Status, trends and conservation of global sea turtle populations

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Sections

Abstract
Introduction
Species distributions and habitat requirements
Threats
Assessing sea turtle populations
Key conservation interventions
Summary and future directions

Abstract

Sea turtles have experienced myriad human impacts during the last century that caused extreme mortality across all seven species and life stages. Extensive conservation efforts have been put in place to protect sea turtles globally and reverse the major declines seen in many of their populations. In this review we assess the status and trends of sea turtle populations around the world and identify conservation priorities to promote population recoveries. Both the IUCN Red List assessments and an analysis of sea turtle abundance time-series reveal that, in general, sea turtle populations are rebounding world-wide, with nest numbers increasing at many nesting sites. However, certain populations are still declining dramatically, such as leatherback populations in the Pacific and Caribbean.

Harvesting of eggs and turtles for consumption and loss of nesting habitats are examples of threats sea turtles continue to face at sites around the world. Key unresolved questions include whether sea turtles can adapt to climate change, which can negatively impact foraging and nesting habitats as well as reproductive output and the impact of growing threats such as increasing plastic pollution. Despite the numerous conservation success stories emerging in this field, we advise for cautious optimism when considering the future of sea turtles in a rapidly changing world.

Introduction

Around the world there have been huge declines in biodiversity and the abundance of many species due to factors such as habitat loss, targeted capture, bycatch mortality, pollution, introduction of invasive species and climate change, leading some to conclude that the world is experiencing its sixth mass extinction[1]. Among the marine taxa that have historically suffered major declines are sea turtles. Historical reports underscore the magnitude of these declines. For example, in the 15th century sailors with Christopher Columbus described being kept awake by turtles bumping into the hulls of their ships, and it has been estimated that there were between 16 and 33 million adult green turtles (*Chelonia mydas*) in the Caribbean at that time[2]. Twenty years ago this number was estimated to have been reduced by around 95%[3]. Similarly, leatherback turtle (*Dermochelys coriacea*) nesting in peninsular Malaysia declined from around 10,000 nests in 1953 to only one or two nests per year by 2003, and leatherback nesting has now essentially disappeared from that region[4]. For Kemp's ridley turtles (*Lepidochelys kempii*), that mainly nest on one beach in Mexico, estimated nesting numbers declined from 121,517 nests per season in 1947 to 702 nests per season in 1985, which represents a >99% decline[5], before more recent recovery. These are just a few examples of the historical declines in sea turtle abundance across species and regions.

Set against this backdrop of decimation, there are many initiatives underway to protect more of the world's oceans and rebuild ocean biodiversity[6]. For example, in December 2022, 190 nations agreed on the Kunming-Montreal Global Biodiversity Framework during the COP15 international biodiversity summit, which sets out to protect and restore 30% of the world's land and seas globally by 2030, the so called "30x30 worldwide initiative[7,8]. In addition to these ongoing global efforts to safeguard more of our planet's oceans, there have been numerous sea turtle conservation measures operating around the world, often for many decades.

Given these many conservation efforts over recent decades and the hopes for increased future protection of ocean areas as part of the 30x30 worldwide initiative, it is timely to assess the status of ongoing sea turtle conservation and identify where the tide of historical declines has been reversed, as well as to identify key areas where enhanced protection is still needed. Here we describe the different species of sea turtles, their habitats and distributions, and the threats they face. We discuss how trends in sea turtle abundance are assessed and highlight where there are important data deficiencies. We then review the status of sea turtles around the world bringing together for the first time the assessments made both through the IUCN Red Listing process as well as the compilation of published abundance time-series from individual nesting beaches. We identify the conservation priorities for this group that may help prevent local and regional extinctions and promote population recoveries across species and around the world.

Species distributions and habitat requirements

There are seven extant species of sea turtle (Fig. 1): the leatherback (*Dermochelys coriacea*), Kemp's ridley (*Lepidochelys kempii*), olive ridley (*Lepidochelys olivacea*), green turtle (*Chelonia mydas*), loggerhead (*Caretta caretta*), flatback (*Natator depressus*) and hawksbill (*Eretmochelys imbricata*). Five of the seven species have a broadly circumglobal distribution, including leatherbacks, olive ridleys, green turtles, hawksbills and loggerheads, with their global population being subdivided into genetically distinct units, often referred to as Regional Management Units[9] (Fig. 1). Two species have a far more restricted distribution: flatback turtles nest only in Australasia and Kemp's ridley turtles nest on only a handful of beaches in the western Gulf of Mexico. For widespread species, their conservation threats and status may vary regionally. Regional Management Units (RMUs) delineate units of protection above the level of nesting populations and below the level of species, with the distribution of each RMU being defined by a combination of genetic data (turtles nesting in different RMUs are genetically distinct), satellite tracking data and mark-recapture studies[9].

All species share the same general life-history feature of nesting on sandy beaches and then having no further parental investment after a nest is completed. Females generally use the same nesting area that they hatched from themselves, a process termed 'natal philopatry'. This process means that colonization of new nesting areas, occurring through occasional breakdowns in nesting area fidelity, is likely relatively rare[10]. Individuals disperse widely as post-hatchlings, recruit to coastal foraging areas or remain in the high seas as juveniles, and as adults shuttle between breeding and foraging areas. Often individual hard-shelled turtles such as green turtles, loggerheads and hawksbills have fidelity to a particular foraging ground that they use throughout their entire adult lives[11], each individual returning to a particular site after each breeding migration. In contrast, leatherback turtles tend to wander more broadly across ocean basins in search of prey[12,13]. Yet even for hard-shelled turtle populations with foraging site fidelity, these sites may be vastly separated. For example, among green turtles that nest in the Chagos Archipelago (Indian Ocean), some individuals forage in the Seychelles, others on mainland Africa, others in Madagascar and yet others in the Maldives, which are sites separated by thousands of kilometers[14]. These large-scale movements and foraging distributions universally span waters of multiple nations, making international collaboration essential for effective conservation[15,16].

Species differ widely in some aspects of their ecology, such as their diet and foraging habitat preference. For example, green turtles tend to feed near the base of the food chain on seagrass and macroalgae[17], hawksbill turtles often—but not always[18]—feed on sponges or other invertebrate prey[19,20], while leatherbacks are one of the few marine vertebrates that feed almost exclusively on gelatinous zooplankton, including scyphozoan jellyfish, urochordates and pyrosomes[21]. With respect to foraging habitat, whereas some species like green turtles, hawksbills, and flatbacks tend to prefer nearshore, neritic foraging habitats as adults, leatherbacks often well in the high seas in search of prey. There are also species such as loggerheads, Kemp's ridleys, and olive ridleys that do both, with foraging strategy strongly linked to region and/or life history phase[22-24].

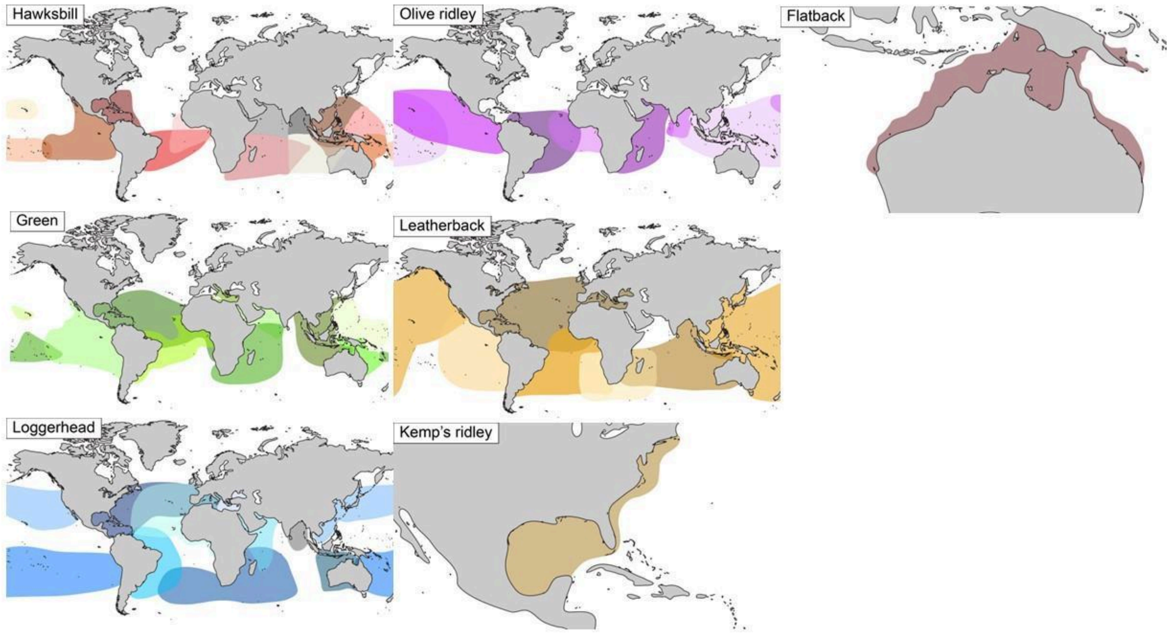


Fig. 1. Turtle species and distribution. There are seven species of sea turtle, the leatherback (*Dermochelys coriacea*), Kemp's ridley (*Lepidochelys kempii*), olive ridley (*Lepidochelys olivacea*), green turtle (*Chelonia mydas*), loggerhead (*Caretta caretta*), flatback (*Natator depressus*) and hawksbill (*Eretmochelys imbricata*). Most sea turtles - all but Kemp's ridleys and flatbacks - have global distributions that are divided into Regional Management Units, represented by the different colours (redrawn from ref 9).

Threats

Turtle mortality occurs naturally via predation. For example, predation of eggs by crabs and other natural predators may exceed 50% of eggs laid on some beaches[25,26] and hatchlings are eaten by fish and seabirds. Even large turtles, including adults, are sometimes eaten by natural predators such as sharks[27] and killer whales[28]. Beyond natural mortality, multiple other threats can negatively affect sea turtle populations (Fig 2). Key anthropogenic threats to sea turtles include, but are not limited to, fishery bycatch, direct take, coastal development, pollution, predation by feral (invasive) predators and climate change. Fishery bycatch includes a broad range of fisheries including pelagic longlines and driftnets, trawls, gillnets and fixed ropes. Direct take can be both legal and illegal and included take of adults and eggs for consumption and to derive other products (e.g. curios). Pollution includes a wide range of contaminants including oil spills and plastics.

Direct take

Direct harvesting of nesting females and developing egg clutches on beaches, as well as turtle hunting in foraging areas, has led to historical declines in abundance. This take of sea turtles and their eggs has always been primarily for food, although these products are also used for traditional medicines and non-consumptive uses[29]. Direct take of eggs and turtles is currently far below historical levels, although it is estimated that 1.1 million sea turtles were hunted illegally between 1990 and 2020[29] - a seemingly unsustainable rate for already depleted populations - and estimates of total global egg harvest are not known. Egg harvest has been implicated in the extinction of the peninsular Malaysia leatherback rookery[4] and was a driver of the species' declines in Indonesia[30], Costa Rica[31] and Mexico[32]. In some areas these practices are still ongoing and legal, with 42 countries reported with legal turtle take in 2014[33], although new laws outlawing turtle take have been enacted since then[34]. Some individual species have been particularly vulnerable to non-consumptive direct take. For example, the killing of hawksbill turtles to extract their prized shell plates for decades supplied the global tortoiseshell trade for making jewellery and other adornments[35]. This trade has sustained largely due to economic need and a lack of wildlife law enforcement at local scales. Despite the closure of the major tortoiseshell trade[36], the killing of hawksbills for their shells continues worldwide at smaller scales[37].

Climate change

Climate change also impacts turtles in a number of ways[38,39]. A key issue is that the life cycle of sea turtles is sensitive to temperature[40] (Fig. 2). Sea turtles exhibit temperature-dependent sex determination, with females being produced at high incubation temperatures[41]. In a 2024 global assessment, it was shown that most sea turtle nesting beaches currently produce highly female-biased primary sex ratios[42]. So as temperatures warm—as forecasted in climate change scenarios—sea turtle populations are expected to become increasingly more female-biased[43] (Fig. 2). In addition, excessively high incubation temperatures increase embryonic mortality and reduce hatchling fitness and survivorship[44,45], meaning that hatchling production is likely to decrease as temperatures increase[46]. Some of these threats could be mitigated, at least partially, by phenological shifts in nesting (Box 1). Furthermore, as climatic patterns are disrupted, increased exposure to extreme storm events or marine heatwaves can impact sea turtle foraging grounds and hence their reproductive output[47-49]. Nesting habitats are also likely to disappear as sea levels rise and beach erosion increases[50], and as sea temperatures warm and oceanic currents change, the distribution of turtles in the oceans may be affected[51].

Bycatch

Turtles suffer mortality as bycatch in longline, driftnet, trawl, anchored gillnet and pot fisheries around the world. For example, leatherbacks have no fixed foraging grounds and their wide-ranging movements place them at an elevated risk of bycatch in various fisheries[52] (Fig. 2). Loggerhead turtles in oceanic developmental habitats are omnivorous and often coincide with productive fishing areas, causing them to suffer high bycatch rates in longline and driftnet fisheries[53]. Many hundreds of thousands of loggerheads may be taken as bycatch in oceanic longline fisheries[54]. Off the coasts of Massachusetts (USA) and Nova Scotia (Canada) leatherbacks are often found entangled in fixed fishing gear (including nets and ropes associated with pot fisheries)[55,56]. Bycatch in the artisanal coastal gillnet fisheries near nesting beaches in Trinidad (Caribbean) has been estimated at 1,000-3,000 leatherbacks per year[57]. For leatherbacks, the threat of bycatch, including longline fisheries, likely extends widely across the world's oceans[13,52,58].

Pollution including plastics

Turtles suffer mortality through exposure to a range of pollutants. Plastics are now an omnipresent threat to turtles in the global ocean[59]. Plastic pollution can cause turtle mortality through entanglement (e.g. ghost fishing nets) and through ingestion. Lethal and sub-lethal effects of plastic pollution include drowning, starvation, gastrointestinal tract damage, malnutrition, physical injury and reduced mobility[60]. Increases in the ingestion of debris by turtles have been reported when long (circa 30-year) time-series have been examined, consistent with increasing levels of plastics in the ocean[59]. Other anthropogenic contaminants, in addition to plastics, may cause immunosuppression and a higher incidence of disease in sea turtles, although these links generally poorly resolved[27,61].

Other threats

In addition to the major threats identified above, turtles also face anthropogenic threats from vessel strikes, feral (invasive) predators, coastal development and light pollution[27].

Turtles can be killed or severely injured by the collision with marine vessels and the problem is a growing concern where this increasing boat traffic[62]. For example, between 1986 and 2014 there were >10,000 stranded sea turtles in Florida with vessel-strike related injuries[63]. Invasive predators, such as rats and pigs, are major predators of developing eggs. For example, in 1700 the famed astronomer Edmund Halley introduced pigs onto the island of Trinidade off the coast of Brazil, with the aim of a fresh supply of meat for future passing ships. These pigs then decimated the nests of green turtles, leading almost to the extinction of this nesting population[64]. The threat from invasive species continues in some areas. For example, feral pigs can still destroy entire clutches for olive ridley and flatback turtles in Australia[65] and leatherbacks in Indonesia[66]. Light pollution in coastal areas poses a threat by disorienting hatchlings as well as nesting turtles[67]. There also are species-specific threats, such as the loss or degradation of seagrass meadows negatively impacting foraging green turtles[68]. Triaging these various threats remains an important challenge[27].

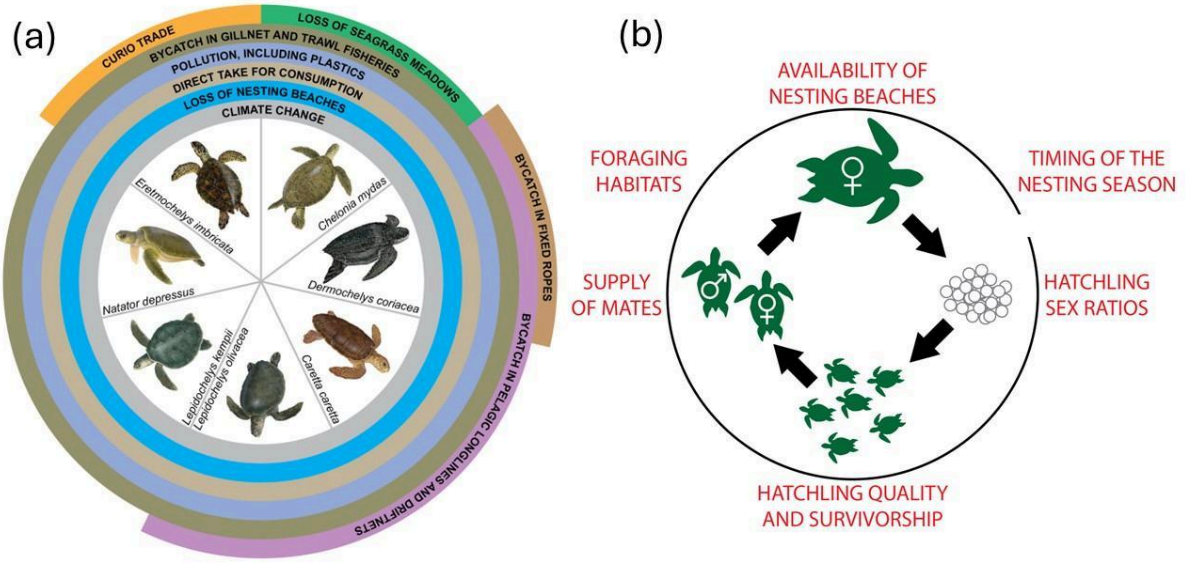


Fig. 2. Some of the important threats that sea turtles face. (a) Sea turtles face a number of threats, some of which impact all species, while others are more species-specific. (b) A schematic illustration of how climate change impacts a number of aspects of the life history of sea turtles. Sand temperature during incubation of eggs impacts the sex ratio of hatchlings, their survival in the nest and their fitness upon emerging. All else being equal, predicted future warming will raise incubation temperatures; fewer male hatchlings will be

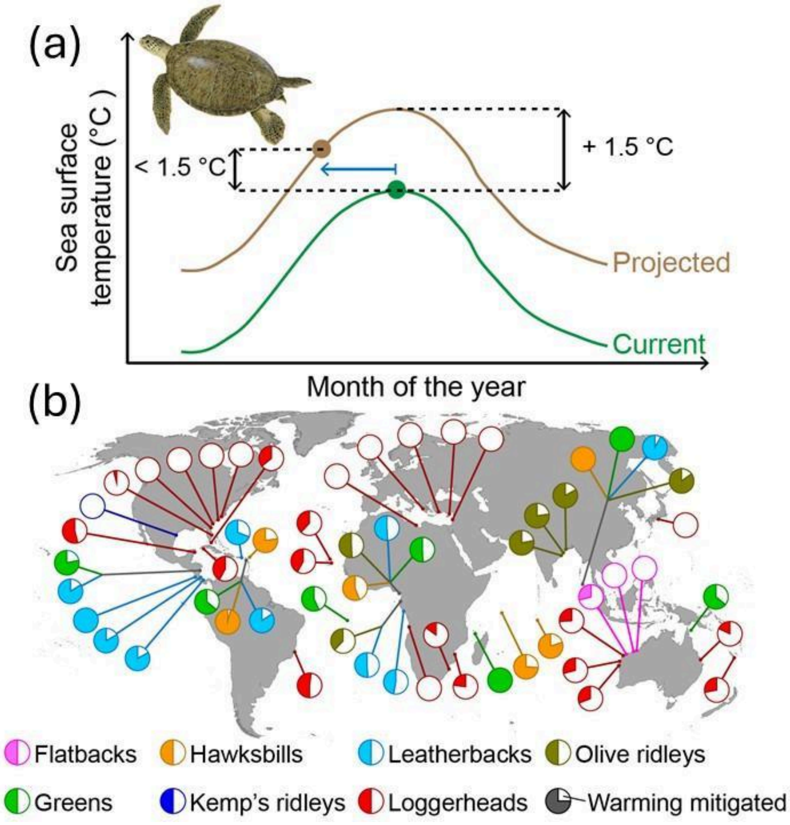
produced and embryonic mortality will increase. Lower production of male hatchlings may subsequently limit the supply of breeding males. Climate change may negatively impact foraging habitats, such as seagrass meadows. Rising sea levels as part of climate change may decrease the availability of nesting beaches. Climate warming may impact the phenology of nesting, causing the nesting season to shift to earlier or later in the year. Changes in environmental conditions, often linked to climate change, might be responsible for some of the increases and decreases in population abundance. For example, at the green turtle rookery on Raine Island, a decrease in hatchling survival has been linked to a worsening of incubation conditions due to rising sea levels and temperatures[155]. In other areas, female-skewed hatchling sex ratios might have helped population recoveries by increasing the number of breeding females so the rate of population increase - through increased egg production - might, if not too extreme, help population recoveries.

Box 1: Turtle resilience to warming

Some aspects of the biology of sea turtles may help them withstand ongoing threats, at least to some extent. The biology of males may help mitigate female-skewed sex ratios. Tracking males has shown their interval between breeding seasons is generally shorter than for females, a finding that is supported by theoretical considerations of the different male versus female energetic investment in breeding[158]. For example, with satellite tracked loggerhead turtles in Zakynthos (Greece), in 13 of 17 cases (76.5%) males bred in successive years, compared to 0 of 8 cases (0%) in females. Hence female-biased hatchling sex ratios may translate into more balanced operational sex ratios, i.e. the ratio of breeding turtles. Furthermore, because a single male may mate with multiple females in a nesting season the negative impact of fewer males is dampened. However, with climate warming it is expected that at some point a scarcity of males will impact female reproductive output.

Rising incubation temperatures as a result of climate warming might be mitigated by a phenological shift in nesting to cooler times of the year. However, calculations for a large number of nesting beaches around the world suggest that even the maximum expected phenological shift will only partly offset rising temperatures[159,160] (Box figure). Hence with climate warming, nest temperatures are expected to increase and thus hatchling sex ratios are expected to become increasingly more female-biased.

Occasional breakdowns in natal homing mean that sometimes new nesting sites are colonized, which could provide an avenue for the occurrence of more nesting beaches in cooler areas. For example, there is some evidence for nesting range expansion to cooler areas in the Mediterranean for loggerhead turtles[161,162]. However, it is expected that the pace of colonization of new cooler nesting areas, will not be sufficient to mitigate expected climate warming. Likewise, colonization of new nesting beaches might occur if existing beaches are destroyed by rising sea levels and/or storms. However, this scenario would need new nesting beaches to occur fairly close (likely within a few 10s of km) to threatened existing sites, which often is not the case.



Box figure. Adaptation to stressors: phenological shifts in nesting. Climate warming poses a threat to sea turtles since the embryos have temperature-dependent sex determination, with females being produced at warmer temperatures. All else being equal, predicted future warming will raise incubation temperatures such that fewer male hatchlings are produced. (a) A phenological shift in nesting might help partly mitigate climate warming. Pictured is a scenario where the temperature warms by 1.5°C but turtles shift to nesting at a cooler time in the year. In this way the warming experienced by nests is reduced. Symbols indicate the middle of the nesting season under current conditions and with 1.5°C warming. (b) The calculated percentage of future warming that would be mitigated by a best-case-scenario 27-day phenological shift in nesting at nesting sites around the world. The filled part of each pie indicates the percentage of warming that would be mitigated. In these calculations, on average 55% (SD = 34%) of future warming would be mitigated, i.e. a phenological shift in nesting is likely to only partly offset climate warming impacts on nest temperatures (adapted from ref. 159).

Assessing sea turtle populations

In this section, we will discuss how turtle abundances are directly measured, how uncertainty is accounted for, and how official population assessments are conducted.

Methods for counting females, males, and juveniles

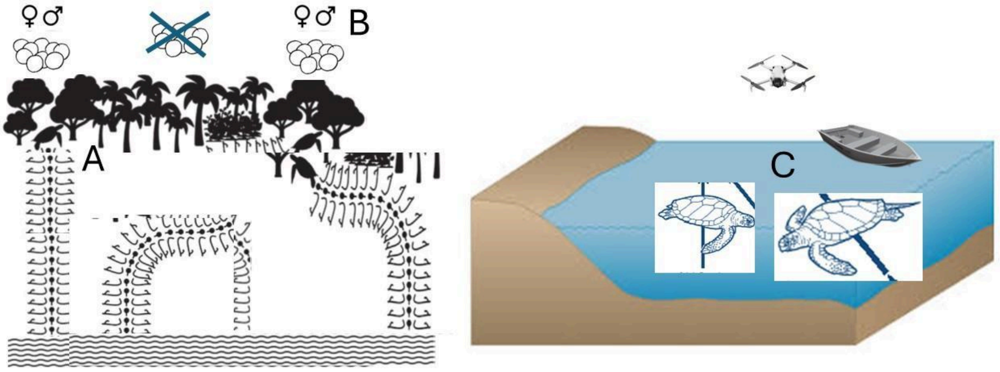
The usual method to assess sea turtle abundance is from direct counts of nesting females, crawl tracks and/or deposited egg clutches (Fig. 3). This sounds simple but is often challenging. Nesting beaches may be in remote hard-to-access areas, they may be very long (many 10s of kms) and there may be many nesting beaches in one area. Track counts must span the nesting season to characterize the seasonal cycle of nesting and be frequent enough to capture day-to-day variation[69]. On beaches used by more than one species, measurements of the track width and the track pattern can often be used to distinguish species. In some cases, new methods and tools are being implemented, such as heat-sensing drones to survey nesting beaches at night[70] or camera traps for remote monitoring of nesting activity. From track counts, the number of clutches can be calculated if nesting success rate is known, and clutch counts can reflect total annual females when annual clutch frequency is known, although these conversions add greater uncertainty to abundance estimates. Furthermore, while flipper tagging can reveal the interval between breeding seasons (termed the remigration interval) for individual females, there is not good information on what proportion of adult females actually nest.

While abundance time-series for nesting adult females are routinely collected, the abundance of adult males remains poorly known (Fig. 3) but is increasingly important as with rising temperatures fewer males are predicted to hatch and a lack of males might ultimately lead to population extinctions. Yet assessing the abundance of males is very difficult because, unlike females, they do not come ashore except for rare basking events. Hence there are no long time-series of male abundance. In-water and drone surveys of adult males adjacent to nesting beaches have been undertaken[71] and, if repeated across years, offer the promise of estimating time-series of male abundance. By using boat or drone surveys to assess the relative abundance of adult males and females on the breeding grounds, the operational sex ratio can be estimated, i.e. the ratio of breeding males to females. This measurement has been made at a few sites[72,73] and if repeated across decades could allow trends in the relative abundance of males to be assessed (Fig. 3e). Assessments of the incidence of multiple paternity across years may provide another approach for assessing the relative abundance of adult males[74].

Furthermore, there are very few time-series of abundance of juveniles. Some notable exceptions—that serve as a benchmark for how these data can be obtained—include time-series of juvenile abundance obtained from net captures extending over many decades[75]. New approaches in this area include counting juveniles at focal sites through drone counts[76,77] and use of citizen science diver photograph surveys[78,79], which if repeated across years may lead to informative time-series.

Accounting for uncertainty

A confounding factor in assessing trends in abundance is that there may often be a high degree of inter-annual variability in nesting numbers[80]. This variability is driven by the fact that individual females of most species do not nest every year. So, in some years a high proportion of the population may attain sufficient body condition to breed leading to a bumper year for nesting, but then in other years only a small proportion of individuals may achieve the body condition required to breed[81]. In extreme cases there may be more than an order of magnitude variation in nesting numbers between successive years[80]. So, abundance assessments often smooth this inter-annual variability by averaging abundance over several years or by looking at trends only in long time-series[82,83].



Variables	Calculation	Role in broader assessments
Nest counts (A) = Total track counts x nesting success	Total annual female abundance = total nests / mean nests per female	Key measurements in RMU-scale assessments, but subject to high interannual variability
Relative abundance of male and female hatchlings (B)	Decrease of male hatchlings linked to climate warming	May highlight need to nest cooling interventions
Direct counts of breeding males and females (C)	Male abundance and operational sex ratio	Limited, owing to insufficient timeseries. Major knowledge gaps.

Fig. 3. Assessing trends in turtle numbers. Tracks of nesting turtles are routinely counted. However, not all tracks lead to a nest. Instead, sometimes turtles abort their nest excavation. The proportion of tracks leading to a nest is termed the nesting success. Individual female turtles may nest several times in a single season. The sex ratio of hatchlings provides an indication of the threat of climate warming. Immatures turtles and adults can be counted at sea from boats or drones, with adult males being identified by their extended tails. The ratio of breeding males to females, termed the operational sex ratio, again indicates where the threat of feminization of populations due to climate warming is most acute. A prediction of climate warming is that a point will be reached where there are so few males that they start to become limiting.

Official assessment frameworks

Trends in sea turtle numbers have been presented in published reports and papers[82,83], national species status reviews[84,85] and IUCN conservation assessments[86,87]. Here we compare these assessment frameworks and provide a synopsis of sea turtle status based on results from the most recent assessment efforts.

Trend assessments for sea turtles often evaluate nesting time-series data across many seasons—often decades—to account for the longevity of turtles and the aforementioned interannual variability in the proportion of females that come ashore. In such cases, long-term trends can be evaluated in the context of environmental and/or harvest data to depict the drivers of exposed trends and identify conservation priorities[88-91].

In contrast to time-series-based assessments, an IUCN Red List assessment (RLA) compares species abundance, typically the annual number of nests or the number of nesting females, at two points in time ('past' and 'present') separated by an interval of 10 years or 3 generations, whichever is longer[92]. For sea turtles, each estimate is usually taken as the mean annual nesting abundance over a 3-year period (or 1 remigration interval) to account for natural inter-annual variability. A species is listed as Critically Endangered if the Present estimates have decreased at least 80% relative to the Past estimate, whereas Endangered and Vulnerable categories are applied when declines reach 50% and 30%, respectively.

Historically a single IUCN 'global' listing was generated for each species, with this listing being updated infrequently. This lack of spatial resolution for globally distributed species such as sea turtles, coupled with the rarity of data from 3 generations past (~100 years) as required for sea turtle IUCN assessments, resulted in significant academic and conservation practitioner skepticism about the value of RLAs for this taxon[93,94]. However, over the last decade the IUCN shifted assessment requirements for sea turtles, first with loggerhead turtles in 2015[87] and more recently with green turtles[95]. Today, the Red List framework still requires a global status assessment, although the IUCN now also recognizes assessments at the RMU scale.

Trends in sea turtle numbers

In addition to the single-species and species-specific regional assessments, there have also been compilations of nesting number time-series that provide holistic views of the global state of sea turtles[82,83]. This approach involves compiling published reports and papers on nesting numbers and then assessing if the trends are upwards, downwards or stable.

Global evaluations show a generally encouraging picture of stable or upward trends for multiple species and subpopulations, although there is considerable variability both regionally and between species (Fig. 4). For example, of 299 annual abundance time-series analysed in 2017, there were almost three times as many significant increases versus significant decreases[82]. In an updated compilation of more time-series published in 2024, there were almost six times as many significant increases versus significant decreases[83]. For green turtles generally stable or upwards trends have been reported. Upward trends in abundance were reported in four of five RMUs where there were sufficient data[82] and in a 2024 analysis in 19 of 19 individual time-series of abundance from nesting sites[83]. For example, the annual number of green turtle nests increased from around 4,000 to 16,000 between 1980 and 2018 at Aldabra (Seychelles, Indian Ocean)[96]. On Ascension Island (South Atlantic), annual nest numbers increased from around 3,500 between 1977 and 1982 up to around 24,000 between 2010 and 2013[97]. The IUCN status for the global population of green turtles was listed as Endangered in 2004, but soon will be shifted to Vulnerable (in 2024, IUCN MTSG), owing to the very positive nesting trends in many areas worldwide. Due to the infrequency of RLAs, some of the upward trends published in the last few years have not yet been recognized by the IUCN, but the generally encouraging news is also reflected in up-to-date IUCN regional assessments for green turtles: least concern in Hawaii[98], Southwest Indian[95], and South Atlantic[99], and near threatened in the Mediterranean[100]. However, some conservation concerns remain. For example, in 2023 alarming declines in nesting were described for green turtles at Tortuguero, Costa Rica[101], a site considered to be among the largest rookeries globally for species[102].

For loggerheads, in the last few years upward trends were reported in 5 of 10 RMUs[87], in 12 of 13 individual time-series from nesting beaches[83]. Some increases in abundance have been staggering. For example, between 2008 and 2020 the annual number of nests increased from around 500 to 35,000 for loggerhead turtles on Sal (Cape Verde, North Atlantic)[103]. Similarly in IUCN regional assessments, loggerheads are now listed as "least concern" in the subpopulation in the Mediterranean[104], North Pacific[105], North West Atlantic[106] and South West Atlantic[107]. Loggerhead turtles, formerly Endangered in the 1996 RLA, were listed globally as Vulnerable in the most recent global assessment[87]. However, conservation concerns remain. For example, a significant downward trend has occurred for loggerhead turtles at Masirah Island (Oman, Arabian Sea), which was formerly the largest loggerhead rookery in the world, where annual nests have declined from around 30,000 to 10,000 between 2008 and 2016[108]. Similarly, the shift from global to regional 'RMU-specific' IUCN assessments is revealing how the status of sea turtles is varying across their range. For example, while the change from Endangered to Vulnerable for the global loggerhead population can be taken as a positive sign, loggerheads in the Northeast and Northwest Indian Ocean[109,110] and South Pacific Ocean[111] regions are listed as Critically Endangered while those in the Northeast Atlantic are listed as Endangered[112].

In contrast to some other species, there remains a lack of extensive data on up-to-date trends for hawksbill and flatback turtles. In the last few years for hawksbills an upward rather than downward trend was reported in one of one RMUs for which there were sufficient data[82] and 7 of 7 (100%) of individual time-series from nesting beaches[83] (Fig. 4). Updated IUCN assessments are required as the last global assessment for hawksbills was completed in 2008. For flatbacks, a downward trend was reported in 2017 in one of one RMUs for which there were sufficient data[82] and there were no newer data reported in a 2024 update[83]. The latest IUCN assessment was completed in 1996 and listed the flatback as "Data Deficient".

In the last few years, upwards trends were reported for five of five individual time-series for olive ridleys and one of one individual time-series for the Kemp's ridley[83]. IUCN assessments are out of date for the olive ridley (last completed in 2008) while for the Kemp's ridley the IUCN status was listed in 2019 as "Critically Endangered" because of the restricted nesting range[113], even though numbers are increasing: on the main nesting beaches for the species in Mexico, annual nests have risen from around 2,000 in 1996 to around 17,000 in 2022[83].

Leatherbacks are the species for which there are the gravest conservation concerns. Upwards trends were reported in only one of seven RMUs[114] and in a 2024 analysis of 61 annual abundance time-series across species, there were five downward trends reported of which four were for leatherbacks, all at sites where nesting numbers have been high in the past[83] (Fig. 4). At Las Baulas (Pacific coast of Costa Rica) the number of nesters has declined from around 1,500 to 15 between 1988 and 2018, in Suriname (Atlantic) the annual number of nests has declined from around 10,000 to around 1,000 and further major declines are seen in Indonesia (western Pacific) and the Caribbean coast of Costa Rica[83]. There are also clear cases where stable or upward leatherback trends had reversed to a downward trend, both in the US Virgin Islands (St Croix, Caribbean) and in French Guiana (West Atlantic)[83]. Current trends in numbers of leatherbacks illustrate the Achilles' heel of the IUCN Red List which is the long delay between species assessment efforts. Leatherbacks were listed globally as Vulnerable in 2013[114], but that assessment did not capture the major declines that have subsequently been reported across many populations. Inaccurate Red List listings due to outdated assessments is nothing new, but in the case for leatherbacks this highlights the value of other assessment efforts—by conservation groups and academia—that operate on shorter time intervals. Only the leatherback, loggerhead and green turtle have official RLAs across regional levels so far, but future RLAs for all sea turtles will presumably contain both global and regional listings.

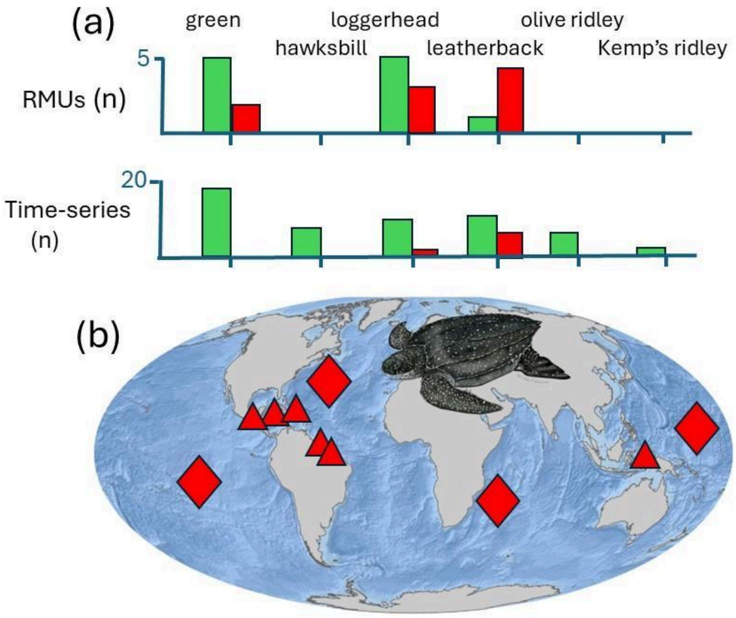
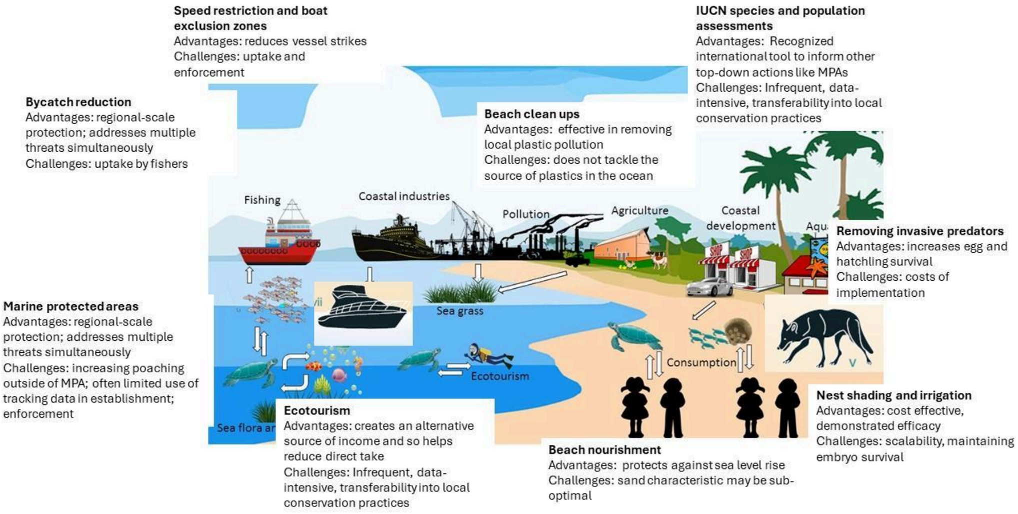


Fig. 4. Recent trends in the abundance of turtles at both focal sites and integrated across broader areas. Compilations of census data have identified both conservation success stories as well as conservation concerns for sea turtles. (a) From recent IUCN assessments, the number of RMUs where numbers are increasing or decreasing, (b) the number of individual time-series (typically individual nesting beaches) where numbers are increasing or decreasing (data extracted from 83), (c) areas and sites around the world where leatherback turtle numbers are decreasing. Large diamonds represent IUCN assessed RMUs and small triangles represent individual time-series.

Editor comment: art editor can develop this schematic from scratch



Speed restriction and boat exclusion zones
Advantages: reduces vessel strikes
Challenges: uptake and enforcement

IUCN species and population assessments
Advantages: Recognized international tool to inform other top-down actions like MPAs
Challenges: Infrequent, data-intensive, transferability into local conservation practices

Bycatch reduction
Advantages: regional-scale protection; addresses multiple threats simultaneously
Challenges: uptake by fishers

Beach clean ups
Advantages: effective in removing local plastic pollution
Challenges: does not tackle the source of plastics in the ocean

Removing invasive predators
Advantages: increases egg and hatchling survival
Challenges: costs of implementation

Marine protected areas
Advantages: regional-scale protection; addresses multiple threats simultaneously
Challenges: increasing poaching outside of MPA; often limited use of tracking data in establishment; enforcement

Nest shading and irrigation
Advantages: cost effective, demonstrated efficacy
Challenges: scalability, maintaining embryo survival

Ecotourism
Advantages: creates an alternative source of income and so helps reduce direct take
Challenges: Infrequent, data-intensive, transferability into local conservation practices

Beach nourishment
Advantages: protects against sea level rise
Challenges: sand characteristic may be sub-optimal

Fig. 5. Conservation interventions to help population recoveries. Conservation interventions are thought to underpin increases in sea turtle abundance that have been observed around the world. But at the same time, threats remain. For example, bycatch in various fisheries is thought to be a key driver of ongoing declines in some leatherback turtle populations.

Key conservation interventions

Despite positive gains for sea turtles, all species will require some level of conservation attention for the foreseeable future due to the persistence of ongoing threats of direct and indirect mortality (Fig. 5). At a global scale, three of the largest threats to sea turtles are (1) killing of sea turtles for human consumption, (2) massive bycatch mortality from artisanal and industrial fishing practices, and (3) the ongoing feminization of sea turtles due to global temperature rise. Each of these threat categories has seen some level of conservation success during the last decade.

International instruments and policies

The migratory status of sea turtles makes international cooperation essential for their survival. Cross-border alliances can yield important benefits such as sharing of technical expertise and cooperation in enactment of legal frameworks designed to protect habitats and curb illegal sea turtle use and trade. An example of a multi-continent effort focused exclusively on sea turtles is the Inter-American Convention for the Protection and

Conservation of Sea (IAC), a legally binding inter-governmental conservation treaty that entered into force in May of 2001 and currently has 16 signatory nations across North, Central, and South America. IAC delegates convene annually to share information, identify emerging threats, and co-develop conservation action plans aimed at recovering sea turtles. These efforts focus on topics such as bycatch reduction, mitigating the Sargassum crisis in the western Atlantic[115], and ensuring sustainable management practices for IAC nations that have ongoing legal egg harvest. Another effort, falling under the Convention on the Conservation of Migratory Species of Wild Animals (CMS, also known as the Bonn Convention), is the Indian Ocean-South-East Asian (IOSEA) Marine Turtle Memorandum of Understanding. This non-binding intergovernmental agreement has 44 member countries and focuses on protection and recovery of sea turtle populations throughout the region, also with annual meetings where the parties work together to pursue mutual conservation goals. Together, the IAC and IOSEA represent perhaps the two most significant international instruments to conserve sea turtles and their habitats, although these and other such efforts still sometimes lack awareness and effectiveness in many of the focal regions[116]. Reasons for the inadequate effectiveness of some international instruments include a lack of proper implementation because instruments tend to become bureaucratic; the inability to control local and/or regional illegal trade in turtle products and poaching, incentives to comply with regulations; problems with translating international conventions into a local, applicable format comprehensible to both government officials and to conservation practitioners in the field and a lack of incorporation into national laws even when a country is a signatory[116].

MPA establishment

Identifying high-use areas of turtles through satellite tracking and/or aerial surveys has driven the creation of conservation zones. In Baja California (Mexican Pacific), high bycatch of loggerhead turtles in a gillnet fishery led to the development of a new loggerhead-focused Fishery Reserve encompassing 8,848 km^2, limiting fishing access to an area where loggerhead occurrence was high as indicated by aerial surveys and satellite tracking[53,117]. Similarly, satellite tracking has been used to help reduce turtle bycatch through the creation of large conservation zones for green and hawksbill turtles off the Yucatan coast of Mexico, leatherbacks off the west coast of the US, and leatherbacks and olive ridleys off Gabon[118]. The creation of a large MPA has also helped green and hawksbill turtles in the

Chagos Archipelago, with increases in nesting numbers for both species[119], while drone surveys have revealed the highest density of hawksbill turtles in the world[77]. While the creation of MPAs can often be linked to an increase in the abundance of sea turtles, MPAs are no panacea and do not always have the intended benefits. In Baja, for example, while loggerhead bycatch has been reduced, poor governance and a lack of enforcement infrastructure has limited this refuge area's effectiveness[120]; similar challenges plague many other MPAs, often relegating them to 'paper park' status[121]. Sea turtles are highly migratory, and so their movements may take them out of protected areas[122]. There can be higher fishing pressure just outside MPAs and hence bycatch of individuals leaving protected areas. There are often issues with enforcement within MPAs and this may be a particular problem with very large MPAs where it is difficult to monitor illegal fishing[123].

Reducing direct take

The targeted capture of turtles is outlawed in many areas by a variety of conservation instruments such as national legislation and marine protected areas. Often locations where targeted capture is banned are the ones with growing populations. In Cape Verde, the increase in nesting numbers of loggerhead turtles coincided with the initiation of local conservation projects which have reduced harvesting of nesting turtles[103]. Similarly, with green turtles at Aldabra (Seychelles, Indian Ocean) a ban on turtle capture was initiated in 1968, following decades of harvesting, and coincided with a nest monitoring programme starting the same year which meant that conservation biologists were on the beaches to help ensure illegal harvesting did not continue. Again, the outcome has been a sustained and rapid increase in nesting numbers[96]. At Ascension Island the green turtle nesting population was subjected to several centuries of exploitation for meat, operating at a commercial scale with "turtle ponds" constructed for holding turtles alive until they could be loaded into passing ships. The long-term increase in nesting numbers reflects the legal protection of green turtles since 1944[97]. At Colola Beach (Pacific Mexico), decades of legal but largely unregulated harvest of adult turtles and eggs nearly wiped out the largest green turtle rookery in the eastern Pacific. However, after a 1990 presidential decree outlawing turtle use[124] the population has steadily increased and today has nesting numbers not seen since the 1960s[125]. These examples show that reducing direct take can be linked to increases in turtle numbers.

While hunting of turtles does still occur in many areas, shifts in social and economic value of sea turtle meat have allowed for greater dialogue among conservation practitioners and communities, resulting in more widespread community engagement and reduced take[126,127]. At a local level, often nesting beaches are patrolled at night by conservation biologists to deter the poaching of adults and their eggs, while at the same time allowing the collection of data on nesting abundance and trends[128].

Demand reduction campaigns are another conservation approach aimed at reducing harvest. For example, a conservation marketing campaign on the island of São Tomé, Central Africa led to a decrease in sea turtle egg consumption and poaching of adult sea turtles[129]. At the same time, around the world the creation of alternative revenue schemes, for example through ecotourism or employing former poachers to protect nests, offer an avenue to reduce harvesting[130].

Bycatch reduction

In terms of bycatch reduction, widespread implementation of bycatch reduction technologies such as turtle excluder devices (TEDs) for trawl fisheries and circle hooks for longline fisheries have generally reduced bycatch in areas where these gear types are used. The mandating of TEDs, for instance, is widely believed to be the primary driver in the recovery of Kemp's ridleys turtles, a species once on the brink of extinction[131]. Finding further workable gear modification to reduce bycatch is also needed, for example from fixed- to on-demand-rope lines in bottom-set trap fisheries[55.56,132]. Often, rapid bycatch assessments (RBAs) can depict where such efforts are needed[133]. By querying fishers across communities and regions via formal surveys, RBAs help define artisanal fishing effort and identify bycatch hotspots. These assessments also offer a means to foster partnerships with fishers when developing bycatch reduction measures, and engaging with the fishing sector at this early stage has strong benefits for widespread adoption of new gear types[134].

Nest protection and headstarting

A practical approach for sea turtle recovery is to focus conservation efforts on the marine turtle life stages with lowest survivorship (e.g. eggs and hatchlings). Whereas protecting eggs can be accomplished via translocation of egg clutches from unprotected beach areas to guarded egg hatcheries[135] or camouflaging nests *in situ*, increasing hatchling survivorship is accomplished by headstarting, by which hatchlings are reared in captivity and released once reaching a size that eliminates many predators. Both approaches have received skepticism due to the challenges of scaling up such efforts to make them effective[136,137]; however, hatcheries have been widely adopted around the world as a main strategy for protecting nests. On the other hand, headstarting was once more widely considered a viable approach[138] and responsible for repopulation of some nesting beaches[139] but today is carried out on few occasions (but see ref 140) as the viability of this approach is questioned due to its high cost, challenging husbandry needs, and unclear results.

Nest cooling

An added benefit of sea turtle hatchery practices, in addition to egg protection, is the ability for managers to modify incubation conditions, through shading or raising humidity, to combat impacts of climate change[141]. On some beaches irrigation is used to cool nests and artificially shading nests (e.g. with shade cloth or palm fronds) has been proposed as a method to cool nests. However, it is still uncertain how to implement these cooling approaches for maximum impact over large areas and, for example with salt-water irrigation, without negatively impacting hatching success[38].

Beach nourishment or modification

Beach renourishment (adding sediment) is a common practice for mitigating sand loss in areas of high erosion and may be helpful for reducing the impacts of sea level rise. While renourishment is usually preferred over beach armouring (using physical structures to protect coastlines from erosion), this practice may adversely impact sea turtles if the sand is too compacted for turtles to nest or if sand imported from another area and has different characteristics from local beach sediments[142]. These factors can alter patterns of nest-site selection, nest excavation success, incubation temperature, and moisture and gas exchange within nests[143,144], which can have negative consequences on embryonic development. However, if done correctly and with a goal of protecting sea turtles and other natural resources, beach nourishment can be an effective tool for replacing lost nesting habitat.

Eliminating marine plastics

While it is well known that individual turtles suffer mortality through plastic pollution, a key unresolved question is the population-level impacts of plastic ingestion and entanglement[60]. Mitigating this threat from plastics is also not straightforward. Removal of plastic waste, e.g. through beach clean-ups, is one solution that is having success in some regions[145]. But ultimately solutions to reducing the sources of plastic waste are needed. It is important to develop methods to trace plastic pollutants back to their source so those responsible can be identified[38].

Reducing vessel strikes

To reduce impacts from vessel strikes typically involves separating vessels and sea turtles through exclusion zones and/or reducing vessel speed through go-slow zones. Such interventions have been made successfully in some parts of the world[146]. Key to successful migration of the threat of vessel strikes is to have good empirical data on space-use by turtles, for example through high-resolution tracking[147] and support from boat operators, which can be helped through education programs[148].

Educational programs

A foundational part of sea turtle conservation is public outreach and education. Sea turtles are among the most charismatic and vulnerable species in marine ecosystems, yet their biology and the roles they play as habitat engineers, predators, prey, and facilitators of nutrient cycling are poorly known by most people. Worldwide educational programs—at zoos, in classrooms, at nesting beach programs, etc.—use sea turtles as ambassadors to foster interest in science and to encourage a change in public perception of the importance of healthy ecosystems[149,150]. These endeavours can also teach the public to make better decisions about their own behaviours as well as for choosing their political leaders.

Summary and future directions

There is widespread good news for sea turtles, with conservation actions leading to increases in abundance across species and ocean basins. These conservation successes reflect the Herculean efforts of 1000s of conservation biologists worldwide. However, it is not a time for complacency in conservation efforts, as several as several sea turtle populations around the world are crashing, especially for leatherbacks[30,58,114]. Others, such as green turtles at Tortuguero (Costa Rica), were very recently considered stable but now show steep declines[101].

There remain several key directions to enhance sea turtle conservation and address top conservation priorities such as mitigating impacts of climate change, reducing bycatch and targeted harvesting, assessing and reducing the impact of pollution including plastics and mitigating the loss or degradation of foraging habitats such as seagrass meadows. Learning how to best address these challenges requires the best-available science, and tools such as satellite telemetry (which can accurately reveal key areas of space use and migration corridors and hence key areas for conservation), genetic techniques (which can help identify distinct regional management units for conservation), and uncrewed aerial drones (which can quantify operational sex ratios and assess the abundance of immature turtles). Such scientific tools give insight to where, when, and how to best protect turtles.

The magnitude of threats is often assessed by semi-quantitative or qualitative expert opinion[27]. So there remains a need for stronger empirical evidence to assess the population-level impacts of threats, including plastics[60], so that effort to mitigate threats can be triaged in an informed way. Implementing conservation actions usually involves human-to-human engagement, and it is increasingly apparent that effective implementation of conservation action requires social science data and good understanding of how best to communicate conservation goals in focal communities[151]. Public comment periods can help conservation practitioners learn not only where the greatest impediments to conservation will be, but also where the greatest opportunities for success are found[152]. To reduce bycatch needs a willingness and genuine engagement by fishers, and conservation biologists must be open to learning from fishers about the most adoptable turtle-friendly gear types. A key priority is to develop gear types that fishers and communities will use when not monitored and not subsidized, which will provide a path to long-term sustainability in bycatch reduction. Fostering alternative livelihoods for fisher families is also a key part of bycatch reduction, as added household income can reduce the need for heavy fishing effort and thus reduce sea turtle exposure to nets and hooks.

Despite many thousands of turtles having been satellite tracked, there are still relatively few examples of where these data have been used to drive conservation management, such as protected zones[118]. So there remains an abundance of under-utilized tracking data[153]. There is, for example, the opportunity to use tracking data to reduce leatherback bycatch more widely, adopting the kinds of dynamic ocean management used successfully off California (USA) with limited areas closed to fishing[154].

There remains a dearth of information about the abundance of male turtles. Yet there are now clear methodologies and successful examples for how to address this knowledge gap (Fig. 3). The challenges of mitigating climate change remain, and while there are methods (e.g. nest shading) to buffer against embryonic sex ratio feminization, the near-ubiquitous nature of this impact has created distinct challenges relating to the required scale of effort necessary to combat the issue. How to cool clutches to produce more males remains an open question needing further research, with promising approaches including nest shading and irrigation.

The best approach to mitigate loss of nesting beaches through rising sea levels and beach erosion remains unknown. Possibilities being considered include the mass movement of eggs to new nesting beaches, as was done in the 1970s and 1980s with Kemp's ridley hatchlings to establish a new nesting beach in Texas (USA)[155]. This effort has been considered a partial success, with now a few hundred nests in Texas each year. It would take a huge amount of work to repeat this type of effort elsewhere, with many hundreds of thousands of eggs likely needing to be moved to establish even a small population, since survival to adulthood of hatchlings is so low. At the same time there is the potential to artificially elevate nesting beaches via sand nourishment to make them more resilient to rising sea levels and increased storms. For example, artificially raising the level of beach sand has been successfully trialed on the green turtle nesting location of Raine Island (Australia)[156], but care needs to be taken that characteristics of the added sand are suitable for successful egg incubation.

Taken together, abundance changes around the world show that conservation measures can often work effectively for sea turtles, but this is not a time for conservation complacency since stable or upward trends in numbers can quickly be reversed. Innovative and inclusive solutions are needed to meet these challenges. Further, it is important to remember that despite increases in abundance at many sites in recent decades, turtle numbers in many areas may still be lower than they were prior to human exploitation. For example, even with local increases in nesting[157], green turtle numbers in the Caribbean likely remain at only a tiny fraction of the numbers that existed prior to the arrival of Christopher Columbus.

References

1. Ceballos, G. et al. Accelerated modern human-induced species losses: entering the sixth mass extinction. *Sci. Adv.* **1**, e1400253 (2015).
2. Jackson, J.B.C. et al. Historical overfishing and the recent collapse of coastal ecosystems. *Science* **29**, 629-638 (2001).
3. Bjorndal, K. A. & Jackson, J. B. Roles of sea turtles in marine ecosystems: reconstructing the past. The Biology of Sea Turtles, Volume 2, CRC Press, p. 259-273 (2002).
4. Chan, E.H. Marine turtles in Malaysia: On the verge of extinction ? *Aquatic Ecosystem Health & Management* **9**, 175-184 (2006).
5. Bevan, E. et al. Estimating the historic size and current status of the Kemp's ridley sea turtle (*Lepidochelys kempii*) population. *Ecosphere* **7**, e01244 (2016).
6. Duarte, C.M. et al. Rebuilding marine life. *Nature* **580**, 39-51 (2020).
7. Convention on Biological Diversity. Kunming-Montreal Global Biodiversity Framework. Decision CBD/COP/DEC/15/4, United Nations Environment Programme (2022).
8. Gilbert, N. Nations forge historic deal to save species: what's in it and what's missing. *Nature*, 19 December 2022.
9. Wallace, B.P. et al. Marine turtle regional management units 2.0: an updated framework for conservation and research of wide-ranging megafauna species. *Endanger. Species Res.* **52**, 209-223 (2023).
10. Carreras, C. et al. Sporadic nesting reveals long distance colonization in the philopatric loggerhead sea turtle (*Caretta caretta*). *Sci. Rep.* **8**, 1435 (2018).
11. Shimada, T. et al. Fidelity to foraging sites after long migrations. *J. Anim. Ecol.* **89**, 1008-1016 (2020).
12. Benson, S.R. et al. Large-scale movements and high-use areas of western Pacific leatherback turtles, *Dermochelys coriacea*. *Ecosphere* **2**, 1-27 (2011).
13. Fossette, S. et al. Pan-Atlantic analysis of the overlap of a highly migratory species, the leatherback turtle, with pelagic longline fisheries. *Proc. R. Soc. Lond. B* **281**, 20133065 (2014).

14. Hays, G.C., Cerritelli, G., Esteban, N., Rattray, A. & Luschi, P. Open ocean reorientation and challenges of island finding by sea turtles during long-distance migration. *Current Biology* **30**, 3236-3242 (2020).
15. Blumenthal, J.M. et al. Satellite tracking highlights the need for international cooperation in marine turtle management. *Endanger. Species Res.* **2**, 51-61 (2006).
16. Gaos, A.R. et al. Signs of hope in the eastern Pacific: international collaboration reveals encouraging status for the severely depleted population of hawksbill turtles *Eretmochelys imbricata*. *Oryx* **44**, 595-601 (2010).
17. Esteban, N. et al. A global review of green turtle diet: sea surface temperature as a potential driver of omnivory levels. *Mar. Biol.* **167**, 183 (2020).
18. Bell, I. Algivory in hawksbill turtles: *Eretmochelys imbricata* food selection within a foraging area on the Northern Great Barrier Reef. *Mar. Ecol.* **34**, 43-55 (2013).
19. Meylan, A. Spongivory in hawksbill turtles: a diet of glass. *Science* **239**, 393-395 (1988).
20. Reynolds, K.S. et al. Diet of hawksbill turtles (*Eretmochelys imbricata*) in the Gulf of California, Mexico. *Aquatic Conservation: Marine and Freshwater Ecosystems* **33**, 917-25 (2023).
21. Hays, G.C., Doyle, T.K. & Houghton, J.D.R. A paradigm shift in the trophic importance of jellyfish ? *Trends in Ecology & Evolution* **11**, 874-884 (2018).
22. Hatase, H., Omuta, K. & Tsukamoto, K. Bottom or midwater: alternative foraging behaviours in adult female loggerhead sea turtles. *J. Zool.* **273**, 46-55 (2007).
23. Whiting, S. D., Long, J. L., & Coyne, M. Migration routes and foraging behaviour of olive ridley turtles *Lepidochelys olivacea* in northern Australia. *Endanger. Species Res.* **3**, 1-9 (2007).
24. Gredzens, C. & Shaver, D.J. Satellite tracking can inform population-level dispersal to foraging grounds of post-nesting Kemp's ridley sea turtles. *Front. Mar. Sci.* **7**, 559 (2020).
25. Butler, Z.P. et al. Predation of loggerhead sea turtle eggs across Georgia's barrier islands. *Global Ecology and Conservation* **2**, e01139 (2020).
26. Stokes, H.J., Esteban, N. & Hays, G.C. Predation of sea turtle eggs by rats and crabs. *Mar. Biol.* **171**, 17 (2024).
27. Fuentes, M.M.P.B. et al. Key issues in assessing threats to sea turtles: knowledge gaps and future directions. *Endanger. Spec. Res.* **52**, 303-341 (2023).

28. Ortega-Ortiz, C.D. et al. Expanding information on the prey items and hunting tactics of the eastern tropical pacific killer whale (*Orcinus orca*) ecotype. *Examines Mar. Biol. Oceanogr.* **6**, 000635 (2023).
29. Senko, J.F. et al. Global patterns of illegal marine turtle exploitation. *Glob. Change Biol.* **28**, 6509-6523 (2022).
30. Tapilatu, R.F. et al. Long-term decline of the western Pacific leatherback, *Dermochelys coriacea*: a globally important sea turtle population. *Ecosphere* **4**, 25 (2013).
31. Tomillo, P.S., Saba, V.S., Piedra, R., Paladino, F.V., & Spotila, J.R. Effects of illegal harvest of eggs on the population decline of leatherback turtles in Las Baulas Marine National Park, Costa Rica. *Conservation Biology* **22**, 1216-1224 (2008).
32. Sarti Martínez, L. et al. Conservation and biology of the leatherback turtle in the Mexican Pacific. *Chelonian Conservation and Biology* **6**, 70-78 (2007).
33. Humber, F., Godley, B.J. & Broderick, A.C. So excellent a fishe: a global overview of legal marine turtle fisheries. *Diversity and Distributions* **20**, 579-590 (2014).
34. Stringell, T.B. et al. Protecting the breeders: research informs legislative change in a marine turtle fishery. *Biodiversity and Conservation* **24**, 1775-96 (2015).
35. Miller, E.A. et al. The historical development of complex global trafficking networks for marine wildlife. *Sci. Adv.* **5**, eaav5948 (2019).
36. Donnelly, M. Busting bekko: The nexus between local and international advocacy to end Japan's import of tortoiseshell. In: Sea Turtle Research and Conservation. Academic Press, pp. 133-139 (2021).
37. Kirishnamoorthie, J., Hideaki, N., James, A., Hussien, M. & Juanita, J. Illegal tortoiseshell harvest of hawksbill turtles (*Eretmochelys imbricata*) in Southeast Asia: evidence from Baturua Reef, Semporna, Sabah, Malaysia. *Journal of Sustainability Science and Management* **18**, 54-67 (2023).
38. Fuentes, M.M.P.B, Fish, M.R. & Maynard, J.A. Management strategies to mitigate the impacts of climate change on sea turtle’s terrestrial reproductive phase. *Mitig. Adapt. Strat. Glob. Change* **17**, 51-63 (2012).
39. Patrício, A.R., Hawkes, L.A., Monsinjon, J.R., Godley, B.J. & Fuentes, M.M.P.B. Climate change and marine turtles: recent advances and future directions. *Endanger. Species Res.* **44**, 363-395 (2021).

40. Maurer, A.S., et al. Population viability of sea turtles in the context of global warming. *BioScience* **71**, 790-804 (2021).

41. Hamann, M., Fuentes, M.M.P.B., Ban, N.C. & Mocellin, V.J.L. Climate change and marine turtles. In The biology of Sea turtles (eds J Wyneken, KJ Lohmann, JA Musick), pp. 353-358. Boca Raton, FL. CRC Press (2013).

42. Laloë, J.-O., Schofield, G., Hays, G.C. Climate warming and sea turtle sex ratios across the globe. *Glob. Change Biol.* **30**, e17004 (2024).

43. Santidrián Tomillo, P. & Spotila, J.R. Temperature-dependent sex determination in sea turtles in the context of climate change: uncovering the adaptive significance. *BioEssays* **42**, 2000146 (2020).

44. Booth, D.T. Influence of incubation temperature on sea turtle hatchling quality. *Integr. Zool.* **12**, 352-360 (2017).

45. Hays, G.C., Mazaris, A.D., Schofield, G. & Laloë, J.-O. Population viability at extreme sex-ratio skews produced by temperature-dependent sex determination. *Proc. Roy. Soc. Lond. B* **284**, 20162576 (2017).

46. Laloë, J.-O., Cozens, J., Renom, B., Taxonera, A. & Hays, G.C. Climate change and temperature-linked hatchling mortality at a globally important sea turtle nesting site. *Glob. Change Biol.* **23**, 4922-4931 (2017).

47. Turkozan, O., Almpanidou, V., Yılmaz, C. & Mazaris, A.D. Extreme thermal conditions in sea turtle nests jeopardize reproductive output. *Climat. Change* **167**, 30 (2021).

48. Hays, G.C., Chivers, W.J., Laloë, J.O., Sheppard, C. & Esteban, N. Impact of marine heatwaves for sea turtle nest temperatures. *Biol. Lett.* **17**, 20210038 (2021).

49. Konsta, A. et al. Marine heatwaves threaten key foraging grounds of sea turtles in Southeast Asian Seas. *Reg. Environ. Change* **22**, 97 (2022).

50. Varela MR et al. Assessing climate change associated sea-level rise impacts on sea turtle nesting beaches using drones, photogrammetry and a novel GPS system. *Glob. Change Biol.* **25**, 753-762 (2019).

51. Poloczanska, E.S., Limpus, C.J. & Hays, G.C. Vulnerability of marine turtles to climate change. *Adv. Mar. Biol.* **56**, 151-211 (2009).

52. Wallace, B. P. et al. Impacts of fisheries bycatch on marine turtle populations worldwide: toward conservation and research priorities. *Ecosphere* **4**, 40 (2013).

53. Peckham, S.H. et al. Small-scale fisheries bycatch jeopardizes endangered Pacific loggerhead turtles. *PLoS ONE* **2**, e1041 (2007).

54. Lewison, R.L., Freeman, S.A. & Crowder, L.B. Quantifying the effects of fisheries on threatened species: the impact of pelagic longlines on loggerhead and leatherback sea turtles. *Ecology Letters* **7**, 221–231 (2004).

55. Hamelin, K.M., James, M.C., Ledwell, W., Huntington, J. & Martin, K. Incidental capture of leatherback sea turtles in fixed fishing gear off Atlantic Canada. *Aquat. Conserv.* **27**, 631-642 (2017).

56. Dodge, K.L. et al. Disentanglement network data to characterize leatherback sea turtle *Dermochelys coriacea* bycatch in fixed gear fisheries. *Endanger. Species Res.* **47**, 155-170 (2022).

57. Laud OPO Network. Enhanced, coordinated conservation efforts required to avoid extinction of critically endangered Eastern Pacific leatherback turtles. *Sci. Rep.* **10**, 4772 (2020).

58. Hamann, M., Limpus, C., Hughes, G., Mortimer, J.A. & Pilcher, N. Assessment of the conservation status of leatherback turtles in the Indian Ocean and South-East Asia. IOSEA Marine Turtle MoU Secretariat, Bangkok, 106 pages (2006).

59. Schuyler, Q., Hardesty, B.D., Wilcox, C., Townsend, K. Global analysis of anthropogenic debris ingestion by sea turtles. *Conserv. Biol.* **28**, 129-139 (2013).

60. Senko, J.F., Nelms, S.E., Reavis, J.L., Witherington, B., Godley, B.J., Wallace, B.P. Understanding individual and population-level effects of plastic pollution on marine megafauna. *Endang. Species Res.* **43**, 234-252 (2020).

61. Mashkour, N., Jones, K., Kophamel, S., Hipolito, T., Ahasan, S., Walker, G. et al. Disease risk analysis in sea turtles: A baseline study to inform conservation efforts. *PLoS ONE* **15**, e0230760 (2020).

62. Fuentes, M.M.P.B., Meletis, Z.A., Wildermann, N.E., Ware, M. Conservation interventions to reduce vessel strikes on sea turtles: A case study in Florida. *Marine Policy* **128**, 104471 (2021).

63. Foley, A.M., Stacy, B.A., Hardy, R.F., Shea, C.P., Minch, K.E., Schroeder, B.A. Characterizing watercraft-related mortality of sea turtles in Florida, *J. Wildl. Manag.* **83**, 1057–1072 (2019).

64. Pereira, J.A., Martins, A.S., Seminoff, J.A., de Azevedo Mazzuco, A.C. Long-term changes in body size of green turtles nesting on Trindade Island, Brazil: signs of recovery? *Mar. Environ. Res.* **186**, 105930 (2023).

65. Nordberg, E.J. et al. An evaluation of nest predator impacts and the efficacy of plastic meshing on marine turtle nests on the western Cape York Peninsula, Australia. *Biol. Conserv.* **238**, 108201 (2019).

66. Pakiding, F. et al. Community engagement: an integral component of a multifaceted conservation approach for the transboundary western Pacific leatherback. *Frontiers in Marine Science* **7**, 549570 (2020).

67. Kamrowski, R.L., Limpus, C., Moloney, J., Hamann, M. Coastal light pollution and marine turtles: assessing the magnitude of the problem. *Endang. Species Res.* **19**, 85-98 (2012).

68. Meylan, P.A., Hardy, R.F., Gray, J.A. & Meylan, A.B. A half-century of demographic changes in a green turtle (*Chelonia mydas*) foraging aggregation during an era of seagrass decline. *Mar. Biol.* **169**, 74 (2022).

69. Casale, P. et al. New methods to derive sea turtle nester abundance from nest counts: Ground truthing and the bias of current approaches. *Biol. Cons.* **275**, 109754 (2022).

70. Sellés-Ríos, B. et al. Warm beach, warmer turtles: Using drone-mounted thermal infrared sensors to monitor sea turtle nesting activity. *Frontiers in Conservation Science* **3**, 954791 (2022).

71. Cuevas, E. et al. First spatial distribution analysis of male sea turtles in the southern Gulf of Mexico. *Front. Mar. Sci.* **7**, 561846 (2020).

72. Casale, P., Freggi, D., Maffucci, F. & Hochscheid, S. Adult sex ratios of loggerhead sea turtles (*Caretta caretta*) in two Mediterranean foraging grounds. *Sci. Mar.* **78**, 303-309 (2014).

73. Schofield, G., Katselidis, K.A., Lilley, M.K., Reina, R.D. & Hays, G.C. Detecting elusive aspects of wildlife ecology using drones: new insights on the mating dynamics and operational sex ratios of sea turtles. *Funct. Ecol.* **31**, 2310-2319 (2017).

74. Hays, G.C., Laloë, J-O, Lee, P.L.M. & Schofield, G. Evidence of adult male scarcity associated with female-skewed offspring sex ratios in sea turtles. *Curr. Biol.* **33**, R1-R15 (2023).

75. Early-Capistrán, M.M. et al. Integrating local ecological knowledge, ecological monitoring, and computer simulation to evaluate conservation outcomes. *Conservation Letters* **15**, e12921 (2022).
76. Schofield, G., Esteban, N., Katselidis, K. A. & Hays, G. C. Drones for research on sea turtles and other marine vertebrates–A review. *Biol. Conser.* **238**, 108214 (2019).
77. Stokes, H.J., Mortimer, J.A., Laloë, J.-O., Hays, G.C. & Esteban, N. Synergistic use of UAV surveys, satellite tracking data, and mark-recapture to estimate abundance of elusive species. *Ecosphere* **14** e4444 (2023).
78. Dunbar, S.G. et al. HotSpotter: Using a computer-driven photo-id application to identify sea turtles. *J. Exp. Mar. Biol. Ecol.* **535**, 151490 (2021).
79. Hanna, M.E. Citizen-sourced sightings and underwater photography reveal novel insights about green sea turtle distribution and ecology in southern California. *Front. Mar. Sci.* **8**, 671061 (2021).
80. Hays, G.C., Mazaris, A.D. & Schofield, G. Inter-annual variability in breeding census data across species and regions. *Mar. Biol.* **169**, 54 (2022).
81. Broderick, A.C., Godley, B.J. & Hays, G.C. Trophic status drives interannual variability in nesting numbers of marine turtles. *Proc. Roy. Soc. Lond. B* **268**, 1481-1487 (2001).
82. Mazaris, A.D., Schofield, G., Gkazinou, C., Almpanidou, V. & Hays, G.C. Global sea turtle conservation successes. *Sci. Adv.* **3**, e1600730 (2017).
83. Hays, G.C. et al. A pulse check for trends in sea turtle numbers across the globe, *iScience* **27**, 109071 (2024).
84. Dobbs. K. Marine turtles in the Great Barrier Reef world heritage area: a compendium of information and basis for the development of policies and strategies for the conservation of marine turtles. Great Barrier Reef Marine Park Authority, 53 pp (2001).
85. Seminoff, J.A. et al. Status Review of the Green Turtle (*Chelonia mydas*) Under the U.S. Endangered Species Act. NOAA Technical Memorandum, NOAA- NMFS-SWFSC-539. 571pp (2015).
86. Seminoff, J.A. *Chelonia mydas*. The IUCN Red List of Threatened Species 2004: e.T4615A11037468 (2004).
87. Casale, P. & Tucker, A.D. *Caretta caretta*. The IUCN red list of threatened species 2015: e.T3897A83157651. Accessed on 5 May 2024 (2015).

88. Snover, M.L., & Heppell, S.S. Application of diffusion approximation for risk assessments of sea turtle populations. *Ecological Applications* **19**, 774-785 (2009).

89. Van Houtan, K.S., & Halley, J.M. Long-term climate forcing in loggerhead sea turtle nesting. *PLoS ONE* **6**, e19043 (2011).

90. Mazaris, A.D., Kornaraki, E., Matsinos, Y.G., & Margaritoulis, D. Modeling the effect of sea surface temperature on sea turtle nesting activities by investigating seasonal trends. *Natural Resource Modeling* **17**, 445-465 (2004).

91. Ceriani, S.A., Casale, P., Brost, M., Leone, E.H., & Witherington, B.E. Conservation implications of sea turtle nesting trends: elusive recovery of a globally important loggerhead population. *Ecosphere* **10**, e02936 (2019).

92. IUCN. Guidelines for using the IUCN Red List categories and criteria. Version 14. Standards and Petitions Subcommittee, IUCN, Gland (2019).

93. Mrosovsky, N. IUCN's credibility critically endangered. *Nature* **389**, 436 (1997).

94. Seminoff, J. A. & Shanker, K. Marine turtles and IUCN Red Listing: a review of the process, the pitfalls, and novel assessment approaches. *J. Exp. Mar. Biol. Ecol.* **356**, 52-68 (2008).

95. Bourjea, J. & Dalleau, M. *Chelonia mydas* (Southwest Indian Ocean subpopulation). The IUCN Red List of Threatened Species 2023: e.T220970396A220970430. https://dx.doi.org/10.2305/IUCN.UK.2023-1.RLTS.T220970396A220970430.en. Accessed on 13 May 2024 (2023).

96. Pritchard, A.M. et al. Green turtle population recovery at Aldabra Atoll continues after 50 yr of protection. *Endang. Species. Res.* **47**, 205-215 (2022).

97. Weber, S.B. et al. Recovery of the South Atlantic’s largest green turtle nesting population. *Biodivers. Conserv.* **23**, 3005-3018 (2014).

98. Chaloupka, M.Y. & Pilcher, N.J. *Chelonia mydas* (Hawaiian subpopulation). The IUCN Red List of Threatened Species 2019: e.T16285718A142098300 (2019).

99. Broderick, A. & Patricio, A. *Chelonia mydas* (South Atlantic subpopulation). The IUCN Red List of Threatened Species 2019: e.T142121866A142086337 (2019).

100. Broderick, A.C. et al. *Chelonia mydas* (Mediterranean subpopulation) (amended version of 2023 assessment). *The IUCN Red List of Threatened Species* e.T4616A259027885 (2024).

101. Restrepo, J., Webster, E.G., Ramos, I. & Valverde, R.A. Recent decline of green turtle *Chelonia mydas* nesting trend at Tortuguero, Costa Rica. *Endanger. Species Res.* **51**, 59-72 (2023).

102. Troëng, S. & Rankin, E. Long-term conservation efforts contribute to positive green turtle *Chelonia mydas* nesting trend at Tortuguero, Costa Rica. *Biol. Conserv.* **121**, 111-116 (2005).

103. Hays, G.C. et al. Changes in mean body size in an expanding population of a threatened species. *Proc. R. Soc. B* **289**, 20220696 (2022).

104. Casale, P. *Caretta caretta* (Mediterranean subpopulation). The IUCN Red List of Threatened Species 2015: e.T83644804A83646294 (2015).

105. Casale, P. & Matsuzawa, Y. *Caretta caretta* (North Pacific subpopulation). The IUCN Red List of Threatened Species 2015: e.T83652278A83652322 (2015).

106. Ceriani, S.A. & Meylan, A.B. *Caretta caretta* (North West Atlantic subpopulation) (amended version of 2015 assessment). The IUCN Red List of Threatened Species 2017: e.T84131194A119339029 (2017).

107. Casale, P. & Marcovaldi, M. *Caretta caretta* (South West Atlantic subpopulation). The IUCN Red List of Threatened Species 2015: e.T84191235A84191397 (2015).

108. Willson, A. et al. Evaluating the long-term trend and management of a globally important loggerhead population nesting on Masirah Island, Sultanate of Oman. *Front. Mar. Sci.* **7**, 666 (2020).

109. Casale, P. *Caretta caretta* (North West Indian Ocean subpopulation). The IUCN Red List of Threatened Species 2015: e.T84127873A84127992 (2015).

110. Casale, P. *Caretta caretta* (North East Indian Ocean subpopulation). The IUCN Red List of Threatened Species 2015: e.T84126444A84126520 (2015).

111. Limpus, C. & Casale, P. *Caretta caretta* (South Pacific subpopulation). The IUCN Red List of Threatened Species 2015: e.T84156809A84156890 (2015).

112. Casale, P. & Marco, A. *Caretta caretta* (North East Atlantic subpopulation). The IUCN Red List of Threatened Species 2015: e.T83776383A83776554 (2015).

113. Wibbels, T. & Bevan, E. *Lepidochelys kempii*. The IUCN Red List of Threatened Species 2019: e.T11533A155057916 (2019).

114. Wallace, B.P., Tiwari, M. & Girondot, M. *Dermochelys coriacea*. The IUCN Red List of Threatened Species 2013: e.T6494A43526147 (2013).

115. Mohan, P. & Strobl, E. Tourism and marine crises: The impact of Sargassum invasion on Caribbean small island developing sates. *Ocean & Coastal Management* **251**, 107091 (2024).

116. Tiwari, M. An evaluation of the perceived effectiveness of international instruments for sea turtle conservation. *Journal of International Wildlife Law and Policy* **5**, 145-156 (2002).

117. Seminoff, J.A. et al. Loggerhead sea turtle abundance at an offshore foraging hotspot in the eastern Pacific Ocean: implications for at-sea conservation. *Endanger. Species Res.* **24**, 207-220 (2014).

118. Hays, G.C. et al. Translating marine animal tracking data into conservation policy and management. *Trends in Ecology and Evolution* **34**, 459-473 (2019).

119. Mortimer, J.A., Esteban, N., Guzman, A.N. & Hays, G.C. Estimates of sea turtle nesting populations in the south-western Indian Ocean indicate the importance of the Chagos Archipelago. *Oryx* **54**, 332-343 (2020).

120. Bojórquez-Tapia, L.A. et al. A continual engagement framework to tackle wicked problems: curtailing loggerhead sea turtle fishing bycatch in Gulf of Ulloa, Mexico. *Sustain Sci* **12**, 535-548 (2017).

121. Rife, A.N., Erisman, B., Sanchez, A., & Aburto-Oropeza, O. When good intentions are not enough… Insights on networks of “paper park” marine protected areas. *Conservation letters* **6**, 200-212 (2013).

122. Hays, G.C., Rattray, A., Esteban, N. Addressing tagging location bias to assess space use by marine animals. *J. Appl. Ecol.* **57**, 1981-1987 (2020).

123. Hays, G.C., Koldewey, H.J., Andrzejaczek, S., Attrill, M.J., Barley, S. et al. A review of a decade of lessons from one of the world’s largest MPAs: conservation gains and key challenges. *Mar. Biol.* 167, 159 (2020).

124. Aridjis, H. Mexico proclaims total ban on harvest of turtles and eggs. *Marine Turtle Newsletter* **50**, 1-3 (1990).

125. Trejo, C.D & Díaz, J.A. Current conservation status of the black sea turtle in Michoacán, México. In: Seminoff, J.A. & Wallace, B.P. Biology of Sea Turtles in The Eastern Pacific Ocean: Advances in Research and Conservation. Univ. Arizona Press, Tucson pp 263-278 (2012).

126. Edwards, R.C., Godley, B.J. & Nuno, A. Exploring connections among the multiple outputs and outcomes emerging from 25 years of sea turtle conservation in Northern Cyprus. *Journal for Nature Conservation* **55**, 125816 (2020).
127. Godley, B.J. et al. Reflections on sea turtle conservation. *Oryx* **54**, 287-289 (2020).
128. Hancock, J.M., Furtado, S., Merino, S., Godley, B.J. & Nuno, A. Exploring drivers and deterrents of the illegal consumption and trade of marine turtle products in Cape Verde, and implications for conservation planning. *Oryx* **51**, 428-436 (2017).
129. Thomas-Walters, L., Vieira, S., Jiménez, V., et al. Challenges in the impact evaluation of behaviour change interventions: The case of sea turtle meat and eggs in São Tomé. *People Nat.* **2**, 913-922 (2020).
130. Marcovaldi, M.A., dei Marcovaldi, G.G. Marine turtles of Brazil: the history and structure of Projeto TAMAR-IBAMA. *Biol. Conserv.* 91, 35-41 (1999).
131. Lewison, R.L., Crowder, L.B., & Shaver, D.J. The impact of turtle excluder devices and fisheries closures on loggerhead and Kemp's ridley strandings in the western Gulf of Mexico. *Conserv. Biol.* **17**, 1089-1097 (2003).
132. Alkire, C. Decline in on-demand fishing gear costs with learning. *Front. Mar. Sci.* **9**, 943552 (2022).
133. Ortiz-Alvarez, C. et al. Rapid assessments of leatherback small-scale fishery bycatch in internesting areas in the Eastern Pacific Ocean. *Front. Mar. Sci.* **6**, 813 (2020).
134. Jenkins, L.D., Eayrs, S., Pol, M. V., & Thompson, K.R. Uptake of proven bycatch reduction fishing gear: perceived best practices and the role of affective change readiness. *ICES Journal of Marine Science* **80**, 437-445 (2023).
135. Evans, S. et al. Investigating the effectiveness of a well-managed hatchery as a tool for hawksbill sea turtle (*Eretmochelys imbricata*) conservation. *Conservation Science and Practice* **4**, e12819 (2022).
136. Heppell, S.S., Crowder, L.B. & Crouse, D.T. Models to evaluate headstarting as a management tool for long-lived turtles. *Ecological Applications* **6**, 556-565 (1996).
137. Bennett, A.M., Steiner, J., Carstairs, S., Gielens, A. & Davy, C.M. A question of scale: replication and the effective evaluation of conservation interventions. *Facets* **2**, 892-909. (2017).
138. Pritchard, P.C.H. The conservation of sea turtles: practices and problems. *American Zoologist* **20**, 609-617 (1980).

139. Bell, C.D. et al. Some of them came home: the Cayman Turtle Farm headstarting project for the green turtle *Chelonia mydas*. *Oryx* **39**, 137-148 (2005).

140. Kanghae, H. et al. First successful head-start program of leatherback sea turtles (*Dermochelys coriacea*) in Thailand and proposed dietary strategy. *Zoo Biology* **43**, 110-122 (2024).

141. Hill, J.E., Paladino, F.V., Spotila, J.R. & Tomillo, P.S. Shading and watering as a tool to mitigate the impacts of climate change in sea turtle nests. *PLoS ONE* **10**, e0129528 (2015).

142. Saengsupavanich, C., Pranzini, E., Ariffin, E.H., & Yun, L.S. Jeopardizing the environment with beach nourishment. *Science of the Total Environment* **868**, 161485 (2023).

143. Ernest RG, Martin RE, Desjardin NA, Scripter MJ, Scarola JC, Kim H, Trindell R. Changes in loggerhead sea turtle nesting behavior on a nourished beach in southeast Florida. *Journal of Coastal Research*. 2024 Aug 20.

144. Shamblott, K. M., Reneker, J. L., & Kamel, S. J. The thermal impacts of beach nourishment across a regionally important loggerhead sea turtle (Caretta caretta) rookery. *Ecosphere* **12**, e03396 (2021).

145. NOAA Fisheries (2024). Marine debris research and removal in the Northwestern Hawaiian Islands. https://www.fisheries.noaa.gov/pacific-islands/habitat-conservation/marine-debris-research-and-removal-northwestern-hawaiian

146. Shimada, T., Limpus, C.J., Jones, R., & Hamann, M. Aligning habitat use with management zoning to reduce vessel strike of sea turtles. *Ocean Coast. Manag.* **142,** 163–172 (2017).

147. Schofield, G., Scott, R., Dimadi, A., Fossette, S., Katselidis, K.A., Koutsoubas, D., Lilley, M.K.S., Pantis, J.D., Karagouni, A.D., Hays, G.C. Evidence-based marine protected area planning for a highly mobile endangered marine vertebrate. *Biol. Conserv.* **161**, 101-109 (2013).

148. Fuentes, M.M.P.B., Meletis Z., Wildermann, N.E., & Ware, M. Conservation interventions to reduce vessel strikes on sea turtles: A case study in Florida. *Marine Policy* **128**, 104471 (2021).

149. Frame, J.R. et al. Measuring of the effects of a sea turtle conservation education program on children's knowledge and attitudes in Grenada, West Indies. *Ocean & Coastal Management* **211**, 105752 (2021).

150. Mascovich, K.A., Larson, L.R. & Andrews, K.M. Talking turtles with tourists: Evaluating the relative conservation impacts of different types of sea turtle education programs at Jekyll Island, GA, USA. *Journal of Interpretation Research* **28**, 95-120 (2023).

151. Liles, M.J. et al. Connecting international priorities with human wellbeing in low-income regions: lessons from hawksbill turtle conservation in El Salvador. *Local Environment* **20**, 1383-1404. (2015)

152. Senko, J. et al. People helping turtles, turtles helping people: understanding resident attitudes towards sea turtle conservation and opportunities for enhanced community participation in Bahia Magdalena, Mexico. *Ocean & Coastal Management* **54**, 148-157 (2011).

153. Hays, G.C., Hawkes, L.A. Satellite tracking sea turtles: opportunities and challenges to address key questions. *Frontiers in Marine Science* **5**, 432 (2018).

154. Hazen, E.L. et al. A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. *Science Advances* **4**, eaar3001 (2018).

155. Bowen, B.W., Conant, T.A. & Hopkins-Murphy, S.R. Where are they now? The Kemp's Ridley headstart project. *Cons. Biol.* **8**, 853-856 (1994).

156. Smithers, S.G. & Dawson, J.L. Beach reprofiling to improve reproductive output at the world’s largest remaining green turtle rookery: Raine Island, northern Great Barrier Reef. *Ocean & Coastal Management* **231**, 106385 (2023).

157. García-Cruz, M. A. et al. Population trends and survival of nesting green sea turtles *Chelonia mydas* on Aves Island, Venezuela. *Endang. Species Res.* **29**, 103-116 (2015).

158. Hays, G.C., Mazaris, A.D. & Schofield, G. Different male vs. female breeding periodicity helps mitigate offspring sex ratio skews in sea turtles. *Front. Mar. Sci.* **1**, 43 (2014).

159. Laloë, J.-O. & Hays, G.C. Can a present-day thermal niche be preserved in a warming climate by a shift in phenology? A case study with sea turtles. *R. Soc. Open Sci.* **10**, 221002 (2023).

160. Fuentes, M.M.P.B. et al. Adaptation of sea turtles to climate warming: Will phenological responses be sufficient to counteract changes in reproductive output? *Glob. Change Biol.* **30**, e16991 (2024).

161. Mancino, C., Canestrelli, D. & Maiorano, L. Going west: Range expansion for loggerhead sea turtles in the Mediterranean Sea under climate change. *Global Ecology and Conservation* **38**, e02264 (2022).

162. Santidrián Tomillo, P., Tomás, J., Marco, A., Panagopoulou, A. & Tavecchia, G. Environmental changes in the Mediterranean Sea could facilitate the western expansion of loggerhead turtles. *Mar. Ecol. Prog. Ser.* **728**, 145-161 (2024).

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Competing interests

The authors declare no competing interests.