidase subunit one gene (*COI*) and the 12S mitochondrial RNA gene (*12S*) to identify genera and likely species. **Key results.** We used genetic sequence data to identify species from tissue samples from 91 fillets labelled as shark. Of these, 64 (70%) were mislabelled, and 9 comprised three species listed as threatened in Australia, the scalloped hammerhead (*Sphryna lewini*), greeneye spurdog (*Squalus chloroculus*) and school shark (*Galeorhinus galeus*). The scalloped hammerhead and greeneye spurdog were being sold under the label 'flake'. Overall, 70% of samples were mislabelled and the proportion of mislabelling was significantly greater in takeaways compared with fish markets and wholesalers. **Conclusions.** High levels of mislabelling of shark product in Australian fish markets and seafood shops was apparent both with respect to the genetically identified shark sample not matching the label and the use of ambiguous labels that do not adhere to the Australian Fish Names Standard. Mislabelling masked the presence of threatened species. **Implications.** Our results reveal labelling practices that are not providing consumers with reliable information to identify shark products, and we demonstrate the utility of molecular methods in seafood trade monitoring.

Keywords: forensic identification, genetic identification, mislabelling, seafood monitoring, shark conservation, shark trade, sustainable seafood, threatened species.

Introduction

Fish are currently one of the most traded food commodities globally, with consumption having doubled in the past 50 years (Food and Agriculture Organization of the United Nations 2018, 2022). An estimated ~750,000 tonnes (Mg) of cartilaginous fishes (sharks, rays, skates and chimaeras) are listed in catch reports around the world each year as both targeted and bycatch species (Oliver *et al.* 2015; Food and Agriculture Organization of the United Nations 2022). Although estimating the global catch rate for all sharks is challenging, it is clear that overfishing is among the most damaging of threats to sharks (Braccini 2015; Davidson *et al.* 2016; Dulvy *et al.* 2021). Currently, approximately one-third of all shark, ray and skate species are threatened with extinction (Dulvy *et al.* 2021) and the abundance of some species of oceanic sharks has declined by more than 70% in the past half century, coinciding with an 18-fold increase in fishing pressures (Roff *et al.* 2018; Pacoureau *et al.* 2021).

Effective management of fisheries involves regular stock assessment and regulation of catch levels to maintain biomass at sustainable and productive levels or to allow stocks to rebuild to productive levels (Melnychuk *et al.* 2021; Pacoureau *et al.* 2023). Regulation that aims to prevent population declines is either applied at the stock-level or more broadly through international and regional agreements and country-level regulations (Gilman *et al.* 2014; Vincent *et al.* 2014; Melnychuk *et al.* 2021). However, the continued decline of shark populations suggests that regulatory control remains inadequate, and this seems to be for myriad reasons (Davidson *et al.* 2016; Cardeñosa *et al.* 2018; Dulvy *et al.* 2021). Sustainable management of shark populations is complicated by incidental bycatch, which is a key driver of population declines and is inherently difficult to monitor (Dulvy *et al.* 2021). Moreover, regulations aiming to reverse population declines can be difficult to enforce where resources are limited and in regions where shark fisheries are important to food security and livelihoods (McClenachan *et al.* 2016; Dulvy *et al.* 2017; Simpfendorfer and Dulvy 2017). Monitoring catch rates is critical for effective management, yet formal stock assessments exist for only 3% of all chondrichthyan species worldwide (Pacoureau *et al.* 2023). Managing catch rates is further hampered by poor traceability (Palin *et al.* 2013; Bellmann *et al.* 2016; Cundy *et al.* 2023), under-reported catch size and composition, and product mislabelling along the supply chain (Xiong *et al.* 2016; Dulvy *et al.* 2017; Shea and To 2017; Fox *et al.* 2018; Hellberg *et al.* 2019; Pazartzi *et al.* 2019).

Internationally, seafood mislabelling is common (Pardo *et al.* 2016), and is particularly high in the shark and ray trade, with reports of up to 94% of shark fillets sold being mislabelled (Griffiths *et al.* 2013; Agyeman *et al.* 2021). Poor labelling can arise at several stages along the supply chain, including at landing, wholesale or retail. Many closely related species are difficult to distinguish by sight even when fully intact at landing; for example, those in the commonly targeted *Squalus* and *Carcharhinus* genera (Miller and Mariani 2010; Hanner *et al.* 2011; Cardeñosa *et al.* 2018). Catch reports often rely on species aggregate or umbrella terms for this reason (Tillett *et al.* 2012). Unreliable identification is exacerbated because distinguishing features are removed during processing such as skin and fins, or from changes to fillet texture and colour from freezing or cooking. Furthermore, at the point of sale, standardised labelling conventions or standards can be lacking, poorly regulated or misplaced (Pazartzi *et al.* 2019; Agyeman *et al.* 2021; Cundy *et al.* 2023).

Genuine taxonomic confusion aside, commercial fraud is a widely acknowledged, but poorly understood driver of mislabelling (Luque and Donlan 2019; Chang *et al.* 2021; French and Wainwright 2022; Neo *et al.* 2022). Financial imperatives can exist for selling mislabelled fish, such as marketing a more valuable or appetising species, or to disguise catch that is protected (Pazartzi *et al.* 2019; Chang *et al.* 2021; Neo *et al.* 2022). Lax labelling regulations or poor enforcement result in a low risk of detection (Reilly 2018). This puts sustainable fisheries at a disadvantage and raises quality and sustainability concerns for both down-market vendors and consumers (Hanner *et al.* 2011; Fox *et al.* 2018). Although the extent of seafood fraud has not been sufficiently quantified (see Luque and Donlan 2019), a plethora of studies across more than 38 countries have found some level of mislabelling, and that the masking of threatened species is widespread (Pardo *et al.* 2016). Some evidence points to mislabelling being worse further along the supply chain; for example, at restaurants and takeaways (Liu *et al.* 2013; Vandamme *et al.* 2016; but see Luque and Donlan 2019).

Seafood mislabelling can also be problematic for food standards and public safety. There is evidence for both inter- and intraspecific variation in levels of heavy metals or pathogens (e.g. Biton-Porsmoguer *et al.* 2018), the presence of microplastics (Karami *et al.* 2017), or variation in nutritional value and allergic potential (Vandermeersch *et al.* 2015). This makes traceability of species and catch location important for quality control and safety.

The use of molecular genetics for taxonomic identification become an important method in food trade compliance monitoring (Hebert *et al.* 2003; e.g. Minhos *et al.* 2013; Sotelo *et al.* 2018, Pazartzi *et al.* 2019; Chen *et al.* 2020). Genetic identification by matching gene sequences with those in reference databases has been used extensively to identify elasmobranchs from raw, dried or degraded fins, and meat or gill plates (e.g. Cardeñosa *et al.* 2018; Fields *et al.* 2018; Hobbs *et al.* 2019; French and Wainwright 2022). It has been tested specifically for shark species in Australian waters (Ward *et al.* 2005, 2008; Holmes *et al.* 2009) but has had limited application in market surveys of traded sharks in Australia (Cundy *et al.* 2023).

It is estimated that over 5000 Mg of shark are landed each year in Australia (Woodhams and Harte 2018), part of the estimated 750,000 Mg of cartilaginous fish recorded globally each year (Food and Agriculture Organization of the United Nations 2022). Targeted fisheries occur in both the northern and southern states, and sharks are often sold at local fish markets and in takeaway shops. Mislabelling has already been identified across various states in Australia, where the label does not represent the taxonomy of the species sold or the label does not adhere to naming codes (Lamendin *et al.* 2015; Cundy *et al.* 2023; Sharrad *et al.* 2023).

The overarching code for food labelling in Australia is the Australia and New Zealand Food Standards Code (ANZFSC), which works in conjunction with state-based food standards to prevent deceptive conduct and protect consumers. These require labelling to be informative enough for purchasers to make informed decisions; however, consistency in the use of fish names is lacking. The Australian Fish Names Standard (AFNS) (AS SSA 5300–2019, Fisheries Research and Development Corporation 2024) aims to provide a consistent label for fish species traded within Australia, and as such has a designated name associated with each species or species group (currently ~250 for elasmobranchs). The AFNS cannot be enforced because it is not incorporated into the ANZFSC and standardised labelling is therefore only voluntary. Australian legislation does require that all raw seafood sold has a mandatory country of origin label, but this does not include adhering to the AFNS (Australian Government 2017). Retailers are instead encouraged to display species labels by the Fisheries Research and

Development Corporation, as well as certification labels from private organisations (e.g. the blue Marine Stewardship Council label; Agnew *et al.* 2014). Despite these initiatives, in the absence of mandatory species labelling and the concurrent accountability, the ability for consumers to make sustainable choices is inhibited.

In Australia, shark meat is sold under a variety of terms, including 'flake', which is listed under the AFNS to describe two species of the genus *Mustelus*. Recent seafood market authentication studies of Australian seafood showed high rates of mislabelling, especially for sharks and rays (Cundy *et al.* 2023; Sharrad *et al.* 2023). Here, we investigate whether shark meat is accurately labelled across six states and territories in Australia, using genetic identification of fillets sold by wholesalers, fish markets and takeaway shops. We look at mislabelling both taxonomically and under the AFNS and compare data collected at the wholesale and 'take away shop' stages of the supply chain.

Materials and methods

Sample collection and storage

Between February and June 2019, we collected a total of 91 shark meat products (fresh and frozen, cooked and uncooked) from 28 Australian suppliers. These included 20 seafood retailers and wholesalers (both termed 'markets') selling fresh seafood, and 8 takeaway shops ('takeaways'), which mostly sold cooked fillets. We approached venues that identified as 'seafood markets', 'fish markets', 'fish and chips shops', 'fish or seafood takeaway shops' or large wholesalers. We purchased Australian-sourced shark products, identified by lacking the mandatory country of origin label for imported raw fish (Australian Government 2017). A maximum of four fillets were taken from each vendor on the same day to minimise the chance of duplication of individual sharks. A tissue sample from each fillet was preserved in 95% ethanol and stored at room temperature. For each sample we recorded the retailer, location, date, product label and, where possible, verbal confirmation of the species from the staff on the day.

Molecular analysis and species identification

Genomic DNA was extracted using the spin column Isolate II Genomic DNA kit from Bioline (Bioline Meridian Bioscience, Australia). Two pairs of universal primers were chosen for amplification of approximately 655 bp from the mitochondrial gene cytochrome *c* oxidase 1 (*COI*) (Ward *et al.* 2005; Table 1). *COI* is widely used to distinguish species, being usually sufficiently variant among, but largely similar within species (Hebert *et al.* 2003; Ward *et al.* 2005, 2008). These primers have been frequently used to distinguish shark species effectively (e.g. Almerón-Souza *et al.* 2018; Pazartzi *et al.* 2019). Amplification was carried out in 10-μL reactions containing 1 μM of each primer, 200 μM of each DNTP, 2 mM of MgCl and 1 unit of *Taq* polymerase. The polymerase chain reaction (PCR) conditions for the amplification of *COI* were the same for each primer pair and were as follows: an initial denaturation at 95°C for 10 min, followed by 45 cycles at 94°C for 30 s, 54°C for 30 s, 72°C for 1 min, and a final elongation phase of 72°C for 10 min. A primer pair targeting the *12S* RNA gene region was also chosen to amplify ~171 bp (Taberlet *et al.* 2018), carried out in 10-μL reactions containing 1 μM of each primer, 200 μM of each DNTP, 2 mM of MgCl and 1 unit of *Taq* polymerase. PCR cycling conditions were as follows: initial denaturation at 95°C for 10 min, followed by 35 cycles at 95°C for 30 s, 59°C for 30 s, 72°C for 1 min and a final elongation phase of 72°C for 7 min.

Polymerase chain reaction purification and Sanger sequencing in the forward direction was conducted by Macrogen (Seoul, South Korea). All samples were re-sequenced three times, as a number of poor quality sequences were returned, indicative of contamination. Sequences were aligned and trimmed using MEGA software (ver. 11.0.13, see https://www.megasoftware.net; Tamura *et al.* 2021). To identify species and genera, individual *COI* sequences were matched to reference sequences in the NCBI's GenBank database using the BLASTn (see https://blast.ncbi.nlm.nih.gov) program with the Megablast algorithm (Altschul *et al.* 1990; Zhang *et al.* 2000). We confirmed species identification when the following conditions were met: the highest percentage identity (PI) was ≥98%, which ensures that the sample is well matched to the reference sequence (Wong *et al.* 2009), and query cover ≥90% (i.e. the extent of overlap between the homologous sequences). Assignments were accepted at *e*-values at

Table 1. PCR primers used for shark identification.

Target gene	Primer name	Primer sequence (5′–3′)	Primer length (bp)	Amplicon length (bp)	Reference
COI	FishF1	5′-TCAACCAACCACAAAGACATTGGCAC-3′	26	655	Ward *et al.* (2005)
	FishR1	5′-TAGACTTCTGGGTGGCCAAAGAATCA-3′	26	655	Ward *et al.* (2005)
	FishF2	5′- TCGACTAATCATAAAGATATCGGCAC-3′	26	655	Ward *et al.* (2005)
	FishR2	5′- ACTTCAGGGTGACCGAAGAATCAGAA-3′	26	655	Ward *et al.* (2005)
12S	Elas02-F	5′-GTTGGTAAATCTCGTGCCAGC-3′	21	171	Taberlet *et al.* (2018)
	Elas02-R	5′-CATAGTAGGGTATCTAATCCTAGTTTG-3′	26	171	Taberlet *et al.* (2018)

0–0.00001, which gives a likelihood estimate of matches by chance in the database. We cross-referenced these assignments with the Barcode of Life Data System (BOLD, see www.boldsystems.org; Ratnasingham and Herbert 2007) for the species where sequences matched with a PI ≥ 98%. To further confirm identification at the taxonomic level of genus we searched the NCBI database for matches with our *12S* sequence data using BLASTn. We assigned the genus where all matches with PI ≥ 97% were from the same genus.

Threatened species identification

Species of shark that are threatened in Australia (local status) refers to any listing under the national *Environmental Protection and Biodiversity Conservation Act* 1999 (EPBC Act) and state-based protections. Threatened species listed as 'Conservation Dependent' under the EPBC Act have management plans in place and can continue to be taken in fisheries. We also acknowledge that these listings may lag behind real conservation concern, we therefore also refer to threatened status according to the Shark Action Plan (SAP; Kyne *et al.* 2021), which applied IUCN criteria to local shark stocks and recommends protection gaps not currently reflected under the Australian system. Global status includes listing as CR (Critically Endangered), EN (Endangered), VU (Vulnerable), NT (Near Threatened) on the IUCN Red List for global assessments (see https://www.iucnredlist.org), as well as listing on the Convention on Migratory Species (CMS) and Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES).

Assessment of labelling accuracy

We identified cases of mislabelling using three definitions: (1) cases where vendor labels were not consistent with the AFNS ('AFNS non-compliant'); (2) where either the species or genus described by the vendors or label did not match with those from the genetic analysis ('taxonomically incorrect'); and (3) both measures under both definition (1) and (2) were combined as an overall measure of mislabelling. We applied a lenient interpretation for label discrepancies that were close to the AFNS though not strictly the same, or that were recently obsolete; for example, we included 'gummy flake' as correctly labelled under the category of flake. Where taxa can be used interchangeably in the common vernacular (e.g. 'carpet shark' for wobbegong), we considered this taxonomically correct but not under the AFNS. Where possible, we asked staff whether the labels were accurate and recorded the descriptions they provided to compare against the labels. We do not make claims as to the vendors intention in any of the cases of mislabelling that we found.

To assess whether the prevalence of mislabelling varies along the supply chain, we compared the number of mislabelled samples at markets with that at takeaways using a Fisher's exact test.

Results

DNA and sequencing evaluation

We obtained sequence matches for 71 of the 91 tissue samples (Table 2). Of these, 46 were identified to species level (*COI* region, PI ≥ 98% from Genbank and BOLD) and 25 to genus only (24 using *12S* region, PI ≥ 97% on Genbank, and 1 using *COI* as above; see Table S1 of the Supplementary material). Matches were inconclusive for 20 samples due to either a low identity match or a high match to a bacterial taxon (suggesting potential sample contamination).

For 16 samples, several congeneric species from 4 genera were in the clusters of matches where PI ≥ 98% (*Carcharhinus*, n = 4; *Orectolobus*, n = 4; *Squalus*, n = 4; and *Mustelus*, n = 4; Table S1). In these cases, we assigned the species with the highest match probability but recorded the congenerics (Table S1). We excluded reads of PI ≥ 98% for less related species if they represented <3% of the top 100 reads, as these were most likely errors in the databases (Tables S1–S2 of the Supplementary material). We believe a lack of resolution with *COI* for distinguishing *Orectolobus*, *Squalus* and *Mustelus* species to be the likely cause of errors. All samples were confirmed to be from shark species, except for four samples from two teleost species (*Mugil cephalus*, n = 3; and *Lates calcarifer*, n = 1); however these genera were not confirmed using *12S*.

Overall, we identified 14 species, 12 genera and assigned these to 10 families (Table 3). The most common genera in terms of sample numbers were *Carcharhinus* (n = 29) followed by *Pristiophorus* (n = 12), and the most common in terms of species diversity was also *Carcharhinus* (n = 3) and *Orectolobus* (n = 3). The most commonly identified

Table 2. Number of samples genetically identified at either the genus or species level.

Location	Markets	Takeaways	Samples collected	Successfully matched
Canberra, Australian Capital Territory (ACT)	15	–	15	14
Sydney and South Coast, New South Wales (NSW)	12	2	14	10
Brisbane, Queensland (Qld)	10	15	25	19
Adelaide, South Australia (SA)	1	4	5	4
Melbourne, Victoria (Vic.)	16	4	20	14
Perth, Western Australia (WA)	12	–	12	10
Total			91	71

Table 3. Family, genus and species assigned to sequence-matched samples.

Family	Genus	Species	Common name	Number of samples	Sample origin
Callorhinchidae	*Callorhinchus*	*C. milii*	Elephantfish	1	Qld
Carcharhinidae	*Carcharhinus*	*C. brevipinna*	Spinner shark	3	Qld
		C. leucus	Bull shark	1	ACT
		C. obscurus	Dusky whaler	4	WA
		–	–	21	ACT, NSW, Qld, SA, WA
Centrophoridae	*Centrophorus*	–	Dogfish spp.	1	Vic.
	Deania	–	Dogfish spp.	1	Vic.
Latidae	*Lates*	*L. calcarifer*	Barramundi	1	NSW
Mugilidae	*Mugil*	*M. cephalus*	Mullet	3	NSW
Orectolobidae	*Orectolobus*	*O. halei*	Gulf wobbegong	3	NSW, Vic.
		O. hutchinsi	Western wobbegong	4	WA
		O. maculatus	Spotted wobbegong	1	NSW
Pristiophoridae	*Pristiophorus*	*P. cirratus*	Common sawshark	12	ACT, NSW
Sphyrnidae	*Sphyrna*	*S. lewini*	Scalloped hammerhead	3	Qld
Squalidae	*Squalus*	*S. chloroculus*	Greeneye spurdog	2	Vic.
		–	–	2	Vic.
Triakidae	*Galeorhinus*	*G. galeus*	School shark	4	Vic.
	Mustelus	*M. antarcticus*	Gummy shark	3	Vic.
	Mustelus	*M. antarcticus*	Gummy shark	1	SA
Inconclusive	–	–	–	20	ACT, NSW, Qld, SA, Vic., WA
Total				91	

species were the common sawshark (*Pristiophorus cirratus*, *n* = 12), followed by school shark (*Galeorhinus galeus*, *n* = 4), gummy shark (*Mustelus antarcticus*, *n* = 4), dusky whaler (*Carcharhinus obscurus*, *n* = 4) and western wobbegong (*n* = 4).

Threatened species identification

Genetic analysis confirmed 17 (23.9%) samples from 6 globally threatened species listed by the IUCN (Table 4), 2 that are Critically Endangered (*Sphryna lewini*, Rigby *et al.* 2019*a* and *G. galeus*, Walker *et al.* 2020), 2 Endangered (*C. obscurus*, Rigby *et al.* 2019*b*; and *Squalus chloroculus*, Walker and Rochowski 2019) and 2 Vulnerable (*Carcharhinus leucas*, Rigby *et al.* 2021; and *Carcharhinus brevipinna*, Rigby *et al.* 2020). In Australia, two of these species (*S. lewini* and *G. galeus*) meet the criteria for Endangered under the EPBC Act and are listed as Conservation Dependent (Kyne *et al.* 2021), whereas *S. chloroculus* is endemic to Australia and listed as Endangered under the IUCN Red List criteria (Kyne *et al.* 2021; Fisheries Research and Development Corporation 2024). The remaining globally threatened species (*C. brevipinna*, *C. obscurus* and *C. leucas*) are not listed as threatened in Australian waters under the EPBC Act nor meet the IUCN Red List criteria for threatened according to the SAP (Kyne *et al.* 2021).

Labelling analysis

Overall, 64 of the 91 samples (70%) were mislabelled, either because the label was not AFNS compliant (17 of 91 samples) or genetic sequence matching indicated that the wrong species was designated to the AFNS compliant label (47 of 71 samples). Fourteen samples were both AFNS compliant and taxonomically correct (Table 5).

AFNS compliance

Across the 91 samples, vendors used 13 labels; however, we counted 'flake fillet' and the now obsolete 'gummy flake' as being labelled 'flake' leaving 11 labels available for analysis. A total of 4 of the 11 labels were AFNS compliant: 'flake', 'gummy shark', 'bronze whaler' and 'school shark'. Flake (and its derivatives) was by far the most common label (*n* = 59). Five labels were taxonomically specific (*n* = 78), these being 'flake' and 'gummy shark' (*Mustelus* spp.), 'carpet shark' (Orectolobidae spp.), 'bronze whaler' (either bronze or dusky whaler under AFNS) and 'school shark' (*G. galeus*). The remaining seven non-compliant labels (*n* = 13) were: 'Aus. shark', 'boneless fillet', 'boneless fillet: roughskin shark', 'boneless sweetfish', 'large boneless fillet' and, 'shark barrel'.

From 19 venues, we received a verbal description from the staff of the species being sold and found that 16 of these did

Table 4. Global and local status of threatened species identified using sequence matching.

Species	Global IUCN, CITES, CMS	Local EPBC Act, SAP, State	Australian distribution	Number of samples	Sample origin
Bull shark (*C. leucus*)	VU ↓ (IUCN)	NL (EPBC Act) LC (SAP)	WA, NT, Qld, NSW	1	ACT
Dusky shark (*C. obscurus*)	EN ↓ IUCN A2 CMS[A]	NL (EPBC Act) NT (SAP)	All – western delineated	4	WA
Greeneye spurdog (*S. chloroculus*)	EN ↓ IUCN	NL (EPBC Act) EN (EPBC Act)	NSW, Vic., Tas., SA	2	Vic.
Scalloped hammerhead (*S. lewini*)	CR ↓IUCN A2 CITES A2 CMS[A]	CD (EPBC Act) EN (SAP) EN (NSW FMA)[B]	NSW, Qld, NT, WA	3	Qld
School shark (*G. galeus*)	CR ↓ IUCN A2 CMS[A]	EN (SAP) CD (EPBC Act)	All, excl. NT	4	Vic.
Spinner shark (*C. brevipinna*)	VU ↓ IUCN	LC but Aust is global refuge (SAP) NL (EPBC Act)	WA, NT, Qld, NSW	3	Qld

IUCN, International Union for Conservation of Nature and Natural Resources; CITES, Convention on International Trade in Endangered Species of Wild Fauna and Flora; CMS, Convention on Migratory Species; EPBC, the *Environmental Protection and Biodiversity Conservation Act* 1999; SAP, Shark Action Plan; CR, Critically Endangered; EN, Endangered; VU, Vulnerable; NT, Near Threatened; LC, Least Concern; CD, Conservation Dependent; NL, Not Listed. ↓ indicates declining populations in IUCN assessment. Globally threatened but important stocks well-managed in Australia under SAP; A2, CITES Appendix 2 (Kyne *et al.* 2021; Department of Climate Change, Energy, the Environment and Water 2024; also see the Red List at https://www.iucnredlist.org).
[A]Australia has exemption for CMS listing under the EPBC Act for these species.
[B]Listed since 2011 under the NSW *Fisheries Management Act* 1994.

not match the vendor's label and 7 responses were not taxon-specific (Table 6). Two species descriptions given verbally matched the genetic identification, but not their shop labels (NSW-06: labelled as 'flake' but the vendor said it was wobbegong and the genetic sequences confirmed it as *Orectolobus halei*; VIC-05: fillet labelled as 'flake', the vendor said it was dogfish, which was confirmed as the green-eyed spurdog (*S. chloroculus*).

Mislabelling by taxon

Five taxon-specific labels were recorded, including 'bronze whaler', 'carpet shark', 'gummy shark', 'roughskin shark', 'school shark' and 'flake' (including its derivatives). Overall, we found taxa (species or genus only) were mislabelled in 47 cases (66%). Matching barcoded taxa to species-specific vendor labels was not possible for 31 samples because of insufficient genetic resolution or uninformative labelling. Two samples were labelled as Bronze whaler but could only be genetically identified to genus level (*Carcharhinus*). A further nine samples were labelled using one of five taxonomically unspecified terms including 'Aus. shark', 'boneless fillet', 'boneless sweetfish', 'large boneless fillet' and 'shark barrel', and therefore matching the genetic sequences with vendor labels was not possible for these. *Carcharhinus* species were the most commonly mislabelled (*C. obscurus*, $n = 4$, *C. brevipinna*, $n = 3$, *C. leucas*, $n = 1$, *Carcharhinus* genus only, $n = 12$) followed by *P. cirratus* ($n = 11$).

Of the 59 samples labelled as 'flake', 88% were not the AFNS-designated species (*Mustelus mustelus* and *Mustelus lenticulatus*) and consisted of 10 genera and 9 species. These included 40 samples where sequences did not match to the AFNS-designated species (Table 5) and 12 samples where sequence matching was inconclusive but the vendor identified a species (Table 6). Three samples labelled as 'flake' were not identified by the vendor and sequence matching was also inconclusive (Table S1). The four samples correctly labelled were all sold as pre-packed fillets. The four verifiable samples labelled 'bronze whaler' were *C. obscurus*, which is compliant as that label can be used for both *Carcharhinus brachyurus* and *C. obscurus*. All fillets labelled 'school shark' were compliant and sequences matched with *G. galeus*.

For the non-compliant labels, 'carpet shark' was used for species of wobbegong (Orectolobidae spp.). This is not compliant because standard advises the label 'wobbegong' should be applied to Orectolobidae spp. However, we counted these as taxonomically correct as 'carpet shark' is a common term for this genus. Other Orectolobidae were labelled as 'flake' or 'boneless fillet'. 'Roughskin shark' most likely refers to the standard name 'roughskin dogfish' but was sequenced as the finfish (*L. calcarifer*) or sequence matching was inconclusive.

Threatened species labelling

We identified nine samples from three species listed as threatened in Australia (Table 4). Only the school shark (*G. galeus*) was correctly labelled with the other two species (*S. lewini* and *S. chloroculus*) incorrectly labelled as 'flake' (Table 5).

Markets *v.* takeaways

Labelling inaccuracies occurred at markets and takeaway venues. In total, 47 of the 66 samples from markets were

Table 5. Taxonomic accuracy of labels determined by sequence matching.

Barcoding result	AFNS name	Vendor label	Mislabelled	Origin	Venue	*n*
Callorhinchus milii (elephantfish)	Elephantfish	Flake[A]	Yes	Qld	Takeaway	1
Carcharhinus brevipinna (spinner shark)	Spinner shark	Flake[A]	Yes	Qld	Takeaway	3
Carcharhinus leucas (bull shark)	Bull shark	Flake[A]	Yes	ACT	Market	1
Carcharhinus obscures (dusky whaler)	Dusky whaler or bronze whaler sharks	Bronze[A] whaler	No	WA	Market	6
Carcharhinus sp.	By species common name, or congeneric group	Flake[A]	Yes	ACT	Market	3
				Qld	Takeaway	6
				SA	Takeaway	3
		Large boneless fillet	Yes	NSW	Market	1
		Shark barrel	Yes	Qld	Market	2
		Aust. shark	Yes	Qld	Market	4
Centrophorus sp.	By species common name, or congeneric group	Flake[A]	Yes	Vic.	Takeaway	1
Deania sp.	By species common name	Flake[A]	Yes	Vic.	Takeaway	1
Galeorhinus galeus (school shark)	School Shark	School[A] shark	No	Vic.	Market	4
Lates calcarifer (barramundi)	Barramundi	Boneless fillet: roughskin shark	Yes	NSW	Market	1
Mugil cephalus (mullet)	Sea mullet or mullet	Flake[A]	Yes	NSW	Market	3
Mustelus antarcticus (gummy shark)	Flake or gummy shark	Gummy[A] flake	No	Vic.	Market	3
		Flake[A]	No	SA	Market	1
Orectolobus halei (gulf wobbegong)	Wobbegong	Flake[A]	Yes	NSW	Takeaway	2
		Gummy[A] flake	Yes	Vic.	Market	1
Orectolobus hutchinsi (western wobbegong)	Wobbegong	Carpet shark	Yes	WA	Market	4
Orectolobus maculates (spotted wobbegong)	Wobbegong or spotted wobbegong	Boneless fillet	Yes	NSW	Market	1
Pristiophorus cirratus (common sawshark)	Common sawshark or sawshark	Gummy[A] shark	Yes	ACT	Market	3
		Flake[A]	Yes	ACT	Market	7
		Boneless sweetfish	Yes	NSW	Market	1
		Flake fillet[A]	Yes	NSW	Market	1
Sphyrna lewini (scalloped hammerhead)	Scalloped hammerhead	Flake[A]	Yes	Qld	Market	3
Squalus chloroculus (greeneye spurdog)	Greeneye dogfish	Flake[A]	Yes	Vic.	Market	2
Squalus sp.		Flake[A]	Yes	Vic.	Market	2

[A]AFNS compliant label.

mislabelled, either taxonomically (n = 31 of 52 barcoded samples) or under the AFNS (n = 17 of 66 label observations). Labels using the term 'flake' (either 'flake', 'flake fillet' or 'gummy flake') comprised 44% of labels at fish markets. All samples from takeaways were labelled as 'flake', and of those that could be confirmed with genetic sequence matching ($n = 17$; the other 8 were inconclusive), none were *Mustelus* species. All of the labels with correct taxon ($n = 14$) were from fish markets. Takeaways showed significantly higher taxonomic mislabelling than markets (Fisher's exact statistic = 0; d.f. = 1, $P < 0.05$) and a greater use of non-compliant AFNS labels (Fisher's exact statistic <0.0001, d.f. = 1, $P < 0.05$).

Discussion

The labelling used by vendors of shark flesh frequently did not adhere to guidelines, and a high proportion of labels were not compatible with the species of shark being sold. Data from 91 shark flesh samples collected from 28 vendors in five Australian states reveal that more than half of the labels were non-compliant with the AFNS, and genetic identification showed that the majority of the five species-specific labels incorrectly represented the species being sold. The most misused label for shark flesh was 'flake', which is supposed to be used for product derived from the sustainable gummy

Table 6. Mismatch between vendor label, verbal response and genetically confirmed identity.

Sample	Vendor label	Vendor response	Genetic identification
ACT-01, 03	Flake	Mako shark	*Carcharhinus* sp.
ACT-02	Flake	Mako shark	*Carcharhinus leucus*
ACT-04, 05, 06, 07	Flake	Gummy shark	*Pristiophorus cirratus*
ACT-08	Flake	Just shark	*Carcharhinus* sp.
ACT-09	Flake	Just shark	Inconclusive
ACT-10, 11, 12	Flake	Gummy shark	*Pristiophorus cirratus*
ACT-13, 14, 15	Gummy shark	Flake is big shark, gummy is small shark	*Pristiophorus cirratus*
NSW-01	Boneless fillet	Shark	Inconclusive
NSW-02	Boneless fillet	Angel shark	*Orectolobus maculatus*
NSW-03, 04, 05	Flake	School shark, caught local	*Mugil cephalus*
NSW-06, 07	Flake	Carpet shark–wobbegong	*Orectolobus halei*
NSW-08	Large boneless fillet	Toothed shark but unsure	*Carcharhinus* sp.
NSW-11	Boneless sweetfish	Baby shark	*Pristiophorus cirratus*
NSW-12, 13	Flake fillet	Sawfish	Inconclusive
QLD-01, 02, 03	Flake	Blacktip reef shark. We also sell Mako shark when it's available.	*Sphyrna lewini*
QLD-04, 05, 06, 07	Flake	Blacktip reef shark	*Carcharhinus brevipinna*
QLD-08, 09	Flake	Imported from Taiwan. The only shark species you can eat.	Inconclusive
QLD-10	Flake	Imported from Taiwan. The only shark species you can eat.	*Callorhinchus capensis*
QLD-11, 12	Flake	The Melbourne species.	Inconclusive
QLD-17	Flake	Blacktip shark	Inconclusive
VIC-05, 06	Flake	Dogfish shark	*Squalus chloroculus*
VIC-09, 10, 11, 12	Flake	Angelshark	Inconclusive

shark fishery (Simpfendorfer *et al.* 2019). Furthermore, product incorrectly labelled as 'flake' was shown to mask the presence of three species listed as threatened in Australian waters, two listed under the EPBC Act and another listed in the Shark Action Plan as meeting the IUCN Red List criteria. Although our findings are based on modest sample sizes, they are consistent with other recent analyses of mislabelling with Australian shark product.

Recent genetic barcoding analyses of Australian seafood, including sharks and rays, are compatible with our results. We found that 70% of samples were mislabelled under the AFNS guidelines, compared with 78% reported by Cundy *et al.* (2023) and the 89% of retailers mislabelling shark product in South Australia (Sharrad *et al.* 2023). Globally, averaged levels of seafood mislabelling were at 5–30%, and generally higher in the elasmobranch trade ranging from 2% (Griffiths *et al.* 2013) to 94% (Agyeman *et al.* 2021) with a 2016 average of ~50% (Pardo *et al.* 2016).

The AFNS prescribes standard fish names for production or trade by retailers and restaurants (i.e. consumer trade) but is not mandated in the ANZFSC. We found non-compliance with the AFNS at takeaways and mislabelling at 26% at markets. The level of taxonomic mislabelling was also significantly higher at takeaways than markets (68 *v.* 47% respectively). Our findings are compatible with previous work showing that mislabelling is generally more prevalent further along the supply-chain, with restaurants and takeaways generally showing lower compliance than retailers (Pardo *et al.* 2016).

The most misused label was 'flake' with 14 vendors misrepresenting 9 species and 10 genera with this label. Under the AFNS, 'flake' is the designated label for gummy shark (*M. antarcticus*) and rig (*M. lenticulatus*) both of which are considered sustainably harvested in Australia (Simpfendorfer and Dulvy 2017; Patterson *et al.* 2019; Simpfendorfer *et al.* 2019). The high level of misuse of the label 'flake' in Australia was also found by Cundy *et al.* (2023) who reported that 67% of samples were incorrectly labelled as 'flake' as opposed to 88% found here. In the past 5 years, commercial take of *M. antarcticus* in the SESSF has not exceeded the annual RBC quota limit (Woodhams and Harte 2018; Petrolo *et al.* 2021). These results highlight the need for accurate labelling to allow for consumer confidence when selecting flake because it is sustainably harvested.

Misuse of the term 'flake' was shown to mask the presence of five species listed as threatened at a global scale by the IUCN: *G. galeus*, *S. lewini*, *C. brevipinna*, *C. leucas* and *S. chloroculus*. Three of these species are listed as threatened in Australia. The scalloped hammerhead shark (*S. lewini*) and school shark (*G. galeus*) are listed as 'Conservation Dependent' under the EPBC Act and population numbers in Australian waters have declined by more than 50% in the last 70–80 years (Kyne *et al.* 2021). In 2022, the green-eye spurdog (*S. chloroculus*) was nominated to receive threatened species listing under the EPBC Act and is currently under assessment, after inferred population declines of >50% over the last 63 years (Kyne *et al.* 2021). Both *S. lewini* and *G. galeus* are listed as Critically Endangered, and *S. chloroculus*, an Australian endemic, is listed as Endangered on the global IUCN Red List of Threatened Species. *S. lewini* has also been listed under CITES Appendix II, which allows for regulated trade, though monitoring may be hampered by frequent mislabelling of this species (e.g. Hobbs *et al.* 2019; Biffi *et al.* 2020; Munguia-Vega *et al.* 2022).

Each of the species listed as threatened in Australia and mislabelled as 'flake' are morphologically distinct from gummy sharks or rig and are unlikely to have been misidentified at capture. However, there are species that are difficult to distinguish from each other using morphological features, and this also contributes to mislabelling. Carcharhinids or requiem sharks are an example of a group threatened by overfishing that may be difficult to distinguish (see the Red List at https://www.iucnredlist.org). This issue is compounded by the current AFNS allowing for umbrella terms for groups of species; for example, both *C. obscurus* and *C. brachyurus* have been assigned the label 'bronze whaler'. Morphological identification is also notoriously difficult for dogfish of *Squalus* spp. In south-east Australia, there have been population declines of up to 97% from 1970 to 1990 mainly due to bottom trawling (Graham *et al.* 2001; Australian Fisheries Management Authority 2012). However, dogfish catch records have been only specified to genera, which presents problems for down-market labelling. Informative labels are crucial to the maintenance of species-specific catch data and the development of more effective protective measures (Barbuto *et al.* 2010; Liu *et al.* 2013; Almerón-Souza *et al.* 2018; Bunholi *et al.* 2018; Pazartzi *et al.* 2019).

Accurate labelling is essential to ensure the authenticity of seafood products, prevent commercial fraud and allow for the sustainable management of fish stocks. Our results demonstrate that the Australian shark trade is consistent with the global problem of product mislabelling, and consequently with the monitoring of sharks being traded and consumed, including threatened species. Australia is signatory to several international agreements and has obligations to manage the trade in protected species. In the absence of standardised and enforced labelling, not only are these obligations difficult to meet, but wider conservation efforts by fisheries, responsible vendors and consumers are negated. We demonstrate how genetic-based identification can be used for market surveys to highlight the hidden trade in shark meat, which can contribute to more effective shark management.

Supplementary material

Supplementary material is available online.

References

Agnew DJ, Gutierrez NL, Stern-Pirlot A, Hoggarth DD (2014) The MSC experience: developing an operational certification standard and a market incentive to improve fishery sustainability. *ICES Journal of Marine Science* **71**, 216–225. doi:10.1093/icesjms/fst091

Agyeman NA, Blanco-Fernandez C, Steinhaussen SL, Garcia-Vazquez E, Machado-Schiaffino G (2021) Illegal, unreported, and unregulated fisheries threatening shark conservation in African waters revealed from high levels of shark mislabelling in Ghana. *Genes* **12**, 1002. doi:10.3390/genes12071002

Almerón-Souza F, Sperb C, Castilho CL, Figueiredo PICC, Gonçalves LT, Machado R, Oliveira LR, Valiati VH, Fagundes NJR (2018) Molecular identification of shark meat from local markets in southern Brazil based on DNA barcoding: evidence for mislabeling and trade of endangered species. *Frontiers in Genetics* **9**, 138. doi:10.3389/fgene.2018.00138

Altschul SF, Gish W, Miller W, Myers EW, Lipman DJ (1990) Basic local alignment search tool. *Journal of Molecular Biology* **215**, 403–410. doi:10.1016/S0022-2836(05)80360-2

Australian Fisheries Management Authority (2012) Upper-slope dogfish management strategy. AFMA-managed Fisheries. October 2012. (AFMA: Canberra, ACT, Australia) Available at https://www.afma.gov.au/sites/default/files/2023-01/Upper-Slope Dogfish Management Strategy.pdf

Australian Government (2017) Country of Origin Food Labelling Information Standard 2016 made under section 134 of Schedule 2 of the *Competition and Consumer Act* 2010. (Australian Federal Government) Available at https://www.legislation.gov.au/Details/F2017C00920 [Verified June 2019]

Barbuto M, Galimberti A, Ferri E, Labra M, Malandra R, Galli P, Casiraghi M (2010) DNA barcoding reveals fraudulent substitutions in shark seafood products: the Italian case of "palombo" (*Mustelus* spp.). *Food Research International* **43**, 376–381. doi:10.1016/j.foodres.2009.10.009

Bellmann C, Tipping A, Sumaila UR (2016) Global trade in fish and fishery products: an overview. *Marine Policy* **69**, 181–188. doi:10.1016/j.marpol.2015.12.019

Biffi D, López-Mobilia A, Kelez S, Williams DA, Chumchal MM, Weinburgh M (2020) Mislabelling and high mercury content hampers the efforts of market-based seafood initiatives in Peru. *Scientific Reports* **10**, 20390. doi:10.1038/s41598-020-77338-x

Biton-Porsmoguer S, B naru D, Boudouresque CF, Dekeyser I, Bouchoucha M, Marco-Miralles F, Lebreton B, Guillou G, Harmelin-Vivien M (2018) Mercury in blue shark (*Prionace glauca*) and shortfin mako (*Isurus oxyrinchus*) from north-eastern Atlantic: implication for fishery management. *Marine Pollution Bulletin* **127**, 131–138. doi:10.1016/j.marpolbul.2017.12.006

Braccini M (2015) Is a global quantitative assessment of shark populations warranted? *Fisheries* **40**, 492–501. doi:10.1080/03632415.2015.1080689

Bunholi IV, Ferrette BLS, De Biasi JB, Magalhães CO, Rotundo MM, Oliveira C, Foresti F, Mendonça FF (2018) The fishing and illegal trade of the angelshark: DNA barcoding against misleading identifications. *Fisheries Research* **206**, 193–197. doi:10.1016/j.fishres.2018.05.018

Cardeñosa D, Fields AT, Babcock EA, Zhang H, Feldheim K, Shea SKH, Fischer GA, Chapman DD (2018) CITES-listed sharks remain among the top species in the contemporary fin trade. *Conservation Letters* **11**, e12457. doi:10.1111/conl.12457

Chang C-H, Tsai M-L, Huang T-T, Wang Y-C (2021) Authentication of fish species served in conveyor-belt sushi restaurants in Taiwan using DNA barcoding. *Food Control* **130**, 108264. doi:10.1016/j.foodcont.2021.108264

Chen P-Y, Ho C-W, Chen A-C, Huang C-Y, Liu T-Y, Liang K-H (2020) Investigating seafood substitution problems and consequences in Taiwan using molecular barcoding and deep microbiome profiling. *Scientific Reports* **10**, 21997. doi:10.1038/s41598-020-79070-y

Cundy ME, Santana-Garcon J, McLennan AG, Ayad ME, Bayer PE, Cooper M, Corrigan S, Harrison E, Wilcox C (2023) Seafood label quality and mislabelling rates hamper consumer choices for sustainability in Australia. *Scientific Reports* **13**, 10146. doi:10.1038/s41598-023-37066-4

Davidson LNK, Krawchuk MA, Dulvy NK (2016) Why have global shark and ray landings declined: improved management or overfishing? *Fish and Fisheries* **17**, 438–458. doi:10.1111/faf.12119

Department of Climate Change, Energy, the Environment and Water (2024) Species profile and threats database. (Commonwealth of Australia: Canberra, ACT, Australia) Available at https://www.environment.gov.au/cgi-bin/sprat/public/sprat.pl

Dulvy NK, Simpfendorfer CA, Davidson LNK, Fordham SV, Bräutigam A, Sant G, Welch DJ (2017) Challenges and priorities in shark and ray conservation. *Current Biology* **27**, R565–R572. doi:10.1016/j.cub.2017.04.038

Dulvy NK, Pacoureau N, Rigby CL, Pollom RA, Jabado RW, Ebert DA, Finucci B, Pollock CM, Cheok J, Derrick DH, Herman KB, *et al.* (2021) Overfishing drives over one-third of all sharks and rays toward a global extinction crisis. *Current Biology* **31**, 4773–4787.e8. doi:10.1016/j.cub.2021.08.062

Fields AT, Fischer GA, Shea SKH, Zhang H, Abercrombie DL, Feldheim KA, Babcock EA, Chapman DD (2018) Species composition of the international shark fin trade assessed through a retail-market survey in Hong Kong. *Conservation Biology* **32**, 376–389. doi:10.1111/cobi.13043

Fisheries Research and Development Corporation (2024) Australian fish names standard. Published 12 May 2022, updated 18 April 2024. (FRDC) Available at https://www.fishnames.com.au/ [Verified September 2019]

Food and Agriculture Organization of the United Nations (2018) The state of world fisheries and aquaculture 2018: meeting the sustainable development goals. (FAO: Rome, Italy) Available at https://www.fao.org/documents/card/en?details=I9540EN

Food and Agriculture Organization of the United Nations (2022) The state of world fisheries and aquaculture 2022. Towards blue transformation. (FAO: Rome, Italy) Available at https://www.fao.org/documents/card/en?details=cc0461en

Fox M, Mitchell M, Dean M, Elliott C, Campbell K (2018) The seafood supply chain from a fraudulent perspective. *Food Security* **10**, 939–963. doi:10.1007/s12571-018-0826-z

French I, Wainwright BJ (2022) DNA barcoding identifies endangered sharks in pet food sold in Singapore. *Frontiers in Marine Science* **9**, 836941. doi:10.3389/fmars.2022.836941

Gilman E, Passfield K, Nakamura K (2014) Performance of regional fisheries management organizations: ecosystem-based governance of bycatch and discards. *Fish and Fisheries* **15**, 327–351. doi:10.1111/faf.12021

Graham KJ, Andrew NL, Hodgson KE (2001) Changes in relative abundance of sharks and rays on Australian South East Fishery trawl grounds after twenty years of fishing. *Marine and Freshwater Research* **52**, 549–561. doi:10.1071/MF99174

Griffiths AM, Miller DD, Egan A, Fox J, Greenfield A, Mariani S (2013) DNA barcoding unveils skate (Chondrichthyes: Rajidae) species diversity in 'ray' products sold across Ireland and the UK. *PeerJ* **1**, e129. doi:10.7717/peerj.129

Hanner R, Becker S, Ivanova NV, Steinke D (2011) FISH-BOL and seafood identification: geographically dispersed case studies reveal systemic market substitution across Canada. *Mitochondrial DNA* **22**, 106–122. doi:10.3109/19401736.2011.588217

Hebert PDN, Cywinska A, Ball SL, deWaard JR (2003) Biological identifications through DNA barcodes. *Proceedings of the Royal Society of London – B. Biological Sciences* **270**, 313–321. doi:10.1098/rspb.2002.2218

Hellberg RS, Isaacs RB, Hernandez EL (2019) Identification of shark species in commercial products using DNA barcoding. *Fisheries Research* **210**, 81–88. doi:10.1016/j.fishres.2018.10.010

Hobbs CAD, Potts RWA, Bjerregaard Walsh M, Usher J, Griffiths AM (2019) Using DNA barcoding to investigate patterns of species utilisation in UK shark products reveals threatened species on sale. *Scientific Reports* **9**, 1028. doi:10.1038/s41598-018-38270-3

Holmes BH, Steinke D,Ward RD (2009) Identification of shark and ray fins using DNA barcoding. *Fisheries Research* **95**, 280–288. doi:10.1016/j.fishres.2008.09.036

Karami A, Golieskardi A, Ho YB, Larat V, Salamatinia B (2017) Microplastics in eviscerated flesh and excised organs of dried fish. *Scientific Reports* **7**, 5473. doi:10.1038/s41598-017-05828-6

Kyne PM, Heupel MR, White WT, Simpfendorfer CA (2021) The action plan for sharks and rays 2021. National Environment Science Program, Marine Biodiversity Hub, Hobart, Tas., Australia.

Lamendin R, Miller K, Ward RD (2015) Labelling accuracy in Tasmanian seafood: an investigation using DNA barcoding. *Food Control* **47**, 436–443. doi:10.1016/j.foodcont.2014.07.039

Liu S-YV, Chan C-LC, Lin O, Hu C-S, Chen CA (2013) DNA barcoding of shark meats identify species composition and CITES-listed species from the markets in Taiwan. *PLoS ONE* **8**, e79373. doi:10.1371/journal.pone.0079373

Luque GM, Donlan CJ (2019) The characterization of seafood mislabeling: a global meta-analysis. *Biological Conservation* **236**, 556–570. doi:10.1016/j.biocon.2019.04.006

McClenachan L, Cooper AB, Dulvy NK (2016) Rethinking trade-driven extinction risk in marine and terrestrial megafauna. *Current Biology* **26**, 1640–1646. doi:10.1016/j.cub.2016.05.026

Melnychuk MC, Kurota H, Mace PM, Pons M, Minto C, Osio GC, Jensen OP, de Moor CL, Parma AM, Richard Little L, Hively D, Ashbrook CE, Baker N, Amoroso RO, Branch TA, Anderson CM, Szuwalski CS, Baum JK, McClanahan TR, Ye Y, Ligas A, Bensbai J, Thompson GG, DeVore J, Magnusson A, Bogstad B, Wort E, Rice J, Hilborn R (2021) Identifying management actions that promote sustainable fisheries. *Nature Sustainability* **4**, 440–449. doi:10.1038/s41893-020-00668-1

Miller DD, Mariani S (2010) Smoke, mirrors, and mislabeled cod: poor transparency in the European seafood industry. *Frontiers in Ecology and the Environment* **8**, 517–521. doi:10.1890/090212

Minhos T, Wallace E, Ferreira da Silva MJ, Sá RM, Carmo M, Barata A, Bruford MW (2013) DNA identification of primate bushmeat from urban markets in Guinea-Bissau and its implications for conservation. *Biological Conservation* **167**, 43–49. doi:10.1016/j.biocon.2013.07.018

Munguia-Vega A, Terrazas-Tapia R, Dominguez-Contreras JF, Reyna-Fabian M, Zapata-Morales P (2022) DNA barcoding reveals global and local influences on patterns of mislabeling and substitution in the trade of fish in Mexico. *PLoS ONE* **17**, e0265960. doi:10.1371/journal.pone.0265960

Neo S, Kibat C, Wainwright BJ (2022) Seafood mislabelling in Singapore. *Food Control* **135**, 108821. doi:10.1016/j.foodcont.2022.108821

Oliver S, Braccini M, Newman SJ, Harvey ES (2015) Global patterns in the bycatch of sharks and rays. *Marine Policy* **54**, 86–97. doi:10.1016/j.marpol.2014.12.017

Pacoureau N, Rigby CL, Kyne PM, Sherley RB, Winker H, Carlson JK, Fordham SV, Barreto R, Fernando D, Francis MP, Jabado RW, Herman KB, Liu K-M, Marshall AD, Pollom RA, Romanov EV, Simpfendorfer CA, Yin JS, Kindsvater HK, Dulvy NK (2021) Half a century of global decline in oceanic sharks and rays. *Nature* **589**, 567–571. doi:10.1038/s41586-020-03173-9

Pacoureau N, Carlson JK, Kindsvater HK, Rigby CL, Winker H, Simpfendorfer CA, Charvet P, Pollom RA, Barreto R, Sherman CS, Talwar BS, Skerritt DJ, Sumaila UR, Matsushiba JH, VanderWright WJ, Yan HF, Dulvy NK (2023) Conservation successes and challenges for wide-ranging sharks and rays. *Proceedings of the National Academy of Sciences* **120**, e2216891120. doi:10.1073/pnas.2216891120

Palin C, Gaudin C, Espejo-Hermes J, Nicolaides J (2013) Compliance of imports of fishery and aquaculture products with EU legislation. (European Parliament: Brussels, Belgium) Available at https://fishwise.org/dive-deeper/resource/compliance-of-imports-of-fishery-and-aquaculture-products-with-eu-legislation/

Pardo MÁ, Jiménez E, Pérez-Villarreal B (2016) Misdescription incidents in seafood sector. *Food Control* **62**, 277–283. doi:10.1016/j.foodcont.2015.10.048

Patterson H, Williams A, Woodhams J, Curtotti R (2019) Fishery status reports 2019. Research by the Australian Bureau of Agricultural and Resource Economics and Sciences, September 2019. (Australian Bureau of Agricultural and Resource Economics and Sciences:

Canberra, ACT, Australia) Available at https://www.agriculture.gov.au/sites/default/files/abares/documents/research-topics/fisheries/00_FishStatus2019_5.0.0_LR.pdf

Pazartzi T, Siaperopoulou S, Gubili C, Maradidou S, Loukovitis D, Chatzispyrou A, Griffiths AM, Minos G, Imsiridou A (2019) High levels of mislabeling in shark meat – investigating patterns of species utilization with DNA barcoding in Greek retailers. *Food Control* **98**, 179–186. doi:10.1016/j.foodcont.2018.11.019

Petrolo E, Boomer J, O'Hare J, Bilgmann K, Stow A (2021) Stock structure and effective population size of the commercially exploited gummy shark *Mustelus antarcticus*. *Marine Ecology Progress Series* **678**, 109–124. doi:10.3354/meps13859

Ratnasingham S, Herbert PDN (2007) BOLD: the barcode of life data system (http://www.barcodinglife.org). *Molecular Ecology Notes* **7**, 355–364. doi:10.1111/j.1471-8286.2007.01678.x

Reilly A (2018) Overview of food fraud in the fisheries sector. (Food and Agriculture Organization of the United Nations: Rome, Italy) Available at https://www.fao.org/3/i8791en/I8791EN.pdf

Rigby CL, Dulvy NK, Barreto R, Carlson J, Fernando D, Fordham S, Francis MP, Herman K, Jabado RW, Liu KM, Marshall A, Pacoureau N, Romanov E, Sherley RB, Winker H (2019*a*) Scalloped hammerhead *Sphyrna lewini*. In 'The IUCN Red List of Threatened Species 2019'. e.T39385A2918526. (International Union for Conservation of Nature and Natural Resources) Available at https://www.iucnredlist.org/species/39385/2918526

Rigby CL, Barreto R, Carlson J, Fernando D, Fordham S, Francis M.P, Herman K, Jabado RW, Liu KM, Marshall A, Pacoureau N, Romanov E, Sherley RB, Winker H (2019*b*) Dusky shark *Carcharhinus obscurus*. In 'The IUCN Red List of Threatened Species 2019'. e.T3852A2872747. (International Union for Conservation of Nature and Natural Resources) Available at https://www.iucnredlist.org/species/3852/2872747

Rigby CL, Carlson J, Smart JJ, Pacoureau N, Herman K, Derrick D, Brown E (2020) Spinner shark *Carcharhinus brevipinna*. In 'The IUCN Red List of Threatened Species 2020'. e.T39368A2908817. (International Union for Conservation of Nature and Natural Resources) Available at https://www.iucnredlist.org/species/39368/2908817

Rigby CL, Espinoza M, Derrick D, Pacoureau N, Dicken M (2021) Bull shark *Carcharhinus leucas*. In 'The IUCN Red List of Threatened Species 2021'. e.T39372A2910670. (International Union for Conservation of Nature and Natural Resources) Available at https://www.iucnredlist.org/species/39372/2910670

Roff G, Brown CJ, Priest MA, Mumby PJ (2018) Decline of coastal apex shark populations over the past half century. *Communications Biology* **1**, 223. doi:10.1038/s42003-018-0233-1

Sharrad AE, Reis-Santos P, Austin J, Gillanders BM (2023) Umbrella terms conceal the sale of threatened shark species: a DNA barcoding approach. *Food Control* **148**, 109606. doi:10.1016/j.foodcont.2023.109606

Shea KH, To AWL (2017) From boat to bowl: patterns and dynamics of shark fin trade in Hong Kong – implications for monitoring and management. *Marine Policy* **81**, 330–339. doi:10.1016/j.marpol.2017.04.016

Simpfendorfer CA, Dulvy NK (2017) Bright spots of sustainable shark fishing. *Current Biology* **27**, R97–R98. doi:10.1016/j.cub.2016.12.017

Simpfendorfer C, Chin A, Rigby C, Sherman S, White W (2019) Shark futures: a report card for Australia's sharks and rays. FRDC Project Number 2013/009. (Fisheries Research and Development Corporation) Available at https://www.frdc.com.au/sites/default/files/products/2013-009-DLD.pdf

Sotelo CG, Velasco A, Perez-Martin RI, Kappel K, Schröder U, Verrez-Bagnis V, Jérôme M, Mendes R, Silva H, Mariani S, Griffiths A (2018) Tuna labels matter in Europe: mislabelling rates in different tuna products. *PLoS ONE* **13**, e0196641. doi:10.1371/journal.pone.0196641

Taberlet P, Bonin A, Zinger L, Coissac E (2018) 'Environmental DNA: for biodiversity research and monitoring.' (Oxford University Press)

Tamura K, Stecher G, Kumar S (2021) MEGA11: molecular evolutionary genetics analysis version 11. *Molecular Biology and Evolution* **38**, 3022–3027. doi:10.1093/molbev/msab120

Tillett BJ, Field IC, Bradshaw CJA, Johnson G, Buckworth RC, Meekan MG, Ovenden JR (2012) Accuracy of species identification by fisheries observers in a north Australian shark fishery. *Fisheries Research* **127–128**, 109–115. doi:10.1016/j.fishres.2012.04.007

Vandamme SG, Griffiths AM, Taylor S-A, Di Muri C, Hankard EA, Towne JA, Watson M, Mariani S (2016) Sushi barcoding in the UK: another kettle of fish. *PeerJ* **4**, e1891. doi:10.7717/peerj.1891

Vandermeersch G, Lourenço HM, Alvarez-Muñoz D, Cunha S, Diogène J, Cano-Sancho G, Sloth JJ, Kwadijk C, Barcelo D, Allegaert W, Bekaert K, Fernandes JO, Marques A, Robbens J (2015) Environmental contaminants of emerging concern in seafood – European database on contaminant levels. *Environmental Research* **143**, 29–45. doi:10.1016/j.envres.2015.06.011

Vincent ACJ, Sadovy de Mitcheson YJ, Fowler SL, Lieberman S (2014) The role of CITES in the conservation of marine fishes subject to international trade. *Fish and Fisheries* **15**, 563–592. doi:10.1111/faf.12035

Walker TI, Rochowski BEA (2019) Greeneye spurdog *Squalus chloroculus*. In 'The IUCN Red List of Threatened Species 2019'. e.T161360A68644464. (International Union for Conservation of Nature and Natural Resources) Available at https://www.iucnredlist.org/species/161360/68644464

Walker TI, Rigby CL, Pacoureau N, Ellis J, Kulka DW, Chiaramonte GE, Herman K (2020) Tope *Galeorhinus galeus*. In 'The IUCN Red List of Threatened Species 2020'. e.T39352A2907336. (International Union for Conservation of Nature and Natural Resources) Available at https://www.iucnredlist.org/species/39352/2907336

Ward RD, Zemlak TS, Innes BH, Last PR, Hebert PDN (2005) DNA barcoding Australia's fish species. *Philosophical Transactions of the Royal Society of London – B. Biological Sciences* **360**, 1847–1857. doi:10.1098/rstb.2005.1716

Ward RD, Holmes BH, Yearsley GK (2008) DNA barcoding reveals a likely second species of Asian sea bass (barramundi) (*Lates calcarifer*). *Journal of Fish Biology* **72**, 458–463. doi:10.1111/j.1095-8649.2007.01703.x

Wong EH-K, Shivji MS, Hanner RH (2009) Identifying sharks with DNA barcodes: assessing the utility of a nucleotide diagnostic approach. *Molecular Ecology Resources* **9**, 243–256. doi:10.1111/j.1755-0998.2009.02653.x

Woodhams J, Harte C (2018) Shark assessment report 2018. (Australian Bureau of Agricultural and Resource Economics and Sciences: Canberra, ACT, Australia) Available at https://www.agriculture.gov.au/abares/research-topics/fisheries/fisheries-research/shark-assessment-report-2018

Xiong X, Guardone L, Cornax MJ, Tinacci L, Guidi A, Gianfaldoni D, Armani A (2016) DNA barcoding reveals substitution of sablefish (*Anoplopoma fimbria*) with Patagonian and Antarctic toothfish (*Dissostichus eleginoides* and *Dissostichus mawsoni*) in online market in China: how mislabeling opens door to IUU fishing. *Food Control* **70**, 380–391. doi:10.1016/j.foodcont.2016.06.010

Zhang Z, Schwartz S, Wagner L, Miller W (2000) A greedy algorithm for aligning DNA sequences. *Journal of Computational Biology* **7**, 203–214. doi:10.1089/10665270050081478

Data availability. The authors confirm that the raw data supporting the findings of this study will be available in DRYAD.

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Author affiliations

[A]School of Natural Sciences, Macquarie University, Sydney, NSW 2109, Australia.

[B]Conservation Genetics Lab, Macquarie University, Sydney, NSW 2109, Australia.