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# MANAGING LEVIATHAN

## Conservation Challenges for the Great Whales in a Post-Whaling World

By Phillip J. Clapham

The Roger Revelle Commemorative Lecture Series was created by the Ocean Studies Board of the National Academies in honor of Roger Revelle to highlight the important links between ocean sciences and public policy. Phillip J. Clapham, the seventeenth annual lecturer, spoke on April 27, 2016, at the National Academy of Sciences.

**ABSTRACT.** Perhaps no group of animals has come to better symbolize human misuse of the global environment than the great whales. Whaling killed almost three million whales in the twentieth century alone, with some populations estimated to have been reduced by 99% of their pristine abundance. Attempts to promote regulated, sustainable whaling by international agreement, notably through the International Convention for the Regulation of Whaling (1946), were almost immediately derailed by over-capitalization and profit-based self-interest. The major whaling nations used uncertainties in abundance estimates to ignore increasing evidence of population declines, and consistently exploited procedural flaws in the Convention to obstruct either the passage of rules designed to enact conservation measures or proposals for independent inspection of the industry. This major failure of regulatory efforts was exacerbated by secret, large-scale illegal whaling by the former Soviet Union and Japan that remained undisclosed for decades. Today, the status of the great whales varies widely: some species or populations are recovering strongly from exploitation, while a few others remain critically endangered. Although some whaling continues, the scale is greatly reduced from that of the twentieth century, and in this largely post-whaling world, other threats to whales are more significant. These include well-documented problems such as ship strikes and entanglement in fishing gear, as well as issues for which population-level impacts are unclear (ocean noise) or largely unknown. The removal of so many whales by whaling likely significantly impacted the ecosystems in which they played a major role as consumers and, through their transport and recycling of nutrients, enhanced primary productivity. As populations recover, the effect of their reintegration into the marine environment represents a fascinating issue in ecosystem dynamics. Overall (and with some notable exceptions), whale populations will likely continue to recover; however, this generally optimistic outlook is clouded by the potential for large-scale oceanic ecosystem changes precipitated by global warming.

## INTRODUCTION

*I see them in hundreds and thousands.*

Thus did the Norwegian whaler Carl Anton Larsen express his astonishment when, in 1903, he first encountered the vast numbers of whales at South Georgia in the South Atlantic. South Georgia, gateway to the Antarctic, was a principal feeding ground for large populations of blue, fin, humpback, and other whales, all of which were at that time virtually unexploited. Larsen established a shore whaling station on the island the following year, and it was not long before other whalers were flocking to the Southern Ocean to claim their shares of the seemingly inexhaustible bounty to be found there (Tønnessen and Johnsen, 1982).

But, of course, no resource is inexhaustible, and it did not take long for the populations concerned to be depleted by the efficient techniques of modern whaling. By the time of the Great War, the stock of humpback whales at South Georgia was essentially extirpated: more than 18,000 had been killed by 1915. The local exploitation of blue whales followed a similar pattern: more than 39,000 were killed at South Georgia in the years 1904–1936, at the end of which period the population had irretrievably crashed.

Worse was yet to come. The introduction into the Antarctic in 1925 of the first stern-slip factory ship freed whalers from their ties to processing stations on shore, and allowed them to roam across the open ocean for months at a time. Suddenly, all whales were vulnerable, even those feeding in the most remote locations.

By the time Antarctic whaling had finally diminished to a relatively small-scale enterprise in the 1980s, great damage had been done. Most populations of the great whales, both there and elsewhere in the world, had been reduced to small fractions of their pristine levels.

With the emergence of the modern environmental movement, whales suddenly became a symbol of human misuse of resources, and of the global environment generally. Today, however, although whaling continues at a modest level in various guises, many whale populations appear to be rebounding well. Here, I begin by providing a brief overview of the history of modern whaling, then examine the current status of whale populations and the threats they face in a largely post-whaling world. I also discuss the surprisingly important role that whales may play in the health of marine ecosystems, and their future in the warmer world so presciently predicted by Roger Revelle in his pioneering work on greenhouse gas and the ocean.

## WHALING: A BRIEF HISTORY

Quite when the first humans attempted the daunting feat of catching a whale is unknown. Subsistence whaling by Native peoples in the Arctic certainly goes back millennia. Neolithic petroglyphs at Bangudae in South Korea represent the earliest record of whaling, with detailed hunting scenes as well as remarkably recognizable depictions of specific baleen whales.

Truly commercial whaling, however—the systematic hunting of whales for profit—likely began in western Europe around the eleventh century when Basque fishermen began to hunt North Atlantic right whales in the Bay of Biscay (Aguilar, 1986). With the discovery of the New World by European explorers, the Basques crossed the Atlantic sometime around 1530; there, they hunted bowhead whales off the coast of Labrador at a time when the Little Ice Age had brought lower temperatures to much of the Northern Hemisphere. The range of this arctic whale was then further south than we see today, a reminder of the plasticity in distribution that whales must exhibit in response to significant changes in climate.

European settlers began whaling off New England in the early 1700s, and by the end of the century, a major industry had been established in the region. Whaling ships from New Bedford, Nantucket, and other ports ranged across the world ocean in their pursuit of whales, whose oil burned in street lamps across the Western world and lubricated the new machinery of the Industrial Revolution.

Initially, New Englanders hunted in the North Atlantic, but with increasingly sophisticated vessel design and the decline of whale populations that had already been exploited for several centuries, new whaling grounds were required. The first whaler entered the North Pacific around 1780. In 1835, a French whaling ship discovered huge numbers of North Pacific right whales in the Gulf of Alaska, after which so many vessels hunted in the region that by 1849 the population was already depleted (Scarff, 1991).

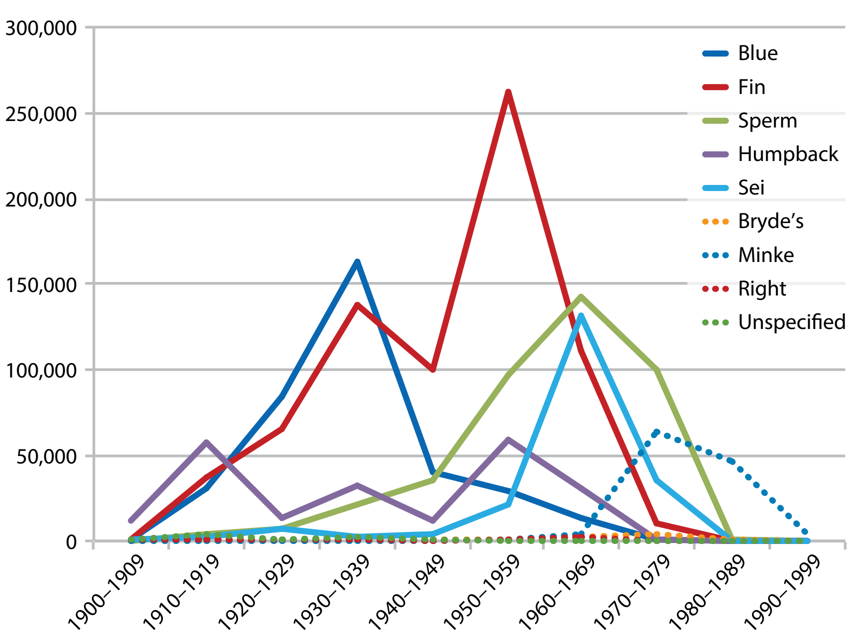


**FIGURE 1.** Southern Hemisphere industrial whaling totals, by decade, 1900–1999. Source: *Rocha et al. (2014)*

In the previous year, the pioneering American whaler Thomas Welcome Roys had been the first non-Native whaler to pass through the Bering Strait; in the waters beyond he found a large population of bowhead whales that, except for a centuries-old subsistence hunt by the local Inuit, was completely unexploited. Elsewhere, sperm whales were being taken in large numbers worldwide for the immensely valuable high-quality oil they yielded, and other grounds were being discovered and exploited.

Although the technology of nineteenth century whalers was based upon hand-thrown harpoons, sail, and the strength of a man's rowing arm, the hunting pressure was sufficiently intense that, toward the end of the century, some populations of the slower whales—sperm whales, humpbacks, grays, rights, and bowheads—had already been severely depleted. Other species that were harder to catch and secure, such as the fast blue and fin whales, remained largely invulnerable to exploitation. However, this changed in the late nineteenth century with two inventions. First, the steam engine suddenly gave whalers the power they needed to chase and catch even the fastest whales. At the same time, the introduction of the explosive harpoon—developed by the Norwegian Svend Føyn (and, rather less successfully, by Roys)—provided a means to much more efficiently kill whales.

With these innovations, the stage was set for modern whaling. The discovery of the vast untouched populations of whales in the Antarctic completed the picture, and thus began a slaughter that, in terms of sheer biomass, was probably unequaled in the history of human hunting. Shore whaling stations gave way to large pelagic whaling fleets, whose huge factory ships could process more whales in a single day than would be captured by a typical nineteenth century New England whaler during the course of a five-year voyage.

Some of the twentieth century catch totals are staggering, particularly for the Southern Hemisphere (Figure 1). The combined catch of blue and fin whales exceeded 300,000 animals during the single decade of the 1930s. Overall, between 1904 and the end of World War II, more than 1,100,000 whales were killed worldwide (Rocha et al., 2014). Clearly, regulation was required if the industry was not going to whale itself out of business.

## THE ERA OF EXCESS

*Fisheries management is endless debate about the status of stocks, until all doubt is removed.* – John Gulland

In 1946, 15 whaling nations signed the International Convention for the Regulation of Whaling. This treaty created the International Whaling Commission (IWC) to oversee management of the industry, conduct research, set catch quotas, and establish various rules and safeguards. The Convention was, in theory, designed to "provide for the proper conservation of whale stocks and thus make possible the orderly development of the whaling industry"—in other words, it aimed to promote sustainable whaling.

This objective was almost from the outset undermined by the desire for continued profit. As such, the whaling industry essentially represents a textbook case of mismanagement, in which heavy capital investment in a finite resource provides a strong incentive to deny the existence of a problem when the resource declines. Consequently, whale catches remained unreasonably high: the 1950s saw almost 614,000 whales killed, of which well over a quarter million were fin whales (Rocha et al., 2014). Even more whales were taken in the following decade: from 1960 to 1969, global catches exceeded 700,000 animals, and almost half of these were sperm whales.

Ignoring mounting evidence of population declines, the whaling nations continued to exploit uncertainty in abundance estimates to oppose more conservative approaches to quota setting, and they used procedural flaws in the Convention to obstruct the passage of rules designed to enact conservation measures. Similarly, proposals for independent inspection of the industry faced consistent obstruction and delay: although the first proposal for an International Observer Scheme was tabled in 1955, it was not until 1972, 17 years later, that it finally passed (Tønnessen and Johnsen, 1982).

One of the main opponents of such an inspection scheme was the USSR, for reasons that are now clear. Unbeknownst to others, the Soviets had been conducting a secret large-scale campaign of illegal whaling that had begun in 1948 (Ivashchenko and Clapham, 2014). Soviet factory fleets worldwide systematically ignored whaling regulations regarding closed areas and seasons, protected species, minimum size, and the prohibition on taking lactating females and calves. To cover up the whaling, the Soviets submitted falsified catch data to the IWC.

Although the fact that the USSR was engaged in illegal whaling was suspected by some within the IWC Scientific Committee, the scale of the deception came as a shock to everyone when it was finally revealed in 1993, after the end of the Cold War (Yablokov, 1994). We estimate that of the 534,119 whales killed by the USSR between 1948 and 1979, 178,726 were not reported (Ivashchenko and Clapham, 2014). Humpback whales in the Southern Hemisphere provide one of the most dramatic examples: the Soviets reported to the IWC that they had killed 2,710 when in fact the actual catch exceeded 48,000 animals. Remarkably, more than 25,000 of these illegally caught whales were killed in just two Antarctic whaling seasons (1959–1961), causing a population crash and the closure of shore whaling stations in Australia and New Zealand.

After the illegal whaling was revealed, it became critical to find the true catch data (which the Soviets had collected for their own research purposes) and correct the IWC's Catch Database; this is because assessments of current whale population status relative to pre-exploitation size rely upon an accurate catch record. Robert Brownell of the US National Oceanic and Atmospheric Administration (NOAA) worked with former Soviet biologists to unearth the true data for the Antarctic whaling fleets. The Soviet North Pacific catches were subsequently corrected by Yulia Ivashchenko, who discovered the true data in Russian archives and worked with former whaling industry biologists to interpret them (Ivashchenko et al., 2013).

The impact of the USSR's illegal whaling on some populations was devastating, although it is important to recognize that the Soviets simply compounded the existing problem, noted above, of excessive "legal" catches by other whaling nations. Nonetheless, as I discuss below, illegal whaling severely reduced some whale stocks, and brought at least one (the North Pacific right whale) to the verge of extinction.

Ironically, the true Soviet data have now been used to expose illegal whaling by Japan (Ivashchenko and Clapham, 2015), although falsification of catch records at Japanese coastal whaling stations was revealed previously (Kasuya, 1999). The Soviet records allowed us to assess the reliability of North Pacific and Antarctic sperm whale catch data submitted by Japan to the IWC, and from these data, it was apparent that Japan had also been engaged in systematic illegal whaling from its pelagic factory fleets in at least the 1960s. Sperm whales bore the brunt of the Soviet and Japanese whaling, with more than 300,000 killed in the North Pacific alone (Figure 2).

In recent years, molecular genetic techniques have been used to identify whale meat samples obtained in Japanese and Korean markets (Baker et al., 2000, 2007). This work has revealed numerous cases in which products on sale are not from legitimate, documented sources (e.g., recent scientific whaling conducted by Japan). It is likely that many of the aberrant products come from bycatch—either incidental or intentional—of whales in local fisheries, although the origin of some samples (e.g., Southern Hemisphere sei whales, which have not been legally hunted since 1979) is much harder to explain.

Overall, the failure of the IWC to ensure sustainable catches, together with the historical ability of whalers to violate whaling regulations on a large scale, has major policy implications for the management of any future whaling (and, by extension, of other living marine resources). More than anything, the history of whaling underscores the need, in any fishery, for an independent, truly transparent system of inspection and enforcement, one that operates at every stage from the catch to the market.

## THE DECLINE OF WHALING

The early 1970s saw the beginnings of a gradual shift in the balance of power at the IWC. Some nations, such as Australia and the United States, having ended their own whaling enterprises, became pro-conservation, while others with a distinctly anti-whaling stance became IWC members. By 1982, the pro-conservation block was sufficiently large to achieve the three-quarters majority vote required to impose a moratorium (strictly speaking, a "zero-catch quota") on commercial whaling, to be implemented in 1986. This represented a major victory for those countries and non-governmental organizations that were opposed to whaling, although two loopholes in the Convention provide a means for the three actively whaling nations to circumvent the ban.

Today, Norway and Iceland hunt whales because the Convention allows members to object to any IWC decision (such as the moratorium) and not be bound by it. Japan uses Article VIII of the Convention, which allows the killing of whales "for the purpose of scientific research" (so-called scientific whaling). At the time the Convention was written, the only practical way to study whales was to kill them, and most research of that period was based upon lethal sampling. The intent of Article VIII has been much debated, but it is unlikely that those who developed and signed the Convention ever imagined that it would be used to circumvent a ban on whaling. Nonetheless, beginning in 1987, Japan developed a program of research in the Antarctic that annually involved the killing of hundreds of whales (mostly Antarctic minke whales). A parallel program was subsequently implemented in the North Pacific, and both continue today.

The validity of the research conducted by Japan has been the subject of considerable debate. Japan has consistently claimed that such research is essential in order to gather the information required to properly manage whale stocks, and to understand the role that whales play in the ecosystem (Morishita, 2006). Opponents have argued that the information collected is either not required for management, or can be obtained as, or more, easily through widely used nonlethal methods (Clapham et al., 2007). Japan's ecosystem approach is seen by many as a way to show that whales compete with humans for fisheries resources, and thus must somehow be controlled; as we shall see, however, recent research suggests that whales represent an essential component of a healthy marine ecosystem and may play an important role in promoting oceanic productivity.

Arguments about Japanese scientific whaling came to a head in 2014, when the International Court of Justice (ICJ) ruled on a case brought against Japan by Australia and New Zealand. The ICJ concluded that the Japanese Antarctic whaling program was "not for the purpose of scientific research" as required under Article VIII, and ordered that the program be ended. Anti-whaling groups hailed the decision, and there was much optimism regarding a possible end to Japanese whaling, at least in the Southern Hemisphere. Such hopes were short-lived: Japan simply developed a new research program (called NEWREP-A), and stated that this complied with the spirit of the ICJ ruling (Clapham, 2014). In 2015, an independent Expert Panel convened by the IWC Scientific Committee to review NEWREP-A concluded unambiguously that Japan had not justified the need for lethal sampling. Despite the finding, in November 2015 the Japanese whaling fleet sailed to the Antarctic, where they killed 333 minke whales under the new program (Brierley and Clapham, 2016).

**FIGURE 2.** Sperm whales killed by a Soviet catcher boat await processing by the factory ship. *Photo credit: MOSCOW Project*

In a move with potentially major policy implications for international fisheries disputes, Japan also attempted to forestall any future legal action by announcing that it no longer recognized the jurisdiction of the ICJ on matters pertaining to marine living resources.

## WHALE POPULATIONS TODAY: GOOD NEWS, BAD NEWS

Today, whales exist in a largely post-whaling world. Whaling has certainly not disappeared. In the North Atlantic, Norway and Iceland continue to hunt a few hundred whales a year under the IWC's objection procedure. Despite extensive criticism of its scientific whaling programs, Japan continues to kill whales of several species in the North Pacific and the Antarctic. There also remain some Native subsistence hunts that take large whales. Despite these various pockets of hunting, and while Japan in particular continues to campaign for a lifting of the IWC's moratorium, it is very unlikely that we will ever again see whaling that approaches the scale of the last century.

That said, there is no doubt that modern whaling had a devastating impact on the great whales. Between Larsen's establishment of a South Georgia whaling station in 1904 and the year 2000, some 2.9 million whales were killed worldwide (Rocha et al., 2014). The majority—more than two million—were taken in the Southern Hemisphere. The legacy of these huge catches is still evident today in many populations, some of which were reduced by 95%–99% of their original numbers.

All cetaceans are of course difficult to study, existing as they do in environments that are inhospitable and often dangerous for human observers, and often far from the convenience of land. Consequently, our knowledge of the status of whale populations today is often hampered by a lack of information. Thomas et al. (2015) give an excellent review of the current status of baleen whales, and statements below regarding abundance and conservation status are in most cases taken from that source.

### Recovering Populations

As a general statement, it is probably reasonable to say that most populations of large whales are recovering from commercial whaling. However, there are major exceptions, and the degree of recovery varies considerably. To date, the only whale population to be removed from the US Endangered Species List is the eastern North Pacific population of the gray whale. Numbering approximately 20,000 individuals, this population may be at carrying capacity, particularly in heavy ice years when their feeding habitat in the Arctic is reduced.

Humpback whales are clearly recovering well in most populations under study. The humpback appears to be a resilient species, and the US National Marine Fisheries Service recently recommended removing several populations from the Endangered Species List. Some populations, such as the one that migrates along the coast of eastern Australia, have been reported as growing at annual rates of 10% or more, which approach or exceed the maximum plausible rate of increase for this species.

Of the four recognized populations of bowhead whales, the one inhabiting the Bering-Chukchi-Beaufort Sea region is the largest at about 17,000, and is believed to be increasing at 3.7% per annum despite being the focus of a well-managed Native subsistence hunt. Bowheads off eastern Canada and Greenland may represent a single stock, which appears to be increasing in size.

Blue whales off California are recovering well, but as noted below, elsewhere the species' status is either endangered or unknown. Fin whales appear to be abundant and recovering in the Northern Hemisphere (although estimates of abundance are often lacking); their status in the Southern Ocean, where almost three-quarters of a million were taken (more than any other species), is less clear. There is some evidence that coastal populations of sei whales were wiped out by whaling, and the global population is believed to have declined by more than 70%.

Of the three species of right whale, the one in the North Atlantic is estimated at around 450 individuals, and is heavily impacted by ship strikes and fishing gear entanglements. As noted below, North Pacific right whales are among the most endangered whales in the world. In contrast, at least some southern right whale stocks appear to be recovering strongly.

Finally, the whales that are today the major target of whaling, the minke and Antarctic minke, are considered to be abundant throughout their range. The known exception is the minke whale population in the Sea of Japan (the so-called "J stock"), which is subject to high fisheries bycatch in Japan and Korea, and may also be impacted by Japanese coastal whaling.

> "Although whaling has now receded, there is, sadly, a sizable list of threats to cetacean populations, almost all of them human-caused. Some of these impacts are well documented, while the effects of others are less tangible."

## The Most Vulnerable Populations

In their review of baleen whales, Thomas et al. (2015, Table 3) list 19 populations whose status is "of greatest concern." Of these, six are considered critically endangered, including bowhead whales in the Sea of Okhotsk and off Svalbard, the Chile/Peru population of the southern right whale, eastern North Pacific right whales, western gray whales, and Arabian Sea humpbacks.

Okhotsk Sea bowheads were the target of Soviet illegal whaling (Ivashchenko et al., 2013), and are thought from recent sighting data to number in the low hundreds. The bowheads off Svalbard (Spitsbergen) in the Barents Sea were the focus of an intensive historical hunt by British and Dutch whalers, and the few sightings in recent times suggest that the population may be functionally extinct.

The population of southern right whales found off Chile and Peru in the southeastern Pacific likely numbers fewer than 50 animals, and is threatened by both entanglement in fishing gear and ship collisions.

North Pacific right whales were severely reduced by historical whaling beginning in 1835, and were commercially extinct by 1900. Thereafter, despite some sporadic twentieth century catches, the population was probably making a slow recovery until the 1960s; tragically, in the first half of that decade, the USSR took what was likely the bulk of the existing population in its illegal whaling, notably in the Bering Sea and Gulf of Alaska (Ivashchenko and Clapham, 2012). The abundance of the eastern stock was recently estimated at 30 individuals (Wade et al., 2011); while this figure may represent an underestimate, the extreme paucity of sightings and acoustic detections (notably in the Gulf of Alaska, where the species formerly enjoyed a widespread distribution) strongly suggests a remnant population on the brink of extinction.

In contrast to the recovered eastern population, the gray whales that feed in summer in the Okhotsk Sea are thought to number about 150 individuals, and are at considerable risk from anthropogenic activities, notably oil and gas development off Sakhalin Island (Weller et al., 2012). The winter breeding ground of this population is unknown, but may lie in Chinese waters. The situation with western gray whales has become more complicated in recent years, with satellite telemetry and photo-identification research showing extreme long-range movements of individuals between the Okhotsk Sea and the traditional calving grounds of the eastern stock in Mexico (Weller et al., 2012; Mate et al., 2015); indeed, at some 22,500 km round trip, this extraordinary migration is the longest of any mammal. It now seems likely that the portion of the Okhotsk population that breeds somewhere in the western Pacific is actually smaller and even more vulnerable than was previously thought.

Although humpback whales are doing well generally, an exception is the population in the Arabian Sea that, unlike humpbacks everywhere else, does not make an annual migration from high-latitude feeding grounds to tropical breeding and calving areas. Monsoon-driven productivity allows humpbacks to remain year-round in the Arabian Sea. However, this population was heavily impacted by illegal Soviet whaling; today it is estimated at just 80 animals (Minton et al., 2011), and it faces serious threats from entanglement, ship collisions, and pollution.

Although not critically endangered, the heavily exploited Antarctic blue whales today are at less than 1% of their pristine abundance. More than 360,000 were killed in the twentieth century (Rocha et al., 2014), and the most recent estimate of 2,300 animals contrasts with about 239,000 before whaling (Branch, 2007).

## A Job Well Done: Extirpated Populations

In 2008, my colleagues and I noted that whaling in some areas was so intensive and efficient that the populations concerned appear to have been completely wiped out (Clapham et al., 2008). We identified 11 populations of baleen whales that had been rendered effectively extinct, in which no repopulation had occurred over periods ranging from a few decades to four centuries. In some cases, it appears that the cultural memory of the existence of the habitat has been lost. One of the more dramatic examples concerns humpback and blue whales at South Georgia, where whalers killed thousands of individuals of both species, and which until 2011 were still not being observed in the region. In a hopeful sign, some humpbacks have finally been seen there in recent years, perhaps because the population elsewhere has now expanded to the point where whales are rediscovering historical habitat.

Elsewhere, North Atlantic right whales have yet to return to the Bay of Biscay (where Basque whaling on this species began almost a thousand years ago), as well as to other formerly major habitats in the eastern North Atlantic. Similarly, blue whales were extirpated off Japan by about 1948, and remain absent from the area decades later.

## Conservation Challenges: Current and Future Threats

Although whaling has now receded, there is, sadly, a sizable list of threats to cetacean populations, almost all of them human-caused. Some of these impacts are well documented, while the effects of others are less tangible. Furthermore, while assessing the effect of a single threat is difficult enough, we know virtually nothing about cumulative impacts on survival and reproduction.

The most obvious threat to whales is entanglement in fishing gear. The introduction in the 1960s of synthetic fishing nets and lines precipitated a huge increase in the number of cetaceans killed by entanglement. A recent study found that, in the past 20 years, at least 75% of odontocete species (toothed whales) and 64% of baleen whales had been recorded entangled in one type of gear alone, the gill net (Reeves et al., 2013). Trap gear and long line are also common sources of entanglement, and in some populations the majority of individuals have gear encounters, often repeatedly (Figure 3). Entanglement is sufficiently prevalent to endanger entire populations in at least a few cases: one species of cetacean (the Yangtse river dolphin, or baiji) has already been driven to extinction in part because of entanglement, while another (the vaquita in Mexico) is currently perilously close to being lost because of bycatch in the local tortuaba fishery.

The other known source of mortality among large whales is ship collisions (Laist et al., 2006). Coastal habitats often overlap with shipping lanes, and mortalities can result. Together with entanglement, ship strike has particularly inhibited the recovery of North Atlantic right whales. With the loss of sea ice in the Arctic, trans-polar shipping traffic will certainly increase, and with it the potential for noise, pollution, and collisions with whales, especially at choke points such as the Bering Strait.

Ocean noise is another major concern, but one whose impacts are difficult to quantify (Nowacek et al., 2007). Ever since 1819, when the steamship *Savannah* subjected a small space in the North Atlantic to the noise of an engine for the very first time, the oceans of the world have been filled with human-generated sound. Today, thousands of large ships regularly ply the sea routes of the world, and the noise that many of these vessels generate is—perhaps sometimes literally—deafening. At very low frequencies—those within the hearing range of some baleen whales—a supertanker or large bulk carrier can be heard tens of kilometers away, and can overwhelm the acoustic calls of the animals (Figure 4). Seismic surveys for oil and gas exploration not only generate noise that can be heard literally halfway across an ocean basin, but do so with great frequency, so that some areas are subjected to a continuous barrage of industrial noise (Nowacek et al., 2015). Elsewhere, naval active sonars have been shown to cause lethal mass

**FIGURE 3.** Two North Atlantic right whales badly entangled in fishing gear. Entanglement and ship strike cause high mortality in this endangered population, and research using scars shows that the majority of individuals suffer repeated encounters with fishing gear. *Photo credit: NOAA Northeast Fisheries Science Center*

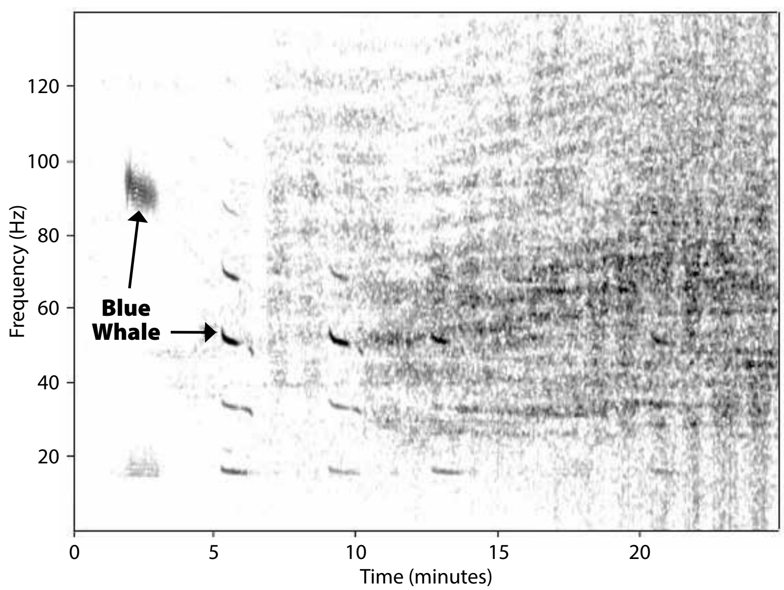



**FIGURE 4.** A blue whale's calling is overwhelmed by noise from a passing vessel (which was over the horizon at the time of the recording). *Source: Chris Clark, Cornell University*

strandings, especially among deep-diving beaked whales. In many places, a host of more "minor" activities such as pile driving or oil rig operations generate additional noise to pollute the waters.

This is of concern because marine mammals such as whales and dolphins live by sound. In a world in which visibility is always limited and often poor, these animals use hearing as their primary sense to communicate and to navigate, to find food and avoid predation. We know remarkably little about the short- or long-term effects of noise pollution on these animals, but it cannot be easy to exist and thrive in an environment that is often so saturated with human noise that the calls on which marine mammals rely for communication are masked or severely constrained. Effects may include anything from disruption of important behaviors to exclusion from habitats, and perhaps even (in extreme cases) physical damage to the animals' hearing apparatus.

Another intangible threat is pollution. This takes two forms. Direct pollution, such as major oil spills, degrades habitat and can cause illness, reproductive dysfunction, or death. Indirect pollution involves whales ingesting contaminants (often biomagnified) through their prey, and few places in the ocean are free of pesticides and other human-made toxins. These may affect immune function or reproduction, but impacts are very difficult to disentangle from the many other (often unquantifiable) variables involved. Because they feed at a lower trophic level, baleen whales generally have lower contaminants than odontocetes; still, the impact of industrial pollutants accumulating in their tissues, and often being passed on to subsequent generations through lactation, is unknown.

Mass mortalities of large whales from biotoxin poisoning (so-called "red tides") appear to have increased in recent years. While these are, strictly speaking, a "natural" occurrence, their increased frequency may well be partly related to freshwater runoff affected by human activities in coastal regions.

## CLIMATE CHANGE: THE BIG UNKNOWN

As we look to the future of the great whales, there is of course one major issue that looms over everything: global climate change. Since Roger Revelle's visionary work on greenhouse gases (Revelle and Seuss, 1957), there has been much debate about the impact of a warmer world on marine ecosystems. The IWC has held three workshops on the topic of climate change and cetaceans, but has reached no firm conclusions—a perhaps inevitable reflection of the huge uncertainty not only about the nature and scope of future ecosystem changes but also how such changes would interact with the many factors affecting the survival and reproduction of individual whales, and the carrying capacity of key habitats.

The impacts may not all be negative. For example, our Arctic surveys are already recording humpback and fin whales expanding their ranges in polar waters, pushing farther north into the Chukchi Sea as sea ice continues to retreat and new foraging habitat becomes accessible. For other species, their vulnerability to climate-related changes will depend upon multiple factors (Laidre et al., 2008), including population size and growth rates, range, habitat requirements, diet specificity, and individual site fidelity, together with environmental variables. Responses to changes may include redistribution, adaptation, or (especially for critically endangered populations) extinction. Arctic species that are closely associated with sea ice (such as bowhead whales) may prove especially vulnerable.

Sorting all this out—that is, attempting to predict the responses of specific populations to highly uncertain future changes in everything from ocean currents to ecosystem dynamics to behavioral responses of whales—is, to say the least, a daunting task. Ecosystem models can be useful in exploring possible scenarios, but accurately measuring the multiplicity of variables involved—let alone understanding how they all interact—is exceedingly difficult.

The problem is not helped by the current disagreements on some key issues, one of the best examples of which is the question of what will happen to krill populations as a result of climate change (Flores et al., 2012). Southern Ocean baleen whales feed almost exclusively on krill, so major changes in the abundance of this prey source have potentially large implications for whale populations. Yet, even without climate change, reliably estimating krill abundance is extremely difficult: some estimates of krill biomass differ by an order of magnitude (Nicol et al., 2000).

Also, a central topic of the current debate is whether krill do better with more or less sea ice. On the one hand, the underside of sea ice provides access to algae and protection from predators for overwintering adult and larval krill, and extensive sea ice also displaces salps, which are krill competitors (Ballance et al., 2006). In this light, major loss of sea ice might have a negative impact on krill. However, an argument has been made that decreases in sea ice may enhance primary production, notably in areas affected by the upwelling of nutrient-rich deep water (Prézelin et al., 2000); krill might fare better in open water as a result (Bettina Meyer, Alfred Wegener Institute, *pers. comm.*, February 2016).

One thing we do know is that the loss of sea ice is already resulting in a breakdown of the separation of Arctic whale populations. Bowhead whales from Alaska, long separated by ice from conspecifics in the Atlantic, are now mixing with them in Canadian waters. Even more dramatically, gray whales—which have been extinct in the North Atlantic since about 1800—are beginning to find their way into that ocean. Will we one day soon see gray whales reestablishing a viable Atlantic population for the first time in more than two centuries?

Looming large over all these issues are some potentially catastrophic scenarios. Will the Atlantic thermohaline circulation collapse as more freshwater enters the ocean from glacial melting (Vellinga and Wood, 2002)? Current opinion is that this is unlikely, but if the Hollywood plotline of a new ice age were to come to pass, how would whales fare? That the size and range of populations would undergo major changes is probably inevitable, but the current suite of whale species have lived through, and apparently adapted to, ice ages and other major past climatic shifts.

Of greater concern is the impact of ocean acidification (Caldeira and Wickett, 2003; Royal Society, 2005). In its most extreme manifestation, this phenomenon could cause catastrophic changes to marine ecosystems through loss of calcifying organisms such as plankton. This is all the more worrying given that acidification has been termed "irreversible." Should the worst-case scenarios come to pass, whales would likely be among innumerable marine species negatively affected—as would the commercial fisheries so important to human food security.

## WHALES: COMPETITORS TO FISHERIES OR ECOSYSTEM ENGINEERS?

*The Southern Ocean is the site of a vast uncontrolled experiment that began when commercial sealing and whaling activities in the nineteenth and twentieth centuries brought some seal and whale populations near extinction.* – R.M. Laws (1977)

Whaling had an obvious and dramatic effect on the abundance of the great whales. But what was the effect on the marine ecosystem? Specifically, how did the removal of three million large predators impact productivity and the food chain?

One of the first scientists to address this question was Richard Laws, who suggested that, in the Antarctic, extensive whaling had created what he termed a "krill surplus" that should now be available to benefit other predators (Laws, 1962, 1977). Put simply: because in the Southern Ocean whales feed largely on krill, then with so many whales killed, there must be a massive excess of krill left uneaten.

The evidence for the effects of a krill surplus has been mixed. Some species, such as Antarctic fur seals, certainly experienced a major population boom after the peak of whaling (Weimerskirch et al., 2003). However, assessing the validity of the krill surplus hypothesis—and whether it is even still relevant so many years after whaling—depends upon reliable estimates of the abundance not only of krill (which, as noted above, is difficult) but of krill predators too.

In recent years, an intriguing alternative idea has emerged: that by recycling nutrients (notably iron and nitrogen) into the upper layers of the ocean through defecation, whales help stimulate the production of the planktonic organisms that underlie much of the marine food web (Figure 5; Roman and McCarthy, 2010; Lavery et al., 2014; Ratnarajah et al., 2014). Thus, if (as some research suggests) krill have actually *not* increased in abundance, this may be partly due to the reduction of iron fertilization by whales removed by whaling, with consequent impacts on primary productivity. Furthermore, as many whale populations

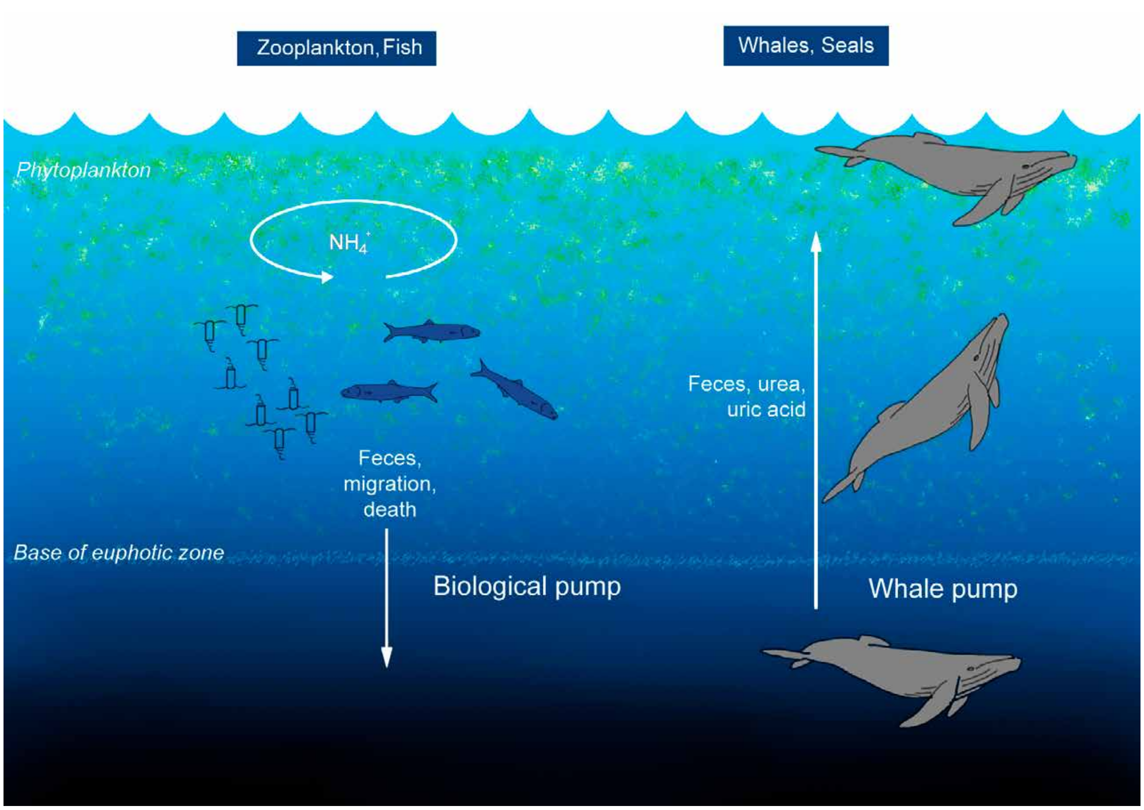
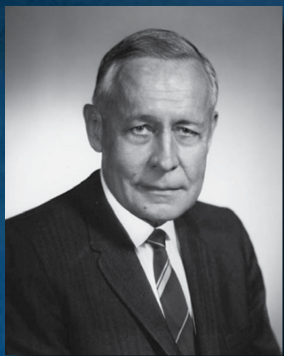



**FIGURE 5.** A conceptual model of what has been termed the "whale pump." In the common concept of the biological pump, zooplankton feed in the euphotic zone and export nutrients via sinking fecal pellets and vertical migration. Fish typically release nutrients at the depth where they feed. By contrast, excretion for marine mammals, which must return to the surface to breathe, occurs at shallower depths than where they feed. *Source: Roman and McCarthy (2010, Figure 1)*



## Roger Revelle

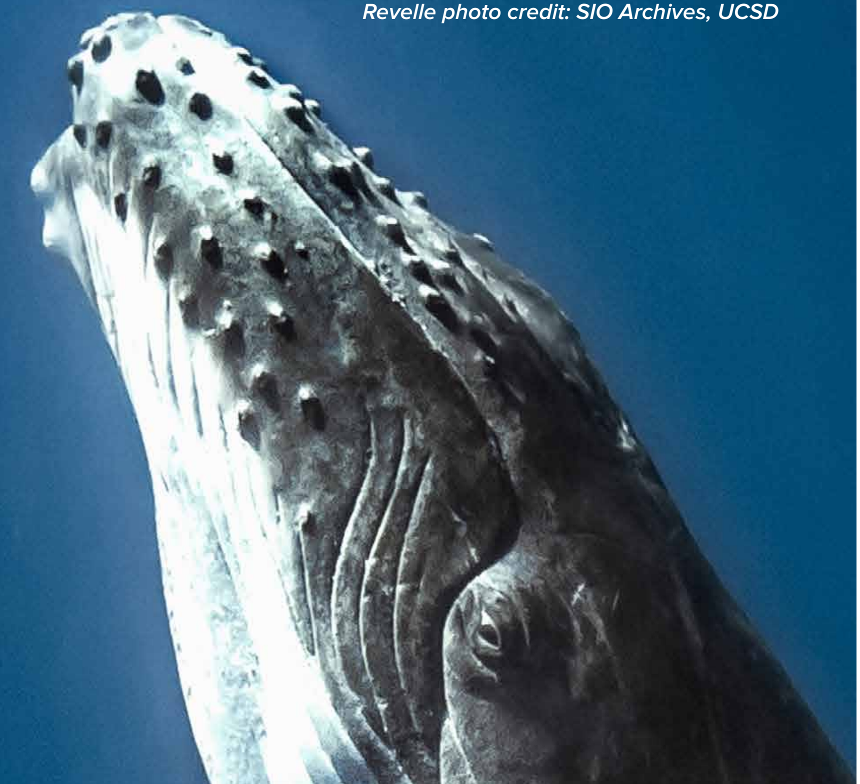
For almost half a century, Roger Revelle was a leader in the field of oceanography. Revelle trained as a geologist at Pomona College, and received his PhD in oceanography from the University of California, Berkeley, in 1936. As a young naval officer, he helped persuade the Navy to create the Office of Naval Research (ONR) to support basic research in oceanography and was the first head of ONR's geophysics branch. Revelle served for 12 years as the Director of Scripps (1950–1961, 1963–1964), where he built up a fleet of research ships and initiated a decade of expeditions to the deep Pacific that challenged existing geological theory.

Revelle's early work on the carbon cycle suggested that the sea could not absorb all the carbon dioxide released from burning fossil fuels. He organized the first continual measurement of atmospheric carbon dioxide, an effort led by Charles Keeling, resulting in a long-term record that has been essential to current research on global climate change. With Hans Suess, he published the seminal paper demonstrating the connection between increasing atmospheric carbon dioxide and burning of fossil fuels. Revelle kept the issue of increasing carbon dioxide levels before the public and spearheaded efforts to investigate the mechanisms and consequences of climate change.

Revelle left Scripps for critical posts as Science Advisor to the Department of the Interior (1961–1963) and as the first Director of the Center for Population Studies at Harvard (1964–1976). Revelle applied his knowledge of geophysics, ocean resources, and population dynamics to the world's most vexing problems: poverty, malnutrition, security, and education.

In 1957, Revelle became a member of the National Academy of Sciences to which he devoted many hours of volunteer service. He served as a member of the Ocean Studies Board, the Board on Atmospheric Sciences and Climate, and many committees. He also chaired a number of influential Academy studies on subjects ranging from the environmental effects of radiation to understanding sea level change.

*Revelle photo credit: SIO Archives, UCSD*



continue to recover from whaling, they may help buffer marine ecosystems from destabilizing stresses (Roman et al., 2014).

From a policy perspective, this is a critical debate. Japan has predicated its scientific whaling programs upon the belief that whales compete with humans for fish and other marine resources, and therefore must be "managed" (i.e., culled; Morishita, 2006). Yet, this simplistic view ignores several key facts (Clapham et al., 2007). First and mostly obviously, human over-fishing (not whales) is the cause of the decline of commercial fish stocks worldwide. Also, the primary predators of fish are not whales, but other fish; and the removal of top predators such as cetaceans can cause major ecosystem perturbations, with negative consequences for fisheries. Finally, a key point is that the sizes of many whale populations today are small fractions of their levels in pre-whaling times when commercial fish populations were considerably larger and much healthier than today. Set within this historical context, the idea that whales have always served as "ecosystem engineers," fertilizing the ocean and promoting productivity and ecosystem health, becomes very plausible.

Simply put, the oceans of the world probably need whales, and so, therefore, do we humans and our fisheries. We may also need whales in the battle against global warming: as suggested recently, whales likely play a significant role in sequestering carbon (Pershing et al., 2009; Lavery et al., 2010). This occurs directly, through storage in the living biomass of the whale, which sinks to the deep ocean when the whale dies. Additionally, iron defecated by whales stimulates phytoplankton blooms and results in increased export of carbon through the biological pump (Figure 5). Consequently, the ability of the ocean to act as a carbon sink may have been significantly diminished by industrial whaling, and restoration of populations to pre-whaling levels would potentially help mitigate global warming. Thus, the continued recovery of the world's great whales is a conservation goal that is not just noble and appropriate but also very much in our self-interest.

Whales have been around for a great deal longer than we have. They have persisted over millions of years through major shifts in the climate and in marine ecosystems. They are also still here, rather improbably, despite centuries of whaling. Let us hope that they can now survive the large-scale changes that humankind has wrought upon this small blue planet that we all share.

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