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REVIEW

Challenges and priorities for river cetacean conservation

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ABSTRACT: River cetaceans are particularly vulnerable to anthropogenic impacts due to their constrained ranges in freshwater systems of China, South Asia, and South America. We undertook an exhaustive review of 280 peer-reviewed papers and grey literature reports (1998–2020) to examine the current status of knowledge regarding these cetaceans and their conservation. We aimed to better understand the scale of threats they face, and to identify and propose priority future efforts to better conserve these species. We found that the species have been studied with varying frequency and that most of the research on threats has focused on habitat degradation and fragmentation (43%, mainly driven by dams and extractive activities such as sand mining and deforestation), and fishery interactions (39%, in the form of bycatch and direct take). These threats occur across all species, but more information is needed, primarily on quantifying the population impacts as a basis for designing mitigation measures. Other threats identified include pollution, vessel collisions, traditional use, and poorly managed tourism. Emerging methods such as environmental DNA and unmanned aerial vehicles are described for studying these species. Promising conservation interventions include cetacean-specific protected areas, natural *ex situ* protection, community-led conservation, and education programmes. However, transnational political will is required for a step change towards broad-scale protection in freshwater environments. In addition, we propose increasing capacity building, developing management plans, working closely with fishing communities, enhancing public awareness, expanding regional collaborations, and diversifying funding.

KEY WORDS: River dolphins · Threat · Management · Bycatch · Dams · Dolphin–fishery interactions · Research prioritisation · Emerging methods

1. INTRODUCTION

River cetaceans are a polyphyletic group, with similar habitats and shared sensory and morphological characteristics (Fig. 1, Table 1). They live exclusively in freshwater habitats in Asia and South America. The group includes the extinct baiji *Lipotes vexillifer* (Turvey et al. 2007, Smith et al. 2017), the Yangtze

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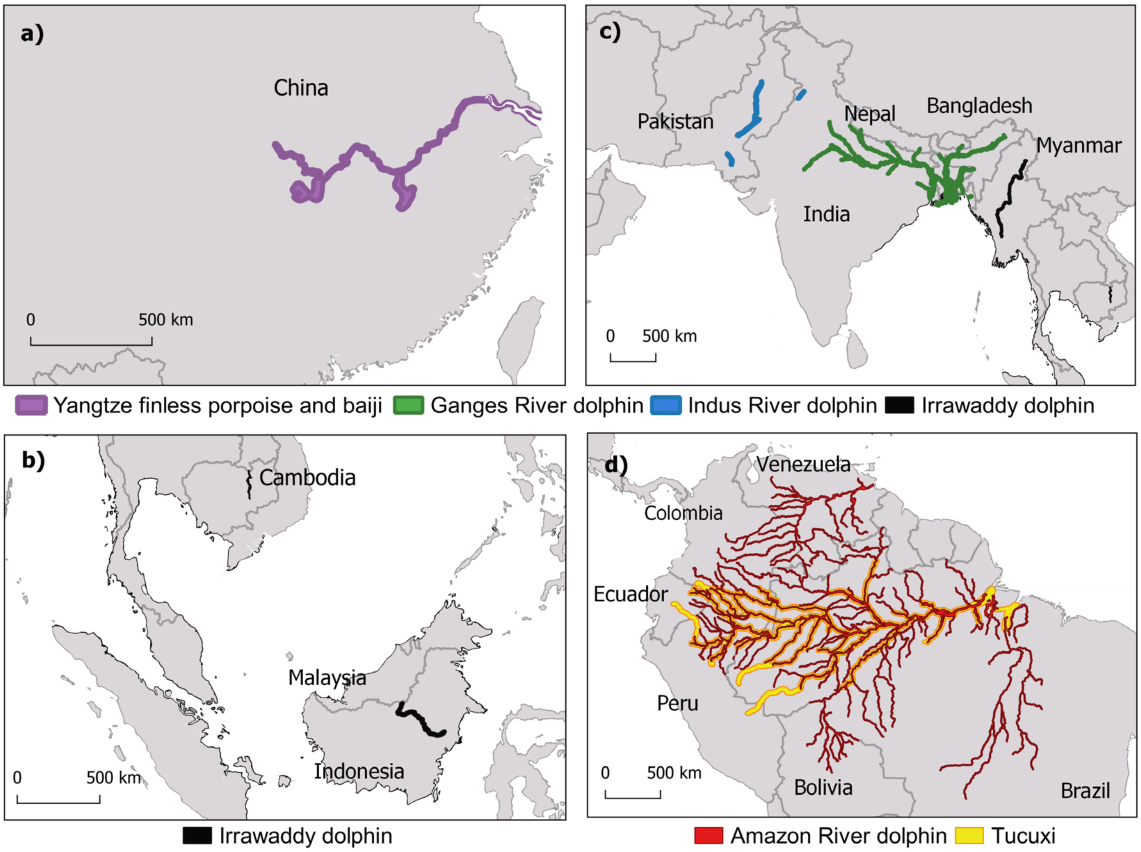

Fig. 1. River cetacean distributions in (a) China, (b) Southeast Asia, (c) South Asia, and (d) South America (line thickness is of no significance). Spatial ranges were obtained from the most recent IUCN Red List assessment (IUCN 2021)

finless porpoise *Neophocaena asiaeorientalis asiaeorientalis*, the Irrawaddy dolphin *Orcaella brevirostris*, the Ganges river dolphin *Platanista gangetica*, the Indus river dolphin *P. minor* (Braulik et al. 2021), the tucuxi *Sotalia fluviatilis* (Caballero et al. 2017), the Amazon river dolphin *Inia geoffrensis geoffrensis* and the Bolivian river dolphin *I. g. boliviensis* (Ruiz-Garcia et al. 2008). Population numbers for the Asian species are in the low thousands (see Table 1 for details) and no accurate estimates are available for South America river cetaceans.

River cetaceans are among the world's most threatened aquatic mammal groups. Their restricted ranges, which overlap with increasing human population needs, make them particularly vulnerable to anthropogenic threats (Reeves & Martin 2009, Raby et al. 2011, Braulik et al. 2015, Brum et al. 2021). River cetaceans depend on waterways often located within intensively human-modified landscapes (Castello et al. 2013, Albert et al. 2021). These waterways are used to extract resources for food, irrigation, construction, and industrial activities; modified to generate energy, reduce flood risk, and improve navigation; and contaminated with discharge from agriculture, industry, mining, and human habitations. These activities result in habitat loss and degradation that effectively reduce distribution ranges for river cetacean species and increase human–dolphin interactions (Braulik et al. 2014, da Silva et al. 2018c, 2020, Aliaga-Rossel & Escobar-WW 2020).

River cetaceans hold ecological, cultural, and economic value in the systems they inhabit. Ecologically, they play a vital role at the top of freshwater food chains (Behera 1995). They have been used to indicate the status of other threatened sympatric species (Turvey et al. 2012) and overall habitat health (Gomez-Salazar et al. 2012c, Smith & Reeves 2012). Culturally, they are often central to local myths and legends (Cravalho 1999, Schelle 2010, da Silva et al. 2017). Furthermore, they can provide livelihoods and economic value as tourist attractions (Romagnoli 2009, Beasley et al. 2010) and serve as flagship species for promoting the conservation of rivers (Burgener et al. 2012).

Table 1. Summary of species range and most recent populations numbers. NA = not currently available

Common name	Scientific name	Range	Population	IUCN Red List
Yangtze river dolphin (Baiji)	*Lipotes vexillifer*	Yangtze River basin (China)	Possibly extinct (Turvey et al. 2007)	Critically Endangered (Possibly Extinct)
Yangtze finless porpoise	*Neophocaena asiaeorientalis* ssp. *asiaeorientalis*	Middle-lower Yangtze River basin and adjacent Poyang and Dong-ting Lakes (China)	1012 (95% CI: 791–1233) (Huang et al. 2020)	Critically Endangered (CR)
Ganges river dolphin (Susu)	*Platanista gangetica*	Ganges- Brahmaputra-Megna and Karnaphuli-Sangu river systems (India, Nepal and Bangladesh)	3500–4000 (UNEP/ CMS/ Concerted Action 13.6 2020)	Endangered (EN)
Indus river dolphin (Bhulan)	*Platanista minor*	Lower Indus basin (Pakistan)	965 (843–1171) (Braulik 2006)	Endangered (EN)
Irrawaddy dolphin	*Orcaella brevirostris*[a]	Ayeyarwady River (Myanmar)	58–72 (Smith et al. 2007);	Critically Endangered (CR)
		Mahakam River (Indonesia)	79 (95% CL 65–99, CV = 3%), (D. Kreb unpubl. data) in 2019;	
		Mekong River (Cambodia, Lao People's Democratic Republic)	80 (95% CL 64–100; Phan et al. 2015) NA	Endangered (EN)
Tucuxi	*Sotalia fluviatilis*	Amazon basin (Brazil, Colombia, Ecuador, Peru)		
Amazon river dolphin (Boto)	*Inia geoffrensis* ssp. *geoffrensis*[b]	Amazon and Orinoco river basins (Brazil, Colombia, Ecuador, Peru, Venezuela)	NA	Endangered (EN; classified at species level)
Bolivian river dolphin (Bolivian bufeo)	*Inia geoffrensis* ssp. *boliviensis*	Iténez-Guaporé, Mamoré, and Rio Grande River basins (Bolivia) Madeira River, (Brazil)	NA	

[a]The Irrawaddy dolphin *Orcaella brevirostris* is a facultative river cetacean which has both marine and freshwater populations

[b]A second *Inia* species, the Araguaian boto *I. araguaiaensis*, has been described (Hrbek et al. 2014) but has yet to be recognised by the Committee on Taxonomy of the Society for Marine Mammalogy because of the need for additional data supporting species designation (Committee on Taxonomy 2020)

Most reviews on river cetaceans have focused on a single species (Smith et al. 2001, Wang 2009, Waqas et al. 2012, Sinha & Kannan 2014, Braulik et al. 2015) or on a specific geographic area (Zhao et al. 2011, Brum et al. 2021). The most recent overarching review, including species from Asia and South America, was completed over 20 yr ago (Smith & Smith 1998). Although there are differences in the resources, cultures, and politics among countries where river cetaceans occur, a comprehensive approach can identify broad trends and compare threats and potential solutions. Therefore, this review aims to (1) provide an updated overview of current threats to all river cetaceans, (2) identify research gaps, novel methodologies, and conservation strategies, and (3) recommend potential measures for improved conservation.

2. METHODS

2.1. Literature search

To compile documentation of threats and management of river cetaceans, we conducted an exhaustive literature search using the online search engines Google Scholar and Web of Science Core Collection. Keywords included the common and species-level scientific names of all the focal species according to the Society for Marine Mammalogy (Committee on Taxonomy 2020), and 'threat', 'conservation', or 'management'. For example, we searched for 'Inia geoffrensis AND threat', and for 'Amazon river dolphin AND threat'. We searched for each species with 'conservation' and with 'management', so each species had a total of 6 keyword combinations. We consulted material published between January 1, 1998, and December 31, 2020 (extracted March 3, 2019, and updated March 16, 2021), reading in full all 626 Web of Science results and the first 500 publications listed in Google Scholar. We included scientific articles, published books, and available 'grey' literature that directly mentioned threats, conservation, or management, or that proposed future conservation efforts (n = 240, Table S1 in Supplement 1 at www.int-res.com/articles/suppl/n049p013_supp1.xlsx). These publications were supplemented by an additional 40 publications identified by co-authors (Table S2 in Supplement 1). The literature gathered through the search and co-author contributions included sources in English, Spanish, and Portuguese.

From the 280 identified source materials, the following information was compiled: (1) the country(ies) where the research took place, (2) the year the study was published, (3) the species under threat, (4) the type of threat, (5) the aims of the research, (6) the methods used, and (7) key findings. We categorised threats (Table 2) and assigned relevant publications to at least 1 threat category. We created an additional category for research that tested new methods applied to conservation efforts.

2.2. Expert elicitation

A total of 41 experts were invited to participate in this review, and 29 accepted (affiliations: 6 Academia and NGO-Private, 11 NGO-Private only, 9 Academia only, and 4 Government). Because we aimed to include at least 2 authors per country per species with diversity in nationality, gender, and seniority, we determined whom to contact by their research location and their recent publications. We asked correspondents who agreed to participate to provide additional, relevant literature that we had not identified, and to complete a questionnaire about the river cetacean species in their region(s) of work. The questionnaire included 4 sections: (1) most significant threats, (2) information gaps, (3) challenges, and (4) opportunities for conservation. Correspondents were allowed to list, in order of importance, a maximum of 5 themes per section. To assess how threats were ranked, we calculated descriptive statistics for broad threats (e.g. fisheries) and sub-threats (secondary, more specific threats, e.g. bycatch). For the other sections (knowledge gaps, challenges, and opportunities), we scaled ranks from 100 (highest priority) to 20 (lowest priority) and calculated averages to synthesise expert opinion across the whole species group and by species. For ties, a median value of 2 ranks was used.

2.3. Presentation of results

The following 2 sections of the review highlight the major results of the literature search (Sections 3 and 4), and the succeeding 3 sections compile the primary themes that emerged from the expert elicitation (Sections 5 to 7). Finally, we present our conclusions and recommendations garnered from the combined approach.

Table 2. Threat classification used in the review publication database

Broad threat categories	Included sub-threats	Impacts	Examples
Fisheries	Bycatch Targeted catch Illegal fishing Overfishing	Increase in mortality Extirpation in parts of range	Kreb et al. 2010, Iriarte & Marmontel 2014, Brum et al. 2015, da Silva et al. 2018a, Brownell et al. 2019
Habitat degradation	Infrastructure (dams, barrages) Climate change Deforestation Sand mining	Population fragmentation Displacement	Karim & Bindra 2016, Pavanato et al. 2016, Aliaga-Rossel & Escobar-WW 2020
Other human interactions	Human populations Vessel collision Tourism Traditional use	Displacement	Aliaga-Rossel 2002, Gravena et al. 2008, Romagnoli 2009
Pollution	Heavy metals Plastic Noise Chemical contaminants	Physiology and health impacts Modifications in communication	Lailson-Brito et al. 2008, Yang et al. 2008, Mosquera-Guerra et al. 2019

3. OVERVIEW OF THREATS

Published research on river cetacean conservation has increased over the past decade, with an average of 6 papers per year from 1998 to 2008 and then an average of 16 per year from 2009 to 2020 (Fig. 2a). By country, work in China has resulted in the most publications (n = 79), followed by Brazil (n = 54) and India (n = 41) (Fig. 2b). Species have been studied to varying degrees, with the most sources focused on the Yangtze finless porpoise (n = 60, 21% of reviewed items) and the fewest on the Indus river dolphin (n = 16, 6%) (Fig. 2c).

The frequency with which a threat appears in the literature may not be the same as the importance of the threat and their impact on extinction risk, but a cross comparison with expert opinion allowed us to prioritise threats that require urgent attention. Habitat degradation was the most frequently mentioned threat in publications (n = 112, 43%) followed by fisheries interactions (n = 102, 39%) (Fig. 3a). Sources mentioned pollution (n = 24, 10%) and other human interactions (n = 21, 8%) less frequently. Expert responses from the questionnaire similarly recognised habitat degradation and fisheries interactions as the most significant threats (Figs. 3b & 4 and Fig. S1 in Supplement 2 at www.int-res.com/articles/suppl/n049p013_supp2.pdf). Fisheries were ranked as the primary threat most frequently (63% ranked it first, 34% ranked it second), followed by habitat degradation (37% ranked it first, 46% ranked it second).

3.1. Fishery interactions

Fishery interactions are a well recognised threat to small cetaceans worldwide (e.g. Read 2008, Brownell et al. 2019, Nelms et al. 2021b) and a primary cause of river cetacean mortality (e.g. Turvey et al. 2007, Zhao et al. 2008, Kelkar & Dey 2020). Identified threats from fisheries include bycatch, targeted catch, overfishing, and electrofishing. Although we discuss these threats separately, several authors observe that they are intertwined and often indistinguishable.

3.1.1. Bycatch

Bycatch was mentioned as a threat to all river cetacean species (58 papers, 73% of co-authors listed bycatch in the questionnaire) (Smith & Hobbs 2002, Mansur et al. 2008, Trujillo et al. 2010, Raby et al. 2011, Iriarte & Marmontel 2014), and it was a principal reason behind the extinction of the baiji (Turvey et al. 2007). Gillnets were the métiers that appeared most frequently in the literature, involving all species (Baird & Beasley 2005, Kreb & Budiono 2005, Mintzer et al. 2015, Khanal et al. 2016, Brownell et al. 2019,

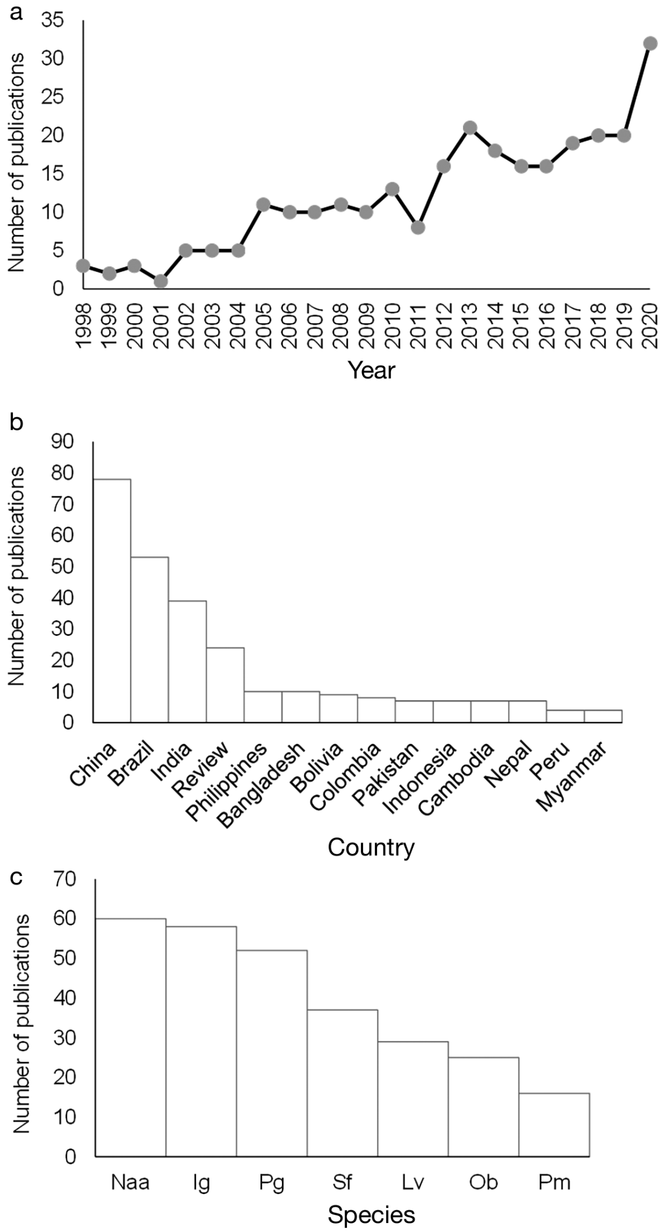

Fig. 2. Publication trends. Number of publications on river cetacean species by (a) year published (1998 to 2020), (b) country where the research was undertaken, and (c) species (Naa: *Neophocaena asiaeorientalis asiaeorientalis*; Ig: *Inia geoffrensis*; Pg: *Platanista gangetica*; Sf: *Sotalia fluviatilis*; Lv: *Lipotes vexillifer*; Ob: *Orcaella brevirostris*; Pm: *Platanista minor*. For common names see Table 1)

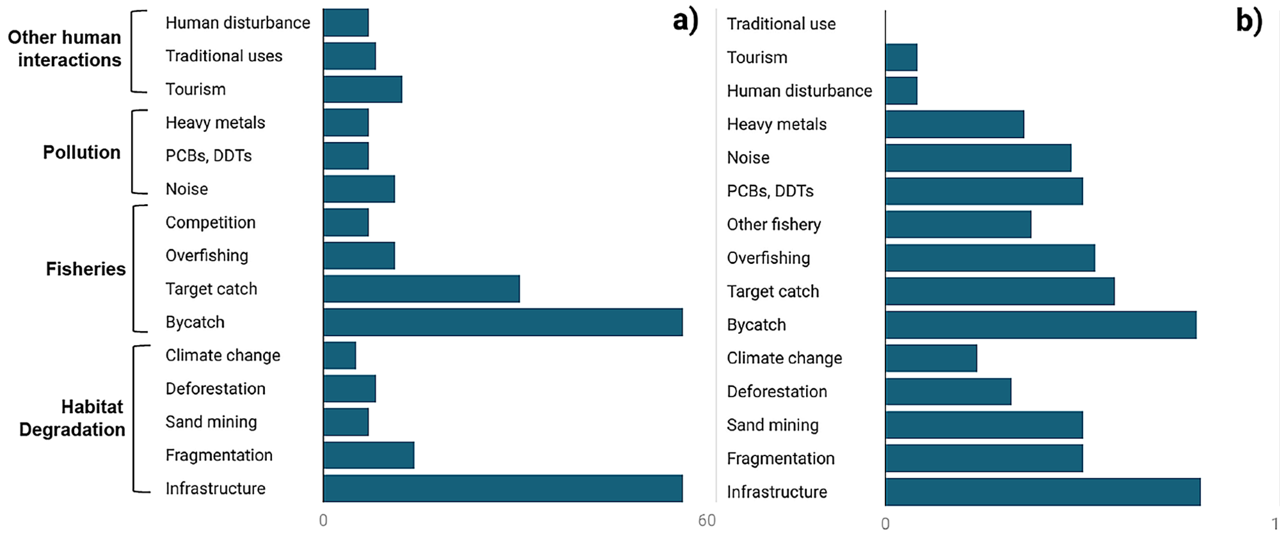

Fig. 3. Overview of threats to river cetaceans. (a) Number of publications that mentioned each threat and (b) proportion of co-authors that mentioned each threat in their questionnaire. We divided threats into 4 overarching themes: Habitat degradation, Fisheries, Pollution, Other human interactions. Subthemes were sorted by prevalence within themes

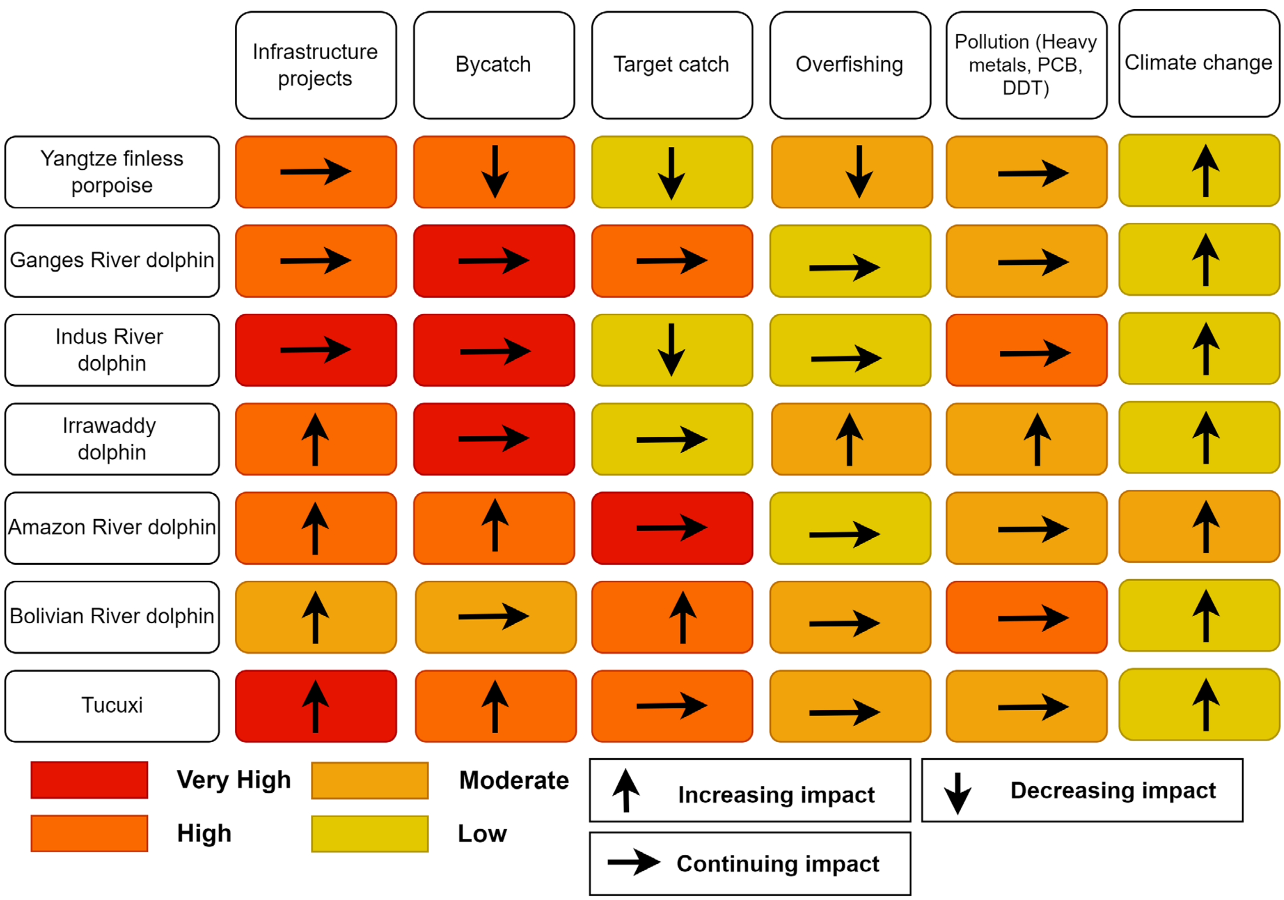

Fig. 4. Threats ranked by their impact on river cetacean species conservation, based on the results of the questionnaires and further discussion among authors. Style after Millennium Ecosystem Assessment (2005), https://www.millenniumassessment.org/

Kelkar & Dey 2020). Set bagnets and seine nets were also identified as risks (Karnaphuli-Sangu River: Dewhurst-Richman et al. 2020, Amazon and Ucayali rivers: Campbell et al. 2020). In the Yangtze River, illegal rolling hooks were also a common cause of mortality, accounting for close to half of the deaths of finless porpoises from 2008 to 2013 (Turvey et al. 2013, Mei et al. 2019) and of baijis in the 1980s to late 1990s (Zhou et al. 1998, Turvey et al. 2007).

Most of the surveyed papers identified bycatch as a significant, observed threat in their research areas, but few contained quantitative data. Those that did used interviews to estimate bycatch rates for the Yangtze finless porpoise (Turvey et al. 2013), Irrawaddy dolphins in the Mahakam River (Kreb et al. 2010, Whitty 2014), and the Ganges river dolphin population in the Karnaphuli-Sangu River complex of Bangladesh (Dewhurst-Richman et al. 2020). The latter estimated annual mortality rates and found that sustainable removal limits were exceeded 3.5-fold (Dewhurst-Richman et al. 2020). In an interview survey in the Brazilian Amazon, 43 % of fishermen reported entanglement of Amazon river dolphins in their nets. Gillnets were used by 74 % of the fishermen (Mintzer et al. 2015). In Peru, interviews helped identify high-risk areas of bycatch for further investigation (Campbell et al. 2020). Strandings also provided data for bycatch estimations. There were 13 deaths from entanglement in fishing gear, 2 deaths from vessel collision, 2 deaths from direct killing, and 9 deaths from unknown causes between 2007 and 2013 (Mansur et al. 2014b).

Research focusing on bycatch management measures is relatively scant. Technical regulations have involved time/area closures, gear modifications/bans, and seasonal to year-round fishing bans. These measures have only been partially effective, as they depend on fisher compliance, and rigorous enforcement (Whitty 2014, Mei et al. 2019). The efficacy of bycatch reduction devices such as pingers requires investigation, as does their long-term effect on dolphin behaviour (Campbell et al. 2020). Preliminary reports are encouraging. One test in the Peruvian Pacaya-Samiria Reserve found reduced dolphin detections at the pinger site as compared to the control site (Campbell 2020). A test of the effects of pingers on Ganges river dolphins indicated subtle displacement in terms of the mean surfacing distance from the pinger but not in the minimum distance of approach (Smith 2013). Additionally, in the Mahakam River, fine-tuned pingers for Irrawaddy dolphins showed dolphins actively avoiding nets with pingers (Kreb et al. 2021).

3.1.2. Targeted killing

Targeted illegal catch of river cetaceans (mentioned in 37 publications and by 48 % of the co-authors) is mostly driven by the demand for meat to use as bait in small-scale fisheries (Mintzer et al. 2018). Dolphin oil and body parts of the Ganges river dolphin are used in India and Bangladesh to attract 2 catfish species (*Clupisoma garua* and *Eutropiichthys vacha*) (Sinha 2002, Wakid 2009, Bashir 2010, Reece et al. 2013, Kolipakam et al. 2020). In South America, the use of Amazon river dolphin and tucuxi as bait for piracatinga catfish *Calophysus macropterus* is an ongoing threat (Estupiñan et al. 2003, Mintzer et al. 2018) and demand remains high (Salinas et al. 2014, Perez 2018). The use of Amazonian dolphins as bait was first recorded in Brazil in the early 2000s (Silveira & Viana 2003, Loch et al. 2009, Mintzer et al. 2013, Brum et al. 2015), and the practise has since extended to Bolivia, Colombia, Ecuador, Peru, and Venezuela (Mosquera-Guerra & Trujillo 2015, Guizada & Aliaga-Rossel 2016, Fruet et al. 2018, Escobar-WW et al. 2020, Trujillo et al. 2020b, Campbell et al. 2020). Such illegal take for use as bait was the primary cause of the halving of both South American river dolphin populations in the Mamirauá Sustainable Development Reserve (Brazil) over a period of 2 decades (da Silva et al. 2018a).

Legal strategies have been put in place with the aim of reducing the targeted catch of dolphins. For example, the Indian Wildlife (Protection) Act (1972) protects the Ganges river dolphin from any use without government authorisation. However, this act has been largely ineffective since *in lieu* of harpooning, fishers position nets in places where dolphins are likely to be captured, a practise referred to as 'assisted incidental capture' (Sinha 2002). Temporary and permanent moratoriums on trade in piracatinga products were imposed by Brazil and Colombia (Instrução Portaria SAP/MAPA n° 271, of 1° July 1, 2021 [Brazil], Resolución 01710 [Colombia]). However, the surveillance of large river basins is complex, especially for border areas with limited monitoring of fish commerce and transportation (Trujillo et al. 2020b). Piracatinga products are sold disguised as other species (Salinas et al. 2014, Cunha et al. 2015, da Silva et al. 2018b).

Alternative bait, another strategy to reduce the use of dolphin bait, has been trialled in the Ganges

(Sinha 2002) and in the Amazon (Franco et al. 2016, Beltrão et al. 2017). Unfortunately, it has not proven effective. Such programmes should be paired with long-term efforts to teach fishermen how and why to use alternative bait (Sinha 2002, Beltrão et al. 2017, Mintzer et al. 2018).

Targeted catch also includes the killing of dolphins by fishers who see them as competitors for fish resources. This almost certainly occurs with all river cetacean species to varying degrees but has been reported specifically as a threat for the Ganges (Behera et al. 2013, Dewhurst-Richman et al. 2020), Amazon, and Bolivian river dolphins (Aliaga-Rossel 2002, Alves et al. 2009, McGuire 2010, Brum et al. 2015, Mintzer et al. 2015, Guizada & Aliaga-Rossel 2016, Campbell et al. 2020).

3.1.3. Overfishing

The potential depletion of dolphin prey due to increasing fisheries is of concern (mentioned in 12 publications and by 53% of the co-authors; Smith & Smith 1998, Wang et al. 2006, Raby et al. 2011). This threat is rarely studied by itself; rather, it is mentioned as a common consequence of the growing presence of commercial fishers using non-selective gear, and it may be a relatively minor threat when compared to directed and incidental capture.

More data are required to understand how competition with fisheries affects cetaceans at the population level. Studies focused on resource competition estimated high levels of spatial overlap in the species and size of fish targeted by fishers and the Ganges river dolphin (Kelkar et al. 2010, Paudel et al. 2020a), but knowledge gaps remain elsewhere.

3.1.4. Electrofishing

Electrofishing occurs widely in rivers in Asia. A recent review of the impacts of the practise on freshwater cetaceans concluded that contact with an electrical current can kill or injure freshwater dolphins and porpoises (Thomas et al. 2019). However, questions remain about the exact nature and scale of the impacts. Thomas et al. (2019) mentioned that previous reports attributing mortality of baijis and finless porpoises to electrofishing are ambiguous (e.g. Zhang et al. 2003, Mei et al. 2019), since death from electrofishing is often inferred when proof of other causes (i.e. propeller wounds, external net marks) is not found.

3.2. Habitat degradation

Habitat degradation in freshwater ecosystems results mainly from water infrastructure development (especially dams), climate change, and deforestation.

3.2.1. Water infrastructure projects

River cetaceans require sufficient water flow to allow movement between deep pools and refuge from high velocity currents (Smith & Reeves 2000a). Development projects have wide-ranging impacts on freshwater flow and affect all river systems inhabited by cetaceans to different degrees. These projects include dams, barrages (low gated dams that divert water), embankments, and river dredging (mentioned in 58 publications and by 80% of the co-authors; Reeves et al. 2000).

Large upstream dams especially threaten the Yangtze finless porpoise, as their habitat is modified by the Three Gorges and Gezhouba dams as well as other smaller dams, regulators, and embankments in tributaries and appended lakes (López-Pujol & Ren 2009, Zhao et al. 2011, Fang et al. 2014). Although the Three Gorges Dam, completed in 2010, is upstream of the current distribution of this porpoise and also of the historical distribution of the baiji, it has altered flow regimes and reduced fish spawning (Zhao et al. 2008, Wang 2009, Fang et al. 2014, Chen et al. 2017).

The Indus and Ganges river dolphins are both affected by extensive irrigation systems with at least 20 dams and 50 barrages that have reduced freshwater flow and fragmented habitats (Smith et al. 2000, Braulik et al. 2014, Sonkar & Gaurav 2020). These dams have reduced sediment transport and the availability of preferred habitats in bars, islands, counter-currents, and deep pools (Reeves et al. 1991, Smith & Reeves 2000a, Paudel et al. 2015, Karim & Bindra 2016). Barrages have been identified as the principal factor in the 80% habitat reduction observed in the Indus river dolphin range (Braulik et al. 2014). Dams can also cause local extinctions. For example, the upstream disappearance of the Ganges river dolphin occurred within 6 to 7 yr of the construction of the Kaptai Dam in the Karnaphuli River in Bangladesh (Smith et al. 2001) and within 12 yr of the construction of the Madhya Ganga Barrage (Bijnor, Uttar Pradesh, India) (Sinha et al. 2010).

Limited water means less physical habitat and warmer and slower rivers (Braulik et al. 2015), particularly during the low-water season (Smith et al.

2009a, 2010, Braulik et al. 2012, Choudhary et al. 2012, Paudel et al. 2015). In some cases, dolphins also enter irrigation canals and become isolated and trapped (Waqas et al. 2012, Aliaga-Rossel & Escobar-WW 2020). From 1992 to January 2021, 194 Indus river dolphins were reported trapped in canals, 163 were successfully rescued and returned, while the remainder died (Sindh Wildlife Department & World Wide Fund for Nature [WWF]-Pakistan unpubl. data). Studies have identified the minimum water flow thresholds to maintain Ganges river dolphin populations and in-stream habitat availability that assists their longitudinal distribution (Paudel et al. 2020b), thus supporting water use planning and conservation.

Water infrastructure development affects Irrawaddy dolphins to a lesser degree. However, there is a strong potential for projects in the planning phase to severely impact all populations of the species (Minton et al. 2017). Dams in Taping River in China have modified the downstream water flow of the Ayeyarwady River and reduced habitat at the confluence (Smith et al. 2007). The construction of the Don Sahong Hydropower Project (International Rivers 2008), a large run-of-the-river dam, has already affected a small group of dolphins inhabiting the Lao/Cambodia transborder deep pool habitat at the far upstream extent of the Mekong River dolphin population, leading to their likely extirpation (Beasley et al. 2013, Krützen et al. 2018). The Sambor and Stung Treng dams proposed for construction across the mainstream of the Mekong River are also of significant concern (Smith et al. 2007, Brownell et al. 2017). However, plans for these dams have been temporarily suspended (Khan & Willems 2021).

Dams in South America are also fragmenting and isolating dolphin populations. To date, 175 dams are operating or under construction in the Andean-Amazon basin, and at least 428 more dams are planned over the next 30 yr (Forsberg et al. 2017, Latrubesse et al. 2017, Anderson et al. 2018, Almeida et al. 2020). These are likely to negatively affect the long-term viability of Amazon river dolphins and tucuxi across their range (Araújo & Wang 2015). Dams impact the Araguaia-Tocantins basin that supports an endemic population of Amazon river dolphin (Araújo & Wang 2015) proposed as a separate species (*Inia araguaiaensis*) by Hrbek et al. (2014). Dolphin densities were 68% lower downstream of the Tucuruí Dam than upstream, and dolphins shifted their habitat use among downstream, reservoir, and upstream subregions (Paschoalini et al. 2020).

3.2.2. Climate change

The impact of climate change on river cetaceans has not yet received much research attention (5 publications) and was not highly ranked in the expert questionnaires (23% of the co-authors, Fig. 3). The ecological requirements of river cetaceans are, however, linked to the entire water cycle in all its complexity, from glacial melt and rainfall patterns to sea level rise and its effects on salinity and sedimentation (Smith & Reeves 2000a). Climate change will exacerbate other ongoing threats, particularly habitat degradation associated with water infrastructure development. A warmer climate is projected to affect all cetaceans through habitat loss, a shift in prey availability, and competition with other displaced species (Simmonds & Isaac 2007, Kaschner et al. 2011). Forecast change (e.g. precipitation, Alter et al. 2010) is expected to lead to increased construction of flood control structures. Local community pressure on fisheries could also grow, potentially leading to an increase in bycatch and prey depletion (Alter et al. 2010).

Although some models predict potential increases in overall water discharge of 17% in the Ganges-Brahmaputra and 44% in the Indus River by 2050 (Palmer et al. 2008), seasonal flow regimes are also projected to change, with potential increases occurring during the high-water season and declines during the dry season, which could result in the loss of river dolphin habitat (Krishnaswamy et al. 2018). This could be exacerbated by dams and, in the Ganges and Brahmaputra, by plans for major inter-basin water transfer and inland water transport projects (Kelkar 2016). Precipitation in the Mekong River catchment is expected to increase during the monsoon seasons, causing more extreme floods, and a decrease during most of the remaining part of the year (Nijssen et al. 2001). However, it is unknown how these changes could affect the Mekong Irrawaddy dolphin population is unknown. Overall, water availability is expected to decrease in the Amazon-Orinoco basin by 18% (Palmer et al. 2008), with the magnitude of potential impacts on river dolphins depending as much on the seasonal timing of the decline as the overall reduction in availability (Mendez et al. 2017, Mosquera-Guerra et al. 2020). Indeed, severe seasons of drought in the Peruvian Amazon have already been related to a decrease in dolphin numbers in locations where they were previously abundant (Bodmer et al. 2018). While it is not currently a problem in the Amazon, as the region grows drier, there may be more interest in water extraction (Intergovernmental Panel on Climate Change [IPCC] 2007, Alter et al. 2010).

Other aspects to consider in climate change models are rising water temperature and sea-level rise. Nijssen et al. (2001) predicted that water temperature in tropical river basins, such as the Amazon and Mekong, would rise evenly throughout the year, with different models showing an increase of 1 to 4°C by 2045. The Indus river dolphin already handles an annual 30°C temperature fluctuation in its environment, possibly making it resilient to temperature variations in climate change scenarios (Braulik et al. 2015). However, more studies are needed to understand how temperature changes will affect river cetacean populations as well as the distribution of the prey they depend on. In addition, sea-level rise will likely affect the salinity of freshwater systems (Smith et al. 2009a). This could reduce available downstream habitat for species that already have restricted ranges. It is likely that obligate river cetaceans will be more vulnerable, as facultative species can adapt to a wider range of salinity.

3.3. Pollution

Due to confined habitats, riverine cetaceans are at a higher risk from pollution than similar marine species (Reeves et al. 2000). Numerous pollutants, from noise to bioaccumulated toxins, may have damaging long-term consequences for this group (Senthilkumar et al. 1999, Kershaw & Hall 2019). However, research on their impacts is limited and long-term effects remain understudied.

3.3.1. Noise

Underwater noise from vessel traffic has been shown to affect river cetaceans (mentioned in 11 publications and by 47% of the co-authors). One primary effect is masking (when noise has similar frequencies to signals of biological interest; Southall 2005), which can reduce the effectiveness of communications, possibly impact foraging, breeding, hazard avoidance (e.g. failing to detect an incoming vessel), and cause long-term physiological damage (e.g. premature ageing) (Wright et al. 2007). Li et al. (2018) found the Yangtze finless porpoises avoided boats and had higher cortisol levels in noisier areas. Ganges river dolphins doubled their acoustic activity and metabolic rate to compensate for the masking effects of high ambient noise (Dey et al. 2019).

3.3.2. PCBs, DDTs, and other chemical contaminants

Chemicals can pollute rivers through direct discharge from agriculture, industry, and shipping (7 publications, 50% of the co-authors, Braulik et al. 2015, Zhang et al. 2020). Chemical pollutants have been identified in the tissue of stranded or bycaught individual Yangtze finless porpoises (Zhang et al. 2020), Ganges and Irrawaddy dolphins (Senthilkumar et al. 1999, Kannan et al. 2005, Yang et al. 2008), and Indus (WWF-Pakistan 2011, Braulik et al. 2015) and Amazon river dolphins (Torres et al. 2007). Identified contaminants included DDT (dichlorodiphenyltrichloroethane) and PCBs (polychlorinated biphenyls), along with other commonly used pesticides (cypermethrin, deltamethrin, and endosulfan). The pathophysiological effects of these chemicals on river cetaceans are unknown. In other aquatic mammals, these contaminants have various physiological effects, including suppression of the immune system, damage to the adrenal cortex, and have affected reproductive success (Reddy et al. 2001, Wright et al. 2007, Durante et al. 2016).

3.3.3. Heavy metals

Mercury pollution can come from natural deposits, mining, and other industrial processes (7 publications, 35% of the co-authors). Tissue samples from Yangtze finless porpoises have shown that mercury accumulation in the liver was correlated with body size and was passed to new-born calves (Dong et al. 2006, Xiong et al. 2019). Mercury concentrations were also correlated with high concentrations of selenium, which seems to be produced by the animal (Xiong et al. 2019), implying a protective function as has been observed in coastal dolphins (Turnbull & Cowan 1998, Kehrig et al. 2016). The use of mercury in small-scale mining to amalgamate gold affects several river basins, including the Ayeyarwady (Smith & Hobbs 2002), Mahakam (Kreb & Budiono 2005), and Amazon-Orinoco (including the Arauca, Tapajós, and Iténez rivers) (Lailson-Brito et al. 2008, Roach et al. 2013, Mosquera-Guerra et al. 2019, Barbosa et al. 2021). Preliminary studies have shown that Amazon river dolphins and tucuxis had high mercury concentrations in all analysed tissue samples (Mosquera-Guerra et al. 2019). The effects of high mercury concentrations in river cetaceans are unknown, but in marine cetaceans, it has been linked to immunosuppression (Cámara-Pellissó et al. 2008, Mahfouz et al. 2014), endocrine disruption (Schaefer et al. 2011), and neurological disorders (Das et al. 2003, Wright et al. 2007, López-Berenguer et al. 2020).

3.3.4. Plastic

Although Smith & Smith (1998) described plastic debris as a growing threat, there has since been limited progress in understanding risks. Recent studies have identified the presence of plastics in dolphin habitats (Schmidt et al. 2017, Li et al. 2018, Rodrigues et al. 2019, Aliaga-Rossel & Guizada 2020). One study concluded that the risk of entanglement of Ganges river dolphins from ghost nets is high (Nelms et al. 2021a). Studies of marine dolphins indicate that they ingest plastics directly or through trophic transfer (Williams et al. 2011, Nelms et al. 2018, Xiong et al. 2018), but this has not yet been documented for river cetaceans.

3.4. Other human interactions

Increasing human populations affect river cetaceans in multiple ways. Bashir et al. (2013) found that as human exposure increased, the local presence of Ganges river dolphins decreased. This is particularly important as the Ganges River often supports large human aggregations close to riverbanks (e.g. due to religious ceremonies) (Bashir et al. 2013). Similarly, Indus river dolphins were more abundant in areas with low human disturbance, especially during the low water season, when habitat was limited but disturbance was high (Khan 2017). Human settlement size can also indicate overall ecological health; for example, in the Amazon-Orinoco basin, human population size is significantly correlated with habitats and water quality degradation (Gomez-Salazar et al. 2012a).

Vessel traffic brings the threat of wounding and death from both propellers and impact. This was especially true for the baiji (Turvey et al. 2007) and continues to endanger the Yangtze finless porpoise (Wang et al. 2000, Turvey et al. 2013, Dong et al. 2015, Mei et al. 2019). Boat strikes have also been reported as a threat to the Ganges river dolphin (Smith et al. 2001) and as being responsible for fatalities in the Irrawaddy dolphin population in the Mahakam River (Kreb & Rahadi 2004). River cetaceans may be more vulnerable to collisions during calving and nursing periods (Reeves et al. 2000). As dams make some rivers easier to navigate and riverine human populations increase, vessel strikes could become an increasing threat.

3.4.1. Tourism

Tourism has been demonstrated to have negative effects on dolphins (12 publications, mentioned by 8% of the co-authors). Tourism brings an increase in human presence, which can lead to collisions with dolphin-watching boats, increased fishing activity and fish consumption to feed visitors, and pollution. Most publications addressing tourism focused on the Amazon river dolphin in Brazil (Romagnoli 2009, Alves et al. 2011, Gravena et al. 2019) and on the Irrawaddy dolphins in the Mekong River and Chilika Lagoon, India (Beasley et al. 2010, Mustika et al. 2017, D'Lima et al. 2018). Poorly managed wildlife-focused tourism affects river dolphin behaviour, especially if feeding is involved (Alves et al. 2011, Gravena et al. 2019). Many poor management practises have been highlighted, including a lack of significant economic input reaching local stakeholders, deficient health and safety infrastructure, and ineffective communication with tourists about conservation (Romagnoli 2009, Beasley et al. 2010, Alves et al. 2013). As wildlife watching is often proposed as an alternative to more traditional livelihoods (e.g. fishing, Alves et al. 2013), the communities dependent on dolphin tourism must understand the long-term benefits that the industry can generate if conducted and managed in a regulated, responsible manner (e.g. Aliaga-Rossel et al. 2014).

3.4.2. Traditional use

Reports on medicinal and traditional uses of dolphin parts were largely focused on the Amazon river dolphin and tucuxi (8 publications, not mentioned by co-authors) where products locally called puçanga, including genitals and eyes, are sold as amulets, and oil is sold as medicine (Cravalho 1999, Aliaga-Rossel 2002, Alves & Rosa 2008, Gravena et al. 2008, Siciliano et al. 2018). Although this is an illegal trade, dolphin products can be found readily in markets in Brazil (Dos Santos et al. 2018), Peru (Schmeda-Hirschmann et al. 2014), and Bolivia (Aliaga-Rossel 2002), suggesting that improved law enforcement and environmental education are needed. Additional sporadic reports involve the use of Irrawaddy dolphin skin as a treatment for skin allergies (Kreb & Budiono 2005), Ganges river dolphin genitals as aphrodisiacs (Choudhary et al. 2006), and oil from Indus river dolphins and Yangtze finless porpoises as liniment (Reeves et al. 1991, 2000, Waqas et al. 2012, Turvey et al. 2013). The impact of the trade in dolphin body parts and products on river dolphin populations is unknown.

4. MOVING CONSERVATION FORWARD

4.1. Emerging research methods

Novel methodologies have the potential to advance river cetacean research and better inform conservation efforts. Most existing data on river cetacean populations have been collected using direct counts (Smith & Reeves 2000b, Kreb 2002, Baird & Beasley 2005, Braulik 2006), distance sampling (Zhao et al. 2008, Gomez-Salazar et al. 2012b, Mei et al. 2014, Huang et al. 2020), and mark-recapture with photo-identification (Kreb 2004, Gómez-Salazar et al. 2011, Ryan et al. 2011, Beasley et al. 2013, Mintzer et al. 2016). These studies can be costly and have logistical limitations (e.g. some areas can be hard to reach; work can be done only in the daytime). Emerging methods can generate new or complementary data more quickly and at a lower cost. Many have been tested in parallel with direct counts and acoustic monitoring to measure their effectiveness, with promising results.

4.1.1. Acoustic monitoring

Passive acoustic monitoring (PAM) can sample and monitor cetaceans by recording the distinctive sounds they make (Sousa-Lima et al. 2013). It is non-invasive and can record for long periods, detect cetaceans when they are submerged, reach areas where visual surveys are difficult to undertake, and operate independently of weather conditions and daylight (Sousa-Lima et al. 2013, Miller et al. 2015). Disadvantages include the equipment costs, the expertise required for data processing and analysis, and most importantly, the need for the dolphins to be vocalising in order for detection to occur. There have been numerous applications of PAM to study river cetaceans, primarily in Asia. It has been used to monitor populations (Kimura et al. 2009), to study foraging behaviour (Tregenza et al. 2007, Kelkar et al. 2018), distribution (Kimura et al. 2012, Yamamoto et al. 2016, Campbell et al. 2017, Wang et al. 2020), and movement patterns (Sasaki-Yamamoto et al. 2012), and to make suggestions for the design of protected areas (Dong et al. 2015). By employing PAM, researchers were able to study how boat presence affects cetacean communication (Wang et al. 2014) and how increasing ambient noise alters dolphin acoustic responses (Dey et al. 2019, Wang et al. 2020). Richman et al. (2014) found that combined visual and acoustic surveys more effectively detected Ganges river dolphin decline than surveys that used only one method. They also showed that among the methods that account for detectability error, acoustic equipment was cheaper than other methods (Richman et al. 2014).

4.1.2. Unmanned Aerial Vehicles

Unmanned Aerial Vehicles (UAVs) have the advantage of improving accuracy and repeatability of data and sample collection, and they can reach survey areas that are isolated or otherwise inaccessible while having a minimum impact on the behaviour of study species (Hodgson et al. 2013, 2017, Torres et al. 2018). Researchers from Brazil and India have used balloon-mounted cameras, drones, and blimps to observe and count river dolphins (Fürstenau Oliveira et al. 2017, Sugimatsu et al. 2017, Oliveira-da-Costa et al. 2020). In the Ganges River, balloon-mounted cameras were successfully paired with observers on boats to compare detection rates of Ganges river dolphins (Sugimatsu et al. 2017, 2019). Unmanned aerial surveys in the Brazilian Amazon showed that detection of groups and individual dolphins was greater in aerial photographs than from canoes (Fürstenau Oliveira et al. 2017). Drones have also been tested in the Juruá River (Brazil) and compared to detections by onboard observers. Although onboard observers made more observations, drones presented certain advantages; for example, researchers could replay recordings and make a more accurate count of individuals in groups (Oliveira-da-Costa et al. 2020). UAVs also have disadvantages since strong winds can affect take-off and landing, and manual processing of data takes time (Sugimatsu et al. 2017, Oliveira-da-Costa et al. 2020). However, as camera resolution increases (Sugimatsu et al. 2017) and better-automated detection algorithms are developed (Oliveira-da-Costa et al. 2020), the efficiency of UAV surveys may well increase.

4.1.3. Environmental DNA

Environmental DNA (eDNA) detection is a relatively new method that works best for detecting cryptic species that occur at low density and/or are logistically difficult to study in non-invasive ways (Ficetola et al. 2008, Jerde et al. 2011, Foote et al. 2012, Rees et al. 2014, Lozano Mojica & Caballero 2021). Initial attempts have been made to detect Amazon river dolphin and tucuxi in Peru (Alfaro-Shigueto et al. 2018), Amazon river dolphins in Colombia (Martinelli-Marin et al. 2020), and Yangtze finless porpoise in China (Ma et al. 2016, Tang et al. 2019, Qu et al. 2020). Tang et al. (2019) had higher detection rates for Yangtze finless porpoise using eDNA compared to direct observations. In the Tian e-Zhou National Nature Reserve in Hubei, China, data on eDNA detections showed how spatial occurrence varied seasonally in breeding and post-breeding periods (Stewart et al. 2017). Methodological constraints include the effect of environmental factors, such as water pH, temperature, and turbidity. However, eDNA has the potential to provide data on river cetaceans using fewer people and less time in the field.

4.2. Potential conservation interventions

4.2.1. Protected areas

Spatial protection, through protected areas (PAs), has been suggested as an important tool for cetacean conservation (Gormley et al. 2012, Notarbartolo di Sciara et al. 2016). However, it is challenging to demonstrate the effectiveness of PAs for highly mobile marine vertebrates (Gormley et al. 2012, Cook et al. 2013). PAs have been designed explicitly for conserving the baiji and Yangtze finless porpoise (Wang 2009, Mei et al. 2014), Irrawaddy dolphin (Kreb & Budiono 2005), and Ganges and Indus river dolphins (Choudhary et al. 2006, Smith et al. 2010, Braulik et al. 2015). Though no PAs have been established specifically for the Amazon river dolphin or the tucuxi, PAs with high densities of both species exist in Brazil, Colombia, Venezuela, Ecuador, and Peru (Portocarrero Aya et al. 2010, Gomez-Salazar et al. 2012c, Mintzer et al. 2016, 2020, Mosquera-Guerra et al. 2018). Population modelling suggests PAs could be an effective conservation tool to protect Amazon river dolphins if redesigned to incorporate essential habitat and managed effectively (Mintzer et al. 2016, 2020).

While many PAs have been established to conserve Asian river cetaceans, too often they lack clear management plans or infrastructure to meet conservation goals (Braulik et al. 2015). Recurring illegal disturbances such as sand mining and even dolphin hunting have been reported inside PAs (Choudhary et al. 2006, Wang 2009, Zhao et al. 2013, Nabi et al. 2018a, Mei et al. 2019). Dams constructed near or within PAs can lead to downgrading, downsizing, or fully removing protections in the area (Thieme et al. 2020). Globally, 14% of proposed dams are in extant PAs (Thieme et al. 2020), with some directly affecting river cetaceans.

PA management should be science-based, community inclusive, and ready to integrate new data (Kingsford et al. 2011, Mintzer et al. 2020). It should include incentives for local communities; community outreach (including interactive exhibitions that result in measurable changes in the knowledge, attitudes, and practises of local communities) (Kreb et al. 2010, Mansur et al. 2014a, Acreman et al. 2020); guidance on reducing or eliminating fatal entanglements in fishing gears; enforcement of fishing rules (including time-area closures and gear restrictions) (Azevedo-Santos et al. 2019); and regulations (e.g. plastic-laminated calendars and maps illustrating time-area closures, and rulers showing legal mesh, fish, and crustacean sizes). Key impediments include getting governments to develop policies, direct funds, and provide adequate management toward supporting PAs (Reeves et al. 2000, Kreb & Budiono 2005, Kreb et al. 2010, Whitty 2015). Sustainable finance is a key consideration. Options evaluated for 3 wildlife sanctuaries for Ganges river and Irrawaddy dolphins in the Sundarbans, Bangladesh, included private sector offset finance, government earmarking of tourism revenue, conservation trust funds, community ecotourism, and payment for ecosystem services (Iyer et al. 2019).

4.2.2. *Ex situ* conservation

Ex situ conservation is an alternate strategy for highly threatened species. In the mid-1980s, 2 *ex situ* semi-natural reserves were developed in China, initially to support conservation of the baiji but secondarily for conservation of the Yangtze finless porpoise (Wang et al. 2006). These reserves, the Tian E-Zhou National Nature Reserve in Hubei Province and the Tongling Reserve in Anhui Province, China, were established to receive translocated cetaceans and isolate them from threats in the Yangtze River, as the basis for an *ex situ* breeding programme. Although only 1 baiji was ever translocated to Tian E-Zhou, this initiative has made positive progress for Yangtze finless porpoise conservation, with natural foraging, reproduction, and population growth occurring in the reserve (Wang 2009). Two further semi-natural porpoise reserves, Hewangmiao/Jicheng and

Xijiang, have been established more recently. Approximately 160 Yangtze finless porpoises are now living in the 4 semi-natural *ex situ* reserves in China (Taylor et al. 2020).

Progress has also been made on another *ex situ* strategy, captive breeding of porpoises at the Institute of Hydrobiology, Wuhan, with the first porpoise calf born in 2005 (Wang et al. 2005). However, subsequent births failed, with all calves dying within 3 to 50 d after birth, until healthy calves were born in 2018 (Deng et al. 2019) and 2020 (D. Wang unpubl. data). Additionally, 2 successful births occurred in a floating pen at the Tian-E-Zhou Reserve (D. Wang unpubl. data). However, the long-term success of these strategies depends on measures being taken to avoid inbreeding (Xia et al. 2005) and to conserve natural habitat (Huang et al. 2017). In the future, if population numbers keep decreasing, this approach may also be necessary for other river cetaceans to avoid extinction.

The International Union for Conservation of Nature (IUCN) has developed the One Plan approach that considers both the *in situ* and *ex situ* conservation communities (Byers et al. 2013). A workshop held in 2018 recommended that knowledge of the status and threats to all species be prioritised, as well as data collection related to small cetacean handling, animal husbandry, and veterinary field protocols (Taylor et al. 2020). Some of these data can be collected during live strandings and tagging work, or when dolphins are entrapped in irrigation canals, providing practical experience and data that can be used if *ex situ* conservation is needed (Taylor et al. 2020). As discovered in the case of the vaquita *Phocoena sinus*, longer-term contingency planning is required before a species becomes critically endangered (Rojas-Bracho et al. 2019).

4.2.3. Community engagement

Community engagement is likely linked to conservation effectiveness, although it is context specific and culturally sensitive (Choudhary et al. 2006, Braulik et al. 2015). The ongoing involvement of local riparian communities in the 'Ganga Mitra' (friends of the Ganges River) and 'Bal Ganga Mitra' (child friend of the Ganges River) projects has led to a sense of ownership and stewardship of the river among local people. The Ganga Mitra plays an active role in educating fellow community members, monitoring the habitat, and persuading policymakers to act for conservation (WWF-India 2017). Another example is the Mamirauá Sustainable Development Reserve (MSDR) in Brazil, in which fishers participate in annual dolphin capture–recapture programmes for scientific studies, environmental education campaigns, and ecotourism initiatives (Martin et al. 2004, Martin & da Silva 2004, 2006, 2018). Interviews found that fishers who participated in MSDR activities had a more positive opinion of Amazon river dolphins (Mintzer et al. 2015). Additionally, a quarter of interviewed fishers reported that their opinions of Amazon river dolphins had changed over time for the better, and some attributed this change to their exposure to dolphin research and conservation activities (Mintzer et al. 2015). Although the use of dolphins as bait for piracatinga is common in and near the MSDR (Iriarte & Marmontel 2013, Mintzer et al. 2013, da Silva et al. 2018b, Trujillo et al. 2020b), communities closer to the management centre appear to kill fewer dolphins (Mintzer et al. 2015).

In Myanmar, Irrawaddy dolphins and fishers work together in a cast-net fishery on the Ayeyarwady River, resulting in increased catches for the fishers and foraging efficiency for the dolphins (Smith et al. 2009b). Fishers also receive economic returns from tourists watching their human–dolphin cooperative fishing activities (Smith et al. 2009b). Since 2019, villagers have been conducting community patrols in the Mahakam River to monitor illegal fishing activities, provide early warning if dolphins enter swamps where they may become trapped, and remove large-mesh sized gillnets set in deep water (D. Kreb unpubl. data). Local communities were involved in the design and implementation of a 430 km^2 aquatic conservation area that obtained a district decree in 2020 and is about to be established at the national level (D. Kreb unpubl. data).

4.2.4. SMART enforcement and monitoring patrols

A successful strategy to protect wildlife around the world is the use of SMART (Spatial Monitoring and Reporting Tool). SMART can improve the effectiveness of enforcement and monitoring patrols in protected areas by enabling the collection, storage, communication, and evaluation of data on patrol effort (e.g. time spent on patrols, areas visited, distances covered) and results (e.g. amount of illegal fishing gear detected and confiscated, arrests made) (Thomas & Gulland 2017). In the Mekong, 72 river guards, comprising fisheries officers, police officers, and local community members operating from 16 posts employed a SMART approach to enforce fishing rules, confiscate illegal gear, and monitor threats (Thomas & Gulland 2017). From 2015 to 2019, the river guards removed an average of >102 km of gillnets annually, as well as long-lines with multiple hooks, with 48 682 hooks removed in 2019 alone. They also arrested 44 people for electrofishing (Thomas & Gulland 2017, Khan & Willems 2021). Between 2016 and 2018, SMART patrols conducted by the Forest Department in the Sundarbans, Bangladesh, resulted in the confiscation of 1143 small boats and 4306 illegal fishing gears (IWC 2020).

5. KNOWLEDGE GAPS

After analysing the results of our expert questionnaire, we can highlight the priority knowledge gaps hindering river cetacean conservation (Fig 5a, see Table S1 in Supplement 2 for list). These gaps are primarily related to status assessments, threats, and ecosystem requirements.

5.1. Abundance estimates

The most frequently mentioned data gap was that of range-wide abundance for all river cetacean species. Despite an increase in data availability, some species and populations still lack population level abundance data (Table 1). The conservation status of river cetaceans demands strategically planned survey coverage, with systematic methods and geographic placement that deliver statistically robust results. We recommend setting up monitoring studies that are repeated periodically, standardised, with the potential to detect population trends at key sites. This type of study has been implemented to monitor Yangtze finless porpoise populations, repeating a standardised method every 5 to 6 yr (Zhao et al. 2008, Mei et al. 2014, Huang et al. 2020). Community interviews are another option that can rapidly provide an index of relative freshwater cetacean abundance. In the Yangtze, interview data was statistically congruent with distribution data obtained from boat-based surveys (Turvey et al. 2013).

5.2. Life history

Second, we need a better understanding of the life histories of these species. Information on reproduction and growth is needed for adequate population modelling. Long-term studies employing mark-recapture methods have, thus far, been the most conducive for understanding key reproduction parameters (Martin & da Silva 2018), life span (Moore et al. 2018), and physiological attributes related to life history (Robeck et al. 2019), and they should be extended. Stranding networks that provide data on population structure, the presence of diseases, and the rates and causes of mortality (Smith et al. 2007, Kreb et al. 2010, Wang et al. 2015) have also been useful; they could be strengthened and replicated in additional areas.

5.3. Fisheries and prey

We identified a significant knowledge gap in data relating to freshwater fisheries and their interactions with cetaceans. We recommend prioritising the gathering of 2 types of data. The first is information about the fisheries that interact with cetaceans, including fishing effort, seasonality, catch composition, and gear attributes (e.g. Whitty 2016, Dewhurst-Richman et al. 2020). The second is information about what these cetaceans eat and the availability of their prey (e.g. Aliaga-Rossel et al. 2010), an important factor for determining habitat preference and that could help to elucidate possible competition with fisheries.

5.4. Spatial/temporal ecology and ecosystem requirements

We need a better understanding of the habitat requirements of river cetaceans. Information on where they live and how they move and how they are affected by temporal and environmental factors (e.g. floodplain flow, levels of productivity) could help delineate new PAs. Minimum habitat requirements are also not well understood. These data will be especially important for conservation efforts in areas where dams have been constructed or are being proposed. Past research has used direct observation (e.g. Martin & da Silva 2004, 2006, Choudhary et al. 2012, Mintzer et al. 2016, Chen et al. 2017), but tracking technologies such as VHF and satellite telemetry have been successful with Amazon river dolphins (Martin et al. 2006, Mosquera-Guerra et al. 2021) and could be applied to other species.

5.5. Human-induced mortality

There are few estimates of the impact of bycatch, deliberate killing, boat strikes, or other human-

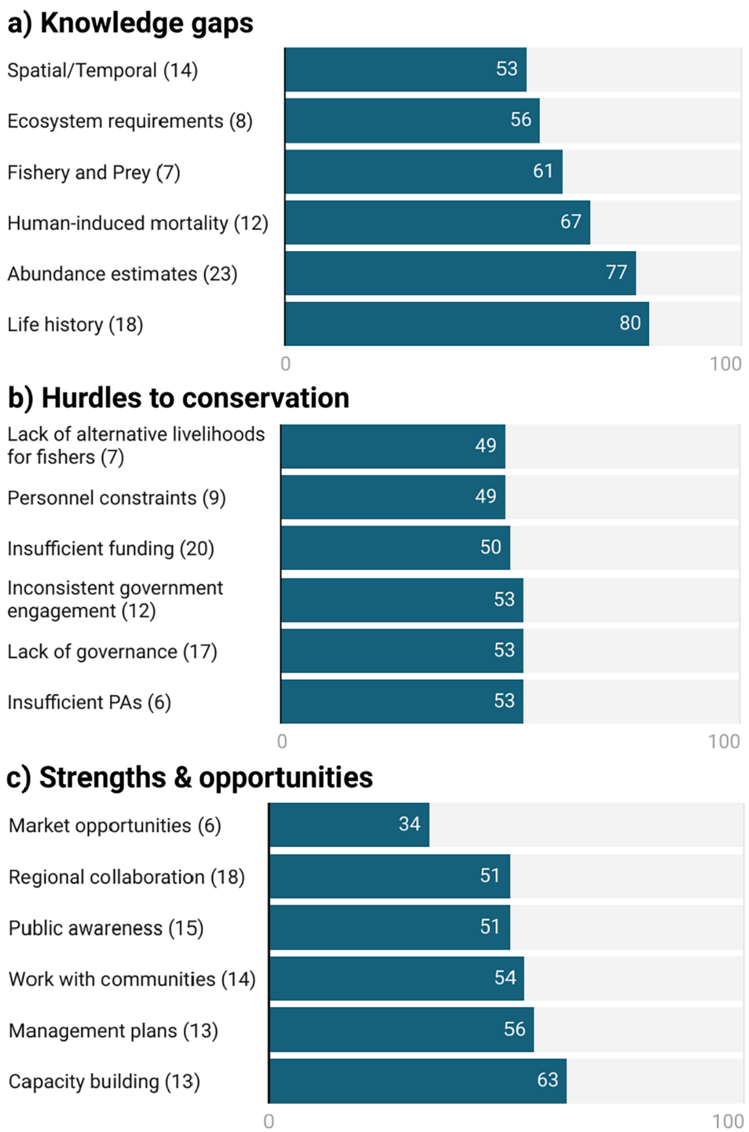

Fig. 5. Questionnaire results where (a) knowledge gaps, (b) hurdles to effective conservation, and (c) strengths and opportunities were ranked by authors. The maximal value is 100 if all authors classified the category as the most important/valuable. The number of times the theme was mentioned is included in parentheses. PA: protected area

caused deaths on cetacean populations. These impacts may vary by species and population. Interview-based assessments of bycatch rates and characteristics are widely considered the most cost- and time-effective method for estimating small-scale fisheries bycatch and have been applied extensively (Moore et al. 2010, Turvey et al. 2013, Pilcher et al. 2017, Whitty 2018, Hines et al. 2020). To complement these data, it will also be important to investigate the relative proportion of bycatch versus targeted catch. This information will help to assess and design mitigation initiatives. Although not without fiscal and logistical challenges, mortality data gaps could alternatively be addressed with onboard or land-based observers (Smith & Jefferson 2002), and voluntary reporting from collaborating fishers (Smith & Jefferson 2002, Dewhurst-Richman et al. 2016). In areas of particular interest, camera technologies could be considered with participating fishers (Bartholomew et al. 2018).

6. PRIMARY CHALLENGES IN CONSERVATION

The authors identified a total of 14 challenges to river cetacean conservation (Fig. 5b, Table S1 in Supplement 2). These challenges include the limited number of existing PAs, lack of long-term projects with participatory management, and difficulty in accessing study areas, as well as the existing knowledge gaps mentioned above. Herein, we provide more detail on challenges that are consistent across all species. They are possibly the most difficult to address in terms of complexity and scale, and we provide suggestions on how the research/conservation community might proceed (summarised in Table 3).

6.1. Lack of governance

One key challenge is a lack of good governance in freshwater systems, which is linked to 2 other issues raised by experts: inconsistent government involvement and corruption. Many countries where river cetaceans are distributed need stronger legislative frameworks, the capacity for enforcement and a means for implementation that is resilient to corruption and changing administrations. Governance in aquatic ecosystems is particularly difficult due to the logistical challenges (including costs and personnel) of accessing and covering some areas. Many strategies to reduce fishery interactions depend on law enforcement, such as the 10 yr fishing ban in the Yangtze River (Xiaoyi & Yameng 2021) and the Colombian (MADR/

AUNAP 2018; https://www.aunap.gov.co/2021/11/15/aunap-prohibe-captura-y-comercializacion-del-pez-mota-en-todo-el-pais/) and Brazilian moratoria on exploitation of piracatinga (Ministério da Agricultura & Secretaria de Aquicultura e Pesca 2020; https://pesquisa.in.gov.br/imprensa/jsp/visualiza/index.jsp?data=15/06/2020&jornal=515&pagina=2&totalArquivos=196). Developmental paradigms need to shift, but this takes time and depends on various factors working in concert (Cowx & Portocarrero-Aya 2011, Cook et al. 2013). Improving law enforcement is not a simple task, but decentralising governance and fishery management could be a practical and realistic approach (Lopes et al. 2021). Aquatic governance could be more resilient to change if it included local governments and marginal and vulnerable groups, as more community-involvement helps build trust, mitigate conflicts, and legitimise goals and decisions (Plummer et al. 2015, see Section 7.4. Work with communities). Co-management leads to better compliance with fishery regulations, reduction in transaction and administration costs for governments,

Table 3. Threats to river cetaceans, the associated knowledge gaps and recommended actions needed to address them. PA: protected area

Threats	Knowledge gaps	Recommended actions	Cross-cutting recommendations
High priority			
Bycatch and targeted catch	– Abundance estimates – Human-induced mortality – Fishery characteristics – Life history	– Establish methods to study abundance, population trends (e.g. stranding networks, periodic surveys, questionnaires, emerging methods) – Develop alternative livelihood schemes – Test bycatch mitigation measures	– Work closely with communities in conservation projects, when establishing PAs and fishery regulations – Regional collaboration for research and conservation actions (e.g. SARDI, IWC Task Teams) – Establish and implement management plans with local government – Continue to build local capacity in range countries – Diversify funding sources
	– Composition of river cetacean diet and availability of their prey	– Work with communities for better law enforcement (e.g. SMART Patrols, Ganga-Mitra programme) – Implement new PAs and strengthen existing ones	
Infrastructure projects	– Spatial/temporal ecology and ecosystem requirements	– Deter the construction of dams – Implement new PAs and strengthen existing ones	
Climate change	– Ecosystem requirements	– Assess tolerance of temperature and salinity variance in cetacean populations	
	– Diet/prey availability	– Research effects of climate change on prey distribution	
Lower priority			
Pollution	– Long-term effects on health of noise, contaminants, and heavy metals – Population consequences of pollution – Life history	– Improve regulations on chemical disposal to reduce the amount of chemicals entering freshwater environments – Establish long term monitoring projects to study reproduction, growth, baseline health status for every species	
Other human interactions	– Abundance estimates – Human-induced mortality	– Establish methods to study abundance (above) – Monitor vessel traffic and collisions – Develop standard protocols for river cetacean ecotourism	

and increased awareness of regulations and participation in local communities (Plummer et al. 2015, Dewhurst-Richman et al. 2016).

6.2. Insufficient funding

Funding for river cetacean research and conservation is scarce, a problem for both initial research and the continuity of longer projects. When duplication of research is eliminated and more regional collaboration exists, funding can go further (Mace et al. 2000). Scientists and practitioners need to spend wisely, and research and prioritisation exercises like this one can help us do that. We could also work to diversify our sources of funding (see Section 7.7. Diversification of funding).

6.3. Lack of alternative livelihoods for fishers

Limited livelihood alternatives for fishers also complicate conservation work. Riverine fishing communities typically have very low incomes and educational opportunities (Bashir et al. 2010, Paudel et al. 2016, Mei et al. 2019), a situation that may worsen if fish stocks are not managed sustainably. Additionally, prohibitive regulations usually come with fiscal penalties that increase these economic woes (Dewhurst-Richman et al. 2020). Diversifying fisher livelihoods could provide a practicable and sustainable solution for reducing fishery interactions, thus lessening the pressure on both cetacean and fish populations. This goal is challenging for developing countries where fisheries are extensive and varied. Governmental agents with economic and social expertise should incorporate fishers' needs and opinions and develop alternative livelihood schemes, prioritising gillnet fisheries. Previous studies have proposed financial compensation schemes, aquaculture programmes (Mei et al. 2019), and wildlife watching (Kelkar et al. 2010), all options that could be more fully explored in many systems.

6.4. Personnel constraints

There is too large a gap between the conservation work that needs to be done and the number of professionals available to do it. The number of institutions working on aquatic mammal conservation in countries with river cetaceans is also limited, so the avenues available for interested students and early career professionals to develop relevant careers are restricted. This limitation also leads to an over-reliance on foreign experts. Moving forward, funders and projects should invest in enhanced capacity of local researchers. This transition appears to be taking place (see Section 7.2. Capacity building), but there are opportunities for it to continue to increase.

6.5. Miscommunication among researchers

Thirteen authors mentioned miscommunication, competition, abuse of power, and animosity among researchers as a hindrance to better conservation action. This is not uncommon in the scientific and conservation fields (Anderson et al. 2007, Fang & Casadevall 2015, Powell 2018), where it can negatively affect data sharing and disrupt relationships. This can be particularly negative for early-career researchers who can be burdened with additional activities (e.g. communicating results, engaging with policy makers) while training in their particular research skills (Cosentino & Souviron-Priego 2021).

7. PRIMARY OPPORTUNITIES IN CONSERVATION

In this section, we describe our top-ranked strengths and opportunities for river cetacean conservation (see Fig. 5c, Table 3, Table S1 in Supplement 2).

7.1. Spatial protection

More work is needed to protect river dolphin habitats, as most existing freshwater PAs were not designed for this purpose. Establishing new PAs and improving existing ones could provide partial habitat protection. Adaptive monitoring approaches for freshwater PAs have been developed that could promote greater protection of freshwater ecosystems (e.g. Kingsford et al. 2011, Hermoso et al. 2016, Acreman et al. 2020). These include frequent evaluations of PA efficacy, designing PAs to incorporate various habitats and their connectivity, and local community participation in regulatory operations (Acreman et al. 2020). River cetacean population modelling, such as that performed by Mintzer et al. (2020), can be used to examine and assess the success of PAs, as well as improve reserve layouts.

7.2. Capacity building

A new generation of scientists is currently being trained in river cetacean research (Fig. 5c). This increase in the number of researchers, coupled with local capacity-building initiatives, will ensure that there are trained researchers in every country with river cetaceans who can collaborate and work together towards cetacean conservation. Capacity building should extend to include conservation practitioners, not just scientists. Indeed, solely focusing on science can contribute to the problem (Clark et al. 2018), as practical conservation is rarely done or communicated by scientists (Pullin & Knight 2001). Collaborating with social scientists would also help understand the human dimensions of the threats we are trying to reduce (Fischer et al. 2011, Bennett et al. 2017). Rangers, reserve managers, other relevant stakeholders in PAs, and community members should be included as well to ensure training in rescue handling and scientific monitoring. Importantly, granting agencies should allow funds to go to sustaining capacity building.

7.3. Management plans

Conservation management plans (CMP) or species management plans (SMP) specify intended objectives for the conservation and management of a species or population, including clearly defined responsibilities and timelines for accomplishing tasks (Burgener et al. 2012). These long-term plans help ensure governmental commitments, as well as coordination among stakeholders. Management plans exist at a national level in China for the Yangtze finless porpoise, in India for the Ganges river dolphin, Indonesia for the Irrawaddy dolphin, and in every Amazon river dolphin and tucuxi range country (e.g. Sinha et al. 2010, Utreras et al. 2013, Trujillo et al. 2014, Mustika et al. 2015). International management plans also exist, such as the Ganges river dolphin concerted action plan supported by the Convention on Migratory Species (CMS) (UNEP/CMS/Concerted Action 13.6 2020) and the IWC CMPs accepted for South American river dolphins (Trujillo et al. 2020a) and proposed for Asian river cetaceans (Khan et al. 2020). Progress on how these goals and activities develop should be regularly assessed to achieve objectives in a timely manner.

7.4. Work with communities

Many authors point to existing community partnerships as a strength because they can expand conservation initiatives that change local people's perceptions of freshwater cetaceans and ecosystems (Kreb & Budiono 2005, Mintzer et al. 2015, Thomas & Gulland 2017). Future research and conservation actions should include local communities, as doing so can lead to a greater sense of ownership, increase wildlife knowledge, promote understanding of natural resource management (Sinha & Kannan 2014), and ensure socially responsible conservation actions. In addition, participatory monitoring can be a useful tool for addressing personnel shortages in data collection (Turvey et al. 2013). Educational campaigns could also help reduce the negative perception of river cetaceans in some communities (Mintzer et al. 2015).

7.5. Growing knowledge and public awareness

In the last few years, an increasing volume of research has been produced on river cetaceans. Public awareness has also grown in many regions. We think that this is in part due to local environmental education and volunteer campaigns run by local and international NGOs (e.g. Mansur et al. 2014a, Mintzer et al. 2015). Traditional media and social media campaigns have also made good use of the charismatic nature of river cetaceans to increase public awareness of their threatened status.

7.6. Regional collaboration

Regional collaboration among researchers was mentioned as a strength in our expert questionnaire. Because riverine species often move across boundaries, conservation and research are more effective when coordinated throughout the full ranges of species. International agreements such as the Convention on Wetlands of International Importance (Ramsar), the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), the IWC, the CMS, and the IUCN have also likely contributed to this increase in collaborative initiatives. The WWF-led South American River Dolphin Initiative (SARDI) and the IWC-South Asian

River Dolphin Task Team (IWC 2020) are examples of regional collaboration. Outputs from these are task-force plans (IWC 2020), research activities implemented at a regional scale (Mosquera-Guerra et al. 2019, 2021), and public awareness activities with events held in every member country (e.g. World River Dolphin Day).

7.7. Diversification of funding

Sustainable funding is critical to the development of research and conservation action (Waldron et al. 2013). Among the available alternatives, the authors particularly recommended supporting conservation and research activities with income from non-traditional sources, if possible. One option is to form partnerships with the private sector, especially with organisations that work in areas where river cetaceans are distributed. Such successful existing partnerships are currently limited but show that the potential exists (Clark et al. 2018). Crowdfunding platforms have also gained popularity as a means for researchers to raise funds independently and have been successful in some cases (Gallo-Cajiao et al. 2018).

Eco-tourism linked to research programmes could be another potential source of funding. These projects must be carefully monitored to minimise their impact on cetacean populations. Education, awareness, and standard protocols (e.g. Beasley et al. 2010, Aliaga-Rossel et al. 2014) for dolphin eco-tourism can also raise the quality of the tourist experience. This will then gradually shift towards sustainability by supporting livelihoods in the local community, creating awareness, and generating a more conscious pool of tourists engaging with river dolphin conservation.

8. CONCLUSION

With this review we have sought to synthesise available information and expert opinions about threats to river cetaceans that should be addressed with urgency, and to suggest possible pathways to overcome obstacles in river cetacean conservation. We have highlighted that significant effort is being expended to undertake river cetacean research, that PAs and fishery regulations have been implemented to protect dolphins, and that local capacity building for research and conservation of river cetaceans has increased. The literature and expert opinion concur that fisheries, mainly through targeted catch and bycatch, and habitat degradation, via the construction and operation of dams, are the most significant threats to river cetacean populations. Important data gaps exist in the understanding of ecosystem requirements, river cetacean life history and spatial distribution, and human-induced mortality. Given the dire status of river cetaceans, we need to focus on conservation actions based on the current best available knowledge. Habitat degradation is expanding and fishery interactions continue to negatively impact populations. Future work should principally focus on reducing these 2 threats. To do this, we propose increasing capacity, developing management plans to promote government involvement, collaborating closely with communities, increasing public awareness and regional collaborations, and diversifying funding.

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