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Managing fisheries in a world with more sea turtles

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For decades, fisheries have been managed to limit the accidental capture of vulnerable species and many of these populations are now rebounding. While encouraging from a conservation perspective, as populations of protected species increase so will bycatch, triggering management actions that limit fishing. Here, we show that despite extensive regulations to limit sea turtle bycatch in a coastal gillnet fishery on the eastern United States, the catch per trip of Kemp's ridley has increased by more than 300% and green turtles by more than 650% (2001–2016). These bycatch rates closely track regional indices of turtle abundance, which are a function of increased reproductive output at distant nesting sites and the oceanic dispersal of juveniles to near shore habitats. The regulations imposed to help protect turtles have decreased fishing effort and harvest by more than 50%. Given uncertainty in the population status of sea turtles, however, simply removing protections is unwarranted. Stock-assessment models for sea turtles must be developed to determine what level of mortality can be sustained while balancing continued turtle population growth and fishing opportunity. Implementation of management targets should involve federal and state managers partnering with specific fisheries to develop bycatch reduction plans that are proportional to their impact on turtles.

1. Introduction

The successful management of wide-ranging marine species with complex life cycles and long times to maturity is confronted by numerous challenges [1–3]. The environmental and anthropogenic drivers of population dynamics can be highly uncertain and predicting (or even assessing) the effectiveness of management actions can be confounded by many variables [4,5]. These issues are exemplified in sea turtle conservation [6–8]. Hatchling sea turtles emerge from nests laid on sandy beaches and quickly swim offshore. For many populations, major nesting areas are situated near ocean current systems that facilitate movement to distant developmental habitats. As turtles grow, most species tend to shift from oceanic to coastal foraging grounds. After a decade or more, turtles reach maturity and return to the vicinity of their natal site to reproduce and nest, after which adults depart to their foraging grounds [8]. Owing to fisheries bycatch, direct harvest of adults and eggs, habitat loss or alterations and a suite of life-history traits that make sea turtles susceptible to extinction, six of the seven sea turtle species are considered vulnerable, endangered or critically endangered [9].

Despite a grim outlook in the early decades of sea turtle conservation, many turtle populations across the globe are now rebounding [9–11]. Particularly in the western Atlantic, extensive protections for turtles (eliminating direct harvest on nesting beaches and reducing fishery bycatch through gear modification, fishing closures and declining fishing effort) appear successful [9]. Nest counts (a proxy of both female abundance and reproductive output) are increasing in many populations [9] and in-water surveys show similar trends at foraging grounds [12–14]. These successes present a new challenge: how do

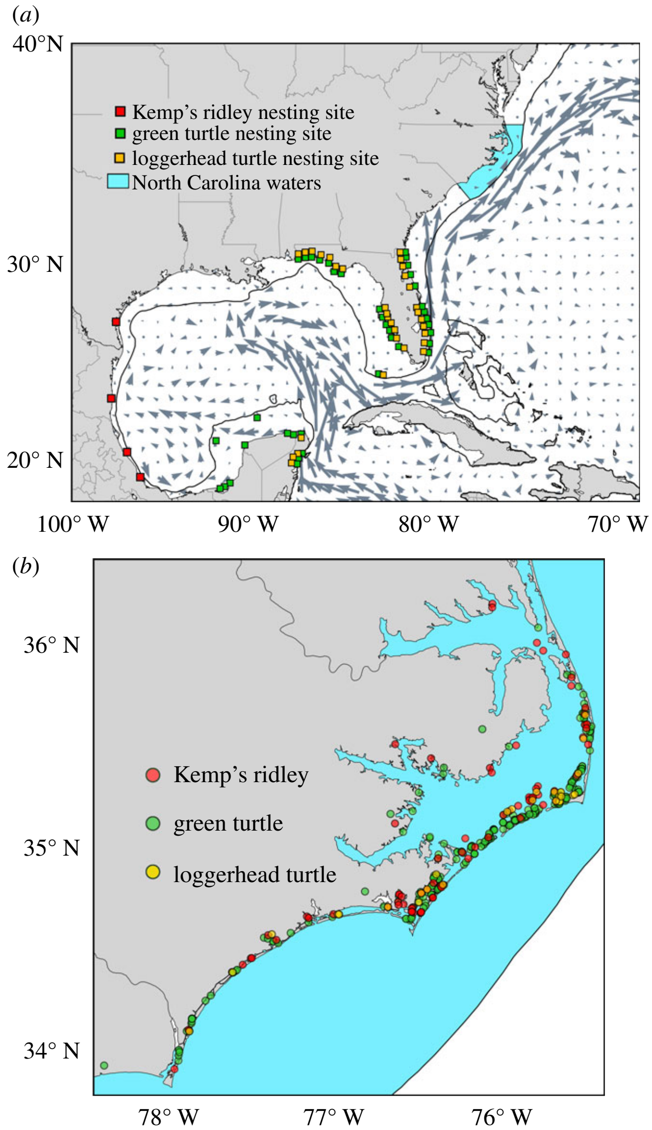

Figure 1. (*a*) Map of the western Atlantic. Arrows indicate average ocean current velocity (based on Global Hybrid Coordinate Ocean Model (HYCOM)surface layer for the year 2015). The thin black line indicates the 75 m isobath. Squares show nesting sites of Kemp's ridley (red = Tamaulipas, Mexico; Veracruz, Mexico and Texas, USA), green turtles (green = Florida, USA; Quintana Roo, Mexico; Yucatan, Mexico; and Campeche, Mexico), and loggerhead turtles (orange = Florida, USA and Quintana Roo, Mexico). Annual hatchling production data from these sites, ICHTHYOP (v.2) particle tracking software and surface velocity fields from Global HYCOM predict annual number of juvenile turtles that move into North Carolina's waters (blue shading) [16]. (*b*) Map of coastal North Carolina showing locations of large-mesh gillnet fisheries interactions with turtles. Colour conventions as in (*a*).

we protect species that are susceptible to negative impacts by anthropogenic activities, but whose growing abundance increases the probability that those interactions will occur? In the United States, these issues are further complicated by precautionary governance policy, which prohibits interactions with sea turtles through the Endangered Species Act (ESA) [15]. Here, we illustrate the importance of raising this question by examining sea turtle bycatch in the inshore/estuarine gillnet fishery of North Carolina, USA (figure 1).

The gillnet fishery is one of North Carolina's most important commercial fisheries operating in inshore/estuarine waters, landing between 4.5 and 13.6 million kg annually over the last 25 years. The value (price paid the fishers) of the anchored gillnet (the most common technique of deploying this gear) has ranged between \$8.2 and \$12.9 million over the same period, consistently ranking it among the top fisheries for North Carolina. Annually, the gillnet fishery has had the most participants of any commercial finfish fishery in the state, ranging from approximately 1000 to 2300 individuals, indicating its importance to the local culture and economy [17].

North Carolina Division of Marine Fisheries (NCDMF), the agency responsible for managing the state's coastal fisheries, has worked to reduce sea turtle interactions by closing certain areas to gillnet fishing when turtles are likely to be present in high numbers, shortening gillnet lengths, requiring observers on a specified percentage of gillnet fishing trips (funded by commercial fisheries), requiring gillnet attendance by fishers and limiting the number of hours gillnets can be left in place [18,19] (electronic supplementary material, table S1). Presently, NCDMF manages turtle-gillnet interactions through an Incidental Take Permit (ITP) from the National Marine Fisheries Service (NMFS) by closing areas to gillnets once a threshold number of sea turtle interactions is reached for any species, in addition to the aforementioned actions [18,20–22].

North Carolina's geography and proximity to the Gulf Stream, a warm northward flowing ocean current, provides foraging habitat for Kemp's ridley (*Lepidochelys kempii*), green (*Chelonia mydas*) and loggerhead (*Caretta caretta*) turtles [13] (figure 1). Sea turtle bycatch in the North Carolina gillnet fishery primarily involves juvenile Kemp's ridley and green turtles at sizes that suggest recent recruitment to coastal waters from oceanic habitats (less than 40 cm curved carapace length (CCL) [23–26]). By contrast, loggerhead bycatch is relatively rare (management actions in the late 1990s and early 2000s preclude gillnet fisheries from operating in the species's preferred habitat in the deep waters of Pamlico Sound) and involves older turtles, probably with established foraging grounds [27,28].

We examined trends in bycatch rates of these species to test whether reducing gillnet lengths or soak times were particularly important for limiting bycatch (in which case a decrease in bycatch rate would be detected) or if growing populations of sea turtles have resulted in an increase in bycatch rate through time. For the latter possibility, we more directly assessed whether changes in gillnet bycatch rates were correlated with indices of turtle abundance that were derived from fishery-independent surveys and strandings. We further determined whether temporal variation in turtle abundance could be accounted for by a recently developed model that predicts the recruitment dynamics of oceanic-stage juvenile turtles to coastal waters based on reproductive output from distant nesting beaches [16]. Finally, we examine the implications of growing sea turtle populations for fisheries and discuss management approaches that can ensure protections to sea turtle populations and allow fisheries to operate.

2. Methods

(a) Fishery data

Data associated with the North Carolina inshore gillnet fishery were provided by NCDMF. The inshore waters of North Carolina's extensive estuarine systems are divided into six management units (A, B, C, D-1, D-2, E), which are designated based on geographical boundaries, similarities of fisheries and knowledge of protected species interactions. For the purposes of this study, we consolidated data on catch and effort that were initially reported by each management unit into statewide totals. We aggregated catch data into statewide, annual values of total kg of fish landed (irrespective of species composition) for small (less than 10 cm ISM) and large (≥10 cm ISM) mesh gillnet fisheries, separately. The small- and large-mesh gillnet fisheries are known to differ in regard to potential sea turtle interactions, and management responses are usually separated using the respective mesh sizes [18,20]. We compiled effort data into the annual number of inshore trips by management unit, using the NCDMF 'trip tickets' system. Commercial fishermen in North Carolina are required by law to fill out a ticket of what is caught for each fishing trip, with other information such as gear, date and location. If no marketable catch occurs or if the catch is not sold a 'trip ticket' will not exist, thus these values should be considered an index of the minimum number of trips within a year. To provide further context for changes in fishing effort, we compiled information on management actions that restricted soak time and length of gillnets (electronic supplementary material, table S1). Fish catch (kg) and effort data (number of trips) were available for the North Carolina gillnet fishery from 1994 through 2016 (electronic supplementary material, tables S2 and S3).

NCDMF provided data for the number of turtle interactions in the large- and small-mesh gillnet fisheries from 2001 through 2016 (programmes 466 and 467) (electronic supplementary material, table S2). The sea turtle ITP requires the observer programme to have at least 7% coverage of large-mesh trips and 1% coverage for small-mesh trips (though NCDMF aims for 10% and 2% observer coverage for large- and small-mesh gillnet fisheries, respectively) [20]. Details on the amount of observer coverage across the state of North Carolina could not be determined for all years in which observed takes were reported. We therefore chose to calculate an annual index of turtle catch per trip based on the number of turtles observed in the large-mesh gillnet fishery divided by the total number of large-mesh gillnet trips. We adopted this approach because we were interested in producing an annual index of turtle interactions for trend analysis, not computing total bycatch.

(b) Turtle data

Abundance indices for loggerhead, green and Kemp's ridley turtles in North Carolina were obtained from two sources, each of which provides information on different aspects of turtle abundance. The years chosen for analysis correspond to the longest possible time series that overlaps with the fisheries data described above. The first source was NCDMF's Gillnet Fisheries Independent Sampling Program (programme 915) for the years 2000 through 2016 (electronic supplementary material, table S4). This programme is designed to sample inshore habitat and has used relatively consistent methodology/effort to supplement age, growth and reproduction studies, to evaluate catch rates and species distribution for use in management plans of coastal fishes [29]. However, over the years, grid and area modifications have been made to reduce turtle interactions. Thus, while this time series provides an annual index of turtles that are susceptible to capture by gillnets in the estuarine waters of North Carolina, the values are likely biased low.

The second source of abundance indices were statewide counts of stranded turtles from http://www.seaturtle.org/strand, as reported by the North Carolina Wildlife Resources Commission's Division of Wildlife Management. We used annual counts spanning 1998 through 2016 that include estuarine and oceanic areas (electronic supplementary material, table S4). While some sea turtle strandings might be linked to gillnet interactions or other fishing activities, they are also shaped by environmental conditions that influence mortality, the probability of washing ashore and the probability of being reported [30]. Our aim was not to ascertain cause, but to use these data as an index of abundance across the state, assuming that the more turtles that are present in an area, the more likely it is that one will wash ashore (for whatever reason) and be reported [16]. This index of turtle abundance may be biased high, because the dataset includes sea turtle that strand outside of estuarine waters, where turtles are not susceptible to gillnet interactions.

In addition to observed indices of turtle abundance, we used a recently developed model that predicts the distribution and abundance of juvenile Kemp's ridley, green and loggerhead sea turtles during their oceanic stage [16]. The approach has been described in detail and appears to accurately depict environmental drivers that contribute to annual variation in turtle distributions [31]. Moreover, the model shows good agreement in predicting spatio-temporal variation in the recruitment of oceanic-stage Kemp's ridley and green turtles to coastal waters in the Gulf of Mexico [16]. For this analysis, we computed the number of 0.5- to 3.5-year-old green and loggerhead turtles, and 0.5- to 2.5-year-old Kemp's ridley that crossed shoreward of the 75 m isobath near the coast of North Carolina (33.8–36.5 N; figure 1; electronic supplementary material, table S4). All age classes of a given species were summed each year for the period 1996–2016.

(c) Analyses

We examined time-series trends in gillnet trips, catch, catch per trip, reported turtle bycatch per trip and abundance indices of turtles in North Carolina's waters using linear and polynomial (quadratic and cubic) regressions. Higher-order equations necessarily produce better fits to the data (higher R^2 values), thus we determined whether increasing the complexity of the regression equation produced a higher R^2 than would be expected by chance ($p \leq 0.05$) [32]. Reported p-values are for the slopes of the regression lines. Pearson's correlation tests were used to compare modelled juvenile recruitment of each species to bycatch and in-water metrics of turtle abundance. We log-transformed observed and modelled turtle abundance data (adding 1 to all values and then computing the logarithm to the base of 10) so that data would conform to the assumption of normality and relationships detected would not be driven by an uncharacteristically high or low data point.

3. Results

In North Carolina's large-mesh gillnet fishery, reported catch per trip of Kemp's ridley and green turtles have increased through time (Kemp's ridley: linear fit $R^2 = 0.306$, $p = 0.026$, $n = 16$; green turtle: quadratic fit $R^2 = 0.770$, $p = 0.000072$, $n = 16$), but loggerhead catch per trip shows no trend (linear fit $R^2 = 0.004$, $p = 0.815$, $n = 16$) (figure 2). Comparing the first 5 years of the dataset (2001–2005) to the last 5 years (2012–2016), Kemp's ridley catch per trip has increased by 318%, and green turtle catch per trip has increased by 676%. Log-transformed Kemp's ridley and green turtle catch per gillnet trip and indices of turtle abundance (fishery-independent gillnet survey and strandings) did not differ from a normal distribution (Kolmogorov–Smirnov test $D \leq 0.26$, $p \geq 0.19$, $n \geq 16$, for each) and were strongly correlated (figure 2, table 1). Log-transformed loggerhead catch per gillnet trip and strandings data did not differ from a normal distribution (Kolmogorov–Smirnov test $D \leq 0.22$, $p \geq 0.38$, $n \geq 16$, for both); though the fishery-independent gillnet survey significantly differed (Kolmogorov–Smirnov test $D = 0.41$, $p = 0.004$, $n = 17$) no relationships were detected between any indices of loggerhead turtle abundance and bycatch rate (table 1).

The trends detected in sea turtle abundance indices in North Carolina (figure 2) correspond to basin-wide patterns apparent in the models of juvenile, oceanic-stage sea turtle

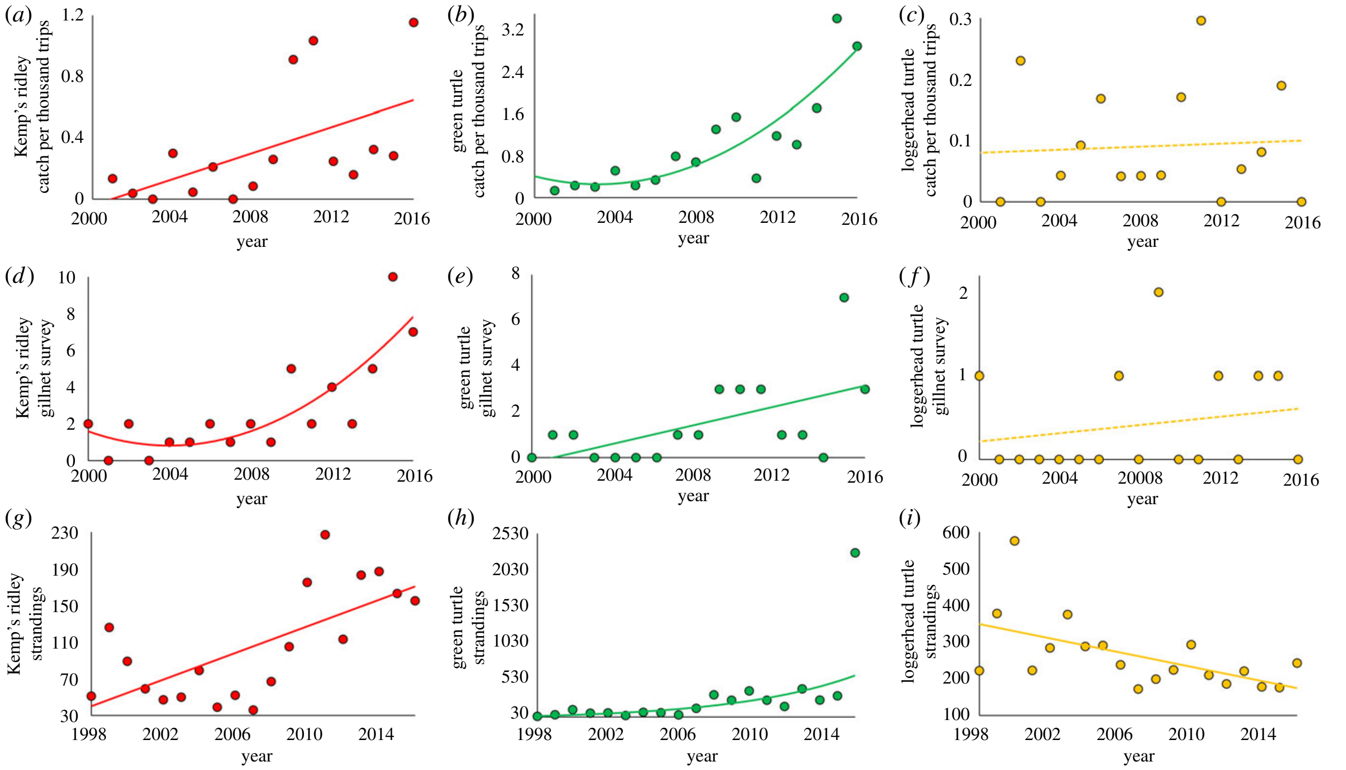

Figure 2. Trends in gillnet fishery bycatch and in-water indices of sea turtle abundance in North Carolina. Statistically significant trends are shown with solid lines, dashed lines denote no detectable trend through time. (*a*) Kemp's ridley bycatch rates (observed turtles in the large-mesh gillnet fishery divided by the annual number of large-mesh gillnet trips) have significantly increased (linear fit, $R^2 = 0.306$, $p = 0.026$, $n = 16$). (*b*) Green turtle bycatch rates have sharply risen (quadratic fit, $R^2 = 0.770$, $p = 0.000072$, $n = 16$). (*c*) Loggerhead turtle bycatch rates show no trend (linear fit, $R^2 = 0.004$, $p = 0.815$, $n = 16$). Within the fisheries-independent gillnet survey the number of turtles caught each year has increased for (*d*) Kemp's ridley (quadratic fit $R^2 = 0.71$, $p = 0.00017$, $n = 17$) and (*e*) green turtles (linear fit $R^2 = 0.33$, $p = 0.015$, $n = 17$), but not (*f*) loggerhead turtles (linear fit $R^2 = 0.04$, $p = 0.441$, $n = 17$). Statewide strandings have increased for (*g*) Kemp's ridley (linear fit $R^2 = 0.464$, $p = 0.00132$, $n = 19$) and (*h*) green turtles (quadratic fit $R^2 = 0.478$, $p = 0.00552$, $n = 19$), but have decreased for (*i*) loggerhead turtles (linear fit $R^2 = 0.316$, $p = 0.0122$, $n = 19$).

abundance (figure 3). Increases in Kemp's ridley and green turtle abundance along the eastern US coast, particularly offshore of North Carolina, are likely to be indicative of increased potential for coastal recruitment in these regions and an increase in the number of turtles susceptible to bycatch (figure 3). The modelled abundance of juvenile Kemp's ridley entering the waters around North Carolina was positively correlated to the number of turtles caught in the NCDMF fishery-independent gillnet survey and strandings, but not bycatch rates (table 1). For green turtles, modelled juvenile abundance was positively correlated to the number of turtles caught in the NCDMF fishery-independent gillnet survey, strandings and bycatch rates (table 1). Predicted juvenile abundance of loggerheads was unrelated to the number of turtles caught in the NCDMF gillnet survey, strandings or bycatch rates (table 1).

For fisheries, the implications of growing sea turtle populations are an increased rate of bycatch and increased regulations (electronic supplementary material, table S1). In the North Carolina gillnet fishery, this has resulted in annual fish catches declining sharply (large mesh: quadratic fit $R^2 = 0.848$, $p = 6.7 \times 10^{-9}$, $n = 23$; small mesh: linear fit $R^2 = 0.47$, $p = 0.0003$, $n = 23$) (figure 4*a*). In the large-mesh gillnet fishery, catches were around 1.36 million kg in the 1990s to early 2000s and decreased by 57% to <0.57 million kg in 2016. The small-mesh gillnet fisheries have seen catches drop 55%, from 1.72 million kg in 2001 to 0.77 million kg in 2016. The number of large-mesh trips in 2016 decreased 66% from their peak number in 1997, with the decline accelerating in recent years (quadratic fit $R^2 = 0.891$, $p = 2.27 \times 10^{-10}$, $n = 23$). Small-mesh gillnet trips have steadily declined over this period (linear fit $R^2 = 0.814$, $p = 4.07 \times 10^{-9}$, $n = 23$) and in 2016 had fallen 57% from their high in 1995 (figure 4*b*). Interestingly, catch per trip data for both small- and large-mesh fisheries exhibited no obvious trend (linear fit $R^2 < 0.148$, $p > 0.069$, $n = 23$, for both fisheries) (figure 4*c*). In the small-mesh fishery, total catch was positively related to the number of trips taken (linear fit $R^2 = 0.57$, $p = 2.9 \times 10^{-5}$, $n = 23$) and total catch in the large-mesh fishery was nearly entirely a function of the number of trips taken (linear fit $R^2 = 0.92$, $p = 5.4 \times 10^{-13}$, $n = 23$). Thus, reduction in fish caught through time does not appear to be attributable to regulations that have shortened net lengths and soak times; rather, closing areas to fishing after a certain number of turtle are caught has restricted the number of trips taken and resulted in reduced harvest.

4. Discussion

The steady increase in catch per trip of Kemp's ridley and the sharper increase of green turtles in the large-mesh gillnet fishery of North Carolina both closely track species-specific abundance indices (table 1), suggesting that bycatch of these species is largely dependent upon how many turtles are within the area. Furthermore, the increasing abundance of Kemp's ridley and green turtles is not unique to North Carolina but is a function of increases in reproductive output at distant nesting sites and the recruitment of juveniles to coastal foraging grounds throughout the region (table 1, figure 3). Interestingly, loggerhead bycatch rate did not increase, and the largest population of loggerhead turtles shows no evidence of growth during

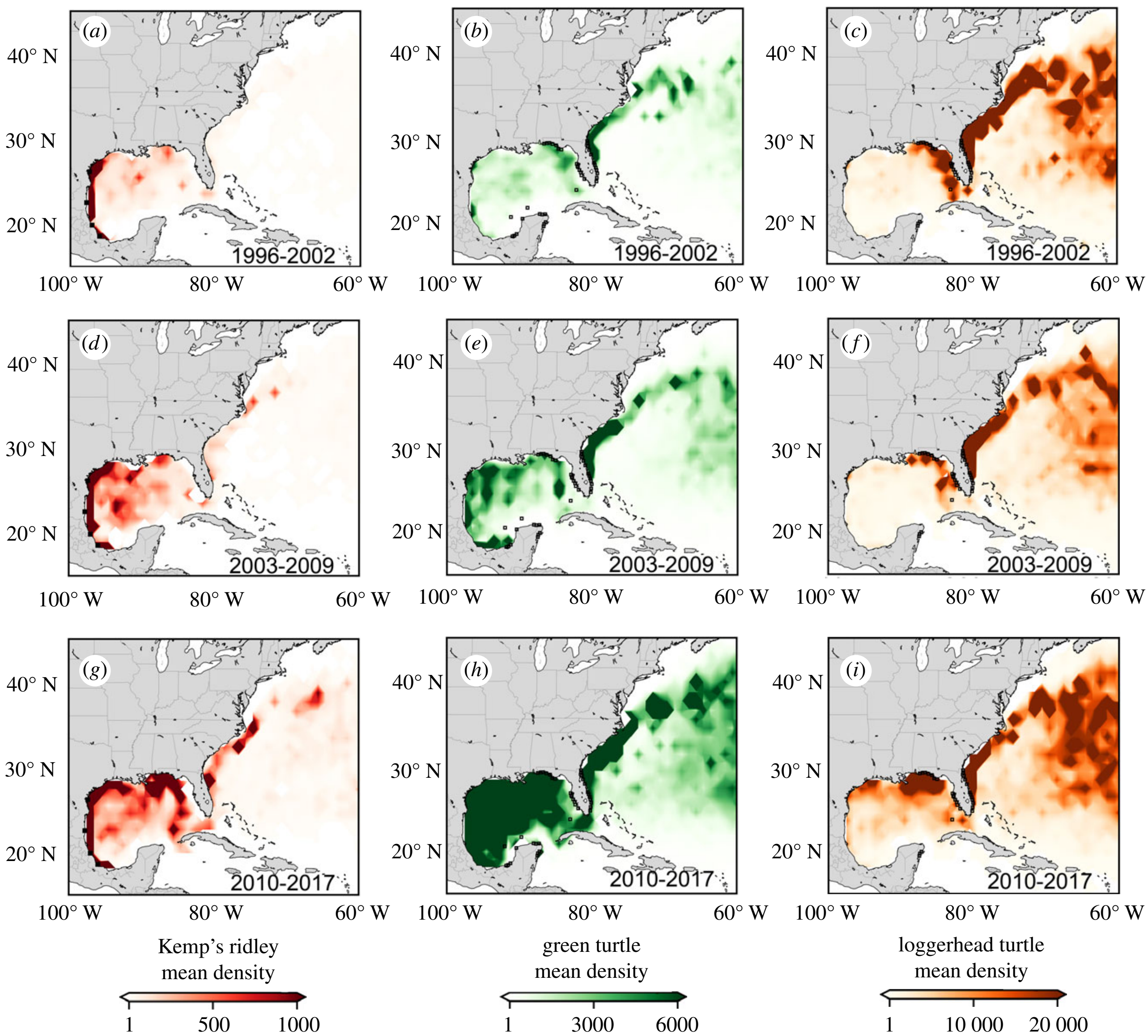

Figure 3. Predictions of oceanic-stage sea turtle abundance across the western North Atlantic for years 1996–2017. Maps show the mean number of predicted turtles within 1° latitude × 1° longitude grid cells across the North Atlantic for turtles aged 0.5 years, 1.5 years, 2.5 years and 3.5 years (owing to the shorter oceanic stage for Kemp's ridley the 3.5-year age class was not computed for that species) [16]. Mean annual abundance summed across age classes is shown for (*a–c*) 1996–2002, (*d–f*) 2003–2009 and (*g–i*) 2010–2017. Large increases in the abundance of Kemp's ridley (red shading) and green turtles (green shading) are predicted in the Gulf of Mexico and off the eastern US coast. Loggerhead turtle (orange shading) abundance appears more stable, though in recent years increased abundance is also predicted across the Gulf of Mexico.

Table 1. Results of statistical tests to relate changes in turtle bycatch rates to metrics of in-water turtle abundance. Values indicate Pearson's correlation coefficient (*r*), *p*-values shown in parentheses below. Significant relationships ($p < 0.05$) are highlighted in italics.

species	bycatch versus survey ($n = 16$)	bycatch versus strandings ($n = 16$)	bycatch versus model ($n = 16$)	survey versus model ($n = 17$)	strandings versus model ($n = 19$)
Kemp's ridley	*0.55 (0.026)*	*0.74 (0.001)*	0.38 (0.15)	*0.61 (0.009)*	*0.52 (0.022)*
green turtle	*0.63 (0.0086)*	*0.79 (0.0003)*	*0.88 (<0.00001)*	*0.49 (0.046)*	*0.79 (0.00006)*
loggerhead turtle	−0.16 (0.55)	−0.02 (0.94)	−0.02 (0.95)	0.22 (0.42)	0.045 (0.85)

this period [33]. Thus, for all three species of turtles bycatch rates appear to follow broad-scale population-level trends and regulations aimed at reducing turtle bycatch do not appear to have kept pace with Kemp's ridley or green turtle population growth.

State fisheries managers and commercial fishers now find themselves in a difficult position. The current strategy of stopping gillnet fishing to ensure only an acceptable number of 'takes' [18] will necessarily result in reduced fishing opportunity and increased regulatory burden because, ironically, conservation efforts have been successful and turtle populations have begun to rebound. It is noteworthy that simply capping bycatch would also be problematic if turtle populations were in decline, as fishing effort could increase as fewer turtles were available to catch and further drive the population toward extinction. Indeed, the management approach is only logical if turtle population abundance is stable.

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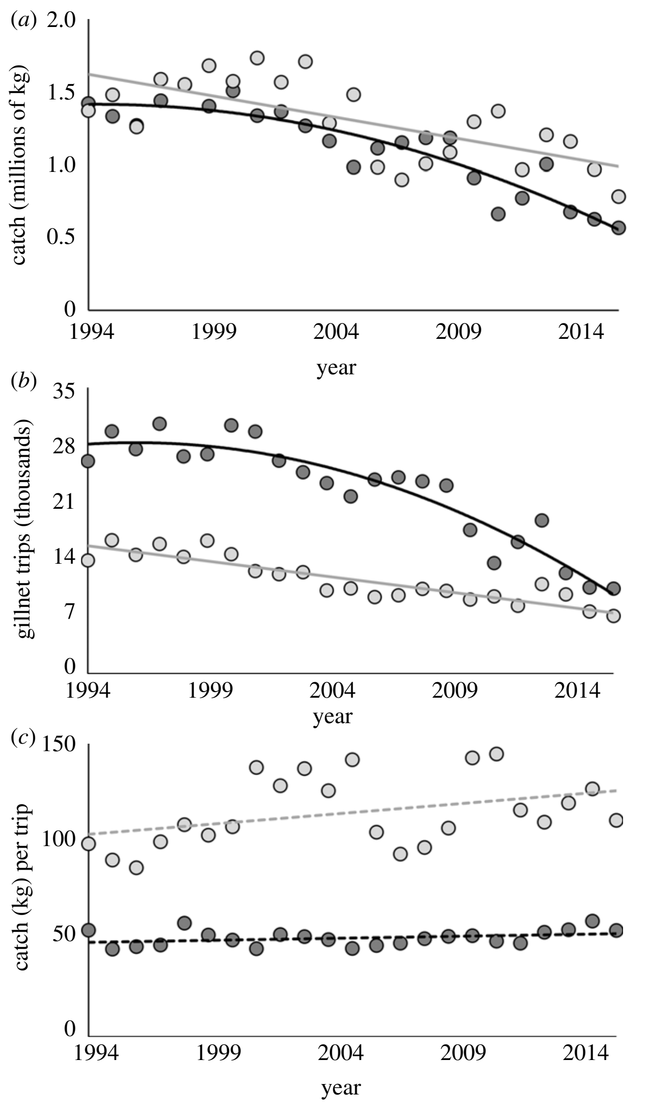

Figure 4. Trends in gillnet fishery effort, productivity. (*a*) Annual catch in the large-mesh (darker grey) and small-mesh (lighter grey symbols) gillnet fisheries. Catch in the large-mesh gillnet fishery has declined sharply (quadratic fit) and steadily declined in the small-mesh fishery (linear fit). (*b*) The number of large-mesh gillnet trips have decreased sharply (quadratic fit) and small-mesh gillnet trips have decreased steadily (linear fit). (*c*) Catch per trip in both fisheries shows no obvious trend (linear fits).

There are mechanisms for North Carolina fisheries managers to request changes in the amount of sea turtle bycatch allowed by the ITP from NMFS [18]. It may be tempting to suggest that fishing opportunity could be sustained if the state annually requests increases that track the per cent increase in reproductive output from nesting populations that use state waters as foraging habitat (figure 1). Formal consultations using §7 of the Endangered Species Act by NMFS with the US Fish and Wildlife Service involving affected fisheries have likewise been used to address sea turtle interactions with fisheries and have prevented extensive or episodic closures for specific fishing gear. However, while reproductive output may be higher now than in previous years, considerable uncertainty remains in the status of these populations [33,34]. Thus, to follow either option in a scientifically meaningful way will require regular population assessments on sea turtles that include estimating reproductive output and natural and anthropogenic mortality across life-stages and throughout their range. Such a comprehensive assessment seems outside of the scope and capacity of state fisheries managers. Given that sea turtles are federally protected in the USA, this responsibility should fall to NMFS. A stock-assessment framework is well suited to generate the needed information and is already commonly applied to commercially harvested marine fishes by NMFS scientists and managers.

NMFS should develop species-specific stock-assessment models for sea turtles that occur within US waters that are annually updated based on reproductive output of relevant populations and the cumulative impacts experienced in the USA and elsewhere. These stock assessments should determine the amount of mortality that can be sustained while maintaining a desirable amount of population growth [35–37]. Within this framework, a better understanding of the population-level implications of management actions would emerge and, in tandem, the ability to make regulations among different resource users proportional to each group's impact on sea turtles. Similarly, this framework would help determine what research to prioritize that could best reduce uncertainty in such a model [38,39].

Developing a framework to conduct annual stock assessments on sea turtles will require considerable interjurisdictional coordination to obtain data on anthropogenic activities that impact sea turtles and an investment in basic research on sea turtle ecology [16,37]. To obtain the needed information, the direct involvement of other government agencies, fisheries, industries, conservation groups, academia and the private sector should be encouraged. A key benefit of developing the stock assessments with an internationally diverse and participatory group is the mutual exchange of information, greater potential for stakeholders to accept regulations and removing the perception of *ad hoc* and arbitrary limits on turtle interactions that differ from one state or sector to another. For implementation, federal and state managers would partner with specific fisheries to determine how to achieve the target reduction in sea turtle bycatch [40].

In the interim, while stock assessments are organized, we recommend establishing working groups for specific fisheries to develop standards for 'compliance based' management [40]. This approach has been successfully implemented in other US fisheries to limit sea turtle bycatch, including shrimp trawls, the summer flounder trawl fishery, the pound net fishery in Chesapeake Bay, the pelagic longlIne fishery in the Exclusive Economic Zone (EEZ) of the Atlantic and Gulf of Mexico and the gillnet fishery in the EEZ in the Mid-Atlantic regions [41]. In the case of the North Carolina gillnet fishery, such an approach is promising for several reasons. First, the greatly lower amount of turtle bycatch in small-mesh compared with large-mesh gillnets (electronic supplementary material, tables S2 and S3) indicates that gillnets are not, necessarily, always a major threat to sea turtles. Likewise, bycatch in gillnets tends not to be fatal (>60% Kemp's ridley and green turtles released alive; >90% of loggerheads released alive) [18–22]. In other regions, hanging longline light-sticks from gillnets reduces sea turtle interactions by 40% to 60%, with minimal impact to target catch [42–44]. Though in open ocean habitat these lights probably attract turtles to hooks [45], illumination may help turtles see gillnets and avoid entanglement [43]. Thus, if given the opportunity, innovative approaches to reduce bycatch and limit its lethality by simple modifications to fishing practices and gear might be achieved with joint participation between fisheries managers and the fishing industry [46–50]. The possible solutions tested in such programmes across the southeastern US would contribute to more sustainable fisheries, the recovery of sea turtles, and provide a valuable indication of how to meet the management targets that are determined once sea turtle stock assessments have been conducted.

Data accessibility. All data used in this paper are provided in the electronic supplementary material.

Authors' contributions. All authors contributed to the study design, interpretation of results, scholarship and writing of this paper. N.F.P. performed the analyses and wrote the initial draft.

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