Freshwater Commercial Bycatch: An Understated Conservation Problem

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Bycatch from marine commercial fisheries has been regarded as a global conservation concern for decades. Fortunately, some headway has been made in mitigating bycatch problems in marine fisheries. Freshwater commercial fisheries, however, have been relatively understudied. Although freshwater yields comprise 11% of the global commercial catch, bycatch research focusing on freshwater commercial fisheries represents only about 3% of the total bycatch literature. This paucity of research is particularly alarming given that so many of the world's threatened species live in freshwater. The limited literature that does exist includes examples of population declines attributed to commercial bycatch (e.g., the Yangtze River dolphin) and illustrates that bycatch is substantial in some systems (e.g., lake trout in Laurentian Great Lakes fisheries). Encouraging results from the marine realm can serve as models for bycatch research and development in freshwater and can lead to measurable gains in the conservation of freshwater ecosystems. We summarize existing work on inland bycatch in an effort to draw attention to this understated and understudied conservation problem.

Keywords: gill net, commercial fishing, bycatch reduction, discards, mortality

Commercial fisheries around the globe represent some of the most valuable natural resources, providing significant amounts of food and economic benefits at both local and global scales. In some cases, however, fisheries are mismanaged, resulting in unsustainable overharvesting of resources, the permanent loss of biodiversity, or alteration of ecosystem structure (Hilborn et al. 2003). Commercial fisheries exploitation is therefore recognized as a primary threat to aquatic biodiversity (Agardy 2000). In recent years, research efforts have been refocused to understand the impacts of commercial fishing on animals not targeted by those fisheries (i.e., bycatch), a new and important frontier in conservation biology that has led to conservation gains for valuable and at-risk species (Hall 1996, Cox et al. 2007). Bycatch is the unintended capture of nontarget animals, including those landed and those that escape from fishing gear (Crowder and Murawski 1998). Wherever it occurs, commercial fishing has the potential to compromise populations of nontarget species through bycatch. Bycatch sometimes can have economic value for the fisher, but it is more often discarded (e.g, dumped overboard). The term "discard" typically is reserved for animals that are caught and released (Hall 1996). Even when discards (i.e., fish, birds, mammals, invertebrates) are released alive from commercial fishing gear, delayed mortality or sublethal impairments (e.g., behavioral changes or injury) can still reduce their fitness over the long term (Davis 2002).

Some media attention and research have been directed at commercial fishing bycatch involving highly charismatic animals (e.g., dolphins) in marine systems, but virtually no attention has been paid to commercial bycatch in freshwater aquatic systems. In fact, some of the most frequently cited commercial fishing bycatch reviews do not even mention freshwater systems (e.g., Alverson 1994, Hall 1996, Hall et al. 2000, Davis 2002). This omission is particularly alarming given the relatively elevated past and predicted species extinction rates of freshwater fauna (Ricciardi and Rasmussen 1999, Jenkins 2003).

For decades, significant research effort has been devoted to understanding freshwater ecosystem stressors and their impacts. Given the diversity and magnitude of these stressors (e.g., recreational angling, invasive species, pollution), it is perhaps not surprising that commercial fishing bycatch has often been overlooked as a potential concern (Dudgeon et al. 2006). In light of the myriad stressors on freshwater aquatic systems, commercial fishing bycatch may not be the main threat to ecosystem integrity, but when combined with other pressures over the long term, it has the potential to cause significant change. In recent years, there has been particular concern about the bycatch of species that are deemed at risk of extinction. The few studies to date on freshwater bycatch have identified serious conservation issues (e.g., Collins et al. 1996, Koed and Dieperink 1999) and in some cases have offered potential solutions (Johnson et al. 2004, Fratto et al. 2008). Further, commercial fisheries bycatch research in inland waters has the opportunity to use, as a foundation, principles developed through extensive research on bycatch in marine systems (Alverson 1994, Hall 1996, Broadhurst 2000, Davis 2002). In some cases, bycatch

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research in the marine environment has led to solutions for major conservation concerns, such as the bycatch of dolphins in the Pacific tuna fishery, where the development of new gear and fishing techniques resulted in an impressive decrease in bycatch rates (Hall 1998). Further, there has been extensive research into the effects of discarding in freshwater recreational fisheries (i.e., catch and release), generating considerable understanding of the survival rates and behavior of discarded fish (Cooke and Wilde 2007, Donaldson et al. 2008). Commercial fisheries in inland waters tend to be small scale, article and for the purpose of this paper we have extended them to include artisanal fisheries, which tend to be common in developing countries.

The three objectives of this article are to (1) draw attention to freshwater commercial bycatch as a potential conservation concern, (2) synthesize bycatch principles from the marine realm that are relevant to freshwater research, and (3) indicate where further research is needed and provide a framework for addressing key issues associated with commercial bycatch in freshwater systems.

Potential scale of commercial bycatch in inland waters

Bycatch in freshwater commercial fisheries is a potentially significant contributor to the alteration of ecosystems (figure 1). As an ethical, ecological, and resource

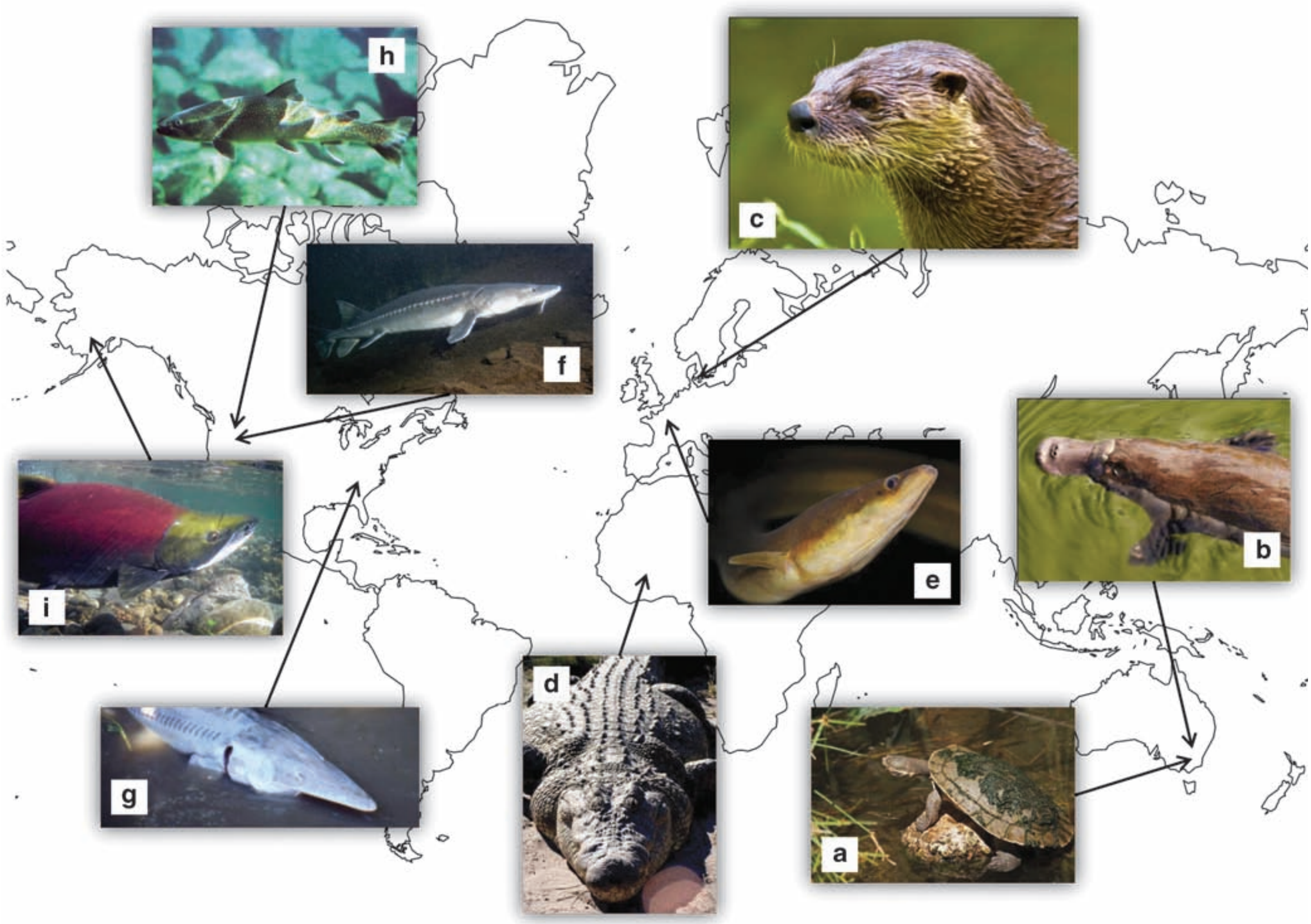

*Figure 1. Examples of nontarget animals caught around the globe. (a) Macquarie turtle (*Emydura macquarii*) caught in carp and eel trap fisheries (Lowry et al. 2005). (b) Platypus (*Ornithorhynchus anatinus*) caught in carp, yabby, and eel trap fisheries (*Grant et al. 2004*). (c) European otter (*Lutra lutra*) caught in eel fyke nets—endangered in Denmark (Koed and Dieperink 1999). (d) Nile crocodile (*Crocodylus niloticus*) caught in various fisheries (Shirley et al. 2009). (e) Critically endangered European eel (*Anguilla anguilla*) threatened by various commercial fisheries in coastal streams and rivers (Bevacqua et al. 2009). (f) White sturgeon (*Acipenser transmontanus*) being killed by lost gill nets in the Columbia River (Washington, Oregon, United States; Kappenman and Parker 2007). (g) Endangered pallid sturgeon (*Scaphirhynchus albus*) caught in a shovelnose sturgeon fishery (Bettoli et al. 2009). (h) Threatened bull trout (*Salvelinus confluentus*) caught as bycatch in river fisheries for other salmonids (Brenkman and Corbett 2005). (i) Sockeye salmon (*Onchorynchus nerka*) escaping gill nets targeting various salmonids (Baker and Schindler 2009). Photographs: (a) Roger Smith, (b) Shane Makinen, (c) Henning Leweke, (d) Geof Wilson, (e) Håkon Haraldseide, (f) Oregon Department of Fish and Wildlife, (g–h) US Fish and Wildlife Service, (i) Sonja Mills.*

management issue, bycatch in marine fisheries has generated significant concern (Crowder and Murawski 1998), and there is little reason to believe that bycatch rates are lower in inland freshwater fisheries. Currently, there is a dearth of freshwater bycatch literature available, and with a handful of exceptions, there is a complete lack of data identifying bycatch species and rates from inland commercial fisheries (figure 2). Commercial fisheries operate in lakes and rivers around the globe. Some of the largest freshwater commercial fisheries are in the Amazon River in South America (McDaniel 1997), the Laurentian Great Lakes of North America (Johnson et al. 2004), lakes Victoria and Malawi in Kenya (Preikshot et al. 1998), the Yangtze and Mekong rivers in China (Allan et al. 2005, Turvey et al. 2007), and the Danube River (Hensel and Holcik 1997), as well as countless additional commercial fisheries operating in smaller inland waters (e.g., Lowry et al. 2005, Siira et al. 2006, Scholten and Bettoli 2007, Fratto et al. 2008, Hyvarinen et al. 2008).

Allan and colleagues (2005) asserted that globally, inland (freshwater) fisheries are being overexploited. If this claim is valid, then it is logical to suggest that bycatch of fish, bird, mammal, and reptile species may be commonplace, given the evidence from marine fisheries (Soykan et al. 2009). Although the global bycatch of marine commercial fisheries has been estimated (Alverson 1994, Kelleher 2005), no such estimates have been attempted for freshwater fisheries. In the absence of estimates for freshwater, we can use target catch as an indicator of the potential scale of bycatch, since target catch is positively correlated with bycatch in most fisheries (Kelleher 2005). The vast majority of the world's documented freshwater commercial catch occurs in the developing world; only 5% of the global catch is taken by commercial fishers in industrialized and transitioning economies, where the focus has shifted toward recreational fishing (Arlinghaus et al. 2002, Allan et al. 2005, FAO 2009). Regardless, more than 10 million metric tons of freshwater commercial catch was reported globally for 2006, a 12.8% increase from each of the previous two years (FAO 2009). Inland commercial catches were greatest in Asian countries (66.9% of the total global capture), followed by African fisheries (23.5%), the Americas (5.9%), Europe (3.5%), and Oceania (0.2%; FAO 2009). Given the somewhat sporadic and incomplete way that inland fisheries capture rates are reported, it is possible that these figures are underrepresentative of the scale of commercial fisheries in some freshwater systems (Allan et al. 2005). Many significant catches are not included in the estimates above because they are taken in unregulated fisheries, including artisanal, subsistence, and aboriginal fisheries, especially in the developing world. Although not commercial, these other fisheries may employ the same fishing gear, such as hoop nets, gill nets, trap nets, seines, and so on, and thus are expected to generate the

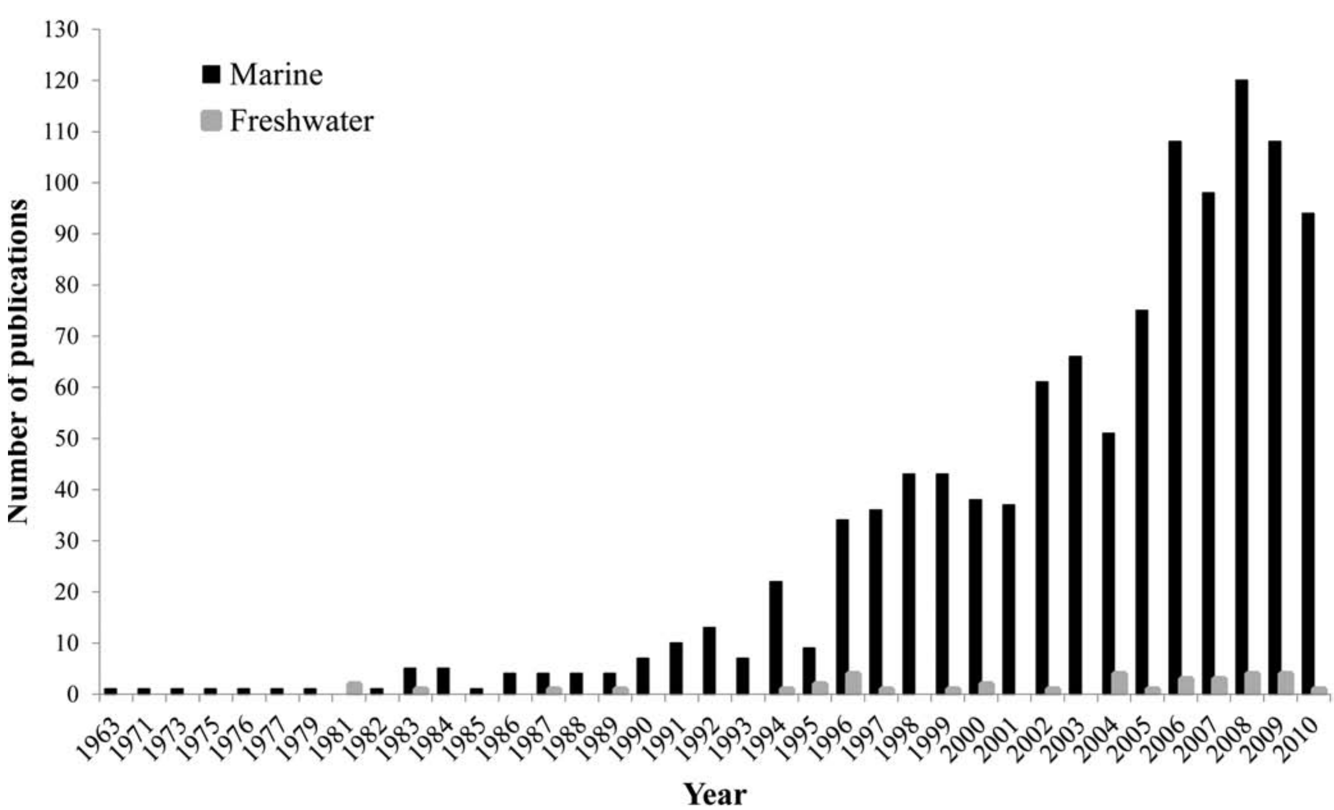

Figure 2. Quantitative comparison of the number of peer-reviewed commercial fisheries bycatch and discard papers from the marine and freshwater environments by year. A total of 1152 papers were found: 1114 from the marine realm and 38 from freshwater.

same bycatch as some commercial fisheries. Further, many inland commercial fisheries, particularly unregulated fisheries in developing countries, have bycatch mortality rates of 100% because bycatch is used in some way instead of being discarded alive (e.g., consumed by the fishers or sold locally). In other words, many of these fisheries may not generate bycatch in a legal sense (i.e., in some countries, there is no regulation against keeping any or all species caught). However, fish species vary widely in economic value, and some species can always be regarded as bycatch. Additionally, undersized individuals of the target species, as well as mammals, birds, and reptiles, may have no market or artisanal value and can be considered bycatch.

Comparative overview of the bycatch literature

We used literature searches to illustrate the relative representation of marine and freshwater commercial fisheries in the bycatch and discard literature (figure 2). The search was conducted using Web of Science with a number of search terms, including bycatch, incidental capture, incidental mortality, incidental catch, discard, ghost fishing, and gear selectivity. The term "by-catch" (with a hyphen) was not used because poor keyword identification led to thousands of results (following Soykan et al. 2008); however, we were still able to locate a large number of these papers using other search terms. Study titles, abstracts, and keywords were used to determine whether papers pertained to commercial fisheries bycatch. We did not include papers on the efficiency of or bycatch caused by fishing gear used for stock assessments. Papers not quantifying bycatch or discard rates from commercial fisheries, but explicitly studying direct and indirect effects (e.g., trophic effects of discarding), were included. In some cases, full articles were examined to determine whether a marine or freshwater categorization was appropriate (e.g., in the case of fisheries targeting anadromous species). The survey was initially conducted 7–11 September 2009 and was updated 28–29 December 2010. We conducted a more exhaustive search to find papers on freshwater commercial fisheries bycatch by including additional search terms in both Web of Science and Google Scholar. In addition, we searched reference lists and "cited by" lists. For simplicity, we included only peer-reviewed journal articles written in English.

We found a total 1152 papers on bycatch and discarding; 1115 of these were from the marine realm and 37 from freshwater. Of the 37 freshwater bycatch papers used (see the online supplementary material online at *www.carleton.ca/fecpl/pdfs/BioScience - Raby et al supplmaterial.pdf*), 31 quantified bycatch rates, 12 examined the fate of discarded animals, 8 evaluated gear modifications for reducing bycatch rates, 4 studied the effects of ghost fishing (unobserved incidental encounter with fishing gear, including nets lost by fishers and animals encountering and escaping from fishing gear before it is pulled), 2 incorporated physiological measures of condition, and 2 used telemetry to track animal movement. None of the 37 papers evaluated predictive measures for postrelease survival (e.g., Davis 2010) or tested devices that aid physiological recovery of animals before they are discarded (e.g., Farrell et al. 2001). Lentic and lotic inland fisheries were represented in the bycatch literature by 17 and 20 papers, respectively. Twenty-three of the 37 papers used data from the United States, 8 from Europe, 4 from Australia, and 1 each from Asia and South America. Despite significant freshwater commercial and artisanal fishing in Africa (e.g., Mkumbo and Mlaponi 2007)—bycatch there is thought to be causing species extinctions (Preikshot et al. 1998)—we found no papers examining bycatch in those fisheries.

We searched more extensively for papers dealing with freshwater bycatch; the 30-to-1 ratio in favor of research in marine fisheries should therefore be considered a conservative estimate of the underrepresentation of freshwater bycatch in the literature. Indeed, the proportion of marine to freshwater studies is probably much higher. It is not surprising that more bycatch literature pertains to marine fisheries given that they are cumulatively about eight times larger in terms of reported catch (FAO 2009). As stated previously, however, there is no evidence to suggest that inland fisheries generate proportionally less bycatch. Moreover, biodiversity has declined and continues to decline in freshwater ecosystems at a greater rate than in marine waters (Ricciardi and Rasmussen 1999, Jenkins 2003). The magnitude of the problems likely to arise from commercial fishing bycatch in freshwater is not reflected proportionally in the literature: freshwater commercial fishing accounts for approximately 3% of the total body of bycatch literature but represents 11% of the global commercial catch (FAO 2009).

Applicability of marine-based bycatch findings

Because the purpose of this synthesis is to convey the applicability of marine bycatch findings to the freshwater realm, we draw mostly from papers that have already summarized those findings. As such, we focus on identifying approaches and lessons that we believe relevant for those intending to study or manage inland commercial bycatch (see table 1). The scientific literature on bycatch has grown steadily, with research examining bycatch of a wide variety of taxa from numerous fisheries employing different gear in the ocean (e.g., Gales et al. 1998, Hall 1998, Broadhurst 2000, Barlow and Cameron 2003). Arguably, the benchmark for success in bycatch research and mitigation has been the tuna purse-seine fishery in the Pacific Ocean, where in only a few years dolphin bycatch was reduced to nearly zero from alarming levels (Hall 1998). Gear modifications were developed, including fine mesh panels and rescue platforms, while fishing techniques and handling practices were improved so that backdown (a vessel maneuver that allows encircled dolphins to escape) and rescue by hand could be used to free dolphins before nets were pulled on deck (Hall 1998). Importantly, the fishery management implemented individual-vessel dolphin mortality limits, which over time selected for captains most skilled in avoiding dolphin bycatch mortality (Hall et al. 2000). The number of dolphins killed as a result of bycatch decreased rapidly from 133,000 in 1986 to 1877 in

Table 1. Characteristics and trends relevant to commercial bycatch issues in marine and freshwater environments.

Criteria	Marine	Freshwater	Reference
Magnitude of global catch (total landings)	81.9 million metric tons	10.1 million metric tons	FAO 2009
Distribution of fishing effort[a]	Global	Focused in developing regions	FAO 2009
Magnitude of global bycatch	7.3 million metric tons estimated	Unknown	Kelleher 2005
Trend in bycatch rates	Declining	Unknown	Kelleher 2005
Number of bycatch studies	1115	37	
Animals caught as bycatch	Fishes, birds, turtles, mammals	Fishes, birds, turtles, mammals[a]	Hall 1996
Overall rate of biodiversity decline	Intermediate	Greatest	Jenkins 2003
Commercial fisheries' relative importance among anthropogenic stressors	Exploitation regarded as most important threat	Usually considered low	Jenkins 2003
Use of bycatch-reducing devices	Common	Rare	
Requirement for reporting bycatch	Somewhat common	Rare	

a. See the online supplementary material at *www.carleton.ca/fecpl/pdfs/BioScience - Raby et al supplmaterial.pdf.*

1998 (Hall et al. 2000). This improvement came at virtually no long-term cost to the tuna fishery, as catch rates for tuna did not substantially decline as a result of improvement in dolphin avoidance (Hall 1998).

Most of the principles of commercial fisheries bycatch that have been formulated from marine research are applicable to freshwater. First, the basic bycatch management objectives outlined by Hall (1996) apply not only to all fisheries but to all natural resource management: (a) avoid the extinction of species, and (b) retain the basic structure and function of ecosystems. Other bycatch management goals that are particularly important for freshwater commercial fisheries are to reduce waste, to maintain fishing opportunities (Hall 1996), and to maintain the welfare status of bycatch (Huntingford et al. 2006). Managers should employ the precautionary principle and take actions to reduce bycatch when it is perceived to be excessive rather than awaiting a full accounting of its ecological significance (Hall 1996). Some strategies employed in ocean fisheries can be applied directly to those in freshwater: (a) modify the spatiotemporal distribution of fishing effort to reduce encounters with nontarget species, (b) upgrade fishing technology to reduce bycatch per unit effort, (c) discard bycatch animals alive, and (d) use the bycatch (particularly dead individuals or species whose postrelease survival is known to be poor; Hall 1996). Additionally, a complete substitution of gear type can sometimes be the most effective way to reduce bycatch. For example, changing from trawls to more selective fixed gear types (e.g., gill nets) can in some cases reduce bycatch while maintaining catch rates of target species (Broadhurst et al. 2007). Particularly where strong regulatory enforcement does not exist (frequently the case for inland fisheries), it is imperative that commercial fishers are involved in decisionmaking processes and that the socioeconomic benefits of fishing activities be maintained. These strategies can be implemented without significantly decreasing target species catches (Broadhurst et al. 2007).

Technological improvements to fishing gear that reduce bycatch (bycatch reduction devices, BRDs) are particularly favorable and have commonly been applied in marine fisheries, but they may be especially effective in inland fisheries of developing countries, where discarding is uncommon (Allan et al. 2005). Further, fisheries regulation of any kind is uncommon in developing countries, a reality that necessitates the use of bycatch strategies that do not require enforcement (i.e., soft approaches to regulation, including guidelines and incentives). Introducing modified fishing gear is ideal in these circumstances because once the gear is in use, bycatch is reduced with minimal enforcement. Modifications of traditional fishing gear to reduce bycatch without affecting the target catch can be as simple as a change in net mesh size, or the installation of modules that allow escape of bycatch species. Particularly for freshwater fisheries in developing countries, modifications must be simple and inexpensive; otherwise, nongovernmental organizations (NGOs) would very likely have to provide financial incentives to fishers. Currently, many inland fisheries in developing countries use 100% of their catch. Even in these cases, gear changes would be desirable if they improve catch efficiency for the fishes with greater market value while reducing the catch of at-risk animals.

Perhaps the most basic change available for bycatch reduction is a substitution in gear type (e.g., changing from a trawl to a selective fixed gear type). These changes often produce higher catch efficiency for the target species (i.e., lower bycatch; Broadhurst et al. 2007). Extensive research has been done on turtle excluder devices (TEDs), gear modifications for shrimp and prawn trawl fisheries that have become mandatory in some countries (Broadhurst 2000). These devices have recently been adapted for freshwater fisheries, but their use is not yet mandatory in most systems (Fratto et al. 2008). In the Bay of Fundy and Gulf of Maine fisheries, high mortality of cetaceans following entanglement in gill nets led to the development of special devices to reduce cetacean bycatch in these nets (Jefferson and Curry 1994, Barlow and Cameron 2003). Modules that emit pinging alarm sounds are attached to gill nets, which can reduce the bycatch of small cetaceans by up to 77% (Hall et al. 2000). Cetacean bycatch occurring in freshwater is particularly common in developing nations with relatively intensive and unmonitored commercial gill net and drift net fisheries (Reeves et al. 2005). Bycatch reduction devices from the marine realm that reduce cetacean bycatch in gill nets should be evaluated for use in freshwater fisheries in which endangered cetaceans are killed incidentally by gill net fishing in multiple systems (Silva and Best 1996, Barlow and Cameron 2003, Mansur et al. 2008, Zhao et al. 2008). Although the development of BRDs has reduced bycatch in the marine realm and holds promise for bycatch issues in freshwater, factors causing nontarget animal encounters and entanglement in fishing gear might, in some cases, be too complex for their development. Even if the technology is available, fishing gear replacement or modification can be costly, rendering it implausible in the absence of regulatory changes or financial incentives.

Discarding has been used widely by fisheries managers to protect populations of nontarget species and even smaller individuals of the target species (Davis 2002); however, this management method assumes that discarded individuals survive and experience negligible impacts to their fitness. Yet in the majority of cases in which discarding is used, there is little scientifically defensible information on the fate of the discarded individuals. Lab and field-based holding experiments have been used to predict the effects of various factors on discard mortality (Chopin and Arimoto 1995, Suuronen et al. 1996). Many of these factors are intuitive: anoxia, air exposure, and handling time each should increase stress and mortality in fishes (Davis 2002). In air-breathing vertebrates, net set duration should play a large role in mortality for obvious reasons; if the net set duration exceeds maximum dive time, the captured animal will die. Further, the stress of being entangled below surface usually induces a stress response that increases cardiac output (higher oxygen demand) through the release of hormones and the exhausting exercise of struggling in the net. Greater oxygen demand during this period means that the amount of time an air-breathing animal can live while entangled below surface could be less than its standard dive duration. Water temperature, light conditions, and animal size can also affect discard mortality rates (Davis 2002). The two causes of death in discarded animals are physiological stress and injury; the severity of and interaction between these two factors determine the fate of discarded animals. Stress and injury are most heavily influenced by handling time (time from the first encounter with fishing gear until release) and handling techniques (type of fishing gear used, on-deck handling by fishing crew).

Factors affecting bycatch as well as discard mortality and fitness are most likely similar in freshwater systems, but the nature of the relationships may be different. The smaller volume-to-surface-area ratio of freshwater systems compared with oceans often leads to a greater fluctuation in water temperatures than in marine systems. Elevated water temperature has been associated with increased discard mortality (in fishes) in field and lab experiments (Suuronen et al. 1995, Davis 2002). Also because of size, freshwater systems tend to be more commonly affected by a range of stressors, including shoreline development, nutrient loading, siltation, and pollution (Dudgeon et al. 2006). Chronic levels of stress in animals caused by frequent and interacting anthropogenic disturbances could impair animals' capacity to survive or recover from stressful capture events.

Overview of bycatch research in freshwater

Examples of commercial fisheries bycatch research in the freshwater realm are relatively sparse (figure 2). Many mentions of freshwater bycatch issues are merely one or two sentences within studies not focused on bycatch (e.g., Vidal et al. 1997). There are, however, a few examples of comprehensive freshwater bycatch studies. Examples of the issues examined (see the online supplementary material at *www.carleton.ca/fecpl/pdfs/BioScience - Raby et al supplmaterial.pdf*) include reduced reproductive success in sockeye salmon (*Oncorhynchus nerka*) escaping gill nets (Baker and Schindler 2009), incidental capture mortality of recreationally valuable black crappie (*Pomoxis nigromaculatus*) in gill net fisheries for gizzard shad (*Dorosoma cepedianum*; Dotson et al. 2009), lost gill nets causing mass mortality of white sturgeon (*Acipenser transmontanus*) in the Columbia River in the United States (Kappenman and Parker 2007), and the incidental capture and drowning of European otter (*Lutra lutra*) in fyke nets (Koed and Dieperink 1999). Animals with long generation times are often of special concern in the context of bycatch because such species are unable to cope with human-caused increases in adult mortality (Lowry et al. 2005).

Sturgeons (the Acipenseridae) have long generation times and are affected by North American and European inland commercial fisheries targeting other species (Collins et al. 1996, Hensel and Holcik 1997, Bettoli et al. 2009). In Lake Erie, the lake sturgeon (*Acipenser fulvescens*) population is believed to have collapsed as a result of bycatch in gill net fisheries (Regier and Hartman 1973). Gessner and Arndt (2006) evaluated the use of a modified gill net designed to take advantage of the benthic habits of sturgeon. The net was designed to rest 30 centimeters above the lake bottom, thereby allowing sturgeon to pass under the net and resulting in a 99% decrease in bycatch of Siberian sturgeon (*Acipenser baerii*). However, this net modification also led to a reduction in the catch of target species (e.g., pikeperch, *Sander lucioperca*; Gessner and Arndt 2006). Although maintaining catch efficiency for target species is desirable, net modifications that significantly reduce or eliminate bycatch of legally protected species can allow fisheries to remain open where they otherwise might be forced to close as a result of bycatch violations.

Paddlefish (Polyodontidae) are the target of gill net fisheries in several US states, but smaller individuals are also caught as bycatch in those same fisheries as a result of size restrictions (Scholten and Bettoli 2007). The bycatch rate documented for Kentucky Lake, where commercial fishers target mature, egg-laden females, was 92%, with high mortality associated with high water temperatures and lengthy handling times (Bettoli and Scholten 2006).

Freshwater commercial fisheries can also compromise populations of economically valuable sportfish. In the Great Lakes, Johnson and colleagues (2004) found that trap net and gill net fisheries for lake whitefish (*Coregonus clupeaformis*) produce excessive lake trout (*Salvelinus namaycush*) bycatch mortality. For a 100,000-kilogram-per-year commercial lake whitefish gill net fishery, lake trout bycatch was estimated to equal the total estimated surplus production of lake trout available for harvest in that same year (Johnson et al. 2004). Johnson and colleagues (2004) found that trap nets produced far less lake trout bycatch mortality than did gill nets, and that closing the fishery during the summer would reduce the annual lake trout incidental mortality by up to 66% while lowering the annual target species catch by only 10%. Evidently, a simple catch and bycatch data set that incorporates temporal, spatial, and environmental data can help reduce bycatch to acceptably low levels.

Like marine bycatch research, much of the freshwater bycatch literature has focused on the incidental killing of turtles. Turtles typically have very long generation times, rendering their populations extremely sensitive to bycatch mortality. Bycatch mortality can be very high for air-breathing aquatic species (i.e., turtles, mammals, and birds) trapped in underwater nets, especially if the nets are set and left for a number of days (which makes asphyxiation more likely; Fratto et al. 2008). Turtle populations can be devastated quickly because, unlike fishes, their life-history characteristics render them unable to cope with harvest pressure. Fortunately, some recent work has provided simple solutions that reduce turtle bycatch without significantly affecting target species catches (Lowry et al. 2005, Fratto et al. 2008). Turtle excluder devices have already been developed and implemented for marine trawl fisheries; they provide a rigid escape window for turtles and have resulted in significant reductions in incidental mortality of loggerhead sea turtles (*Caretta caretta*) (Crowder et al. 1994, 1995). Lowry and colleagues (2005) adapted concepts from the marine realm and evaluated two TED designs for use in inland commercial fisheries targeting carp (*Cyprinus carpio*) and eels (*Anguilla* spp.). A rigid 100-millimeter exclusion ring for the eel trap prevented large turtles from entering and reduced the total number of turtles caught by 85%, with no effect on the size or number of eels caught. Also, escape chute modifications used in carp traps enabled turtles to escape, reducing turtle bycatch by 77% without affecting carp retention. Lowry and colleagues (2005) demonstrated that concepts can be successfully borrowed from marine bycatch studies to prevent the unwanted bycatch of long-lived vertebrates: These TEDs were eventually implemented as a result of the research (Michael B. Lowry, New South Wales Department of Primary Industries, personal communication, 20 September 2009).

Unfortunately, one of the best examples of the effects of bycatch from commercial fishing involved the first human-caused extinction of a cetacean: the Yangtze River dolphin (also known as the baiji; *Lipotes vexillifer*). Turvey and colleagues (2007) reported that the species had been extinct since the last confirmed sighting in 2002, having fallen in population from 400 individuals in 1979–1981 to 13 in 1997–1999. The authors cite unsustainable bycatch rates in commercial fisheries (employing rolling hooks, gill nets, fyke nets, and electro-fishing) as the primary cause of extinction. Vidal and colleagues (1997) predicted the extinction of the baiji and also suggested that commercial fisheries threaten riverine dolphins elsewhere, including those inhabiting the Amazon River (Silva and Best 1996). The unsustainable bycatch rates that led to the baiji's extinction are also cited as a chief threat to the Yangtze finless porpoise (*Neophocaena phocaenoides asiaeorientalis*), which is listed as endangered by the International Union for Conservation of Nature (Zhao et al. 2008).

Research opportunities for freshwater commercial bycatch

The eastern Pacific dolphin bycatch saga is unlikely to be matched in scale by any freshwater bycatch management issue. The intense attention, first from environmental groups and subsequently from the public, drove research and development and forced the fishery to adopt new methods (Hall 1998). Because dolphins are charismatic and highly valued by society, it was possible for a bycatch-reduction drive from environmental groups to gain traction with the public and fisheries managers. A comparable scenario is unlikely to arise for freshwater commercial fisheries bycatch because most bycatch problems do not involve charismatic megafauna that engender strong public sympathy. Lower-profile conservation issues require simpler, quicker, and less costly solutions than dolphin bycatch received. Fortunately, many bycatch problems can be solved using (a) knowledge of what bycatch is occurring where and when; and (b) an understanding of the behavior, spatial ecology, and life histories of the species at risk.

Data on the spatiotemporal distribution of bycatch is typically gathered by observer programs, which have been crucial in identifying and describing bycatch species and rates in the marine realm (Hall 1996). Many inland fisheries, particularly in developing countries, operate at small scales, however, and the use of observer programs may be impractical (e.g., no room on the vessel). As such, there may be opportunity for self-reporting of bycatch rates. Given that many inland commercial fisheries in developing countries are unregulated, a mechanism for reporting bycatch in those situations remains elusive. Nonetheless, determining bycatch rates is an obvious starting point for the identification of potential problems that require study and management action. In artisanal fisheries in developing countries, it is likely that much of the bycatch is consumed rather than discarded but there is little quantitative data to support that supposition. Observer or self-reporting programs are an essential first step to quantifying bycatch and should be implemented in inland commercial fisheries where species of special concern may be affected by the fishery. Such programs can achieve two objectives: (1) identify bycatch issues of concern, and (2) collect both quantitative and qualitative data on those issues. Once this basic step begins to return data, simple solutions that reduce bycatch without affecting target catch should be sought. Similar data can be gathered by commissioning fishers to conduct fishing operations solely for the purpose of research (Johnson et al. 2004). These data can then reveal the catch-to-bycatch ratio of fishing in different periods of time, or with different gear types (Johnson et al. 2004). These research steps represent an effort to reduce the encounter rate between fishing gear and nontarget species and, as such, represent a first line of defense (Hall 1996).

The study of organismal behavior and spatial ecology to determine bycatch risk is more difficult because it requires a species-specific approach, but fortunately a great deal of ecological knowledge is already available for many inland aquatic systems where species listed as threatened, rare, or of ecological significance have been well studied. Such information can help focus fishing effort spatially and temporally to reduce encounters with nontarget species (Johnson et al. 2004). Once again, however, developed countries targeting economically important species are more likely to have ample data on the ecology of target species and bycatch, whereas species in developing countries may be poorly studied.

The second type of research that should be part of bycatch reduction efforts is that which seeks to improve the selectivity of the gear being used (e.g., Barlow and Cameron 2003). This research area represents a second line of defense for bycatch management. Although encountering and subsequently escaping fishing gear can be harmful to animals, it should be considered preferable to the requirement that fishers pull their gear and release the animals, a process that has the potential to exacerbate stress and injury among discards. Some of the few freshwater commercial fisheries bycatch studies to date provide examples of the research opportunities in this area. With an understanding of the morphology and behavior of nontarget species of concern, modifications to existing net designs can be made (Lowry et al. 2005, Gessner and Arndt 2006). Independent of scale, many types of fishing gear employed by commercial fisheries in marine systems are identical to those used in freshwater fisheries; therefore, most of the BRDs developed for marine fisheries should be adaptable to freshwater.

The final pursuit in a bycatch research strategy should be to develop an understanding of the fate of discards and animals that have escaped fishing gear. As part of an adaptive management cycle for bycatch programs, studying discards provides the opportunity to determine whether certain gear modifications or handling techniques improve the sustainability of populations. By controlling environmental variables, gear types, and handling techniques, researchers can identify the factors influencing discard fate and apply that knowledge to fishing practices (e.g., Olla et al. 1998). Understanding discard fate for marine species so far has been largely limited to examining immediate mortality in the lab (Davis 2002). Because of their smaller size, freshwater environments provide a novel opportunity to develop a detailed understanding of the fate of discarded animals through the use of biotelemetry (remote monitoring of animal behavior, physiology, or energetics; Cooke et al. 2004). To date, only two studies of freshwater commercial fisheries discards have used biotelemetry (i.e., Makinen et al. 2000, Armstrong and Hightower 2002), but biotelemetry is widely used to study fish released by recreational fishers (Donaldson et al. 2008). Other promising tools for commercial bycatch in freshwater that are currently being developed in marine systems are predictive measures of postrelease mortality (Davis 2010) and the use of recovery techniques to improve postrelease survival (Farrell et al. 2001). Additionally, the use of physiological sampling to understand the stress of capture events (i.e., conservation physiology; Wikelski and Cooke 2006) remains underused in discard research in both marine and freshwater environments.

Of 37 freshwater commercial bycatch papers yielded by our search, 35 presented research on issues in developed countries. This finding provides two conclusions: (1) there is ample opportunity for research on freshwater bycatch in developed countries, and (2) commercial bycatch is especially underresearched in the inland waters of developing countries. The need to increase research efforts in the developing world is particularly pressing given data that show most of the inland commercial catch occurs there (FAO 2009). In fact, the catch estimates for inland waters may be grossly underestimated, given how poorly monitored freshwater fisheries in developing countries are. Addressing the need for bycatch research in freshwater systems of developing countries will most likely require funding and support from NGOs and the United Nations, similar to funding models for other conservation research in the developing world. Involving local researchers in these research programs is crucial, particularly in obtaining authorization to conduct research. Achieving conservation objectives through bycatch mitigation in developing countries will also require the involvement of NGOs, local stakeholder groups, soft regulatory approaches (e.g., guidelines and incentives), and other creative solutions. Nevertheless, consideration of mitigation options is predicated on knowledge of bycatch issues through research. In both developed and developing countries, this research represents a potentially vast and currently untapped potential for generating gains in conservation.

Conclusions

Commercial fisheries bycatch in freshwater systems is an area that requires additional study to document the extent of the problem and to identify means of reducing bycatch and discard mortality. To date, freshwater conservation concerns have received less public attention than problems in terrestrial and marine ecosystems. Conservation research in freshwater systems has been directed at the litany of ecosystem-altering anthropogenic stressors, and commercial fisheries bycatch has been ignored—a shortcoming that we must now address. The few studies on freshwater bycatch indicate that bycatch rates can be substantial and can lead to species decline and even extinction (Turvey et al. 2007, Shirley et al. 2009), but effective solutions can be found (e.g. Johnson et al. 2004, Lowry et al. 2005). Conducting research on the impacts of bycatch in freshwater commercial fisheries is a unique opportunity not only because of the pressing need for such research but also because this research can benefit from important insights gleaned in the marine realm. Research on freshwater commercial bycatch can also benefit, wherever possible, from using tools and technologies borrowed from the recreational fisheries catch-and-release literature (Donaldson et al. 2008). Commercial fisheries bycatch in freshwater therefore has tremendous potential not only to address pressing conservation problems but also to inform bycatch studies in the oceans, particularly with respect to the fate of discarded organisms. An obvious starting point is to simply quantify inland bycatch levels, a challenging task because many inland commercial fisheries are poorly regulated and occur in jurisdictions where even basic metrics such as harvest rates are not monitored. We believe there is a need for research aimed at documenting and identifying problems with inland bycatch, and more important, for developing strategies to reduce bycatch and ensure that fisheries are sustainable. We sincerely hope that this review will stimulate such monitoring and research and bring greater attention to bycatch in inland fisheries.

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