Vol. 40: 285–296, 2019
https://doi.org/10.3354/esr00994

ENDANGERED SPECIES RESEARCH
Endang Species Res

Published December 5

Contribution to the Special 'Marine vertebrate bycatch: problems and solutions'

REVIEW

Bycatch in gillnet fisheries threatens Critically Endangered small cetaceans and other aquatic megafauna

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ABSTRACT: The conservation status of small cetaceans has significantly worsened since the 1980s, when the baiji was the only species of small cetacean listed as Endangered by IUCN. Now the baiji is almost certainly extinct and 13 other species, subspecies, or populations (hereafter units-to-conserve or units) of small cetaceans are listed as Critically Endangered (CR) on the IUCN Red List. Bycatch is the main threat to 11 of the CR units. Entanglement in gillnets contributed to the extinction of the baiji and is responsible for the imminent extinction of the vaquita. Unfortunately, there is no simple technical solution to the problem of bycatch of small cetaceans. If the 8 CR units with 100 or fewer remaining individuals are to be saved, conservation zones must be established where gillnets are eliminated and bans on their use are strictly enforced. Recent experience with the vaquita in Mexico demonstrates that enforcement of such conservation zones can be very difficult. Ineffective enforcement is also a problem for at least 4 of the other CR units. Time is very short and, unless major efforts are made now to address the bycatch problem, the prospects for CR small cetaceans and other at-risk aquatic megafauna are grim. The ultimate long-term solution to the bycatch problem is the development of efficient, inexpensive, alternative fishing gear that can replace gillnets without jeopardizing the livelihoods of fishermen. Good fishery governance and the direct involvement of fishing communities are also essential to the successful conservation of most threatened populations of small cetaceans.

KEY WORDS: Bycatch · Gillnet · Small cetacean · Dolphin · Porpoise · Extinction · Conservation

1. INTRODUCTION

Almost 30 yr ago, Brownell et al. (1989) argued that, although most species and populations of large whales had been protected from commercial whaling, many of the world's smaller cetaceans were in danger of extinction. Those authors called for increased conservation efforts to save the world's dolphins and porpoises. Of greatest concern in 1989 was the baiji *Lipotes vexillifer*, found only in China's

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Yangtze River. The baiji is still formally listed as Critically Endangered (CR) on the IUCN Red List, but is almost certainly extinct (Turvey et al. 2007).

For almost half a century, bycatch has been recognized as the most widespread threat to populations of small cetaceans (Mitchell 1975, Perrin et al. 1994). Synthetic gillnets were widely introduced into the world's fisheries as a durable and inexpensive fishing gear after World War II (Potter & Pawson 1991). Since the 1960s, aid agencies (e.g. United Nations Development Programme (UNDP) and Food and Agriculture Organization (FAO)) and national governments have provided gillnets to fishermen and promoted their use, radically changing the nature of fishing in coastal and freshwater ecosystems around the world. These synthetic nets are less expensive and easier to maintain than older nets made of cotton and hemp (Potter & Pawson 1991). Unfortunately, in promoting their use, these agencies have not given adequate consideration to the impacts of unintentional mortality of non-target species, such as small cetaceans, sea turtles, and other vulnerable megafauna. In the latter half of the last century, bycatch in gillnets became the primary driver of population declines in many species of marine megafauna, including elasmobranchs, sea turtles, seabirds, and marine mammals (e.g. Lewison et al. 2004, Read et al. 2006, Wallace et al. 2010, Žydelis et al. 2013, Huang 2015, Werner 2018). Gillnets are especially attractive to small-scale fishermen because they can be set and retrieved from small vessels; their use does not require expensive equipment, large mechanized vessels, or specialized skills (although considerable knowledge is necessary to find and catch targeted species); and they can be profitable because they are set to function passively and require less fuel consumption than mobile gears such as trawls. In some areas, the unintended bycatch of marine mammals or sea turtles in gillnets can supplement targeted catch (Robards & Reeves 2011). Even when non-targeted species are discarded, their capture is not detrimental to fishermen as long as there is no penalty for it, no increase in handling time, and no damage to the gear. As a result, gillnets are widely popular in both artisanal and industrial fishing fleets throughout the world and are responsible for the deaths of hundreds of thousands of cetaceans each year (Read et al. 2006). Effective mitigation of this bycatch tends to be population- and situation-specific, with no single method applicable to all cases (Dawson et al. 2013).

Here we review information on the status and current threats for the 13 small-cetacean units presently red-listed as CR (not including the baiji) and briefly discuss the conservation actions needed to save them. Our main findings are that bycatch in gillnets remains the greatest threat to these small cetaceans and that very little progress has been made over the past 30 yr to reduce this threat. We discuss why progress has been so elusive and suggest possible ways to limit the impending loss of coastal and riverine small cetaceans, as well as aquatic megafauna in other taxa, caused by bycatch.

2. THE CRITICALLY ENDANGERED SMALL CETACEANS

2.1. Vaquita *Phocoena sinus* (species)

This porpoise is endemic to the upper Gulf of California, Mexico, and has the smallest range of any cetacean species. Due to its limited range, the population has likely always been relatively small (Rojas-Bracho & Taylor 1999). When described as a new species in 1958, the vaquita was probably already declining due to bycatch in gillnets set for totoaba *Totoaba macdonaldi*, a large marine sciaenid fish. The totoaba fishery was closed by the Government of Mexico in 1975 because of overexploitation, but enforcement of this measure has always been ineffective. Vaquitas continued to be killed in illegal totoaba gillnets and in a variety of other gillnet fisheries (Vidal 1995, D'Agrosa et al. 2000). Despite repeated recommendations by scientists in the Comité Internacional para la Recuperacion de la Vaquita (CIRVA) and the Scientific Committee of the International Whaling Commission (IWC SC) stretching back into the 1990s, stressing the need for changes in fishing practices to reduce the bycatch risk (Rojas-Bracho et al. 2006), few effective conservation actions were taken until recently. Periodic abundance estimates showed a rapid decline in the vaquita population from 567 (95% CI: 177–1073) in 1997, to 245 (95% CI: 68–884) in 2008 (Gerrodette et al. 2011), 59 (95% CI: 22–145) in 2015 (Taylor et al. 2017), 30 (95% CI: 8–96) in 2016 (Thomas et al. 2017), and less than 19 at the end of the 2018 fishing season (Jaramillo-Legorreta et al. 2019).

Bycatch is the only documented threat to the species (Rojas-Bracho & Taylor 1999). Vaquitas have been killed at unsustainable rates (Gerrodette & Rojas-Bracho 2011) in gillnet fisheries for finfish, elasmobranchs, and shrimp (Vidal 1995, D'Agrosa et al. 2000). Since 2012, a resurgence of the illegal fishery for totoaba, driven by the extremely high value of totoaba swim bladders in China (approximately US$46 000 kg^{-1} in 2018), has greatly accelerated the vaquita's decline. Mexican authorities declared a temporary range-wide ban on all gillnet fishing in April 2015. This was made permanent in June 2017, but the vaquita's decline has continued due to non-compliance and inadequate enforcement. Fishermen were compensated not to fish, but programs to help them switch to using vaquita-safe fishing methods or pursue alternative livelihoods were ineffective. In October to November 2017, an effort was made to capture vaquitas and establish a captive population in the upper Gulf of California, with the ultimate goal of releasing animals back into the wild once gillnets were eliminated. This effort was suspended when an immature individual had to be released due to stress and an adult female died from stress soon after capture (Rojas-Bracho et al. 2019). Despite enhanced enforcement and a massive net removal effort, illegal totoaba fishing has continued through the 2019 fishing season.

A new Federal government took office in December 2018, just weeks before the start of the 2019 totoaba fishing season. Shortly thereafter, CIRVA met and emphasized that the only way to save the species at that point would be to eliminate immediately all gillnets, especially large-mesh totoaba gillnets, from the small area where the few remaining vaquitas were thought to congregate. Instead, the new government eliminated compensation to fishermen without providing alternative gear to replace gillnets, and this simply accelerated illegal gillnet fishing for shrimp, totoaba and other finfish. As a result, the vaquita is on the very brink of extinction.

2.2. Atlantic humpback dolphin *Sousa teuszii* (species)

Atlantic humpback dolphins are found in shallow coastal waters of tropical and subtropical western Africa, ranging from Dahkla Bay (Rio de Oro) in Western Sahara (23° 52′ N, 15° 47′ W) to Tombua (Namibe Province) in Angola (15° 46′ S, 11° 46′ E) (Collins et al. 2018). These dolphins depend on nearshore habitat, which greatly increases their susceptibility to anthropogenic threats. Fewer than 3000 (1500 mature individuals) are thought to remain. They occupy a few fragments of their former range, with most local populations numbering in the low hundreds or less. Exceptions may be populations in the Saloum Delta (Senegal) and Gambia River Estuary (Weir 2016) and the waters of Guinea Bissau (Leeney et al. 2016). Declines have been observed or are suspected for all known populations, and continued declines seem inevitable given the ongoing expansion of identified threats throughout the species' range (Collins et al. 2018). Bycatch, mainly in gillnets, is the principal cause of the declines: gillnet bycatch has been identified or suspected everywhere the species has been studied. Directed killing has also been identified or suspected in several areas and may have developed as a consequence of the animals' value coming to be recognized because of consumption of bycaught dolphins. Major threats to habitat from coastal development (including the construction of ports in estuarine habitat) are increasing (Van Waerebeek et al. 2004, Perrin & Van Waerebeek 2012, Collins 2015). Measures to protect habitat and reduce mortality from bycatch and hunting are limited across the range and, in the absence of targeted and sustained conservation efforts, long-term prospects appear grim. Given that gillnet fisheries in multiple range states are the most significant threat, conservation actions that reduce bycatch need to be identified and implemented at key sites to secure as many local populations as possible.

2.3. Māui dolphin *Cephalorhynchus hectori maui* (subspecies)

This subspecies occurs only off the southwest coast of North Island, New Zealand. A risk assessment concluded that the current bycatch rate is about 5 dolphins per year (95% CI: 0.3–8.0; Currey et al. 2012), far more than this small population can sustain. The subspecies has declined to 57 individuals (95% CI: 44–75) older than 1 yr (Cooke et al. 2018) as a result of bycatch in gillnet and trawl fisheries, and its range has contracted. Fishery closures have been implemented to reduce the risk of bycatch, but these closures are too small to ensure full protection (IWC 2018). Two fishing companies have announced their intention to reduce the use of entangling gear in part of the dolphins' range, but this gesture accounts for only a very small part of the total inshore fishing effort.

Given the critical status of this subspecies, the highest-priority management recommendation is to eliminate bycatch (IWC 2017, p. 354). With such a small population, the death of even a few individuals each year is unsustainable, so all bycatch must be eliminated (IWC 2017, p. 354) if the subspecies is to survive.

2.4. Taiwanese humpback dolphin *Sousa chinensis taiwanensis* (subspecies)

This subspecies (Wang et al. 2015) occurs only in a narrow strip of shallow coastal waters, about 250 km long and 750 km^2 in area, off western Taiwan (J. Y. Wang et al. 2016). It is geographically isolated and phenotypically distinguishable from other populations of the species (Wang et al. 2015, X. Wang et al. 2016). Fewer than 75 individuals remain (J. Y. Wang et al. 2012, 2016). Two independent population viability analyses have concluded that the population faces a serious risk of extinction in the near future (Araújo et al. 2014, Huang et al. 2014). The most immediate and direct threat is bycatch, although habitat loss, pollution, reduced freshwater input to maintain the dolphins' estuarine habitat, and anthropogenic noise are also threats. Within most of their range, an average of 32 fishing craft operate per km of coastline (Slooten et al. 2013). No quantitative data on bycatch are available but almost 60% of known individuals have signs of prior anthropogenic trauma likely to compromise their health, survivorship, and reproductive potential (Wang et al. 2017). Legal gillnet fishing (mostly with trammel nets) and illegal bottom trawling within 3 nautical miles of shore continue, although in 2019 the local coast guard promised stricter enforcement. Stronger, better-enforced conservation measures are called for, including a complete ban on all fishing operations using gillnets and other gear known to kill and injure dolphins (Ross et al. 2010).

2.5. Yangtze finless porpoise *Neophocaena asiaeorientalis asiaeorientalis* (subspecies)

This porpoise occurs in a portion of the Yangtze River (between Yichang and Shanghai) and its adjoining lakes and was sympatric with the baiji. Estimates of population size declined from around 1800 porpoises in 2006 to about 1040 in 2012 (Mei et al. 2014). A range-wide survey in late 2017 found similar numbers as in the 2012 survey, a hopeful sign (Mei et al. 2018), but additional surveys are needed to determine the current trend of the population. These porpoises are threatened by bycatch in several types of non-selective fishing gear, including gillnets and bottom-set 'rolling-hooks longlines', as well as by, to a lesser degree, electrofishing (Thomas et al. 2019), ship strikes, sand dredging, pollution, and water development projects (Mei et al. 2012).

Three semi-natural *ex situ* reserves have been established to protect this subspecies and provide animals for introduction into other reserves as well as to supplement the wild population. These *ex situ* reserves are the Tian-e-Zhou Oxbow near the city of Shishou, the He-Wang-Miao Oxbow in Hubei Province, and a smaller Xijiang Oxbow in Anhui Province. The population in the oldest reserve (Tian-e-Zhou) has increased rapidly, especially since 2010, and contained about 80 individuals by 2017. Approximately 110 Yangtze finless porpoises are now held in the 3 semi-natural reserves, and work is ongoing to increase the population size and genetic diversity of the *ex situ* metapopulation. Chinese authorities are continuing efforts to conserve the wild population while increasing the populations in the reserves, and the combined strategy shows promise. However, increased efforts are still needed to reduce bycatch and protect and restore habitat to conserve finless porpoises in the wild and to establish a safe environment for eventual releases of individuals from the reserves into the wild.

2.6. Mekong River dolphin *Orcaella brevirostris* (subpopulation)

The accepted common name of *Orcaella brevirostris* is Irrawaddy dolphin. We refer to the various geographical units-to-conserve by their area of occurrence. This population inhabits 6 deep pools along a 200 km stretch of the Mekong River from the Laos-Cambodia border downstream to Kratie, Cambodia. The population presumably suffered from bombing that targeted the Mekong River (which the Viet Cong used for transportation of supplies) during the USA-Vietnam War, when the USA dropped 2.7 million tons of explosives on Cambodia (Owen & Kiernan 2006). Abundance estimates from 2007 to 2015 were all in the range of 80 to 90 individuals (Phan et al. 2015). Over the last 15 yr, the deaths of most adults for which cause of death could be determined were caused by gillnet entanglement. The number of carcasses recovered annually has declined since 2006, with 6 recovered in 2016, but even this level of mortality is unsustainable.

Carcass recovery rate is not a reliable index of actual mortality rate as not all dead dolphins are recovered. In addition to the on-going threat of bycatch, hydropower dams represent a significant long-term threat to the population through habitat fragmentation and impacts on the ecology and hydrology of the Mekong. If proposed dams within core dolphin habitat are built, it will almost certainly lead to extirpation of the population (Ryan 2014, Brownell et al. 2017). Efforts to reduce gillnet mortality downstream of the Laos border include a ban on gillnet use and special protection of the deep pool areas during the dry season, and special protection throughout the range during the wet season when the dolphins disperse. In addition, the Cambodia Fisheries Administration, together with the World Wildlife Fund (WWF-Cambodia), is combining gillnet confiscation with community engagement; 'river guards' (park rangers) removed several thousand gillnets from 2014 to 2016 (Thomas & Gulland 2017). There is an urgent need to eliminate the threat of gillnet entanglement and to curtail dam construction in the river mainstem.

2.7. Mahakam River dolphin or pesut *O. brevirostris* (subpopulation)

These dolphins are isolated in the Mahakam River of East Kalimantan, Borneo (Indonesia); they inhabit about 240 km of the main river and its tributaries (Kreb 2004). Abundance estimates since 2005 indicate that only around 80 to 90 dolphins remain, and their core range has contracted since the early 2000s (D. Kreb unpubl. data). The main threat is bycatch in gillnets, which accounted for two-thirds of the deaths with a known cause between 1995 and 2016. Other threats include deaths from vessel strikes, deliberate hunting, possibly electrofishing (but see Thomas et al. 2019), habitat degradation, prey depletion caused by over-fishing, the conversion of fish spawning areas into palm oil plantations, and sedimentation of lake habitat (Kreb et al. 2007, Thomas & Gulland 2017). At a minimum, bycatch and direct takes must be eliminated if this population is to be saved.

2.8. Irrawaddy dolphin *O. brevirostris* (subpopulation)

This isolated population occurs almost 1000 km upstream from the sea in a 400 km stretch of the Ayeyarwady (Irrawaddy) River in Myanmar. The length of the river inhabited by dolphins has decreased by almost 60% since the early observations of Anderson (1879). No rigorous estimate of population size is available, but a direct count in 2004 suggested that there were 59 to 72 individuals in 3 river segments with limited demographic exchange (Smith & Tun 2007). Subsequent direct counts in 2006 to 2016 produced similar numbers (31 to 72) (Thomas & Gulland 2017). Between 2002 and 2017, an average of 2.5 dolphin deaths was reported annually. The greatest threat is entanglement in gillnets, but there is also concern about possible mortality related to electrofishing (see Thomas et al. 2019). Sedimentation and mercury toxicity from gold mining and dams on the Taping and Shweli tributaries have degraded the dolphins' habitat (Smith & Tun 2007). In December 2005, a 74 km river segment between Mingun and Kyaukmyaung was declared a protected area by the Myanmar Department of Fisheries, potentially protecting about a quarter of the dolphin population. However, 25 of the 36 dolphin deaths recorded between 2006 and 2017 were in that protected area (A. M. Chit unpubl. data). Bycatch and any mortality related to electrofishing must be eliminated throughout the limited range of these dolphins if they are to survive.

2.9. Malampaya Sound dolphin *O. brevirostris* (subpopulation)

This isolated population occurs in the inner section (ca. 130 km^2) of Malampaya Sound, Palawan, Philippines. Available abundance estimates are: 77 individuals (CV: 27.4%; 95% CI: 45–130) in 2001 (Smith et al. 2004a) and 35 (CV: 22.9%; 95% CI: 22–55) in 2012 (Whitty 2016). The bycatch rate has been unsustainable since the early 2000s (Smith et al. 2004a), with at least 8 bycatch-related deaths documented from 2009 to 2011 (Whitty 2016). Entanglement in bottom-set crab gillnets (matang quatro) and crab pots is the primary threat (Dolar et al. 2002, Smith et al. 2004a, Aquino et al. 2006). Mavic Matillano, former leader of WWF's local dolphin project, reported to one of us (M. Louella L. Dolar) that a specimen was bycaught in Malampaya Sound in December 2017 and that small numbers of dolphins are still seen regularly in the area. If these dolphins are to survive, bycatch must be eliminated. This will require enforced restrictions on crab gillnets and pots and a shift in livelihoods toward higher-value fisheries with low bycatch risk, aquaculture, or both.

2.10. Songkhla Lake dolphin *O. brevirostris* (subpopulation)

This population inhabits Songkhla Lake, a brackish water body connected to the Gulf of Thailand (Smith & Beasley 2004). No scientifically rigorous estimate of abundance is available, but in the early 2000s, the population was thought to consist of fewer than 20 individuals (Beasley et al. 2002, Smith et al. 2004b, Kittiwattanawong et al. 2007). The major threat is bycatch in gillnets, with additional reported mortality in fish traps. The minimum annual total mortality rate based on strandings was 5.6 dolphins from June 2001 through December 2003 (Kittiwattanawong et al. 2007). No information has become available to assess the status of this population since the report by Smith & Beasley (2004), but newspaper reports from Thailand quote local scientists confirming that small numbers of dolphins were still present in 2012 (Thai News Agency 2012) and dolphin carcasses had been found in the lake through 2018 (Bangkok Post 2018). Smith et al. (2004b) concluded that the large number of fixed fish traps indirectly threatened these dolphins by eliminating the potential for demographic interaction with individuals in the Gulf of Thailand. However, the continued presence of dolphins in the lake, despite the reportedly high mortality rate, suggests that either the lake population was considerably larger in the early 2000s than assumed or the population is not as isolated from the dolphins in the Gulf of Thailand as previously believed — possibly due to the removal of fishing traps in the lower portion of the lake. To determine the current status of these dolphins, new information is needed on abundance, interchange with the Gulf of Thailand, and bycatch.

2.11. Baltic Sea harbor porpoise *Phocoena phocoena* (subpopulation)

Harbor porpoises in the Baltic Sea are distinct from those in the Kattegat, Skagerrak, and North Sea (Wiemann et al. 2010, Galatius et al. 2012). During the second half of the 20th century, this population declined and its range contracted (Berggren & Arrhenius 1995). Abundance estimates are: 599 (95% CI: 200–3300) in 1995 (Gillespie et al. 2005) and 497 (95% CI: 80–2091) in 2012 (IWC 2017, p. 357). The primary threat to this population is bycatch in gillnets (Berggren et al. 2002). Other potential threats are increased pollutant loads (Berggren et al. 1999) and underwater noise resulting from construction of wind farms. The IWC SC has repeatedly recommended that all Baltic states assess and mitigate bycatch and other anthropogenic mortality in the context of cumulative impacts throughout the porpoises' range (IWC 2017, p. 357).

2.12. Cook Inlet beluga *Delphinapterus leucas* (subpopulation)

This population resides year-round in Cook Inlet, Alaska (Shelden et al. 2015), and is geographically and genetically distinct from other beluga populations. Alaska Natives have hunted these belugas since prehistoric times (de Laguna 1975). Abundance estimates are: ~1300 in 1979, ~1000 in 1991 (Shelden et al. 2015), and 328 in 2016 (95% CI: 279–386) (Shelden et al. 2017). In the 1990s, when local subsistence harvests ranged from 30 to more than 100 annually (Mahoney & Shelden 2000), the population declined by almost 50% (Hobbs et al. 2015). The hunt was first regulated in 2000 (Mahoney & Shelden 2000) and suspended after 2005, but the population continued declining (Shelden et al. 2017). Since 2008, 81% of the total population, on average, has occupied the Susitna River Delta (upper Cook Inlet) in early June, compared to roughly 50% in the past (Shelden et al. 2017). A contraction in range first documented by Rugh et al. (2010) has persisted. Since management of the hunt began in 2000, the population has been declining at 0.4% yr^{-1} (SE = 0.6%). The geographic range of these belugas from 2009 to 2016 was only 29% of that observed in 1978 to 1979. Entanglement in salmon driftnet and setnet fisheries is known to occur (Burns & Seaman 1986), but it is now probably infrequent since no mortality or serious injury was recorded by the observer program in 1999 or 2000 (Manly 2006). Factors that may be limiting population recovery include: changes in prey availability or quality; anthropogenic noise; vessel traffic; urban discharges and runoff (mainly from Anchorage); and construction projects, including oil and gas activities (Shelden et al. 2015). Ongoing studies to evaluate the relative importance of these anthropogenic threats should be continued to determine what additional protective measures are needed to allow this struggling population to increase.

2.13. Fiordland bottlenose dolphin *Tursiops truncatus* (subpopulation)

These dolphins are found along the southwest coast of South Island, New Zealand. There are 3 demographically isolated units: Northern Fiordland, Doubtful-Thompson Sound, and Dusky-Breaksea Sound. Total abundance in 2008 was 205, including calves (95% CI: 192–219) (Currey et al. 2009). The Doubtful-Thompson Sound group declined by more than 30% from 1994 to 2007, mainly due to decreased survival of calves and juveniles less than 3 yr old (Currey et al. 2011). An assessment of population viability across Fiordland suggested a high likelihood of ongoing decline, and about one-third of model runs predicted a decline of more than 80% over the next 3 generations (Currey et al. 2009). Threats include disturbance and boat strikes associated with tourism in Milford and Doubtful Sounds, increased freshwater discharge into Doubtful Sound from hydroelectric power generation, and reduced prey availability caused by environmental degradation and overfishing throughout Fiordland. These threats are likely exacerbated by a high degree of demographic stochasticity in the 3 small population units (Brough et al. 2016). The New Zealand Department of Conservation introduced several conservation measures in 2008, including dolphin protection zones in Doubtful Sound and a prohibition on vessels actively seeking encounters with dolphins. All 3 of the isolated units would benefit from long-term monitoring to assess the efficacy of these conservation measures.

3. STATUS OF SMALL CETACEANS CONTINUES TO WORSEN

The global status of small cetaceans has significantly worsened since the 1980s when the baiji was correctly regarded as the most endangered species. Thirty years ago, the vaquita population was declining but still viable, but now this species is at imminent risk of extinction. Eight of the 13 CR small cetaceans reviewed here have population sizes less than 100, 2 have populations between 200 and 500, and only 3 consist of 500 or more individuals (Table 1). Most of the CR small cetaceans are declining, some catastrophically.

4. BYCATCH IS THE MOST COMMON PROBLEM

Eleven of the 13 CR small cetaceans are threatened by bycatch (Table 1). Bycatch is also a problem for many of the small cetaceans red-listed as Endangered, Vulnerable, and Near Threatened. Furthermore, the problem is larger and more widespread than indicated by the Red List, because the data required to assess and list many species and populations affected by bycatch are lacking. For example, Burmeister's porpoises *Phocoena spinipinnis* occur in coastal waters from northern Peru to southern Chile and from southern Argentina to southern Brazil. The distribution of these porpoises between the Atlantic and Pacific coasts is likely discontinuous and there is no abundance estimate for any part of their range. Very high estimates of gillnet mortality in Peru (Rosa et al. 2005) come from studies conducted decades ago (Grimwood 1969, Van Waerebeek et al. 1997). The species was recently red-listed as Near Threat-

Table 1. Threats and population status of the 13 small cetaceans (except for the extinct but still-listed baiji) listed as Critically Endangered on the IUCN Red List as of December 2017. Cases are listed in the order that they are discussed in Section 2. References are given in the accounts for each case

Case number	Common name	Bycatch	Fishing status	Electro-fishing	Ship strike	Habitat loss	Dams	Distur-bance	Region	Population size	Year
1	Vaquita	Yes	Illegal	No	No	No	No	No	Mexico	<19	2018
2	Atlantic humpback dolphin	Yes	Legal	No	No	Yes	No	?	Western Africa	<3000	2017
3	Māui dolphin	Yes	Legal	No	No	No	No	No	New Zealand	57	2017
4	Taiwanese humpback dolphin	Yes	Legal	No	No	Yes	No	Yes	SE Asia	<75	2010
5	Yangtze finless porpoise	Yes	Illegal	Yes	Yes	Yes	Yes	Yes	SE Asia	1000	2017
6	Mekong River dolphin	Yes	Illegal	Yes	No	Yes	Yes	No	SE Asia	80	2015
7	Mahakam River dolphin	Yes	Legal	Yes	Yes	Yes	No	No	SE Asia	76	2016
8	Irrawaddy dolphin	Yes	Illegal	Yes	No	Yes	Yes	No	SE Asia	72	2004
9	Malampaya Sound dolphin	Yes	Illegal	No	No	No	No	No	SE Asia	35	2012
10	Songkhla Lake dolphin	Yes	Legal	No	No	Yes	Yes	Yes	SE Asia	20	2004
11	Baltic Sea harbor porpoise	Yes	Legal	No	No	No	No	Yes	Europe	500	2012
12	Cook Inlet beluga	No	Legal	No	No	Yes	No	Yes	Alaska	328	2016
13	Fiordland bottleNose dolphin	No	Legal	No	Yes	Yes	No	Yes	New Zealand	205	2008
	Totals	11	5	4	3	9	4	7			

ened, with a strong recommendation that the Peru subpopulation be assessed separately (Félix et al. 2018).

Similar recommendations are found in the IUCN Red List for numerous other small cetaceans that occur in areas with gillnet fisheries, especially in coastal and riverine habitats, e.g. *Tursiops aduncus*, *Orcaella* spp. *Sousa* spp., and *Neophocaena* spp. The true number of such populations threatened by coastal gillnets could be in the hundreds. For many species and populations not listed as CR, there is still time to adopt fishing practices that would allow their continued existence. For example, 2 dolphins endemic to South America, the franciscana *Pontoporia blainvillei* and the Guiana dolphin *Sotalia guianensis*, have been subject to very high levels of bycatch in gillnets for decades and are red-listed as Vulnerable (see Zerbini et al. 2017) and Near Threatened (Secchi et al. 2018), respectively. Both have relatively large ranges, spanning multiple countries, and are still abundant (both more than 10 000 individuals), so there is still time to develop and adopt fishing practices that cause less bycatch.

5. NO EASY SOLUTIONS

The vaquita will soon be extinct, despite the fact that we have known for over 50 yr that gillnets threaten the existence of this species (Mitchell 1975). The fate of the vaquita shows the difficulty of addressing the bycatch problem. It takes years to obtain estimates of population size, trend, and bycatch rate needed to formally assess the severity of the problem and convince authorities to act. Additional time is required to develop, enact, and secure funding for mitigation. When conservation measures are enacted in a top-down manner, strict enforcement of regulations is necessary, which has proven extremely difficult for both financial and social reasons. For example, the vaquita has continued to decline rapidly despite greatly increased funding dedicated to enforcement by the Mexican government, including deployment of the Navy (IWC 2018). Enforcement of conservation measures, such as protected areas and gillnet bans, in the Gulf of California have been undermined by corruption, fueled by the extremely high value of totoaba bladders on the Chinese dried seafood import market.

Gillnets are equally effective at capturing targeted and non-targeted species of particular sizes. The efficiency of this gear frequently leads to overfishing of the targeted fish species, thereby reducing incomes. Even in cases where the harvest of targeted species is sustainable, mortality rates of non-targeted species such as marine mammals, sea turtles, and elasmobranchs are likely to be unsustainable, because of their slow rates of population growth. Failing to address the bycatch problem leads to further degradation of the ecosystems upon which fishermen depend.

Unfortunately, very few technical solutions are available to reduce the risk of small cetacean entanglement in gillnets (Werner 2018), and for small populations, risk elimination, rather than just risk reduction, must be a priority if extinction is to be avoided. Acoustic deterrents or 'pingers' used on gillnets can reduce bycatch rates for some species, but these devices are expensive and require maintenance. Available data suggest that pingers are most likely to be successful with species like harbor porpoises that are neophobic and easily startled, and perhaps also those with low levels of philopatry, which might delay habituation to the sound of the pingers (Dawson et al. 2013). Pingers have proven successful, at least so far, in eliminating bycatch of *Mesoplodon*, a genus of beaked whales, in the California drift-net fishery (Carretta & Barlow 2011). Coastal delphinids, such as bottlenose dolphins, with flexible feeding behavior and high site fidelity, are much less deterred by pingers (Dawson et al. 2013). Commercially available pingers are likely to be effective only in affluent countries that have the financial resources to support their long-term use (Leaper & Calderan 2018). However, low-cost pinger alternatives are being tested (Berggren et al. 2017). Regardless, the development and implementation of an effective pinger program is not straightforward, even for valuable commercial fisheries in developed countries (Dawson et al. 2013).

Market forces, such as the 'dolphin-safe' labeling of canned tuna, have encouraged the reduction of dolphin bycatch in purse seines by influencing consumer behavior (Teisl et al. 2002). However, the most serious threat to many endangered small cetaceans (including most of those reviewed in this paper, with the exception of the vaquita and the Māui dolphin) comes from small-scale fisheries that provide products for domestic consumption rather than export. The recent seafood import rule intended to ensure that fisheries exporting products to the USA are subject to bycatch reduction requirements equivalent to those imposed under the US Marine Mammal Protection Act (Williams et al. 2016) will be of limited help to the small cetaceans described here because most fisheries of concern do not export their products.

The ultimate long-term solution is the development of efficient, inexpensive, alternative fishing gear that can replace gillnets without jeopardizing the livelihoods of fishermen (Leaper & Calderan 2018, Werner 2018). Gillnets can be replaced with other gear types that pose less risk to small cetaceans. For example, cod pots are as effective as gillnets for at least part of the year in the Baltic Sea inshore cod fishery (Königson et al. 2015). Despite clear promise, however, the extensive multi-year efforts to develop, test, and generate regulatory and user acceptance of viable alternative gear (e.g. small trawls, fish traps, hook-and-line) in the shrimp and finfish fisheries of the Upper Gulf of California have been thwarted by resistance from fishing cooperatives, the failure of Mexican fishery agencies to implement national directives, and the financial lure of the illegal gillnet fishery for totoaba. Until gear alternatives are developed and embraced by the fisheries themselves, firm governance will be necessary to enforce gillnet bans or restrictions, and the use of less efficient gear may be necessary. This may require some form of compensation to fishermen, whether through market mechanisms or direct government payments. Good fishery governance depends on a stable, non-corrupt political framework where there is both the will and the capacity to implement effective conservation policies (Kuiper et al. 2018). It may be too late for some of the species and populations considered here, but institutions with the responsibility, legal authority, expertise, and resources to pursue conservation as a top priority can help head off similar crises in the future, particularly if local communities are involved in a manner that rewards and reinforces their commitment. Local advocates can highlight the benefits of conservation in terms of building and sustaining fisheries and protecting biodiversity and provide vital links among fishing communities, government agencies, and external sources of technical expertise and funding. We emphasize that effective, durable solutions to bycatch problems can only be achieved with the direct involvement of fishing communities — the skill and experience of the fishermen are invaluable when searching for approaches to bycatch reduction that will work in practice and be widely adopted in the fishery.

6. FUTURE PROSPECTS

Many of the CR small cetaceans reviewed here will go extinct unless critical threats are mitigated effectively without delay. For some populations, this will require the establishment of conservation zones of adequate size, where the use of gillnets is forbidden. Such zones will have to be strictly enforced, and alternative fishing gear will need to be provided to affected communities. However, strict enforcement is always a problem for financial and social reasons.

If major reforms are implemented now, it may be possible to prevent the extinction of 3 of the currently listed CR small cetaceans with the largest population sizes: the Baltic harbor porpoise, the Yangtze finless porpoise, and the Atlantic humpback dolphin. In the case of the Baltic harbor porpoise, spatial-temporal fishery closures and gear modifications (including pingers) may be successful. In the case of the Yangtze porpoise, there is an urgent need to 'identify river and lake segments with the highest porpoise concentrations and enforce appropriate, year-round protection measures (including fishing bans)' (IWC 2017, p. 351). In contrast to many other CR small cetaceans, which are restricted to very small areas, the Atlantic humpback dolphin has an extensive, though fragmented, range along the west coast of Africa. Populations of these dolphins may persist in some countries that have good fishery management (e.g. Senegal; Weir 2016) or a large, well-managed system of marine protected areas (e.g. Gabon; T. Collins unpubl. data).

We hope that this paper will raise awareness of the bycatch problem threatening small cetaceans in coastal and riverine habitats throughout the world and spur the development of effective solutions, such as low-cost alternative gear that reduces bycatch.

Acknowledgements. This work was supported by dozens of grants to the various co-authors. We thank the anonymous reviewers for constructive comments on the manuscript.

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Editorial responsibility: Jeremy Kiszka, North Miami, Florida, USA

Submitted: March 4, 2019; Accepted: September 21, 2019
Proofs received from author(s): November 26, 2019