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REVIEW

Shark recreational fisheries: Status, challenges, and research needs

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Abstract For centuries, the primary manner in which humans have interacted with sharks has been fishing. A combination of their slow-growing nature and high use-values have resulted in population declines for many species around the world, and to date the vast majority of fisheries-related work on sharks has focused on the commercial sector. Shark recreational fishing remains an overlooked area of research despite the fact that these practices are popular globally and could present challenges to their populations. Here we provide a topical overview of shark recreational fisheries, highlighting their history and current status. While recreational fishing can provide conservation benefits under certain circumstances, we focus our discourse on the relatively understudied, potentially detrimental impacts these activities may have on shark physiology, behavior, and fitness. We took this angle given the realized but potentially underestimated significance of recreational fishing for shark conservation management plans and stock assessments, in hopes of creating a dialogue around sustainability. We also present a series of broad and focused research questions and underpin areas of future research need to assist with the development of this emergent area of research.

Keywords Fishing · Marine · Recreational · Resource · Sharks

INTRODUCTION

Beyond the numerous socio-economic benefits of recreational fishing (Arlinghaus and Cooke 2009; Tufts et al. 2015), it is increasingly recognized that this leisure activity can also have negative consequences on individual fishes, their populations, and even aquatic ecosystems (Cooke and Cowx 2006; Lewin et al. 2006; Cooke et al. 2014). Therefore, there have been calls to better recognize the role of recreational fisheries in contemporary ecosystem-based fisheries management (FAO 2012). Recreational fishing accounts for an estimated 10% of the total global fishing harvest, with estimates of 47 million fish landed per year (Cooke and Cowx 2004). Moreover, there is evidence that recreational catches can exceed their commercial counterparts in some parts (McPhee et al. 2002; Schroeder and Love 2002), and the collapse of certain fisheries have even been attributed to recreational fishing (Post et al. 2002).

Due to their relatively low reproductive output, high extinction risk, and intrinsic vulnerabilities to overexploitation, there is a growing and urgent research need to understand the impacts of fisheries interactions on marine predators such as sharks (Stevens et al. 2000; Gallagher et al. 2012). Commercial fisheries exploitation is widely recognized as the largest threat to shark populations and the primary driver of their risk of extinction in the twenty first century (Worm et al. 2013). Sharks have also been subject to recreational fishing for decades, and this activity could represent a large and growing risk to sharks. While recreational fishing has been previously recognized in conservation and management plans and stock assessments for sharks for decades (see Compagno et al. 1997; National Marine Fisheries Service 2006), relatively few studies have addressed it in the scientific literature by investigating the scale, practices, economics, human dimensions, and the biological/ecological consequences of these practices (Gallagher et al. 2012).

Commercial and recreational fishing practices using hook and line are similar in that they both expose sharks to the process of capture, an interaction which, regardless of gear type used, includes hooking, a period of fight or struggle, and lastly some type of handling (Cooke and Cowx 2006). In both sectors, a component of the catch is also released to comply with regulations or voluntarily as a

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result of conservation ethic. As compared to commercial fisheries that target sharks mostly for their fins and meat, recreational anglers appear to primarily target sharks for sport and the thrill of capturing a large fish (Babcock 2009; Shiffman and Hammerschlag 2014; Gallagher et al. 2015; McClellan Press et al. 2015). Unlike commercial fishing boats which often capture sharks using hook and line on longlines (either directly or indirectly as bycatch; Molina and Cooke 2012), recreational shark fishing (i.e., rod and reel angling, for the purposes of this paper) can occur from shore, along the coasts, offshore, and in hard-to-access or sensitive ecosystems (e.g., back-country, flats, coral reefs; Fig. 1). Moreover, recreational fishing practices can occur year-round and are not necessarily always dependent on seasonality (except for temperate fisheries) or driven by stock abundance. These spatial and temporal differences mean that recreational angling of sharks can occur across a more diverse set of temperatures, water depths, and angling gear/tactics. Since we are just beginning to understand how fishery-related variables affect shark survival in commercial fishing practices (e.g., Gallagher et al. 2014a), it is clear that similar work under recreational settings is highly context-dependent thereby making broad generalizations challenging. Recent data also suggest that, at least in the United States (in 2013), the annual landings of sharks in recreational fishing (4.5 million pounds) can exceed that of the commercial sector (3 million pounds; National Oceanic and Atmospheric Administration [hereafter 'NOAA'] Fisheries, Shiffman 2014).

In catch-and-release fisheries (hereafter referred to as 'CR'), it is often assumed that most (if not all) fishes released alive will survive (Cooke and Schramm 2007). However, research involving a variety of teleost fishes has revealed that this is not always the case, with CR mortality rates exceeding 90% for some species and according to the gear used, fishing practice, and the environment in which it occurs (Muoneke and Childress 1994; Bartholomew and Bohnsack 2005). Recent research involving coastal and pelagic sharks (primarily Carcharhinid species) has also evaluated that the survival of sharks in response to capture have also found high variability in survival rates (see reviews by Skomal and Bernal 2010; Skomal and Mandelman 2012), but the vast majority of this work has involved commercial fishing interactions and not recreational angling (Molina and Cooke 2012; Gallagher et al. 2015). The growing realization that sharks could be negatively affected by CR fisheries interactions has spawned a handful of studies focusing on recreational angling (e.g., Campana et al. 2006; Robbins et al. 2013; Danylchuk et al. 2014; French et al. 2015), including some human dimensions work (Babcock 2009; Shiffman and Hammerschlag 2014; Gallagher et al. 2015; McClellan Press et al. 2015), but many significant gaps in knowledge and research remain. Mortalities from recreational fishing are a form of fishing mortality, and thus they are important for stock assessments and fisheries management plans, although this information is not always available [i.e., the Southeast Data Assessment and Review; SEDAR (e.g., Atlantic sharpnose shark, blacktip shark, bonnethead shark) NOAA Fisheries 2006; Shiffman and Hammerschlag 2016a].

Here we provide a wide overview of recreational shark fishing, defined as the purposeful targeting and catching of sharks for non-commercial and non-artisanal purposes. We summarize the general history of shark recreational fisheries and the current status of fishing practices from a variety of regions and countries where these practices are most common (or where information was most available). We further examine the challenges the recreational fishing sector presents to conservation and management of sharks. We also present a series of research areas and questions to help guide future investigation of recreational shark fishing and offer a basic set of shark catch-and-release fishing guidelines (e.g., best practices) based on current research and employing a precautionary approach. While recreational fishing can generate a number of direct and indirect conservation benefits for sharks under certain circumstances similar to other forms of ecotourism (discussed in Cooke et al. 2014), our discourse focuses on the relatively

Fig. 1 Examples of the scale and scope of recreational fishing practices over time, evidenced by differences in practices, angling gear, context, and species types/age classes targeted: **a** historical recreational capture of a large tiger shark (*Galeocerdo cuvier*) captured with basic rod and reel off Haiti in the 1920's; **b** beach angling for medium to large coastal species (**a** blacktip shark *Carcharhinus limbatus* is pictured); **c** coastal or offshore charter boat fishing for large coastal or pelagic species (**a** lemon shark *Negaprion brevirostris* is pictured). Photos used under Creative Commons License (**a**–**b**, Flikr; **c**, Wikimedia Commons).

understudied negative impacts these fishing activities may have on shark physiology, behavior, and fitness given its significance for conservation management. It is our hope that this paper will highlight the conservation challenges and areas of research opportunities within the context of recreational shark fishing, and spur dialogue around sustainability for the future of the recreational fishing for sharks.

BRIEF HISTORY OF RECREATIONAL SHARK FISHING

Sharks have been fished around the world for centuries. Records from the Chinese Song Dynasty (960–1279) describe the use of shark-fin soup as a traditional banquet staple (Templer 1999). Commercial shark fisheries became established in the Unites States of America between 1935 and 1950, in response to a high demand for vitamin A, primarily for the fortification of poultry feed (Wagner 1966). However, recreational shark fishing is a relatively new phenomenon. Historically, sharks were perceived as a nuisance to recreational anglers (Castro 2013). The social prestige and thrill bestowed on anglers from catching large predatory sharks can be seen in historical photographs on various online blogs from around the world dating back to as early as the 1920s (Authors, direct observation). Historically, recreational shark fishing was classified as "game fishing," with early popularization seen off New Zealand (1915, Francis 1998) and Australia (1950s, Young et al. 2014). In fact, recreational spearfishing for gray nurse sharks (*Carcharias taurus*) off New South Wales almost extirpated the species from local waters, one of the first examples of how recreational fishing for sharks can (a) have large effects on species abundance at the local scale and (b) be used to estimate and track the relative abundance of sharks over time. South Africa also became a leader in landing sharks with recreational gears, and from the late 1940s to the mid 1970s, the Bowman trophy was awarded to the angler with the heaviest shark caught from shore (Klimley and Ainley 1998). In the 1950s, Australian recreational angler Alf Dean gained notoriety for catching a number of large sharks, including a record white shark of ~1208 kg (2664 lbs.) off Australia in 1959 in the 1960s. The recreational landing of large sharks in North America gained popularity in the 1960s from Frank Mundus, a fishing Captain off Montauk, New York, United States of America (Mundus and Wisner 1971). In order to attract customers, Captain Mundus started calling shark fishing "monster fishing" which gained notoriety when he harpoon-captured a massive white shark off Montauk that he estimated at ~2000 kg in 1964 (4500 lbs.). Mundus later went on to land the largest shark ever captured on rod and reel (~1550 kg/3427 lbs shark in 1986; Hevesi 2008).

Recreational shark fishing received another significant boost in popularity in 1975 after the release of the blockbuster movie *Jaws*. In this film (based on a book by Peter Benchley), a giant white shark terrorizes a small island town off New England (USA). The movie unintentionally gave rise to widespread shark recreational fishing for the thrill and notoriety of killing a 'man eater' (Castro 2013). Following the release of the film, shark fishing clubs and tournaments around the world emerged (Babcock 2009). It was common to allocate prizes for "the most sharks killed" and the "greatest number of pounds of shark landed" (Castro 2013). By 1979, recreational anglers captured an estimated 1.2 million sharks in the southeast United States alone (Hueter 1991). Recreational shark fishing has also been popular off Ireland since 1970 (Fitzmaurice and Green 2000).

Recreational shark fishing became particularly popular in the United States in the late twentieth century, where most information relating to the history of the practice was also available. The 1980s saw increased developments of shark fishing tournaments in the United States, especially within southeastern states, such as Florida (Hueter 1991). Between 1979 and 1986, the estimated number of sharks captured from Florida recreational fishing increased from 450 000 to 733 000 (a 63% increase in seven years; Hueter 1991). In fact, a survey of Florida's recreational shark fishery found that over 200 shark tournaments involving more than 22 500 anglers were held in Florida waters alone between 1971 and 1991 (Hueter 1991). Fishing rodeos and shark tournaments also became popular in the Gulf of Mexico states off the southern United States of America from the 1980s onwards (Fisher and Ditton 1993; Powers et al. 2013). However, the largest and longest running shark fishing tournament was known as the Monster Shark Fishing Tournament, occurring off Oak Bluffs, in Martha's Vineyard, where the movie *Jaws* was filmed. This tournament ran for 27 years before changing names and venues in 2014, during which time it saw more than 25 000 sharks landed (Moroney 2014). Canada's recreational shark tournaments, known as 'shark derbies' which were kill tournaments, became increasingly popular in the Atlantic in the summers of the 1990s and 2000s (Campana et al. 2006). Similar patterns are evident during this time frame in Australia and New Zealand as well (Pepperell 1992; Francis 1998), with ~1.2 million sharks caught recreationally per year off Australia (~1 million of them were released, McLoughlin and Eliason 2008). Recreational landings for sharks in the United States peaked in the 1990s and began declining into the 2000s, a trend marked by the growing conservation ethic amongst the sport fishing community globally, resulting in a gradual switch to catch-and-release practices (Babcock 2009; Skomal et al. 2009).

The world's first 100% CR shark fishing tournament was initiated by MOTE Marine Laboratory based out of Sarasota USA as a means to survey local shark population in

Florida's Gulf coast (Hueter and Manire 1994). The tournament ran from 1989–1998, its peak involving 180 anglers from Madeira Beach to Cape Sable, Florida (Hueter, pers. com.). Today, shark fisheries and clubs worldwide capture hundreds of thousands of sharks per year and release between 70 and 100% of their catch (Babcock 2009). In the state of Florida (USA), for example, 88% of the over 1000 000 blacktip sharks caught by recreational fishermen between 2004 and 2011 were released (National Marine Fisheries Service 2002).

CURRENT STATUS OF PRACTICES

Recreational shark fishing occurs worldwide. However, recreational shark fisheries appear to be most prevalent across a handful of nations such as Australia (Pepperell 1992), New Zealand (Cox and Francis 1997), South Africa (Babcock 2009), Canada (Campana et al. 2006), the United States (Skomal et al. 2009), the United Kingdom (Babcock 2009), and throughout numerous countries in the Mediterranean Sea. Certain countries in the European Union also have established angler shark tagging programs (i.e., United Nations Environment Program, Scottish Sea Angling Conservation Network).

A variety of techniques and gears are used in recreational shark fishing (Florida Museum of Natural History, Florida Sea Grant, NOAA Fisheries, Shiffman and Hammerschlag 2014; Gallagher et al. 2015; McClellan Press et al. 2015; Authors personal experience). For example, anglers targeting small sharks in nearshore tidal flats and reefs may use fly-rods or light tackle fishing from small skiffs, whereas trophy fishers may venture hundreds of kilometers offshore to target large pelagic sharks using heavy tackle in deep water and fishing from large charter boats (for more examples, see Fig. 1). Anglers also fish for sharks from shore (e.g., via surf casting), where sharks are usually brought on land prior to release. In the USA alone, more large sharks (i.e., non-dogfish) were landed by recreational anglers than commercial fishers in 2013 (Lowther and Liddel 2014; Shiffman 2014).

Fig. 2 Signage at a marina in the Bahamas depicting the 'Shark-Free Marina' initiative whereby marinas agree to prohibit the landing of recreationally caught sharks (*Photo* Jillian Morris Brake)

Due to widespread decreases in many shark populations (Worm et al. 2013), combined with an increasing angler conservation ethic and growing pressure from environmental advocates, there is a developing trend of recreational anglers switching from catch and kill to CR. In 2010, the "Shark-Free Marinas" initiative was launched to lower recreational fishing mortality on sharks by persuading marinas to ban the landing and killing of sharks on their docks (Fig. 2). As of the writing of this paper, the program has been expanded to 130 marinas worldwide. This sociocultural paradigm shift is also corroborated by recent human dimensions studies showing that in Florida, a recreational fishing epicenter (Shiffman and Hammerschlag 2014), hundreds of individual shark anglers are concerned about shark population declines, and as a result practice almost exclusively CR shark fishing for sporting purposes (Shiffman et al. 2014; Gallagher et al. 2015). Similar attitudes have been found for shark recreational anglers in the Great Barrier Reef Marine Park, Australia (Lynch et al. 2010) and throughout European nations such as Sweden, the Netherlands, and Ireland (e.g., The Shark Alliance, Pew Charitable Trusts). Moreover, recreational anglers have significantly aided in the collection of scientific knowledge on shark movements and behavior, as seen in mark-recapture studies (Kohler et al. 1998).

These shifts at the individual angler level, alongside mounting opposition to the recreational killing of large sharks from the conservation advocacy community, are now being seen in a gradual shift from shark kill tournaments to CR (Fig. 3). Several prominent shark kill tournaments that had been ongoing since the 1970s in the United States are now being shut down by local officials due to mounting public opposition, waning public interest, and critique from the conservation biology community (e.g., Oak Bluff's Monster Shark Fishing Tournament off Martha's Vineyard, the Ocean City Shark Tournament off New Jersey; Rutenberg 2013; Moroney 2014). For those tournaments still in operation, many are now adding catch-and-release categories or switching to exclusively CR techniques for all sharks (e.g., the Montauk Marine Basin off Long Island, New York, the Alabama Deep See Fishing Rodeo off Alabama [the largest fishing tournament in the world], respectively), awarding prizes to the largest sizes and quantities of sharks caught and released boatside (Alabama Deep Sea Fishing Rodeo 2016). Some CR tournaments are also advocating for the involvement of scientists or encouraging participants to aid in data collection through tag and release (Fig. 3).

Kill tournaments still persist today in the United States, for example, but with lower rates of participation, and often face backlash citing ethical and ecological concerns from advocates on social media (Authors, direct observation). In Australia similar patterns are evident. A recent survey of tournament anglers off Australia found that about half (55%) of all anglers practiced catch and release of pelagic sharks, and game fishing tournaments issued awards for both capture as well as for tag and release (Heard et al. 2016). Tournament angler responses revealed that tagging for competition ranked as the most important reason given for releasing sharks, while retaining sharks for competition ranked second as a reason for landing pelagic sharks (Heard et al. 2016).

Despite a lack of published time-series data on recreational fishing activity and catch rates in most jurisdictions (but see monitoring that has been in place in the USA since 1982, Marine Recreational Information Program, NOAA Fisheries), the industry appears to be in the middle of a dramatic cultural shift (e.g., McLoughlin and Eliason 2008, Fig. 2). Recreational shark fishing is still a highly popular activity and could become more widespread (given declines in other sportfish, Powers et al. 2013); however, the conservation ethic among shark anglers and tournament organizers is also steadily growing. Kill tournaments are decreasing in popularity and the future may well see the end of weight-based world angling records for sharks that require landing the sharks, and instead use length or girth-based estimates to estimate weight, so that sharks can be captured and released (Shiffman et al. 2014, 2015).

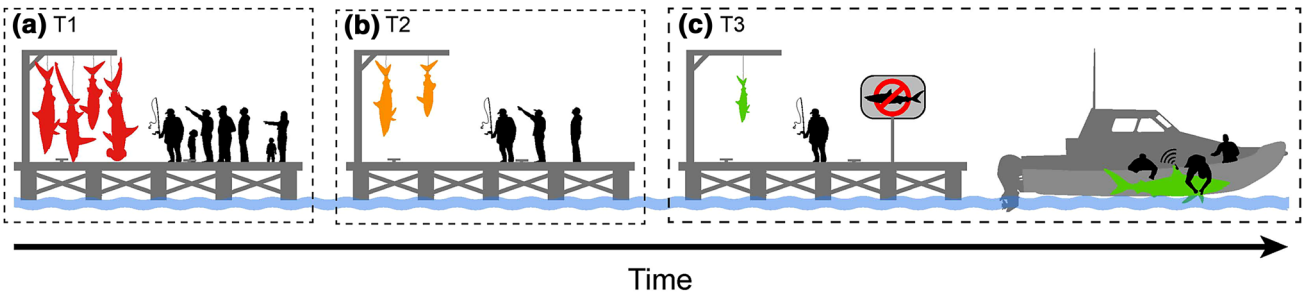

Fig. 3 The evolution of recreational shark fishing tournaments over time (*T*# = time period), depicted by gradual social-cultural changes over the last 50–70 years and patterns in shark size and abundance reported in Powers et al. (2013): **a** *T1* 1950s–1970s. Large numbers of sharks killed (shown as relative size and number of sharks hanging on dock) and great public interest; **b** *T2* 1980s–2000s. Moderate, but decreasing numbers of sharks killed and decreased public interest; **c** *T3* 2010s–present day. Cultural shift to switch away from killing and towards catch-and-release techniques, the emergence of shark conservation initiatives such as 'Shark-Free Marinas' (depicted by *signage*), and the integration of science and tagging programs (depicted by *boat with researchers*). Illustration by Simon Brandl

ISSUES SURROUNDING PRACTICES

While commercial shark fishing involves a relatively large number of hooks on fewer boats, recreational angling involves relatively few hooks per angler, but potentially more individual anglers fishing. Catching sharks via hook and line is a form of leisure, however, negative repercussions of recreational angling on shark survival and fitness can occur even if fish are released (Skomal 2007, which does not always occur). Recreational angling for sharks that are killed for records can be analogous to trophy hunting of terrestrial 'big game' (Shiffman et al. 2015), where the intensions are to target the largest and most fierce individuals in the population (Milner et al. 2006). If the motivations of recreational anglers are to target sharks for harvest (or if incidental mortality occurs), then this could remove individuals from the population that have the highest fitness and contribute disproportionately to the maintenance of local populations. As with any segment of anglers, the motivations are quite variable (Gallagher et al. 2015) and there is certainly much need to better characterize and understand the motivations of anglers and what those motivations mean for angler behavior and shark populations.

Fishing-induced directional selection has been demonstrated for commercial and recreational harvest fisheries that target teleosts (Law 2007), with the cascading effects influencing a suite of interrelated life history and behavioral traits, including scope for growth (Enberg et al. 2012), age of maturity (Enberg et al. 2010), competitive ability (Cooke et al. 2007), and fitness (Sutter et al. 2012); however, this has not yet been shown for sharks (Shiffman et al. 2015). Continual, large-scale removal of the largest (and more reproductively active) individuals could be quite deleterious (Birkeland and Dayton 2005), especially for local shark populations, given their relatively late age of maturity and long generation times (Cortés 2000; Shiffman et al. 2014) and the fact that the largest individuals are often in strong condition with sufficient energy reserves needed to drive fecundity (Gallagher et al. 2014c).

While it remains uncertain as to whether harvest-based recreational fisheries could be contributing to the global downward trends in the abundance of sharks, it should not be overlooked, especially for species that are already threatened or in decline, despite the fact that numerically its harvest (and fishing mortality more broadly) is lower than targeted commercial fisheries (Pine et al. 2008). A greater characterization of recreational catches of sharks should be a goal for a better understanding of how fishing mortality affects sharks, and this can be achieved through better standardization of reporting of records and quantification of time-series data. In some jurisdictions shark recreational fisheries monitoring (e.g., through creel surveys or log books) is integrated into routine stock assessment as a component of science-based management. For example, the Marine Recreational Information Program is designed to provide evidence-based estimates of recreational fishing activities in the United States for the purposes of informing regional fisheries management and stock assessments, while also engaging stakeholder needs and educating partners to produce reliable data (NOAA Fisheries 2006).

Negative impacts of recreational angling could also occur even if sharks are not harvested but rather caught and released (Arlinghaus et al. 2007). Elements of CR angling events, including capture, handling, and release, can impose physical injury and physiological stress that can potentially reduce fitness and affect survival (Cooke and Suski 2005; Cooke et al. 2013). At the individual level, impacts associated with CR of sharks can include physical damage from hooking and handling (Borucinska et al. 2002), physiological stress related to capture and air exposure (Hoffmayer and Parsons 2001; Skomal and Chase 2002; Brill et al. 2008; Heberer et al. 2010; Kneebone et al. 2013), and post-release mortality (Hoffmayer and Parsons 2001; Gurshin and Szedlmayer 2004). Physical injury from fisheries capture were also shown to negatively influence release condition among small coastal sharks (Hyatt et al. 2016), whereas blacktip reef sharks (*Carcharhinus melanopterus*) were shown to have high capacity for wound healing following physical injuries (aggression, mating scars, anthropogenic damage; Chin et al. 2015). In a study focused specifically on recreational shark CR, Danylchuk et al. (2011) showed that physical injury and physiological stress in combination with warm water temperatures affected the post-release activity patterns and short-term survival of juvenile lemon (*Negaprion brevirostris*) sharks. However, unlike for teleost fishes, the numbers of studies that have assessed the impacts of recreational angling on sharks are quite few, making it difficult to move beyond broad generalizations that are often used for developing best practices for the CR of fishes (Cooke and Suski 2005).That being said, the above handful of studies do shed early light into the wide ranging vulnerabilities of sharks to recreational angling.

Many more species-specific studies on the impacts of recreational angling on sharks are needed, especially as the shift continues from harvest to CR as a conservation tool for of these animals (Skomal 2007; Gallagher et al. 2012). Continuing to quantify individual-level responses to CR is an important step to understanding how recreational angling can influence population-level traits (Cooke et al. 2013) including declines in global shark stocks (Stevens et al. 2000; Worm et al. 2013). Catch-and-release shark fishing tournaments are becoming more common and popular among recreational anglers, and these events are often the focus of research efforts that quantify metrics such as movement, energetics, diet, and stress, in addition to the traditional catch rates, body size and sex ratios, and age and

growth studies that have been obtained opportunistically for decades in kill tournaments (Estrada et al. 2003; Babcock and Skomal 2008; Heberer et al. 2010; Calich and Campana 2015). Data obtained on the physical injury and physiological stress imposed on sharks by capture, handling, and release during tournaments can also provide information needed to develop more robust best practices that could minimize impacts at individual-level and population-levels.

Given the global participation rates of recreational angling across developed and developing nations, the absolute number of encounters with sharks as either a target species or as bycatch (Molina and Cooke 2012) could be greater than the encounter rates sharks have with some commercial fisheries (Cooke and Cowx 2004, 2006). Global estimates for shark recreational landings do not exist, nor is there an international repository for these data as seen in the FAO (Camhi et al. 2009). Among recreational fisheries it is very uncommon to require participants to report bycatch, harvest, and mortality of discards (Post et al. 2002; Granek et al. 2008), including sharks. As such, lack of reporting could lead to a poor understanding of the impacts of recreational angling for sharks, even if the fishery is CR (Gallagher et al. 2012). However, if best practices for the CR of sharks can be developed based on rigorous and empirical science, then it might be easier for recreational anglers to implement such guidelines since they generally interact with one shark at a time, rather than commercial fishers that might have numerous sharks on gear (e.g., long lines) for much longer durations (Holts et al. 1998). Indeed, there are a variety of regional guidelines and best practices that have been issued from various countries, legislative organizations, and NGOs (synthesized in Box 1). The overall effectiveness of best practices for the CR of sharks will be also be contingent upon the attitudes and perceptions of recreational anglers (Gallagher et al. 2015), which may differ regionally and depending on whether anglers are targeting sharks or encountering them incidentally (Arlinghaus and Cooke 2009; McClellan Press et al. 2015). With such complexity, an important challenge to overcome will be developing education and outreach strategies that are checked by fishery biologists for the purposes of accurately and persistently disseminating guidelines for the CR of sharks spanning the diversity of recreational angling communities (McClellan Press et al. 2015).

Box 1 Precautionary best practices for catching and releasing sharks in recreational fishing activities, synthesized from the peer-reviewed literature, governmental literature (NOAA Fisheries[a]), as well as an NGO (WWF[b])

- Be prepared
  - Have appropriate release gear before recreational fishing
  - Make sure members of fishing team understand their roles in release
- Gear
  - Use circle hooks to reduce deep hooking
  - Use corrodible non-stainless hooks
  - Use barbless hooks for faster removal
  - Use heavy tackle and fight harness to minimize fight time
- Handling
  - Minimize fight time to reduce exhaustion and stress
  - Avoid foul-hooking sharks
  - Follow hooked sharks to gain line and reduce fight duration
  - Do not gaff sharks
  - Do not remove sharks from water
- Release
  - Resuscitate exhausted shark prior to release by keeping water flowing through mouth and over gills
    - Maintain mouth against current direction or keep shark in forward direction at all times (do not motion both forward and backward like teleosts)
    - Remove hook/line by (1) cutting hook with bolt cutters/de-hooker; (2) cutting line as close to hook as safely possible
- General
  - Avoid fishing in warmer waters that tend to have lower dissolved oxygen and make recovery more difficult
  - Avoid fishing in silty water that can clog shark gills
  - If species captured is known to be sensitive to capture stress (e.g., hammerheads, threshers), then cut line immediately after trying to gain as much line as possible back in a short time

[a] http://www.fisheries.noaa.gov/stories/2013/08/best_fishing_practices_sharks.html

[b] http://awsassets.wwf.ca/downloads/shark_fishing___best_catch__handle_and_release_practices.pdf

RESEARCH AGENDA

As evident from this overview, the peer-reviewed literature on shark recreational fisheries is relatively sparse, yet other information exists in anecdotal form or embedded within technical reports or the gray literature. That is not to imply that important work is not underway nor to devalue what has been done—indeed, research on this topic and the themes contained therein have certainly increased dramatically in recent years. Nonetheless, there are many research gaps that remain. The list provided here is not exhaustive but if these research questions were to be answered, we would be in a much better position to provide detailed science advice to support sustainable management of recreational fisheries that either target or interact with sharks.

Scope, scale, and consequences of shark recreational fisheries

A fundamental component of effective science-based fisheries management and conservation is the ongoing population assessment of a given biological resource and those that exploit it. In general, the biological status (population size, demographics, trends) of many shark populations remains unclear. And for some sharks, including some of those species that are large and highly prized in certain fisheries (e.g., great hammerhead sharks, thresher sharks), we have limited information on their natural history and life history correlates (Dulvy et al. 2014), further impeding management. This significant knowledge gap is relevant to recreational fisheries management as well as shark conservation and management more broadly. Beyond characterizing population status (Punt et al. 2000; Hayes et al. 2009) there is also a need to characterize the scope and scale of recreational fisheries, especially since these practices seem to remain popular and could be increasing (although there are some regional examples of monitoring programs, as noted above and throughout). What level of fisheries effort is expended by anglers? What are the capture rates? What are the harvest and release rates? What are the characteristics of sharks being targeted, harvested, or released? How does recreational harvest or fishing mortality relate to commercial fisheries? What is the scale of boat-based shark fishing compared to land-based fishing? How do post-release mortality rates differ between boat-based and land-based fisheries? How do fishing practices differ between shark recreational angling sectors and individuals? To what extent is recreational fishing a threat to shark populations? And what are the consequences of recreational fishing activities on sharks on fish assemblages and ecosystems?

Unlike commercial fisheries where, at least in developed countries, there are clear mechanisms in place to document the scope and scale of shark fisheries (Bonfil 1994; Bradshaw et al. 2013; Davidson et al. 2016), characterizing often diffuse recreational fisheries is more difficult. Creel surveys (on water/beach or implemented at harbors), angler diaries, and log books and charter boat logs represent well-established tools that have much promise for addressing some of the aforementioned knowledge gaps (Pollock et al. 1994). New developments in smart phone apps that enable anglers to self-report their fishing activities in "real time" (see Papenfuss et al. 2015) might provide opportunities for generating these data. Social science surveys (see human dimension research below) can also be used to solicit information on effort, catch, and harvest as Shiffman and Hammerschlag (2014) recently did with charter boat captains in Florida. For boat-based recreational fisheries for sharks, mapping effort with GPS loggers could be an effective tool. Of course, all of these methods have limitations and biases with the need for calibration and validation before data can be interfaced with management activities.

Management interventions and shark recreational fisheries

Given the potential significance of recreational fishing practices for shark mortality or fitness, fundamental questions remain related to the effectiveness of different management actions related to recreational shark fisheries (indeed all sectors) (see Francis 1998; Ward-Paige et al. 2012) as they do for many species that have been actively managed for even longer periods than sharks. To what extent do protected areas (and what type across the spectrum) serve as a relevant tool in shark management? Do seasonal closures to recreational fishing benefit shark populations? Can size-based harvest limits be used to generate sustainable recreational shark fisheries? What populations can sustain harvest and if so, at what level? For catch-and-release fisheries, what level of release mortality is acceptable? And of course, how do the threats from recreational fishing relate to the broader suite of fisheries (e.g., commercial harvest, bycatch) and other stressors (e.g., climate change, habitat alteration, noise pollution) that they face in the wild? In the face of a lack of information, there is a clear need for increased data collection and opportunity to translate knowledge into relevant policy.

Catch-and-release science and sharks

There has been extensive research on the effects of CR on a variety of teleost fishes (over 300 studies; see Arlinghaus

et al. 2007) yet there has been comparatively less work focused on sharks—both those targeted or those that are captured incidentally (Molina and Cooke 2012). There are a number of generic research priorities related to CR (see Arlinghaus et al. 2007) that are equally relevant to sharks. However, there are also a number of areas where there are particular needs. For example, it is unclear the extent to which different hook styles and sizes influence catch rates, injury, and survival. Given that anatomical hooking location is one of the biggest single drivers of CR outcomes (deep hooking in esophagus being bad; Cooke et al. 2012), selection of hooks that minimize deep hooking (e.g., circle hooks; Cooke and Suski 2004; Serafy et al. 2012) shows much promise for shark recreational fisheries that use bait but more research is needed (Serafy et al. 2012). Another issue relevant to large toothy fish such as sharks is tackle failure where line breaks and sharks retain hooks. Opportunistic research with relatively low sample sizes has revealed pathological consequences (Borucinska et al. 2001, 2002) but the long-term fitness consequences of hook retention in sharks are unknown. Similarly, the frequency of tackle loss when fishing for sharks is unknown but may be quite high. There may be opportunity to explore different hook materials to identify materials that break down to facilitate hook expulsion or disintegration (e.g., corrodible hooks), which could be useful for some species for which researchers have actually recommended that cutting the line could promote survival under certain instances (e.g., inexperienced anglers catching hammerhead sharks, Gallagher et al. 2014b).

Another issue that may arise in shark fisheries is post-release predation. Often sharks are fingered as the culprit for post-release predation on teleost fish (see Raby et al. 2014), but they may also predate upon released sharks (con-specifics or other shark species). The extent to which this occurs is unknown but is certainly worthy of study given that sharks sometimes occur in predator-rich environments. There have been some attempts to understand the effects of different levels of exhaustion on shark physiology and how this varies among species and sharks of different body sizes (e.g., Skomal 2007; Mandelman and Skomal 2009; Gallagher et al. 2014c) but in general our knowledge of stress thresholds or post-release behavioral alterations or mortality is poor. Moyes et al. (2006), Gallagher et al. (2014c), and Hutchinson et al. (2015) all tried to link post-release fate (measured via electronic tagging) to physiological status at time of tagging which is a powerful approach for developing predictors of survival and identifying relevant thresholds (e.g., how much air exposure or fight time is too much). More such studies with an explicit CR focus are needed, since many of the previous studies have actually used commercial gear to exhaust fish. This enables one to make loose inferences about recreational fisheries but it is not a direct measurement. Some specific types of fisheries also demand focused research attention. For example, beach- or shore-based fisheries where sharks are often dragged onto the beach or landed in shallow water may cause additional stressors not encountered in boat fisheries (e.g., air and sun exposure).

Human dimensions research on shark recreational fisheries

Human dimensions of fisheries management (Decker et al. 2001) and conservation social science (Mascia et al. 2003) have emerged as important areas of study. Understanding human behavior and the basis of those behaviors can be used to identify barriers to action and opportunities for behavioral modification (Schultz 2011). Characterizing values, attitudes, opinions, and perspectives can guide management which economic valuation can help to justify the basis for different management decisions (Neis et al. 1999; Decker et al. 2001). There are many research needs related to the human dimensions of recreational shark fisheries. There have been several studies that have explored the perspectives of shark anglers in several regions of eastern North America (see McClellan Press et al. 2015; Gallagher et al. 2015) and Australia (Lynch et al. 2010). More of such studies are needed as they can be used to quantify effort and harvest, understand the demographics of participants, and to understand their preferences (Lynch et al. 2010; Shiffman and Hammerschlag 2014). If such studies are repeated through time it is possible to track trends in catch, harvest, fish size, participation rates, fisher demographics, and their perspectives. Understanding the motivations of shark anglers (especially if compartmentalized for harvest-oriented and catch-and-release-oriented anglers) could help to identify mechanisms of reducing consumptive use (e.g., Calvert 2002).

To date, there has been relatively little research on the perspective of the broader public on shark recreational fisheries (but see O'Bryhim and Parsons 2015) which would be useful for characterizing public concerns or support for different recreational fisheries (see Simpfendorfer et al. 2011), practices, or management interventions. Some efforts to understand how the media portrays sharks and what it means for conservation have been undertaken (see Muter et al. 2013) which may also be relevant to recreational fisheries management. The authors reported that in the USA there were increasing examples of media stories based on recreational fisheries in recent years (Muter et al. 2013). There has been one study on the perspectives of the shark research community exploring preference for different conservation policies (Shiffman and Hammerschlag 2016b) which serves as a useful template for soliciting expert opinion. There is also a need to quantify the economic value

of recreational shark fisheries, particularly those that are based on catch and release. Exploring "willingness to pay" and characterizing opinions of stakeholders could be used to consider responses to possible management actions which for sharks are quite diverse (Hepp and Wilson 2014). There is also a need to understand the basis for whether an angler will harvest or release a captured shark (and what the economic values are for keeping versus releasing), understanding the extent to which anglers are aware of and embrace conservation-oriented behaviors for fish that will be released (e.g., appropriate gear choice and handling approaches), and more broadly how they obtain their knowledge about sharks.

RESEARCH CHALLENGES

There are a number of inherent challenges to overcome when conducting recreational fisheries science on sharks. This is a function of the diffuse nature of recreational fisheries, complex behavior of anglers, as well as the realities of working with large and mobile top predators. It is therefore not surprising that so many research gaps currently exist. The fact that the scale, scope, and consequences of recreational fisheries for sharks are relatively poorly documented is inherently limiting as it makes it difficult to focus research efforts on meaningful issues/problems. Various tools for tracking anglers and sharks using technology (e.g., smart phones for anglers, electronic tags for sharks) enable the research community to potentially combine the "behavior" and tendencies of both to better understand recreational fisheries for sharks (see Arlinghaus et al. 2013). The overlap of commercial and recreational fisheries in many locations combined with lack of knowledge on shark life history and population status for certain species (e.g., demography, abundance) makes it challenging to understand the long-term consequences of recreational fisheries or to identify suitable management strategies. At the organism level, studies that attempt to understand the extent to which different fisheries practices are stressful suffer from the challenges of obtaining control data from large, free-living animals (see Brooks et al. 2011 for underwater blood sampling as a creative option). Although there are challenges to advancing the recreational fisheries science of sharks, we believe they can be overcome by combining expertise and existing knowledge with creativity and technology.

CONCLUSIONS

We are still a long way from having a comprehensive understanding of the effects of recreational fishing on shark populations, although the slowly growing body of scientific literature is showing us that this is complex, context-dependent, and likely to be dependent on behavior and practice of anglers. The science in this realm is not uniform in terms of its geographic coverage; the majority of the examples that we found were based in the USA with additional examples from other countries, most of which speak English. There is much room for research on the status, characteristics, and consequences of recreational shark fisheries from other jurisdictions. Future work on recreational shark fisheries will benefit from the lessons we have learned from four areas of study, and applying them to generate research questions within a recreational angling setting: (1) applied commercial fisheries research on elasmobranchs, particularly those using risk assessment and analysis; (2) CR science on elasmobranchs stemming from commercial (i.e., longline) studies; (3) recreational CR science (physiological and behavioral assays) on teleost fishes; and (4) human dimensions research on recreational fishing of teleosts. Clearly, recreational shark fishing can have an impact on sharks, but ascertaining the survival and fitness-level impacts for many species will provide useful endpoints for policy makers charged with managing these fisheries that are complex, diverse, and widespread.

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