Rev Fish Biol Fisheries (2012) 22:719–737
DOI 10.1007/s11160-012-9269-3

REVIEW

Trends in shark bycatch research: current status and research needs

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Received: 23 December 2011 / Accepted: 21 May 2012 / Published online: 3 June 2012

Abstract Over the last few decades, much effort has been devoted towards quantifying and reducing bycatch in marine fisheries. Of late, there has been a particular focus on sharks given that bycatch is a frequently listed threat for sharks on the International Union for the Conservation of Nature Red List. However, currently there are no quantitative reviews or syntheses that explore the issue of shark bycatch globally which is problematic given that such a synthesis could inform conservation actions and identify pressing research gaps. We performed a qualitative and quantitative survey of the peer-reviewed literature to characterize trends in shark bycatch research with a particular goal of identifying research needs and opportunities. Using a structured literature review we identified 103 papers that met our search criteria, with the first one published in 1993. Early research efforts focused on documenting the scope of bycatch (i.e., determining that sharks were indeed captured as bycatch), but more recently there have been increased efforts devoted to developing and evaluating bycatch reduction strategies for sharks. Research activity was most common in the North Atlantic (~40 % of the total articles analysed) with comparatively less research in other areas such as the Indo-Pacific region where shark bycatch is regarded as particularly common and problematic. Most studies were observational with comparatively fewer experimental and modeling studies, and even fewer that combined research approaches. Gear modifications (e.g., hook size and type for long lines, net size and mesh design for nets) were the most commonly evaluated strategy for reducing shark bycatch; however, development and use of techniques like repellents, or seasonal area closures, or a combination of strategies, offer interesting possibilities that require further study. In addition, although many sharks are discarded, little is known about post-release survival or sub-lethal consequences of fisheries interactions, or evaluations of different fish handling strategies, making it difficult to quantify the true cost of bycatch or to recommend handling strategies to fishers. Although there are some inherent challenges with developing and testing shark bycatch reduction strategies, there is an urgent need to do so and this would be best achieved through interdisciplinary research that spans field, laboratory, and modeling realms.

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Keywords Sharks · Bycatch · Trends · Conservation · Review

Introduction

Sharks and other chondrichthyans are a relatively conserved group of fishes that have successfully functioned in diverse marine ecosystems for over 400 million years (Camhi et al. 2007). Sharks in particular play an important role in structuring marine communities by influencing mortality rates and behaviour of mesoconsumers and other organisms (Heithaus et al. 2008). The life history of these fishes is characterized by late maturity, long life spans, long gestation periods, and few well developed offspring (Dulvy et al. 2008). Additionally, some sharks gather in schools by age, sex, and reproduction states, while others have restricted distributions (Barker and Schluessel 2005). These life history traits confer a low intrinsic rate of population increase and growth, rendering sharks extremely vulnerable to fishing mortality (Dulvy et al. 2008). Indeed, globally shark populations are in decline (Camhi et al. 2007) as a result of a variety of stressors and threats including fishing mortality arising from targeted harvest and incidental capture (i.e., bycatch). From the 176 species of shark monitored by the International Union for the Conservation of Nature (IUCN), 27.27 % were reported to be Near Threatened, 22.72 % Vulnerable, 6.25 % Endangered, and 5.68 % Critically Endangered (based on an analysis conducted by J. Molina on June 1, 2011). This means that approximately 62 % of the total shark species are facing major conservation threats. In addition, there are also 63 species of sharks that are categorized as data deficient, for which there is simply insufficient validated information available about their status and threats but for which surely more of them are imperiled.[1]

Bycatch is the accidental capture of non-targeted species or undesirable size ranges of the target species by non-selective fishing gear (Hall 1996; Crowder and Murawski 1998). Species with low resilience to fishing practices can be severely affected by bycatch, which poses a serious conservation concern in a variety of ecosystems and for a variety of taxa (e.g., Barker and Schluessel 2005; Raby et al. 2011). Moreover, much of the discarded catch is not documented, which makes a proper evaluation of bycatch more difficult (Romanov 1999; Barker and Schluessel 2005). Early work on bycatch identified that between 17.9 and 39.5 million tons of fish were discarded annually in marine commercial fisheries (Alverson et al. 1994), but more recent estimates suggest that the number may be closer to 6.8 million tons (Kelleher 2005). Although it is unclear why this apparent reduction has occurred, there is some evidence that awareness of bycatch as a conservation concern and the associated development and implementation of bycatch reduction strategies may be contributing factors (Kelleher 2005). There have been a variety of syntheses on bycatch (e.g., Davis 2002; Broadhurst et al. 2002; Hall and Mainprize 2005; Soykan et al. 2008) and even some that briefly discuss sharks (e.g., Lewison et al. 2004; Zydelis et al. 2009) or focus entirely on sharks (e.g., Ward and Hindmarsh 2007; Mandelman et al. 2008; Watson et al. 2008; Blaber et al. 2009). Of the reviews available that focus shark bycatch, they tend to be limited to a particular species (e.g., Watson et al. 2008), certain location (Mandelman et al. 2008; Blaber et al. 2009), or specific type of fishing practice (Ward and Hindmarsh 2007; Gilman et al. 2007), with no global synthesis of trends in shark bycatch research. Bycatch is the most frequent threat for sharks, accounting for 66.9 % of shark species reported by the IUCN that are facing conservation threats (see footnote 1). However, currently there are no quantitative reviews or syntheses that explore the issue of shark bycatch globally. An authoritative and contemporary overview of the threats from non-retention shark fisheries could inform conservation actions and identify pressing research gaps.

The aim of this study was characterize trends in shark bycatch research and identify key research needs and opportunities. Given that shark bycatch is already recognized as a problem, we focus much of our analysis on the evaluation of strategies to reduce bycatch or to improve the fate of sharks that are captured and discarded. To do so, we performed a qualitative and quantitative survey of the peer-reviewed literature dealing with shark bycatch.

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[1] All shark species listed in the IUCN red list of endangered species until 2011 were analyzed. Species conservation category, population status and threat information was extracted and used to create a database, from which percentage of each category, and occurrence of each mayor population threat was calculated, in order to describe the conservation status, and find at which extent bycatch represents the major threat for sharks.

Materials and methods

Structured literature searches were conducted to generate a database of shark bycatch literature for the quantitative review. We recognize all elasmobranchs are susceptible to bycatch but for the purpose of this review we focus on sharks (i.e., Selachii) and exclude the rays and skates (i.e., Batoidea). In addition, we focused our synthesis on bycatch associated with commercial or artisanal fisheries and excluded recreational fisheries where fish are discarded but where they may be intentionally targeted as part of a practice known as catch-and-release angling (Arlinghaus et al. 2007). There is certainly a growing interest and body of research on recreational catch-and-release angling impacts on sharks (e.g., Gurshin and Szedlmayer 2004; Lynch et al. 2010), but we consider those issues to be sufficiently different such that we excluded excluded recreational fisheries from the current review. Some papers, especially those that were experimental, used generalized techniques to induce stress and did not specify whether their study was focused on recreational or commercial fisheries (e.g., Brill et al. 2008) so those studies were not excluded. Searches were performed using Web of Science, Scopus, and Google Scholar, with the Boolean search terms: bycatch, by-catch, shark*, incidental catch, and discard*. We recognize that this approach has the potential to miss articles that could otherwise be found by using cited reference searches, trolling through websites for individual researchers, or looking through literature cited lists but this structured approach means that our search could be replicated which is an essential element of quantitative literature reviews (Pullin and Stewart 2006). As noted below, we do refer to and cite additional relevant papers that we found via means other than our structured search, but they were relatively sparse such that we are confident that the trends characterized in the structured review is indeed representative of the broader literature and knowledge base. Only peer-reviewed articles written in English were included in the structured literature review. We recognize the potential bias associated with this approach but the majority of international journals are published in English. We excluded non-peer reviewed literature (e.g., thesis papers, technical reports from governments) because their likelihood of being available in English was much reduced and thus we were concerned with further biasing the sample towards areas such as North America, Australia and Europe. The literature search was conducted between January and April 2011 and updated in April 2012. The quantitative literature review focused on papers prior to 2012, however, papers from 2012 (including those emanating from special "shark focused" issues of Journal of Fish Biology and Comparative Physiology and Biochemistry A) were cited where appropriate. After the structured database was generated, each paper was examined individually and those that were false positives (i.e., did not have to deal with shark bycatch; ~30 %) were excluded yielding a total of 103 papers on shark bycatch. These papers were then read and information extracted and entered into a database (MS Access 2007) by the same individual to ensure consistency. For each article, multiple data elements were extracted including the type (e.g., laboratory experiment, field experiment, modeling study, review, observational study) and general objective of the article (e.g., reduce capture, reduce mortality, supply information, analyze species' bycatch, analyze fleet bycatch, provide management strategies), type of fishery (e.g., subsistence, commercial) and the scale (artisanal small-scale or industrial), location of the fishery (e.g., north and south Atlantic, north and south Pacific, Indian and Mediterranean oceans), fishing gear (e.g., longline, trawling nets, gill nets, purse seine, etc.), target species, number of shark bycatch species reported/studied, scale of the consequences (e.g., community/assemblage, population, or individual mortality, as well as sub lethal effects, like injury, behaviour, and physiological effects), and proposed changes to reduce bycatch (e.g., changes in gear, fishing practices, handling, use of repellents, etc.). Where summary statistics are presented as means the error term represents one standard deviation.

Findings

Characteristics of shark bycatch literature

In total, we found 103 papers on shark bycatch (Table 1). The first paper (Russell 1993) on shark bycatch was published in 1993 with a reasonably steady increase in publications through to current day. The maximum number of studies per year was in 2011 when 15 articles on shark bycatch were published.

Table 1 Literature (organized alphabetically by author last name) located by the structured literature search and synthesized as part of qualitative and quantitative review of trends in shark bycatch research

Author (year)	Article type	Article objective	Scale of the fishing fleet	Location of the fishery	Fishing gear used	Target species	Scale of the consequences	Proposed changes
Afonso et al. (2011)	Field experiment	Reduce mortality	Large scale	South Atlantic	Long lines	Large osteicht	Mortality	Type/Size of hooks
Alverson et al. (1994)	Review	Supply management strategies	Large scale	Multiple	Multiple types		Assemblages	Multiple
Arocha et al. (2002)	Observational	Supply information	Large scale	North Atlantic	Long lines	Large osteicht	Population	No change suggested
Baeta et al. (2010)	Observational	Fleet bycatch analysis	Artisanal	North Atlantic	Trammel nets	Polyspecific	Assemblages	No change suggested
Barker and Schluessel (2005)	Review	Supply management strategies	Large scale	Multiple	Multiple types		Assemblages	Type/Size of nets
Beerkircher et al. (2000)	Observational	Supply information	Large scale	North Atlantic	Long lines	Large osteicht	Mortality	Fishing time
Benjamins et al. (2010)	Review	Supply information	Large scale	North Atlantic	Gill nets	Polyspecific	Population	No change suggested
Blaber et al. (2009)	Review	Supply management strategies	Artisanal	Indian	Multiple types	Small elasmobranch	Assemblages	Fishing practice
Belcher and Jennings (2011)	Observational	Fleet bycatch analysis	Large scale	North Atlantic	Trawling nets	Shrimp	Assemblages	No change suggested
Bonfil (1995)	Review	Supply management strategies	Large scale	Multiple	Multiple types	Polyspecific		No change suggested
Brewer et al. (1998)	Field experiment	Reduce capture	Large scale	Indian	Trawling nets	Shrimp	Assemblages	Type/Size of Nets
Brill et al. (2008)	Laboratory experiment	Reduce capture	Large scale	North Atlantic	Long lines	Large osteicht	Sub-lethal: behaviour	Repelents
Broadhurst et al. (2002)	Field experiment	Reduce capture	Large scale	Indian	Trawling nets	Shrimp	Population	Type/Size of Nets
Burgess et al. (2005)	Review	Species bycatch analysis	Large scale	North Atlantic	Multiple types	Polyspecific	Population	No change suggested
Camhi et al. (2007)	Observational	Supply information	Large scale	Multiple	Multiple types	Polyspecific	Assemblages	No change suggested
Campana et al. (2009a, b)	Review	Fleet bycatch analysis	Large scale	North Atlantic	Long lines	Large osteicht	Sub-lethal: injury	No change suggested
Carbonell (2003)	Observational	Species bycatch analysis	Large scale	Mediterranean	Trawling nets	Shrimp	Population	No change suggested
Carruthers et al. (2009)	Observational	Fleet bycatch analysis	Large scale	North Atlantic	Long lines	Large osteicht	Mortality	Type/Size of Hooks
Carruthers et al. (2011)	Field experiment	Reduce capture	Large scale	North Atlantic	Long lines	Large osteicht	Population	Fishing practice
Cartamil et al. (2011)	Observational	Fleet bycatch analysis	Artisanal	North Pacific	Multiple types	Small osteicht	Assemblages	No change suggested
Clarke (2002)	Observational	Species bycatch analysis	Large scale	North Atlantic	Multiple types	Polyspecific	Population	No change suggested
Coelho and Erzini (2008)	Observational	Supply information	Large scale	Mediterranean	Multiple types	Polyspecific	Population	No change suggested
Coelho et al. (2003)	Field experiment	Fleet bycatch analysis	Artisanal	North Atlantic	Long lines	Small osteicht	Assemblages	Fishing practice
Connolly and Kelly (1996)	Observational	Fleet bycatch analysis	Large scale	North Atlantic	Multiple types	Polyspecific	Assemblages	No change suggested

Table 1 continued

Author (year)	Article type	Article objective	Scale of the fishing fleet	Location of the fishery	Fishing gear used	Target species	Scale of the consequences	Proposed changes
Cortés et al. (2009)	Modeling	Supply management strategies	Large scale	North Atlantic	Long lines	Large osteicht	Mortality	No change suggested
Cramer et al. (1998)	Observational	Supply information	Large scale	North Atlantic	Long lines	Large osteicht	Population	No change suggested
Curran and Bigelow (2011)	Field experiment	Reduce capture	Large scale	North Pacific	Long lines	Large osteicht	Assemblages	Type/Size of hooks
de Silva et al. (2001)	Observational	Fleet bycatch analysis	Large scale	North Atlantic	Purse-seine	Small osteicht	Assemblages	No change suggested
Diaz and Serafy (2005)	Observational	Fleet bycatch analysis	Large scale	North Atlantic	Long lines	Large osteicht	Mortality	No change suggested
Dulvy et al. (2008)	Review	Supply management strategies	Large scale	Multiple	Multiple types	Polyspecific	Population	No change suggested
Fennessy and Isaksen (2007)	Field experiment	Reduce capture	Large scale	Indian	Trawling nets	Shrimp	Population	Type/Size of nets
Fogarty and Murawski (1998)	Observational	Fleet bycatch analysis	Large scale	North Atlantic	Multiple types	Polyspecific	Assemblages	No change suggested
Fortuna et al. (2010)	Observational	Fleet bycatch analysis	Large scale	Mediterranean	Trawling nets	Small osteicht	Population	No change suggested
Francis and Duffy (2002)	Observational	Species bycatch analysis	Artisanal	North Atlantic	Trawling nets	Polyspecific	Population	No change suggested
Francis et al. (2001)	Observational	Fleet bycatch analysis	Large scale	South Pacific	Long lines	Large osteicht	Population	No change suggested
Frick et al. (2010)	Laboratory experiment	Supply information	Large scale	South Pacific	Trawling nets	Polyspecific	Sub-lethal: physiological	Fishing practice
Gilman (2011)	Review	Supply information	Large scale	Multiple	Purse-seine	Large osteicht	Mortality	Multiple
Gilman et al. (2007)	Observational	Supply management strategies	Large scale	Multiple	Long lines	Polyspecific	Assemblages	Multiple
Godin and Worm (2010)	Review	Supply management strategies	Large scale	Multiple	Multiple types	Polyspecific	Population	Multiple
Grantham et al. (2008)	Field experiment	Supply management strategies	Large scale	South Atlantic	Long lines	Large osteicht	Assemblages	Fishing closure
Gurshin and Szedlmayer (2004)	Field experiment	Supply information	Artisanal	North Atlantic	Long lines		Sub-lethal: behaviour	No change suggested
Hall et al. (2000)	Review	Supply information		Multiple	Multiple types	Polyspecific	Assemblages	No change suggested
Heithaus et al. (2008)	Modeling	Supply information	Large scale	Multiple	Multiple types	Polyspecific	Assemblages	Multiple
Hill and Wassenberg (2000)	Observational	Fleet bycatch analysis	Large scale	Indian	Trawling nets	Shrimp	Assemblages	Type/Size of nets
Huang (2011)	Review	Supply management strategies	Large scale	North Pacific	Long lines	Large osteicht	Assemblages	Multiple
Huang and Liu (2010)	Observational	Fleet bycatch analysis	Large scale	Indian	Long lines	Large osteicht	Population	Type/Size of hooks
Jones et al. (2011)	Observational	Fleet bycatch analysis	Large scale	Indian	Multiple types	Polyspecific	Population	No change suggested
Jordan et al. (2011)	Laboratory experiment	Reduce capture	Large scale	North Pacific	Long lines	Large osteicht	Sub-lethal: behaviour	Repelents

Table 1 continued

Author (year)	Article type	Article objective	Scale of the fishing fleet	Location of the fishery	Fishing gear used	Target species	Scale of the consequences	Proposed changes
Kaplan et al. (2007)	Modeling	Reduce capture	Large scale	North Pacific	Long lines	Large osteicht	Assemblages	Type/Size of hooks
Kerstetter and Graves (2006)	Field experiment	Reduce mortality	Large scale	North Atlantic	Long lines	Large osteicht	Mortality	Type/Size of hooks
Krogh and Reid (1996)	Observational	Fleet bycatch analysis	Artisanal	South Pacific	Gill nets	Large elasmobranch	Population	No change suggested
Levesque (2008)	Review	Supply information	Large scale	North Atlantic	Long lines	Large osteicht	Population	Multiple
Lewison et al. (2004)	Review	Supply information	Large scale	Multiple	Multiple types	Polyspecific	Assemblages	No change suggested
Mandelman and Farrington (2007)	Laboratory experiment	Species bycatch analysis		Multiple	Trawling nets		Sub-lethal: injury	Fishing practice
Mandelman et al. (2008)	Review	Fleet bycatch analysis	Large scale	North Atlantic	Long lines	Large osteicht	Assemblages	Multiple
Maunder and Punt (2004)	Review	Supply information	Large scale		Multiple types	Polyspecific	Assemblages	No change suggested
McKinnell (1998)	Observational	Fleet bycatch analysis	Large scale	North Pacific	Driftnets	Mollusc	Population	No change suggested
Megalofonou and Deflorio (2005)	Observational	Fleet bycatch analysis		Mediterranean	Long lines		Mortality	No change suggested
Minami et al. (2007)	Modeling	Supply information	Large scale	North Pacific	Purse-seine	Large osteicht		No change suggested
Morgan et al. (2009)	Observational	Fleet bycatch analysis	Large scale	North Atlantic	Long lines	Large elasmobranch	Assemblages	No change suggested
Musyl et al. (2009)	Observational	Supply information	Large scale	North Atlantic	Long lines	Large osteicht	Mortality	No change suggested
O'Connel et al. (2011)	Field experiment	Reduce capture	Large scale	North Atlantic	Multiple types		Sub-lethal: behaviour	Repelents
Ordines et al. (2006)	Field experiment	Reduce capture	Artisanal	Mediterranean	Trawling nets	Polyspecific	Population	Type/Size of nets
Pajuelo et al. (2010)	Observational	Fleet bycatch analysis	Artisanal	Mediterranean	Long lines	Small osteicht	Population	No change suggested
Perez and Wahrlich (2005)	Observational	Fleet bycatch analysis	Large scale	South Atlantic	Gill nets	Small osteicht	Assemblages	No change suggested
Petersen et al. (2009)	Observational	Fleet bycatch analysis	Large scale	South Atlantic	Long lines	Large osteicht	Population	No change suggested
Philippart (1998)	Modeling	Fleet bycatch analysis	Large scale	North Atlantic	Trawling nets		Population	No change suggested
Poisson et al. (2009)	Observational	Fleet bycatch analysis	Large scale	North Pacific	Long lines	Large osteicht	Sub-lethal: injury	Fish handling
Polovina et al. (2002)	Observational	Supply information	Large scale	North Pacific	Long lines	Large osteicht	Assemblages	No change suggested
Punt et al. (2006)	Modeling	Supply information	Large scale	South Pacific	Long lines	Polyspecific	Population	No change suggested
Revill et al. (2005)	Field experiment	Fleet bycatch analysis	Large scale	North Atlantic	Trawling nets	Polyspecific	Mortality	No change suggested
Richards (1994)	Review	Fleet bycatch analysis	Large scale	South Pacific	Driftnets	Polyspecific	Mortality	No change suggested
Robbins et al. (2011)	Field experiment	Reduce capture	Artisanal	South Pacific	Hook and line	Polyspecific	Sub-lethal: behaviour	Repelents
Rodríguez-Cabello et al. (2005)	Observational	Species bycatch analysis	Large scale	North Atlantic	Trawling nets	Polyspecific	Mortality	No change suggested
Rodríguez-Cabello et al. (2005)	Observational	Supply information	Large scale	North Atlantic	Long lines	Large osteicht	Mortality	No change suggested
Rogan and Mackey (2007)	Observational	Fleet bycatch analysis	Large scale	North Atlantic	Driftnets	Polyspecific	Mortality	No change suggested
Romanov (1999)	Observational	Fleet bycatch analysis	Large scale	Indian	Purse-seine	Large osteicht	Assemblages	No change suggested

Table 1 continued

Author (year)	Article type	Article objective	Scale of the fishing fleet	Location of the fishery	Fishing gear used	Target species	Scale of the consequences	Proposed changes
Romine et al. (2009)	Modeling	Species bycatch analysis	Large scale	North Atlantic	Long lines	Polyspecific	Mortality	Fishing closure
Russell (1993)	Observational	Fleet bycatch analysis	Large scale	North Atlantic	Long lines	Large osteicht	Population	No change suggested
Samaranyanka et al. (1997)	Field experiment	Fleet bycatch analysis	Artisanal	Indian	Driftnets	Large osteicht	Population	No change suggested
Schindler et al. (2002)	Modeling	Supply information	Large scale	North Pacific	Long lines	Large osteicht	Population	No change suggested
Shepherd and Myers (2005)	Field experiment	Supply information	Large scale	North Atlantic	Multiple types	Polyspecific	Assemblages	No change suggested
Skomal (2007)	Review	Supply information	Large scale	North Atlantic	Long lines	Large osteicht	Sub-lethal: physiological	No change suggested
Stobutzki et al. (2001)	Observational	Fleet bycatch analysis	Large scale	Indian	Trawling nets	Shrimp	Assemblages	Multiple
Stobutzki et al. (2002)	Observational	Fleet bycatch analysis	Large scale	Indian	Trawling nets	Shrimp	Assemblages	No change suggested
Stoner and Kaimmer (2008)	Laboratory experiment	Reduce capture	Large scale	North Atlantic	Long lines	Large osteicht	Sub-lethal: physiological	Repelents
Storai et al. (2011)	Observational	Fleet bycatch analysis	Artisanal	Mediterranean	Multiple types	Large osteicht	Assemblages	No change suggested
Swimmer et al. (2011)	Field experiment	Reduce capture	Large scale	North Pacific	Long lines	Large osteicht	Assemblages	Type/Size of hooks
Thorpe and Frierson (2009)	Field experiment	Reduce capture	Artisanal	North Atlantic	Gill nets	Small osteicht	Assemblages	Fishing practice
Trent et al. (1997)	Observational	Fleet bycatch analysis	Large scale	North Atlantic	Driftnets	Small elasmobranch	Assemblages	No change suggested
Valenzuela et al. (2008)	Observational	Supply information	Artisanal	South Pacific	Long lines	Polyspecific	Population	No change suggested
Vega and Licandeo (2009)	Field experiment	Fleet bycatch analysis	Large scale	South Pacific	Long lines	Large osteicht	Assemblages	Fishing practice
Walker et al. (2005)	Field experiment	Fleet bycatch analysis	Large scale	South Pacific	Multiple types	Small elasmobranch		No change suggested
Ward and Hindmarsh (2007)	Review	Fleet bycatch analysis	Large scale	North Pacific	Long lines	Large osteicht	Assemblages	No change suggested
Ward et al. (2008)	Field experiment	Reduce capture	Large scale	South Pacific	Long lines	Large osteicht	Population	Type/Size of hooks
Ward et al. (2009)	Field experiment	Reduce capture	Large scale	South Pacific	Long lines	Large osteicht	Population	Type/Size of hooks
Watson et al. (2008)	Modeling	Supply management strategies	Large scale	North Pacific	Purse-seine	Large osteicht	Population	Fishing closure
Whoriskey et al. (2011)	Observational	Fleet bycatch analysis	Large scale	North Pacific	Long lines	Small osteicht	Assemblages	No change suggested
Yamandú et al. (1998)	Observational	Fleet bycatch analysis	Large scale	South Atlantic	Long lines	Large osteicht	Population	No change suggested
Yokota et al. (2006)	Field experiment	Reduce capture	Large scale	North Pacific	Long lines	Large osteicht	Population	Type/Size of hooks
Zeeberg et al. (2006)	Field experiment	Reduce mortality	Large scale	North Atlantic	Trawling nets	Small osteicht	Mortality	Type/Size of nets
Zhou et al. (2011)	Modeling	Supply information	Large scale	Multiple	Multiple types	Polyspecific	Assemblages	No change suggested
Zollett (2009)	Observational	Supply information	Large scale	North Atlantic	Multiple types	Large osteicht	Assemblages	No change suggested

We found several temporal trends in the literature reviewed. In general, the early studies tended to focus on trawl fisheries, while more recent studies have focused on long line fisheries. Moreover, early studies tended to not explore reduction strategies, while nearly all current studies explore potential solutions to bycatch rather than just emphasizing the problems. Early studies mainly analyzed levels and composition of bycatch (i.e., observational studies aboard fishing vessels) while recent studies have been more diverse focus, with modeling, laboratory, and field experiments. Also in recent years, a variety of biological endpoints have been studied. Early literature focused exclusively on population-level parameters or mortality consequences whereas recent papers include sublethal endpoints such as physiological stress (e.g., Mandelman and Farrington 2007), behaviour (e.g., Brill et al. 2008), and injury (e.g., Poisson et al. 2009; Campana et al. 2009a) (Fig. 1a).

Published research on shark bycatch that has been conducted in the North Atlantic Ocean represents almost 40 % of the total articles analysed, while the North Pacific Ocean accounted for 14.4 %. Studies that involved multiple locations comprised 14.4 % of papers. FAO (food and agricultural organization of the United Nations) statistics as presented by Barker and Schluessel (2005) show that most elasmobranch catches occur in developed countries of the Indian (10.6 %) and Pacific Oceans (South Pacific Ocean comprised 10.6 % of the studies). Interestingly, comparatively few peer reviewed studies dealing with shark bycatch the Indo-Pacific region were found.

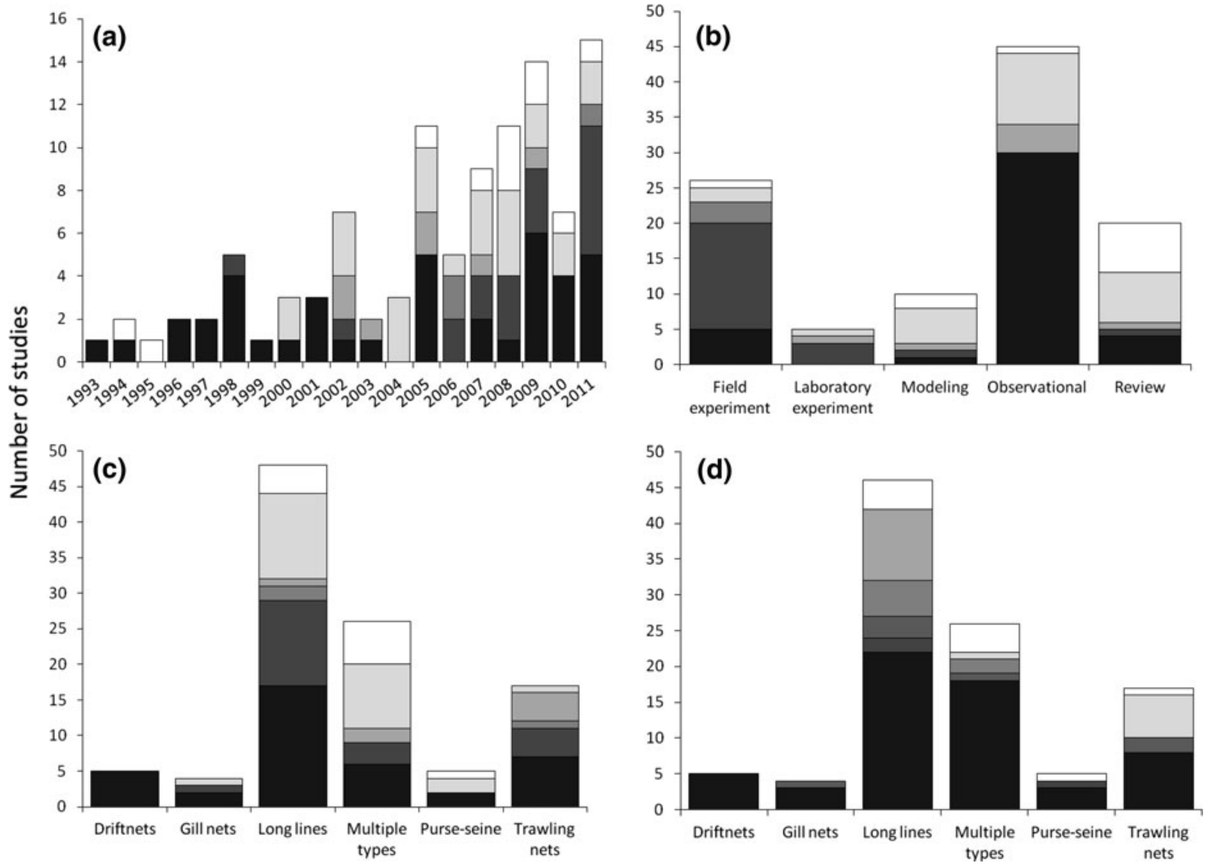

Fig. 1 Number of articles for **a** each year, **b** each article type, **c** each fishing gear by article objective (□ Supply management strategies, □ Supply information, ▨ Species bycatch analysis, ▨ Reduce mortality, ■ Reduce capture, ■ Fleet bycatch analysis) and **d** for each fishing gear by suggested bycatch reduction strategies (□ Multiple types, □ Type/Size of nets, ▨ Type/Size of hooks, ▨ Repelents, ■ Fishing practice, ■ Fishing closure, ■ No change suggested). *Note*: For better interpretation, Trammel nets and hook and line gear, and Fishing time and fish handling bycatch reduction strategies were ecluded since they only comprised one article each

Literature collected for South Atlantic and Mediterranean Oceans was scarce; 4.8 and 6.7 % respectively.

Studies of shark bycatch tended to focus on either one species (e.g., Campana et al. 2009a, b) or on many species (e.g., Petersen et al. 2009; Morgan et al. 2009; Godin and Worm 2010; described as many as 25, 26 and 28 shark bycatch species, respectively). Because of the great disparity in the number of species studied, measures of central tendency (i.e., the average was 6.13 ± 6.61 species) fail to characterize the pattern appropriately. The modal number of species was 1, accounting for 25 % of all studies.

Most studies found dealt with the analysis and description of shark bycatch in a particular fishery (38.4 % of the total studies). Observational studies where "observers" monitored and recorded shark bycatch information that was subsequently synthesized in the context of a real fishery (on occasion as part of government research fishery activities) comprised a substantial amount of the published shark bycatch research (28.4 % of the total studies; Fig. 1b). In general, observational studies predominated (43.3 %) although a fair amount of field experiments (23.1 %) and reviews (19.2 %) were also conducted.

There was a particular focus on large-scale long line fisheries for tunas and swordfish (44.8 % of the total studies) seconded by multispecies fisheries (31.2 %). Other types of fisheries represented less than a 10 % of the total studies. The focus on the tuna fishery can be explained by the importance of tuna landings, being the third most landed fish worldwide, with values over six million tons per year (FAO 2008).

Long line fisheries reviews and studies accounted for 44.6 % of the studies analysed, of which 34.7 % were aimed to reduce bycatch. Trawling fisheries were the focus of 16.5 % of the studies examined of which 29.4 % were aimed at reducing bycatch (Fig. 1c). Trawling, specially bottom trawling, represents one of the most destructive fishing methods, as it not only represents the bulk of the near 30 million tons of bycatch discarded annually, it also destroys bottom structures and communities, which have key roles in the recruiting of young fish (Pauly 2002). Cook (2003) found that trawl fisheries, in particular shrimp trawl fisheries (3 million tons per year; FAO 2008), have high bycatch rates compared to long line fisheries. Hill and Wassenberg (2000) found that 98 % of the total fish discarded from trawling vessels were dead. This is of interest because research by Poisson et al. (2009) shows that the mortality of sharks (at haul-back—no information on delayed mortality) in long line fisheries for tunas and swordfish is relatively low for the species they analyzed. Mandelman et al. (2008) and Beerkircher et al. (2000) also conducted mortality assessments on longline fisheries in the USA, and found only three species of sharks (namely *Carcharhinus signatus*, *C. falciformis* and *Sphyrna lewini*) of the ten species assessed to have mortality rates over 50 %. Our results suggest that studies dealing with shark bycatch are often focused on tuna and swordfish longline fisheries. Although relevant given the apparently variable at-vessel mortality among shark species for longline fisheries and the fact that pelagic longline fisheries are the dominant mode of capture for sharks globally, trawl fisheries deserve future attention given the high bycatch and mortality rates, reduction in recruit biomass and habitat loss associated with that gear. Mortality rates on trawling vessels for some species of sharks seems to be lower when tow duration remains lower than 30 min, and fish are returned to the sea in less than 30 min (Rodríguez-Cabello et al. 2005).

Literature reviewed tended to focus on large-scale industrial fisheries (86.1 % of the total studies), while artisanal fisheries were less frequently studied (13.9 % of the total studies). At this point it is unclear if that pattern signifies there are fewer incidences of shark bycatch for small-scale artisanal fisheries or if it simply reflects the fact that industrial fisheries tend to operate out of developed countries where governance structures require bycatch reduction research and research capacity exists to conduct such studies. Considering the study by Pauly (2002) the case seems to be the former.

Trends in research on strategies for reducing/mitigating bycatch

Bycatch reduction strategies were suggested in 41.6 % of the reviewed articles. Net size (e.g., Sobrino et al. 2000) and mesh design (e.g., Broadhurst et al. 2002; Ordines et al. 2006) were the most frequent change suggested for trawl fisheries (66.7 % for studies on this fishing gear). For longline fisheries, hook size and type (e.g., circle hooks; Kaplan et al. 2007; Ward et al. 2009) were the most frequently suggested change (45.4 % for studies on this fishing gear; Fig. 1d), but some studies also noted an important role of bait type (e.g., Watson et al. 2005). Historically, gear selectivity has been an issue for fisheries managers who attempt to minimize the capture of undersized target species, providing escapement opportunities in the gear design (Armstrong et al. 1990; Dawson 1991; Millar 1992). This issue has been addressed by many authors (MacLennan 1995; Sobrino et al. 2000; Smith and Jeremy 2005), and different solutions exist. However, reducing bycatch is a more complex problem, since size is not the only variable to be taken into account. For instance, sharks taken as bycatch are often very different in shape and often several times larger than target species. This has been observed in the New Zealand commercial trawl fishery (Francis and Duffy 2002). Design changes, such as the ones proposed by Brewer et al. (1998), Broadhurst et al. (2002), Zeeberg et al. (2006) and Chosid et al. (2012) for trawl nets which recognize the differences between target species and bycatch such as sharks could be effective for reducing shark bycatch. In general, there is little work on strategies to reduce the high mortality rates associated with trawl nets caused by fish packing in the net and fish handling once on board (Frick et al. 2010).

Regulations on fishing zones (i.e., area closures/restrictions) and the timing (i.e., temporal closures/restrictions) of commercial fishing activities were only reported in 9.9 % of the studies that we reviewed (e.g., Beerkircher et al. 2000; Watson et al. 2008; Romine et al. 2009). Regulations involving closure of fishing zones in combination with regulated fishing times are common practices used to reduce bycatch levels (Alverson et al. 1994). In this type of scenario, fishing fleets are allowed to operate only in a certain area at a certain time, in order to avoid high concentrations of bycatch species, or to encounter high concentration of target species. However, information about the seasonal and diel variation in fish distribution (both of target and bycatch species) is needed for this strategy to be implemented properly, which is not the case for many fisheries. Hoffmayer et al. (2012) studied the seasonal variation in stress response of *Rhizoprionodon terraenovae* and found summer to be the most vulnerable season for this species. This type of information combined with regulations on fishing zones and timing might prove an effective bycatch reduction strategy. However, basic information on movement and spatial ecology is lacking for all but a few species making use of area and time closures challenging and ineffective.

Repellent agents (including electricity, magnets and surfactants) have been used worldwide to protect bathing beaches, divers, and aquaculture gear form shark attack (e.g., Kalmijn 1982; Sisneros and Donald 2001). There is also potential for such deterrent devices to be used on fishing gear to reduce shark bycatch (discussed in Gilman et al. 2007), however, there remain challenges with the implementation of such tools. Many repellents that involve electricity or magnets are large, expensive, and not practical for wide-scale use in fisheries (Frick et al. 2010). As part of the quantitative literature review we only found 5 papers (4.9 % of total studies analysed) focused on exploring the potential use of rare-earth (lanthanide) metals and alloys and permanent magnets that could be incorporated into hooks to repel sharks (Brill et al. 2008; Kaimmer and Stoner 2008; Jordan et al. 2011; O'Connel et al. 2011; Robbins et al. 2011). However, we found additional 2 papers outside of the structured literature review (e.g., Stoner and Kaimmer 2008; Tallack and Mandelman 2009) emphasizing that some of those studies do not use keywords or title elements related to bycatch so were missed by our structured search. The results from most of the studies on rare-earth (lanthanide) metals and alloys are promising, although the use of this bycatch reducing strategy is still rather undeveloped, and further studies on the subject needed to assess its applicability in large-scale commercial fisheries. Use of chemical-based repellents also has promise but it is necessary to understand how such repellents influence target species.

Research needs and opportunities

Our synthesis revealed a number of limitations with current knowledge on shark bycatch which leads to a number of research needs (i.e., in the context of management and conservation) and opportunities. Below we provide a list of what we regard as critical research needs as well as a rationale and discussion of how these research needs could be addressed.

Need for studies that combine approaches (e.g., field, lab and modeling)

In our survey we found few articles combining laboratory and field experiments with modeling studies on sharks. Combined approaches have led to important findings in the field of bycatch assessment. For example, Goldsworthy and Page (2007) identified important mitigation opportunities to reduce pinniped bycatch produced by Australian fisheries by performing a risk assessment using data from different realms. Also working with a marine mammal, the harbour porpoise (*Phocoena phocoena*), Orphanides (2010) revealed that bycatch estimates were more stable when using a combined approach, than using only the ratio estimate approach. Of particular benefit would be the ability to scale experimental laboratory and field research to the ecosystem level using modeling techniques. There is also much benefit from combining controlled laboratory experiments with field observations whereby mechanisms and detailed aspects can be evaluated in the laboratory and then the innovations (e.g., say in a gear modification) can be tested in the field. Not surprisingly, given the size of sharks there have been relatively few laboratory studies on fisheries interactions but there are a number of large research aquaria around the world where studies could occur. It is also possible to use field mesocosms such as large pen enclosures as has been used to study lemon shark energetics at Bimini, The Bahamas (Shepard et al. 2008) or adult whitetip reef sharks (*Triaenodon obesus*) in a lagoon in Kaneohe Bay at the Hawaii Institute of Marine Biology (Whitney et al. 2007). In such facilities captive sharks can be studied to examine the long-term consequences of fisheries interactions including healing of injuries, delayed mortality, and to generate stress profiles. Moreover, it would be possible to design experiments to evaluate post-release behaviour (and physiology using devices like heart rate loggers) relative to different types of fisheries interactions.

Need for experimental studies on shark repellents or other aspects of sensory physiology relevant to shark bycatch reduction

The Ampullae of Lorenzini in sharks is a unique organ that is used for electroreception. This organ is not found on bony fishes; therefore, a repellent that affects this sensory organ of sharks would be selective. Permanent magnets have been shown to be deterrent agents for sharks, and do not require power input, making them potentially ideal for use in fisheries and as bycatch reduction devices (Rigg et al. 2009). Other rare-earth (lanthanide) metals and alloys are also being investigated. However, few studies outside of strictly laboratory experiments exist that assess the applicability of this deterrent agent to reduce bycatch. Chemical agents have also been studied, although their effectiveness is limited (Sisneros and Donald 2001). An effective repellent for sharks with applicability on large-scale fishing fleets would be a key tool for the conservation of sharks worldwide. Research that combines laboratory and field experiments, along with physiological studies on shark behaviour is needed to develop such a tool. As recently done for sea turtles (reviewed in Southwood et al. 2008), linking sensory physiology with bycatch research for sharks could produce interesting results and help to advance the field.

Need for studies that explore the handling component of bycatch

Studies dealing with the handling component of bycatch were poorly represented in the shark bycatch literature. In the recreational fisheries literature (e.g., Cooke and Suski 2005; Arlinghaus et al. 2007) and bycatch work on other non-shark fisheries (see Davis 2002), there is a strong recognition that how animals are handled by fishers has an influence on their eventual fate. Indeed, appropriate handling of specimens onboard is vital for some species' survivability, although other species, like the lesser spotted dogfish (*Scyliorhinus canicula*), shows great resilience to onboard handling (Revill et al. 2005). Although there is benefit in preventing bycatch in the first place, the reality is that it does occur and it is unrealistic to assume that it can be totally eliminated so fishers will continue to play an important role in the handling and release of sharks. Ideally, research efforts would inform fishers on proper handling techniques (e.g., hook removal, when to cut the line, air exposure thresholds) for minimizing post release mortality. An example of tow duration, air exposure and crowding effects on mortality can be found in Frick et al. (2010). There is undoubtedly much variation among gear types and species so there is much opportunity for research on this topic. In the recreational catch-and-release literature, Cooke and Suski (2005) called for species-specific research on how fish respond to fisheries interactions given the inter-specific variation in size, dentition, feeding mode, environmental tolerances, physiological capacity, etc. that exists.

Also relevant here is the growing interest in fish welfare (Diggles et al. 2011) and the recognition that the actions (or inactions) of fishers influence the outcome of the event for discarded sharks. Hyatta et al. (2012) is a good and recent example, providing handling suggestions to reduce the level of stress in three species of sharks. The provision of science-based best handling practices would go a long way towards improving welfare status of discarded sharks as has occurred in the recreational sector for a variety of gamefish that are angled and released (Arlinghaus et al. 2007).

Need to examine the condition and fate of sharks that are discarded

To date, very few studies have addressed post-release mortality of sharks that are discarded from fisheries. Indeed, most mortality estimates are based solely on quantifying initial mortality (i.e., mortality at time of haul-back/landing) and assume that discards survive. Clearly not all sharks survive upon release. Not incorporating the post release mortality component in bycatch assessments risks an underestimation of real mortality produced by discards (Coggins et al. 2007) and thus undermines conservation and management actions. Evaluating post-release mortality can be done by holding sharks in cages, pens, or tanks or alternatively by releasing sharks with electronic tags. Donaldson et al. (2008) reviewed the various ways in which electronic devices such as pop-up satellite tags (PSAT) or acoustic transmitters can be used to assess post release mortality in a recreational catch-and-release context and those techniques could readily be applied to shark bycatch studies. Although published after we conducted our quantitative review and thus excluded from formal analysis, a recent paper by Musyl et al. (2011) provided an example of where PSAT tags were used to document post release mortality of five species of pelagic sharks. A challenge with shark work will be obtaining control fish but that can be overcome by contrasting different gear types and methods (e.g., compare mortality using hook timers to identify sharks on long lines for brief vs long duration periods; Brooks et al. (2012) used hook timers to evaluate various levels of physiological disturbance for Caribbean reef sharks (*Carcharhinus perezi*) captured on experimental long-lines). Documenting mortality post-release could identify the mechanisms of mortality including physiological exhaustion, metabolic scope and capacity, environmental correlates (e.g., water temperature, water depth), severe injury, and when one or several of those mechanisms facilitate post-release predation by other sharks and animals (Skomal and Bernal 2010).

Beyond mortality, there are also a range of sublethal consequences associated with injury and stress of capture. For example, sharks could experience behavioural impairments post release which could influence their ability to find prey or avoid predators. Physiological disturbances in the short term could restrict exercise capacity and thus ability to escape and in the long term could contribute to problems with immune function and disease (reviewed in Skomal and Mandelman 2012). Presence of hooks in fish that are released could also lead to a variety of pathogenic problems as has been documented in the recreational sectors (Borucinska et al. 2002). There are a number of studies that we documented that compared the physiological consequences of different types of capture stressors or on multiple species (e.g., Mandelman and Skomal 2009; note—not a reference that was part of the quantitative review) but none of these studies evaluated the longer term consequences of those physiological disturbances (but see Frick et al. 2012). A suite of tools (such as field physiology techniques, molecular markers, oxidative stress measures) now exist that could be applied to studies of sharks to advance the study of sublethal effects and a better understanding of the factors that contribute to mortality (Gallagher et al. 2010; Hyatta et al. 2012; Marshall et al. 2012; Renshaw et al. 2012; Skomal and Mandelman 2012). In fact, a recent special issue of the journal Comparative Biochemistry and Physiology A contains numerous papers on sublethal aspects of shark-fisheries interactions (e.g., Brooks et al. 2012; Frick et al. 2012; Renshaw et al. 2012; Skomal and Mandelman 2012) emphasizing the opportunity in that realm. Injury produced by the fishing gear is a factor that has been better documented in the reviewed literature; however, only 11 (10.9 %) studies dealt with sublethal effects on shark bycatch so there is a pressing need for more research on this topic. Relatedly, there is also a need to develop and validate tools to predict mortality of released sharks (Renshaw et al. 2012) which may involve using novel techniques such as reflex indicators (Davis 2010). Moyes et al. (2006) provided the first attempt to do so for sharks.

Knowledge of the factors that lead to mortality can be used to identify thresholds for stress and injury and to estimate post-release mortality in the absence of actual post-release mortality studies. The conservation physiology toolbox (Wikelski and Cooke 2006) has the potential to inform shark bycatch research and would best do so if able to establish relationships between stress and relevant population-level endpoints (Cooke and O'Connor 2010).

Need for research that covers more regions, fisheries (gear types), and species

As revealed by our review, there are many research gaps with respect to regions, gear types and species. For example, from a regional perspective, the Indian, South Atlantic and both north and south Pacific oceans have seen comparatively little research activity on shark bycatch relative to the north Atlantic. This is particularly problematic as there is intense and growing fishing pressure in these regions including industrial shrimp trawling, squid driftnet, and coastal varied bottom trawling fisheries, all of which could result in shark bycatch. With respect to species, shark bycatch has been thoroughly studied for several charismatic species such as white, basking and blue sharks, species which distributional ranges include developed countries (mainly North Atlantic Ocean), or species for which the accidental catch affects the commercial profit of certain fisheries (i.e., spiny dogfish, *Squalus acanthias*). Many commercially unimportant shark species (most of the species of the order Hexanchiformes and Orectolobiformes) remain unstudied despite being captured as bycatch. While the importance of charismatic umbrella species is undeniable for incentivizing conservation efforts that help protect less charismatic species, specific research on these species is needed to understand how to reduce mortality arising from bycatch.

Large scale fisheries were the focus of most of the literature reviewed (>80 % of the articles). Although it is assumed that these are the ones that produce the largest amount of bycatch, small-scale fisheries can also yield a significant amount of bycatch (Thorpe and Frierson 2009; Alfaro-Shigueto et al. 2010; Baeta et al. 2010). Among large scale fisheries, several authors have described and highlighted the importance of trawl fisheries bycatch on shark populations, pinpointing it as an issue for shark conservation worldwide (e.g., Frick et al. 2010; Hill and Wassenberg 2000). Providing adequate management strategies, incentivizing research on shark bycatch, and publishing of the results in peer reviewed journals would help to identify in which region shark bycatch predominates, which species are more affected, and why, and what type of fishery contributes mainly to the discards.

Need for human dimensions studies related to shark bycatch

Bycatch of sharks and bycatch in general, has important social, economic, and cultural components. We have addressed so far the more technical problems and up to date information on the ecological, biological and physiological impacts for sharks from bycatch. We have also explored the range of bycatch reduction technologies for sharks. However, the existence of a good technological means to reduce bycatch does not mean that it can be implemented on fisheries worldwide, even if it technically possible. The human dimension such as fisher adoption of gears is critical to their success (Gilman et al. 2007; Campbell and Cornwell 2008). Moreover, fishers themselves can be the source of innovations in bycatch reduction. Engaging them in the process of bycatch reduction can actually yield practical solutions that may not have been considered by managers or researchers. In addition, the development of management plans for conservation of bycatch species such as sharks face particular issues in the social, cultural, and economic realms. Fishers might not be prone to adopt a given BRD (Bycatch Reduction Device) if they are not convinced that the bycatch species are really threatened. They also may resent resources spent in the conservation of what they may regard as uncharismatic species (i.e., in their minds, sharks; See Simpfendorfer et al. 2011). Implementing BRD might also put the fishers at an economic disadvantage, if the adoption of that BRD is not shared internationally. Defence of traditional fishing practices, fear of losing independence, and resentment of the marginalization of their activity are all cultural factors influencing the acceptance or rejection of a particular BRD. When addressing these variables, fisheries management agencies often make assumptions to fill in the void of information and data regarding these important components of bycatch. Recent efforts to incorporate human dimensions research into bycatch reduction have been encouraged (Campbell and Cornwell 2008) but there remain few examples in the literature. There is much opportunity in this realm for research on the human dimensions of shark bycatch.

Conclusion

Bycatch in general is a serious threat for biodiversity worldwide, and sharks seem to be particularly vulnerable to bycatch. Indeed, shark bycatch threatens to wipe out these top predators that structure many marine habitats, with possible catastrophic consequences for ecosystems and the services that they provide. The fact that shark bycatch is regarded as the primary threat facing so many of the imperiled shark species provides direction to those interested in or responsible for their conservation and management. We have described the characteristics and trends in the published research on shark bycatch, and conclude that there are a number of knowledge gaps that make it difficult to reduce shark bycatch or to understand the consequences of that activity. New technology offers potential solutions to reduce bycatch, but studies concerning them are scarce. Also, most research is focused on the impact of large industrial-scale fisheries, which undoubtedly contribute in great measure to global bycatch of shark, but failure to consider the impact of artisanal fisheries would be unwise. Our study has identified what we believe to be the most pressing research needs that must be addressed including the need for multidisciplinary studies that combine different approaches, development and testing of bycatch reduction devices, understanding the fate of discarded sharks, expanding research coverage to other regions, fisheries, and gear types (including more work on the recreational sector which we did not cover here), and finally incorporating human dimensions science into the study of shark bycatch reduction. Although there are some inherent challenges with developing and testing shark bycatch reduction strategies, there is an urgent need to do so and this would be best achieved through interdisciplinary research that spans field, laboratory, and modeling realms. It is our desire that this review stimulates research activities that will improve our understanding of shark bycatch, but more importantly yields practical advances related to bycatch reduction and improving the survival and welfare of those sharks that are captured and discarded, that can be readily adopted by the fishing community and/or incorporated into regulations and policies.

Acknowledgments Molina was supported by the Emerging Leaders in the Americas Program during a visit to Carleton University in 2010. Cooke was supported by the Canada Research Chairs Program and the Ontario Ministry of Research and Innovation. We thank members of the Cooke Lab, Bs. M.E. Croce, Dr. A.C. Lopez Cazorla, and two anonymous referees for critiques on the paper.

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