NRC Research Press
PERSPECTIVE

Transboundary movements, unmonitored fishing mortality, and ineffective international fisheries management pose risks for pelagic sharks in the Northwest Atlantic

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Abstract: The shortfin mako (*Isurus oxyrinchus*), porbeagle (*Lamna nasus*), and blue shark (*Prionace glauca*) are three frequently caught shark species in the northwestern Atlantic Ocean. Satellite tagging studies show that all three species range widely across many national boundaries but spend up to 92% of their time on the high seas, where they are largely unregulated and unmonitored. All are caught in large numbers by swordfish and tuna fishing fleets from a large number of nations, usually unintentionally, and all are unproductive by fish standards, which makes them particularly sensitive to fishing pressure. Landing statistics that grossly underrepresent actual catches, unreported discards that often exceed landings, and high discard mortality rates are threats to the populations and roadblocks to useful population monitoring. The influence of these threats is greatly magnified by inattention and ineffective management from the responsible management agency, the International Commission for the Conservation of Atlantic Tunas (ICCAT), whose prime focus is the more valuable swordfish and tuna stocks. Although practical management options are available, none will be possible if organizations like ICCAT continue to treat sharks like pests.

Résumé : Le requin-taupe bleu (*Isurus oxyrinchus*), le requin-taupe commun (*Lamna nasus*) et le requin bleu (*Prionace glauca*) sont trois espèces de requin fréquemment capturées dans le nord-ouest de l'océan Atlantique. Des études reposant sur les étiquettes satellites montrent que les trois espèces sont réparties sur de vastes territoires chevauchant de nombreuses frontières nationales, mais qu'elles passent jusqu'à 92 % de leur temps en haute mer, où elles ne font l'objet de presque aucune réglementation ni surveillance. Toutes ces espèces sont capturées en grand nombre par des flottes de pêche à l'espadon et aux thonidés de nombreux pays, généralement de manière non intentionnelle, et il s'agit dans les trois cas d'espèces de poissons non productives, ce qui les rend particulièrement sensibles à la pression de la pêche. Des statistiques sur les débarquements qui sous-représentent nettement les prises réelles, des rejets non signalés qui dépassent souvent les débarquements et des taux élevés de mortalité par rejet sont autant de menaces pour les populations et d'obstacles à la surveillance efficace de ces dernières. L'influence de ces menaces est grandement amplifiée par l'inattention et une gestion inefficace de l'agence de gestion compétente, la Commission internationale pour la conservation des thonidés de l'Atlantiques (CICTA), dont les efforts sont principalement axés sur les stocks d'espadons et de thonidés de plus grande valeur économique. Si des options de gestion pratiques existent, aucune ne sera possible si des organismes comme la CICTA continuent de considérer les requins comme étant des animaux nuisibles. [Traduit par la Rédaction]

Introduction

Sharks are fish. Although this fact should be obvious to all, it is often overlooked amidst the public and conservationist attention accorded the larger species of this taxon. Indeed, the attention given to many sharks is more in line with that given to some other, equally charismatic but phylogenetically different aquatic organisms such as whales. Whales are mammals, of course. Perhaps counterintuitively, it is some of the characteristics of the sharks that are almost mammalian in character and that distinguish them from their teleost cousins that makes sharks and other chondrichthyans considerably more sensitive to fishing pressure than many teleosts. Predatory reputation aside, sharks are in far more danger from people than people are from sharks, but not for the same reasons that threaten terrestrial top predators such as lions and wolves (Ripple et al. 2014).

The shortfin mako (*Isurus oxyrinchus*), porbeagle (*Lamna nasus*), and blue shark (*Prionace glauca*) are three frequently caught shark species in the northwestern Atlantic Ocean (NW Atlantic), with the blue shark being the most abundant large pelagic shark in the world. All three of these species are relatively large pelagic sharks, of high profile in the public eye, that frequent the waters of the North Atlantic across numerous maritime national boundaries and into the high seas (international open oceans). Each is represented by only one (blue and shortfin mako) or, at most, two (porbeagle) populations in the North Atlantic (Kohler et al. 2002; Campana et al. 2008). Collectively, all three species ignore national boundaries and migrate freely and widely over their range (Mejuto et al. 2005). All are caught (and often killed) in large numbers by fishing fleets from a large number of nations, usually unintentionally (Worm et al. 2013), and all are unproductive by fish standards, with almost mammalian life history characteristics, which make them particularly sensitive to fishing pressure (Musick 1999). The result has been stocks that are at, or below, sustainability levels in one or both of their North Atlantic populations (International Commission for the Conservation of Atlantic Tunas (ICCAT) 2014; International Union for the Conservation of Nature (IUCN) 2016), with a likelihood of further decline. The

Received 30 October 2015. Accepted 26 February 2016.

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Can. J. Fish. Aquat. Sci. **73**: 1599–1607 (2016) dx.doi.org/10.1139/cjfas-2015-0502

Table 1. A side-by-side comparison of characteristics of human female and female porbeagle, blue shark, and bluefin tuna.

Characteristic	Human	Porbeagle	Blue shark	Bluefin tuna
Adult mean length (cm)	163	220	220	220
Age at sexual maturation (years)	13	13	6	8
Mode of fertilization	Internal	Internal	Internal	External
Gestation period (months)	9	9	12	Indeterminate
Birth	Live	Live	Live	Pelagic eggs
Mean number of young per year	1	4	35	10 000 000
Mean length at birth (cm)	44	65	45	0.3
Longevity (years)	80	40	20	40

source of the decline comes not only from immediate and delayed fishing mortality, but also from the inattention that accompanies stock assessment and management by regional fisheries management organizations (RFMOs) whose prime focus is the more valuable swordfish, tuna, and groundfish stocks. There is no reason that this inattention need occur — the predictable fecundity and external sex characteristics of elasmobranchs should make them at least as easy to manage as teleost stocks — but the track record for shark management worldwide has been poor (Dulvy et al. 2008). Are transboundary shark populations destined to go the way of their far less charismatic elasmobranch cousins, the skates and rays, whose population numbers have declined by over 90% in some regions (Shepherd and Myers 2005; McPhie and Campana 2009)? In this perspective, I will argue that shark life history characteristics and their transboundary migratory habits put them at greater risk from fishing pressure than possibly any other group of fishes in the North Atlantic.

Life as a shark: always on the move

The life history characteristics of sharks that render them less productive than most teleosts, and more akin to mammals, includes their longevity, modes of reproduction, low fecundity, and a delayed age at sexual maturation (Table 1). Take, for example, the porbeagle. A side-by-side comparison of female porbeagle and human female characteristics highlights some remarkable similarities (Table 1).

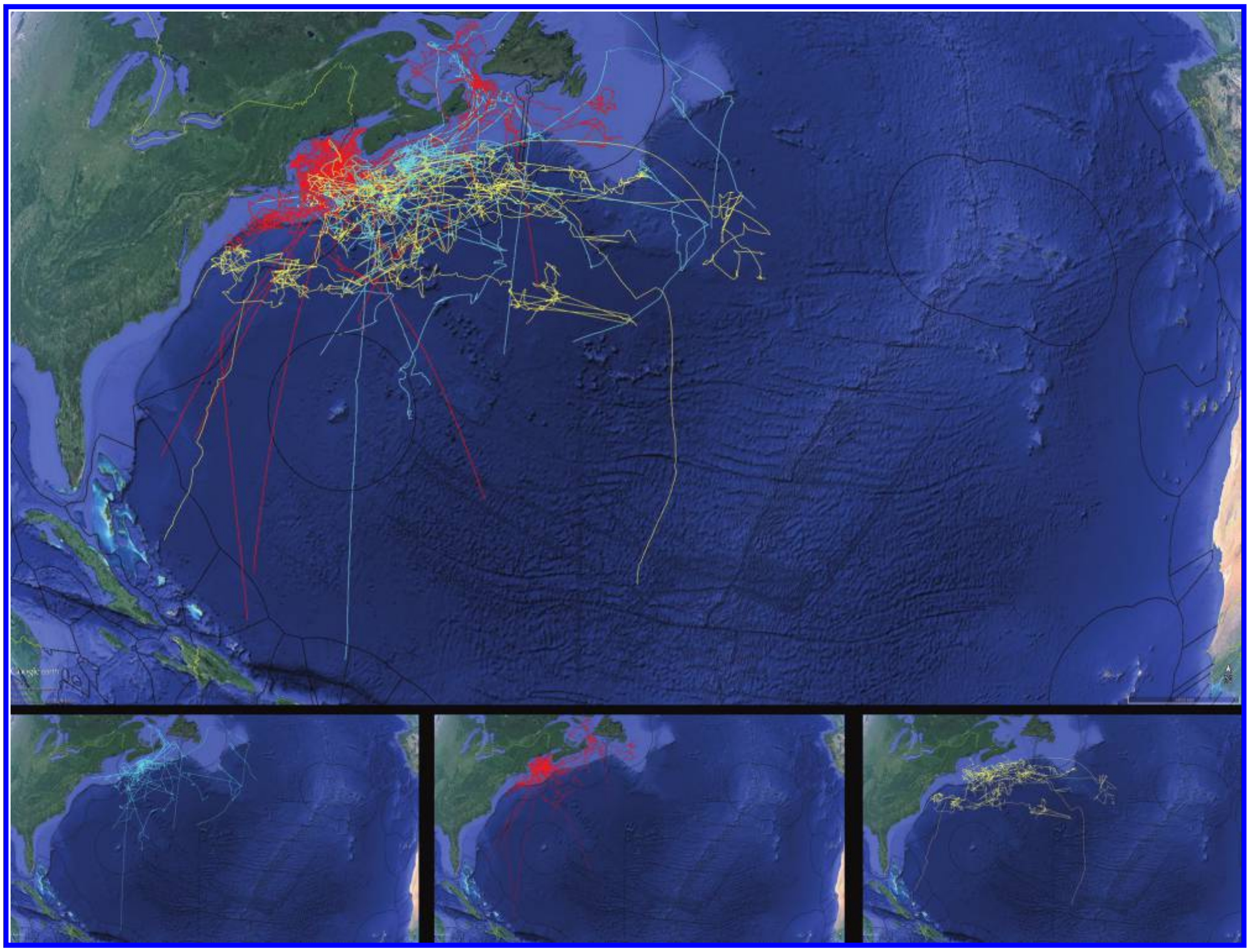
Two features in particular stand out for porbeagle compared with most other fishes: a delayed age at sexual maturation and very low fecundity. The result is a population productivity for porbeagle that is not markedly higher than that of humans. Measures of the maximum intrinsic rate of population increase ($r_{\max}$) for porbeagle are on the order of 0.05 (Campana et al. 2015*b*), whereas for humans, it is about 0.03 (Quinn and Deriso 1999). In contrast, the $r_{\max}$ value for a comparably sized teleost, the bluefin tuna, is a factor of six higher, at about 0.34. An even greater source of contrast between porbeagle and bluefin tuna is with respect to their potential for unexpected population growth. There is no such thing as a “strong year-class” for porbeagle. Reproductive output is largely fixed at four young per year for porbeagle and is reasonably predictable for all elasmobranchs; the maximum annual increase in population abundance is about 5% in porbeagle, with very little variance around the expected (high) survival to age 1. In tuna, on the other hand, the huge production of fertilized eggs leaves open the possibility of good larval survival conditions and recruitment strengths, which can literally double stock abundance in the space of a year. Thus, there is a random component to population fluctuations in teleosts that can serve as a “safety net” that is simply not present in elasmobranchs.

Blue sharks are considered one of the most productive species of elasmobranchs (Cortés et al. 2010). With an $r_{\max}$ of about 0.29, their capacity for population growth is about six times higher than that of porbeagle and much closer to that of bluefin tuna. Nevertheless, blue sharks experience a predictable recruitment rate similar to that of porbeagle and most other elasmobranchs, implying that there will be no rapid improvements to stock status once depleted; recovery times from even modest overfishing can be expected to take decades for many elasmobranch species (Musick 1999; Campana et al. 2015*b*). This is not to imply that overfishing of teleosts is somehow less important or that teleost recruitment variability cannot push the stock down almost as quickly as it can push it up. However, it does highlight the fact that the life history characteristics of sharks tend to make them unproductive relative to other fish — billfish and tunas are two to three times more productive than most pelagic sharks (Au et al. 2008) — and thus necessarily slower to recover once depleted.

A second life history feature of large pelagic sharks that puts them at greater risk with fishers is their highly migratory behaviour. Like all fishes, sharks swim, but unlike all teleost fishes, pelagic sharks must swim. Sharks are slightly negatively buoyant and lack swimbladders, so they must use the hydraulic lift from swimming to maintain depth and to avoid sinking to the bottom of the ocean. In coastal waters, this would not necessarily be a problem; in the open ocean over abyssal depths, it needs to be avoided. Combine continual swimming activity with a large body size and you have the possibility of large-scale movements and hence a higher probability of encountering fishing gear. Indeed, recent research using archival satellite pop-up tags (see Appendix A, Supplementary methods) indicates that displacement distances of hundreds or thousands of kilometres for shortfin mako, porbeagle, and blue sharks are the norm, not the exception (Fig. 1). Unfortunately, sharks refuse to acknowledge national boundaries, with 65% of the tagged sharks spending time within the Exclusive Economic Zones (EEZ) of more than one country. Perhaps more importantly, these species also spend a great deal of their lives in the high seas; between 59% and 74% of the shark tags popped off while they were in international waters, and 92% of the sharks strayed outside of the EEZ (Canadian) where they were tagged. As a result, no one country “owns” these fish or can take responsibility for their assessment and management. As will be seen later, this is a huge problem.

There are several marine species that transit the high seas of the North Atlantic. What makes pelagic sharks any different? Swordfish, tunas, whales, leatherback turtles, and other pelagic sharks such as great whites and basking sharks are all large-bodied and highly migratory in the high seas. However, with the exception of the sharks, they are all considered either commercially valuable (and hence monitored) or are under some sort of international conservation protection. Moreover, given their predatory nature, the pelagic sharks compete with, and are often found in association with, the targets of pelagic longline fishing gear (Mejuto et al. 2008). Indeed, the overall distribution and swimming paths of the large pelagic sharks (Fig. 1) overlap very nicely with most of the areas of intensive pelagic longline fishing by many nations (Fig. 2). Thus, it is almost inevitable that sharks will be caught in large numbers. Being caught and counted is not necessarily a problem; being caught, killed, and discarded without being counted is a huge problem because the unrecorded mortalities are not included in any assessment of population status.

Fig. 1. Reconstructed swimming paths of 52 pelagic sharks tagged with archival satellite pop-up tags off the coast of eastern Canada: porbeagle (n = 17; red lines), mako (n = 15; yellow lines), and blue shark (n = 19; blue lines) tags were attached to the shark for periods of 10–370 days. EEZ boundaries are indicated by black polygons.

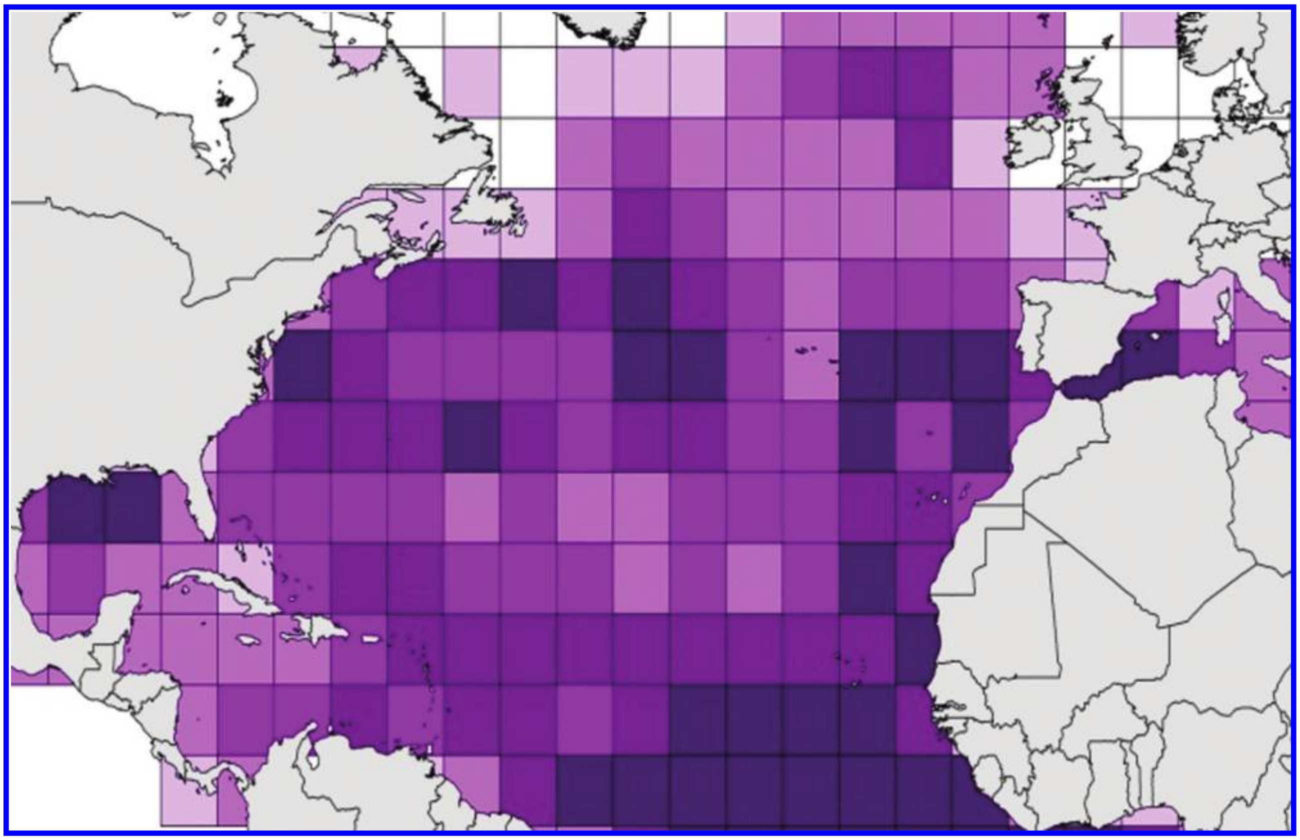


Fisheries management by RFMO: kids in a sandbox

The challenge of trying to count millions of swimming fish that are effectively hidden under hundreds of metres of water means that stock assessment and fisheries management will never be easy. Nevertheless, the track record for elasmobranchs is worse than most. A comprehensive analysis of 1041 chondrichthyan species on the International Union for the Conservation of Nature (IUCN) Red List reported that 17% of the species were considered threatened with extinction (critically endangered, endangered, or vulnerable; Dulvy et al. 2014). Assessed shark and ray species with large body sizes were considered to be in the most danger. Although sustainable shark fisheries are theoretically possible, most industrial fisheries targeting elasmobranchs have been characterized by a "boom and bust" trajectory of landings, culminating in a major depletion of the exploited population (Castro et al. 1999; Campana et al. 2008). A few such fisheries that are apparently sustainable are now in place, but they have required more conservative benchmarks and perhaps a higher level of enforcement (Walker 1998; Gedamke et al. 2007). All of these "success stories" have been managed nationally, not internationally. Indeed, there is evidence of progress at the national level in that 88% of the 26 major shark-fishing nations have at least a draft National Plan of Action on Sharks in place, even if 25% of those only attempt to regulate shark finning (Fischer et al. 2012). Unfortunately, many nations are losing the battle to halt the decline of their own chondrichthyian resources (Davidson et al. 2016).

So where does that put the large pelagic shark species such as shortfin mako, porbeagle, and blue shark, whose territory lies largely in the high seas and outside of national boundaries? It puts them in the realm of Regional Fisheries Management Organizations (RFMOs), quasi-cooperative alliances among countries that agree to work together towards a common goal, which ultimately is money (at least from the perspective of the nations, not necessarily the individuals involved). In the NW Atlantic, both the Northwest Atlantic Fisheries Organization (NAFO) and ICCAT regulate transboundary and high-seas fisheries, although it is ICCAT that is responsible for the pelagic longline fisheries for swordfish and tunas that catch almost all of the pelagic shark species. To say that sharks are a low management priority for ICCAT is to understate the situation. ICCAT represents 48 contracting parties (nations or groups such as the European Union), that collectively fish more than 127 million hooks each year in the North Atlantic (ICCAT 2012). Their prime focus (and some would say their only real focus) is tunas, swordfish, and billfish. To this end, there are carefully crafted management plans designed to ensure that each member country gets every last ounce of tuna, swordfish, and billfish quota to which it is entitled by previous agreement. The management plans, in turn, are based on rigorous stock assessments, which are updated regularly. That is not to say that the resulting catch quotas are necessarily based on precautionary values recommended by science; the hardened negotiators who represent each country at the table are usually more concerned about

Fig. 2. Density distribution of hooks fished by longline fisheries for North Atlantic tuna and tuna-like species from 1950–2007 (adapted from ICCAT 2010).



increasing (or protecting) their share of the pie rather than ensuring that the overall pie is sustainable. Although some countries do try to take the high road in terms of precautionary management, they are often forced to change their stance to protect themselves from other countries who will try to trick the system to increase their share. Overall, it is like kids in a sandbox, with some kids trying to play fair and others kicking sand in their face while they steal the toys.

That is the situation for the teleosts. How about the sharks? Well, if the tunas and other teleosts are being managed in the sandbox, the fate of the sharks is being decided in a gravel pit. There are no international catch quotas for any of the pelagic shark species. As a matter of fact, until recently, there was effectively no high-seas management for any of the shark species other than prohibitions on shark finning. This has changed in the last few years with the introduction of catch prohibitions for bigeye thresher sharks (*Alopias superciliosus*), oceanic whitetip sharks (*Carcharhinus longimanus*), and hammerhead sharks of the family Sphyrnidae, all of which have been listed under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) to restrict international trade. However, other forms of shark management are conspicuously absent. Reporting of shark catches by member nations is recommended, but enforcement is the responsibility of the same member nation (ICCAT 2016). Reporting of shark discards (which account for far more than the landings) is "encouraged", but few countries do so. There are no catch or discard allocations by country. There are no attempts to measure or compensate for discards, discard mortality, or hooking mortality. There are no observer programs or fishery-independent surveys for sharks in international waters, even though some exist for the teleosts. There is no enforcement or punishment of any kind if contracting parties do not submit any shark catch data. In other words, sharks are of minimal interest to ICCAT, and what management measures are in place are largely due to pressure from environmental nongovernmental organizations (ENGOs) and CITES.

Is it possible that the challenges of working with so many countries makes precautionary management impossible? This is a fair question, but one that was recently answered by the actions undertaken by ICCAT after CITES proposed listing bluefin tuna under Appendix I, which would have effectively closed the Atlantic bluefin tuna industry. Almost overnight, the ICCAT contracting parties agreed on new, precautionary management measures that, for the first time in decades, put recovery efforts for bluefin tuna on scientifically defensible ground. Clearly, proper fisheries management by multinational RFMOs is possible if the will is there.

Are all of the issues concerning high seas pelagic sharks in the North Atlantic due to failures by ICCAT? The answer is "no". Although stock assessments have been completed for North Atlantic shortfin mako, porbeagle, and blue sharks, the uncertainty around shortfin mako and blue shark status is so broad as to encompass almost the entire range between a lightly fished population and one that is overfished (ICCAT 2014). This stock assessment uncertainty is not the fault of the scientists who conducted the ICCAT assessments, as the underlying data are so incomplete. A large portion of the data gaps can be attributed to some of the ICCAT member nations, who provide wildly varying data accuracies for all of their fisheries. In addition, there are several major fishing nations fishing the North Atlantic who are not party to ICCAT and do not provide any shark catch data to anyone. Thus, there are obvious challenges in trying to assess shark stock status. Nevertheless, the very different standards applied by ICCAT to sharks compared with tunas, swordfish, and billfish highlights the conclusion that sharks are viewed as a nuisance, not as a concern.

Table 2. Independent estimates of total catch (tonnes) compared with reported landings (tonnes) for blue shark and shortfin mako in the North Atlantic in 2006.

Estimation method	Blue shark	Mako	Source
ICCAT reported	23 215	3 370	ICCAT Task 1
ICCAT adjusted	26 795	3 564	ICCAT (2009)
Fin trade	61 845	5 996	ICCAT (2009) based on Clarke (2008)
Mass ratio: Canada	107 495		Campana et al. (2006) for year 2000
CPUE: North Atlantic	91 353		Campana et al. (2009)
CPUE: Canadian–Spanish regional	139 481	8 104	This study, prorated by Mejuto et al. (2005)
CPUE: US observer		5 349	Cortés (2013)
CPUE: Portuguese observer	135 663	12 642	Coelho et al. (2012)
CPUE: Spanish	135 014		Mejuto et al. (2005)
Ratio to mako: Japan	59 960		Senba and Nakano (2005)
Ratio to mako: China	125 916		Dai et al. (2009)
Ratio to mako: Portugal	64 157		Coelho et al. (2012)
Ratio to mako: Canada observed	160 093		This study
Ratio to mako: Spain	48 568		Mejuto et al. (2008)

Note: Estimation methods are described in the Appendix A, Supplementary methods.

Die now, die later

There are no directed fisheries for large pelagic sharks in the North Atlantic; therefore, all of the pelagic sharks are caught as bycatch, usually by pelagic longlines targeting swordfish and tunas (ICCAT 2014). Bycatch species are seldom recorded in fishers' logbooks unless they are commercially valuable, which results in few records of discarded individuals. Shortfin makos are of sufficient landed value that two-thirds of them are often retained after capture, but the situation is much different for the lower value porbeagle, where 84% of them are discarded after capture (Campana et al. 2015*b*; James et al. 2015). As for blue sharks, discard rates are much higher, as they have no commercial value in North America. How much higher? Blue shark discard rates in the U.S. and Canadian swordfish and tuna fisheries approach 100% (Mandelman et al. 2008), and those for most countries other than Spain are also substantial. Given that blue shark catch rates often exceed that of the target species (especially swordfish), the quantities of blue sharks that are discarded annually in the North Atlantic are believed to be about 3 million sharks, or 100 000 tonnes (t) (Campana et al. 2009). The quantities of shortfin mako and porbeagle that are discarded annually are considerably less in absolute terms, but in terms of relative stock biomass, they are still substantial (Clarke 2008).

In theory, fish that are discarded from a fishery are of no consequence to the population and do not require data records or integration into the stock assessment as long as they are released uninjured back into the environment. In practice, some level of mortality is both inevitable and potentially important to the stock status of unproductive species such as sharks. Large pelagic sharks are subject to four different types of fishing-induced mortality, all but one of which differ from values for comparably sized teleosts: (1) landing; (2) finning; (3) unintentional capture (hooking) mortality; and (4) postrelease mortality. Landed sharks are treated like any other landed fish and are generally recorded by most fishing nations, and thus they are accounted for in any stock assessment or yield calculation. In contrast, the fins of sharks that are cut off and kept while the still-living carcass is dumped in the ocean ("shark finning") are almost never recorded because finning has been banned by most countries (Fischer et al. 2012). With a total estimated market value of about US$350 million, the lucrative fin trade is a strong motivator for retaining shark fins and (or) bycatch (which also includes fins of landed sharks, whether legal or illegal) and has been linked to a median annual global estimate of 26–73 million dead sharks (Clarke et al. 2006, 2013; Worm et al. 2013). Estimates of the numbers of fins for sale in Asian markets, coming from the North Atlantic, greatly exceed the reported (nominal) shark catch (Clarke 2008), indicating that illegal finning continues to be a problematic and major source of shark mortality on the high seas. Given that there is no analogous market for teleost fins, the shark fin trade is a source of mortality that is unique to sharks.

Hooking mortality affects all fish species caught on pelagic longlines. If the dead fish is retained for landing, the cause of death is irrelevant, but if the fish that dies on the hook is subsequently discarded, then hooking mortality becomes an important and often unrecorded source of fishing mortality. Sharks are usually discarded. Hooking mortality rates differ across species, fishing fleet, fisher, and water temperatures, but porbeagles, shortfin makos, and blue sharks caught by pelagic longlines in the North Atlantic experience hooking mortality rates of 15%–44% (Mandelman et al. 2008; Coelho et al. 2012; Campana et al. 2016). Is this any different from hooking mortality rates for comparably sized teleosts? Probably not (Carruthers et al. 2009), despite the fact that hooked sharks have restricted swimming movements, thus compromising their breathing as ram ventilators. However, while the hooking mortality rates may be similar between sharks and teleosts, the much larger numbers of sharks that are subsequently discarded results in a much higher proportion of dead shark discards compared with most teleosts.

Postrelease mortality is only an issue for fish that are discarded alive, so once again, it is a much more important source of mortality for sharks than for valuable (and retained) tunas and swordfish. Postrelease mortality rates have been calculated for relatively few fish species, given that they usually require application of satellite pop-up tags to monitor survival in the ocean after discarding. In the case of shortfin makos, porbeagles, and blue sharks, postrelease mortality rates of 10%–31% have been estimated for shark discards from swordfish fisheries in the NW Atlantic (Campana et al. 2016). Thus many of the sharks being released alive are subsequently dying, with no record of their mortality.

So where does all of this put us with respect to the number of sharks that are killed each year in the North Atlantic? We do not really know, and the reason that we do not know is that the observer programs, data records, and enforced reporting that would usually be required for a nationally managed fishery and that could be used to estimate unreported discards and discard mortalities are absent for the high seas in the North Atlantic. Nevertheless, broad estimates are possible using several independent approaches. Shark catches (landings plus discards) as reported to ICCAT grossly underestimate shark mortalities based on the shark fin trade in Hong Kong (Table 2). Therefore, effort-independent catch ratios and effort-dependent CPUE estimates from different countries were compiled to produce additional independent estimates of blue shark and shortfin mako catches across the entire North Atlantic (see Appendix A, Supplementary methods). These approaches (including that from the fin trade) provided estimates of the 2006 North Atlantic blue shark catch ranging from 48 568 to 160 093 t, with an overall mean of 102 686 t (Table 2). This estimate of catch is four times higher than the value reported to ICCAT. The comparable catch estimates for shortfin mako range from 5349 to 12 642 t, with an overall mean of 8698 t, which is more than double that reported to ICCAT (Table 2). If we assume that the 61 845 t mortality estimate based on the shark fin trade represents the actual blue shark mortality due to landing and (or) finning, that would still leave 40 841 t of blue sharks discarded annually, which, in turn, would be subject to a 23% combined hooking and postrelease mortality (Campana et al. 2016), or 9393 t. Therefore, about 72 000 t of blue sharks are being killed annually in the North Atlantic, out of 102 686 t being caught. That's a lot of sharks, about 2 million individuals, actually, and only 25% of the total catch is being reported to ICCAT.

What is a sustainable mortality level for a discarded shark species?

Pelagic sharks that are caught in Canadian or national waters of any other country are still part of a North Atlantic wide population and thus are subject to assessment and regulation by ICCAT. Although ICCAT has completed a stock assessment for blue and shortfin mako sharks, which ICCAT itself acknowledges as uncertain, no reference points have been set and there are no catch or mortality regulations (ICCAT 2009, 2012). At present, therefore, there are no limits, biological reference points, or estimates of sustainable mortality in place for blue or shortfin mako sharks anywhere in the North Atlantic, and there are no national allocations of catch, discards, or overall mortality, even though such exist for many of the tuna and swordfish species.

There are several possible approaches to calculating sustainable national allocations of a transboundary fish stock, one of which is the use of national catch (landings plus discards) histories. However, the use of catch histories has no scientific basis for determining biological reference points and appears particularly unsuitable for a discarded bycatch species for which few countries have reported estimates of discard mortality. As an example of the arbitrarity of catch histories for blue shark, Canada's reported blue shark catch and discard mortality would be 0% of the North Atlantic reported blue shark longline catch if based on the most recent 5 years, but 3.1% if based on the 10 years leading up to the last (2008) stock assessment. Catch histories based on landings, as opposed to discard mortalities for which only Canada has reported statistics, would be very close to 0% for Canada. Clearly, catch histories based on reported blue shark catches would not provide any meaningful information for determining if national blue shark discard mortalities are biologically sustainable.

ICCAT uses maximum sustainable yield (MSY) as a target reference point for its tuna and swordfish fisheries. Although MSY is known to be a nonprecautionary target yield, it is still a biologically determined reference point and therefore still useful. However, MSY is typically estimated from landings, which is a poor approach for a largely discarded species. In principle, there is no reason why MSY could not be estimated using all sources of fishing-induced mortality (i.e., landings, dead discards, and postrelease mortality). Furthermore, there is no reason why MSY based on all sources of fishing mortality could not be estimated for blue and shortfin mako in the North Atlantic, and there is no reason why sustainable mortality targets or quotas could not be set for each species, even if reference points other than MSY needed to be used (Curtis et al. 2015). So why haven't those targets been set?

National responsibility for a discarded, transboundary shark species

There is no incontrovertible method for calculating the national "share" or allocation of sustainable mortality of a transboundary population such as blue shark, even if the sustainable mortality of the entire population is known. The disadvantages of national catch histories were discussed earlier. Another possible and more scientifically defensible approach is to determine the sustainable mortality of the entire North Atlantic blue shark population and then prorate it based on the country's share of the catch of targeted ICCAT fisheries that also catch blue sharks. The catch statistics for valued (targeted) ICCAT species are considered to be much more accurate than those of discarded species, thus making them far more useful in calculations.

As an example of how a national allocation might be calculated, blue shark bycatch in Canadian fisheries was examined. The most recent stock assessment for the North Atlantic blue shark stock was conducted using data up to the end of 2007. Estimates of blue shark MSY based on the most reasonable of the models tabled at the assessment ranged between 29 330 and 133 200 t, with a mean of 69 800 t (Campana et al. 2015*a*). Because more than 96% of the reported blue shark catches in the North Atlantic are caught by pelagic longlines, any calculations based on overall blue shark MSY yield can be largely restricted to this fishing gear. So, for example, Canada fishes several ICCAT-managed target species whose pelagic longline fisheries also catch blue sharks and swordfish, as well as albacore, bigeye, yellowfin, and bluefin tuna. In 2007 (the year of the last full blue shark assessment), the Canadian catch (including dead discards) of swordfish was 1387 t of the total North Atlantic longline catch (plus discards) of 11 748 t. Equivalent values for longline-caught North Atlantic albacore (27 t Canadian/3237 t total), Atlantic bigeye (144/46232), and western Atlantic yellowfin (276/13557) were based on smaller Canadian catches, as was the 55 t of Canadian bluefin allocated to longline bycatch (out of a total western bluefin longline catch of approximately 600 t). Despite the fact that Canada's allocation of the tuna species is relatively small, blue sharks are caught throughout the North Atlantic and thus the blue shark MSY catch must be apportioned across all countries fishing pelagic longlines in the North Atlantic. For example, even if Canada was allocated and caught 100% of the North Atlantic swordfish quota, it would not mean that they were entitled to 100% of the blue shark MSY, as blue sharks are caught in large numbers by other countries fishing tunas. Canada's combined swordfish–tuna catch was 2.5% of the total North Atlantic swordfish–tuna longline catch. Applying this percentage to the range of blue shark MSY values would result in a Canadian "allocation" of blue sharks of between 733 and 3330 t, with an overall mean of 1550 t. Thus, the recent annual catch mortalities of about 400 t from the Canadian pelagic longline fleet are probably sustainable. This approach for determining "acceptable" national allocations of shark mortality assumes that the proportion of blue sharks relative to each of the five targeted ICCAT species are similar and that the proportion is spatially invariant throughout the North Atlantic. These assumptions are unlikely to be correct, but the same assumptions are made by ICCAT in estimating blue shark catch throughout the Atlantic Ocean (ICCAT 2009). Based on this approach, blue shark mortality associated with fishing (landings, dead discards, and postrelease mortalities) of less than about 1550 t annually should be sustainable by the Canadian pelagic longline fleet, whether fishing in national or international waters, assuming that the overall MSY estimation is accurate and that all other nations assume local responsibility for blue sharks in the same way.

In principle, the same approach could be used to calculate national allocations of all shark species managed by ICCAT, or indeed any high seas fish species for which there are no ICCAT allocations. Why is this necessary? There are currently no restrictions on any one country catching or killing unlimited numbers of any or all pelagic shark species in the North Atlantic, other than those listed by CITES. Because discard mortalities are seldom regulated in international fisheries, discard mortalities of a less productive fish such as a shark need to be viewed in a very different light than that of more productive teleost species.

Mitigation options

RFMOs need to get serious about pelagic shark assessment and management, but to this point, they have shown little interest in acting on their own. After all, RFMOs ultimately act to maximize fishery profits across nations, and shark management has the potential to reduce their profits (although it need not do so). External pressure is likely the answer here, as evidenced by the profound change in Atlantic bluefin tuna management that resulted from the threat of CITES trade restrictions.

Bycatch mitigation is a global problem, and many solutions have been offered to deal with it (Erickson and Berkeley 2008; Oliver et al. 2015). Unfortunately, many of those options are not easily adapted to fisheries that catch large pelagic sharks on the high seas. Reduced bycatch is usually the preferred option, as it results in both reduced mortality and reduced loss of fishing gear and bait (and therefore increased profits) by fishers. However, spatial or seasonal fishery closures are not effective when the target species and the bycatch (in this case, pelagic sharks) share similar habitat and prey items. Similarly, reserves or shark sanctuaries on the high seas may be considered impractical given the large home range of shortfin mako, porbeagle, and blue sharks (Fig. 1). Bycatch can also be reduced through modifications to fishing gear; for example, the introduction of the circle hook has reduced shark hooking mortality relative to the traditional J hook (Kaplan et al. 2007). However, other attempts to reduce shark catchability through use of rare earth metals and electrical fields have largely been disappointing (Godin et al. 2013).

So, do realistic options exist for improved pelagic shark management? Absolutely, and many of the options can be implemented through only a change of practice, with little additional cost or impact on fishery profits. Better catch monitoring would be an excellent start. Optimal management of any population is very challenging if the status of the population is unknown. Mandatory reporting of all shark landings and discards by each fishing nation is clearly required; the key will be how this mandatory reporting will be enforced on the high seas. Linking national shark reporting to the national quota allocations of the target species is one possibility, but it would be preferable to pick a mechanism for which there is less incentive for false reporting. Inclusion of estimates of dead discards and postrelease mortality rates in the ICCAT shark stock assessments would also lead to improved assessments of population status and thus simplify management efforts. Perhaps the single most influential improvement to the current system would be the introduction of a scientific observer system for each nation fishing as part of the RFMO. Observer coverage of 5%–20% on commercial fishing vessels is commonplace among nationally managed commercial fisheries; why is it completely absent in international fisheries where it could benefit the assessment and management of both the target species and the bycatch species such as sharks? Observer systems could provide not only the bycatch and discarding data so desperately required for shark management, but also more accurate catch and discard data for the tunas and swordfish and even the research platforms sometimes required by RFMO-requested science questions. It seems like a no-brainer.

Once the catch statistics have been improved (and even before they have been improved), some form of shark quota allocation to the member countries of ICCAT is important. This allocation needs to include all forms of fishing mortality (i.e., landings and both hooking and postrelease mortality) and could be implemented using the calculation strategy described earlier. Quota allocations based on MSY estimates would be preferable, but some form of quota allocation can begin even if MSY estimates are missing.

Mandatory release of pelagic sharks is another option. Although ICCAT has already implemented mandatory release for CITES-listed shark species, it is not necessarily a good option for shortfin mako and blue sharks (porbeagle are currently being managed nationally by the EU and Canada–US). Neither shortfin mako nor blue sharks are considered to be in imminent danger of collapse, although one or both may be overexploited. As a result, mandatory release may be considered biologically unnecessary and would perhaps increase the rate of unreported finning. It may also punish the few countries that are now freely reporting their shark catches (i.e., Spain).

The key link in the shark management conundrum is the fins. The fin trade is one of the primary drivers of global shark mortality. Bans on fin sales have been adopted by some cities and in some US states on the presumption that sales would decline in the absence of a legal market. It remains to be seen if that is the case. Customer education in some Asian markets appears to be reducing the demand for wedding soup and thus fin sales (Eilperin 2011). However, shark fins continue to command a high market price and are readily concealed on a fishing vessel, making it logistically difficult to enforce fin landing regulations. Therefore, any mechanism that serves to disrupt the ready sale of shark fins in the most important market (the Asian market) could be quite influential. International trade restrictions on fin importing and exporting may be the most effective measure for curtailing demand and thus the motivation by fishers to harvest shark fins, and CITES may be the most appropriate international agency for implementing those trade restrictions. CITES trade restrictions appear to be strictly enforced in many countries, making them difficult to circumvent (Wells and Barzdo 1991). CITES usually restricts trade in all body parts of a listed species, so it is not clear if CITES trade restrictions could be limited to just the fins (as opposed to managed and sustainable fisheries for the carcass). However, if the trade in shark fins could be restricted like the trade in ivory, CITES trade restrictions on shark fins could prove to be a valuable aid to the collection of reliable shark statistics and, at the same time, to reducing undocumented fishing mortality.

The days when the high seas could be considered a vast reserve for marine fishes appears to be long gone, and the days for ignoring pelagic shark bycatch as a cost of doing business in "more valuable" fish species, needs to be gone. It's time for RFMOs such as ICCAT to start taking responsibility for their actions on the high seas, even if some of them are unintended.

Acknowledgements

I sincerely thank Warren Joyce, Anna McDonnell, Mark Fowler, and Mark Showell for their help with the satellite tagging. Enric Cortés provided helpful interpretations of the shark assessment models. Two reviewers provided very helpful suggestions for improving the manuscript. I especially thank Troy Atkinson for his continued support of shark research and his willingness to host future shark researchers on swordfish vessels. The satellite tagging was funded by Fisheries and Oceans Canada; however, it is safe to say that the views expressed in this paper are unlikely to represent the views of Fisheries and Oceans Canada.

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Appendix A: Supplementary methods

Tagging

The movements of blue sharks (*Prionace glauca*), shortfin mako (*Isurus oxyrinchus*), and porbeagle (*Lamna nasus*) were studied using pop-up satellite archival tags (PSATs) applied to sharks caught on Canadian pelagic longline vessels targeting swordfish (*Xiphias gladius*), tuna (primarily bigeye tuna, *Thunnus obesus*), or porbeagle in the Northwest Atlantic. Nylon umbrella tag tips were inserted into the dorsal musculature of the shark just lateral to the posterior end of the first dorsal fin, either with a pole, while the shark was on the line and in the water, or after being brought aboard to allow easier handling. Both healthy and injured sharks were tagged. A variety of PSATs were used: Wildlife Computers (WC) Model 4 PATs in 2005–2006, Mk-10 PATs in 2006–2013, and mini-PATs and Microwave Telemetry (MT) X-tags in 2013. PSAT tags were programmed to record depth (±0.5 m), temperature (±0.1 °C), and light intensity at intervals of 10 s to 1 min for a period of 2–12 months after release. Full tagging methods are described in Campana et al. (2016).

A total of 109 of the 131 tags applied from pelagic longliners transmitted successfully after release from the shark, as did an additional four PSATs applied to porbeagle on an otter trawler. For mapping purposes, subsamples of each species (porbeagle, $n = 17$; shortfin mako, $n = 15$; and blue shark, $n = 19$) that had remained at liberty between 10 and 370 days were selected for geolocation analysis, with subsample selection based only on maximum time at liberty. The 10-day minimum period effectively excluded any sharks that were seriously injured or died after release. Shark location at the time of pop-up was determined with an accuracy of <1 km through Doppler-shift calculations provided by the Argos Data Collection and Location Service. The reconstruction of the migration pathway between the time of tagging and pop-up was based on state–space model estimation using ambient light at depth and sea surface temperature (SST) measurements as recorded by the PSAT. Wherever possible, two independent state–space models were fit to the geolocation data from each shark: (*i*) the model ukfsst (Nielsen and Sibert 2007), which was fit to observations of twilight and SST; and (*ii*) the proprietary diffusion-based movement model GPE3 (Wildlife Computers), which was fit to observations of twilight and SST as constrained by bathymetry and dive depth. In most cases, the two models provided broadly similar track reconstructions for any given shark, although the GPE3 model avoided any estimated movements onto land. Because the GPE3 model provided daily geolocation estimates for each shark, its output was mapped for Fig. 1.

Estimation of shark catch

Shark catches (landings plus discards) as reported to ICCAT grossly underestimate shark mortalities based on the shark fin trade in Hong Kong (Table 2). Alternate (and presumably more accurate) catch estimates are possible using various approaches:

(*a*) ICCAT adjusted — The ICCAT shark stock assessment routinely estimates pelagic shark catches by nonreporting nations through comparison with catch ratios of reporting nations. In reporting nations, the mass ratio of each shark species is calculated relative to the target species (sum of tuna, swordfish, and billfish catches). This ratio is then applied to the nations that reported target species catches, but not shark catches (ICCAT 2009). This method does not require estimates of fishing effort, but does assume that the shark catches reported by reporting nations are as accurate as those of the target species.

(*b*) Mass ratio (Canada) — Using the same method described in (*a*) above, the ratio of scientifically observed species-specific shark catches to the sum of observed tuna and swordfish catches (in the same sets) in the Canadian pelagic longline fishery was used to prorate the reported ICCAT landings for tuna and swordfish across all nations (Campana et al. 2009). The use of scientific observer data ensures that the observed mass ratios are accurate. However, the method assumes that the shark to target species mass ratios in the NW Atlantic are similar to those elsewhere in the North Atlantic.

(*c*) CPUE (North Atlantic) — The mean recent pelagic longline CPUE of blue sharks across several nations fishing for sharks in the North Atlantic was 18.4 sharks·1000 hooks^{-1}, corresponding to 430 kg·1000 hooks^{-1} (Campana et al. 2006). North Atlantic pelagic longline effort was the value used in Campana et al. (2009).

There are no undisputed estimates of pelagic longline effort in the North Atlantic as they would apply to blue sharks in a representative year (2006). Ortiz (2014) reported that 32 million hooks were directed at swordfish in the North Atlantic. Lewison et al (2004) used a rigorous grid approach to estimate 206 million hooks in the North Atlantic, but noted that more of the effort was directed at tuna rather than swordfish (swordfish-directed sets tend to catch more blue sharks than tuna-directed sets). Campana et al. (2009) reported a similar value for North Atlantic effort of 212 million hooks. ICCAT (2012) reported 135 million hooks for the North Atlantic in 2006; however, this value of effort came only from vessels that reported catch–effort data (T2 data) and ignored vessels that reported only catch (T1 data). This issue was not a problem for swordfish (T1 and T2 data were similar for swordfish in the North Atlantic), but of considerable magnitude for tuna. While one could normally prorate T2 effort data using the ratio between T2 and T1 swordfish + tuna catches, T1 data are often aggregated across both the North and South Atlantic, as well as the Mediterranean. Calculations from ICCAT T1 and T2 data showed that 50%–56% of the North Atlantic T2 data was accounted for in the Atlantic-wide T1 data for each of swordfish, tuna, shortfin mako, and blue sharks (mean = 53%). Therefore, the North Atlantic pelagic longline effort in the year 2006 was calculated as the number of hooks that caught swordfish plus the number of remaining hooks divided by 0.53, or 162 million hooks.

(*d*) CPUE (Canadian–Spanish regional) — Scientifically observed Canadian longliner blue shark CPUE in ICCAT region 91 (NW Atlantic) between 2010 and 2014 was 1374 kg·1000 hooks^{-1}. Spatial variations in CPUE across other regions of the North Atlantic were accounted for by prorating the observed Canadian CPUE value by regional CPUE values reported by Spanish longliners fishing throughout the North Atlantic (Mejuto et al. 2005). The effort value of 162 million hooks was calculated in (*c*) above.

(*e*) CPUE (US observer, Portuguese observer, Spanish) — CPUE values were taken directly from the publication sources shown in Table 2, with effort calculated as in (*c*) above.

(*f*) Ratio to mako — As a high-value catch, shortfin mako catches are more likely to be recorded than are lower value blue sharks. Therefore, the within-study catch ratio of blue shark to shortfin mako (as calculated from the publication source) was used to prorate the total North Atlantic shortfin mako catch (estimated from the shark fin trade) to estimate the total blue shark catch.