The Impact of Turtle Excluder Devices and Fisheries Closures on Loggerhead and Kemp's Ridley Strandings in the Western Gulf of Mexico

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Abstract: *The Sea Turtle Stranding and Salvage Network has been monitoring turtle strandings for more than 20 years in the United States. High numbers of strandings in the early to mid-1980s prompted regulations to require turtle excluder devices (TEDs) on shrimping vessels (trawlers). Following year-round TED implementation in 1991, however, stranding levels in the Gulf of Mexico increased. We evaluated the efficacy of TEDs and other management actions (e.g., fisheries closures) on loggerhead (*Caretta caretta*) and Kemp's ridley (*Lepidochelys kempii*) turtle populations by analyzing a long-term, stranding data set from the western Gulf of Mexico. Our analyses suggest that both sea turtle population growth and shrimping activity have contributed to the observed increase in strandings. Compliance with regulations requiring turtle excluder devices was a significant factor in accounting for annual stranding variability: low compliance was correlated with high levels of strandings. Our projections suggest that improved compliance with TED regulations will reduce strandings to levels that, in conjunction with other protective measures, should promote population recoveries for loggerhead and Kemp's ridley turtles. Local, seasonal fisheries closures, concurrent with TED enforcement, could reduce strandings to even lower levels. A seasonal closure adjacent to a recently established Kemp's ridley nesting beach may also reduce mortality of nesting adults and thus promote long-term population persistence by fostering the establishment of a robust secondary nesting site.*

El Impacto de Dispositivos Excluyentes de Tortugas y del Cierre de Pesquerías sobre Varamientos de Tortugas de Carey y de Kemp en el Occidente del Golfo de México

Resumen: *La Red de Varamiento y Salvamento de Tortugas Marinas ha monitoreado los varamientos de tortugas en los Estados Unidos por más de 20 años. En la primera mitad de la década de 1980 hubo un gran número de varamientos lo que impulsó regulaciones que exigen que los barcos camaroneros (de arrastre) cuenten con dispositivos excluyentes de tortugas (DET). Sin embargo, después de la implementación de DET en 1991, los niveles de varamiento incrementaron. Evaluamos la eficacia de DET y otras medidas de manejo (por ejemplo, el cierre de pesquerías) sobre las poblaciones de tortuga de carey (*Caretta caretta*) y de Kemp (*Lepidochelys kempii*) mediante el análisis de un conjunto de datos de varamientos de largo plazo en el occidente del Golfo de México. Nuestros análisis sugieren que tanto el crecimiento poblacional de las tortugas como la actividad camaronera han contribuido al incremento observado de varamientos. El cumplimiento con las exigencias de uso de DET fue un factor significativo en la variabilidad de los varamientos anuales: baja observancia de la regulación se correlacionó con un número alto de varamientos. Nuestras proyecciones sugieren que una mejor observancia de las regulaciones DET junto con otras medidas de protección reducirá los varamientos a niveles que promoverían la recuperación de las poblaciones de tortugas de carey y de Kemp. El cierre por temporadas de las pesquerías locales junto con el cumplimiento con la exigencia de*

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uso de DET, podría reducir los varamientos a niveles aún más bajos. El cierre por temporada de una zona adyacente a una playa donde recientemente anidan tortugas de Kemp también podría reducir la mortalidad de adultos anidantes y así promover la persistencia de la población a largo plazo al propiciar el establecimiento de un sitio robusto de anidación secundaria.

Introduction

The Sea Turtle Stranding and Salvage Network, established by the National Marine Fisheries Service (NMFS) in 1980, has been monitoring turtle strandings along the Gulf of Mexico for more than 20 years. Strandings, in which turtles are found immobile, injured, or dead, have been a source of concern for sea turtle scientists and conservationists and are considered an indicator of the effect of commercial fisheries, in particular shrimp trawling, on imperiled turtle populations (National Research Council 1990; Crowder et al. 1994, 1995; Caillouet et al. 1996; Shaver 1998). To address these concerns, in June 1987 the NMFS proposed regulations requiring shrimp trawlers larger than 25 feet to use approved turtle excluder devices (TEDs). A TED is a metal grid of bars fitted into the neck of a shrimp-trawl net. Shrimp slip through the bars and are caught in the bag end of the trawl net, and large animals, such as turtles and sharks, strike the grid bars and are ejected through an opening in the net. Regulations requiring turtle excluder devices were contested in at least 10 court cases, and year-round TED regulations were upheld in 1991 (NMFS 1992).

Two sea turtle species, in particular, experience high levels of trawl-related mortality in the Gulf of Mexico: the loggerhead (*Caretta caretta*) and Kemp's ridley (*Lepidochelys kempii*). The loggerhead turtle was listed as threatened in 1978 under the U.S. Endangered Species Act (ESA). The U.S. Atlantic loggerheads were initially thought to be one panmictic population, but more recent mitochondrial DNA evidence suggests that there are at least five distinct nesting subpopulations (Bowen et al. 1993; Encalada et al. 1998; Francisco Pearce & Bowen 2001). The number of loggerhead nests in the South Florida subpopulation, considered the primary source for loggerheads encountered by trawlers in the Gulf of Mexico (Francisco Pearce & Bowen 2001), is believed to be increasing 3–4% annually (Turtle Expert Working Group 2000). Kemp's ridley turtles were recognized as endangered throughout their range in 1970 as a result of a dramatic decline in the nesting population at Rancho Nuevo, Tamaulipas, Mexico (Marquez 1994). Rigorous conservation efforts by Mexican and U.S. agencies have reversed this trend, and in recent years there has been an 11.3% annual increase in Kemp's ridley nests (Turtle Expert Working Group 2000).

Turtle excluder devices have been the focus of much controversy and attention (Donnelly 1989) and are often cited as a "success story" of fisheries bycatch mitigation (e.g., Melvin et al. 1999). However, beyond a 2- to 3- year decline in strandings immediately after year-round TED regulations were passed in 1991, turtle strandings in the Gulf of Mexico and south Atlantic have increased. Several authors have proposed various hypotheses for the observed increase, including improper use or operational problems with legal TEDs; incidental capture from trawl nets not required to use TEDs (non-shrimp vessels); inadequate size of TED openings; and poor TED compliance (Caillouet et al. 1996; Shaver 1998; Epperly & Teas 1999). Although beneficial TED effects have been suggested in other regions in the southeastern United States (Royle & Crowder 1994; Crowder et al. 1995; Royle & Crowder 1998), a TED effect has not been demonstrated clearly with long-term data (i.e., >3 years post-TED regulation). We evaluated the effect of TEDs in the Gulf of Mexico, home to the largest U.S. shrimp fishery, for the two most affected species, the loggerhead and Kemp's ridley turtles.

We also evaluated the concurrent impact of a second management action, temporal and spatial fisheries closures. Specifically, we explored the effects of an existing fisheries closure—"Texas closure"—and a recently implemented seasonal closure off Padre Island in southern Texas. The Texas closure, instituted by the Texas Park and Wildlife Department (TPWD) in 1981, prohibits shrimping at designated distances off Texas shores. In 1990 the Texas closure was extended to include waters from Gulf of Mexico shores to 200 nm. The closure is set by statute for 15 May–15 July but may be changed at the discretion of the TPWD Commission based on yearly biological assessment of shrimp stocks. The purpose of the Texas closure is to delay the harvest of small shrimp emigrating from the bays to promote their growth, thus increasing the value of the catch and reducing discard or waste of smaller shrimp. Although the goal of the closure is to enhance shrimp harvests, it may also reduce turtle-trawler interactions and lead to a temporary reduction in turtle strandings.

A second closure has recently been implemented along the south coast of Texas, off Padre Island. Like the Texas closure, its intent is to promote shrimp growth and enhance harvests. However, the Padre Island closure may also protect nesting Kemp's ridley turtles. For the last two decades, scientists, government agencies, and conservationists have collaborated to establish a second nesting colony of Kemp's ridley turtles on Padre Island, which is north of Rancho Nuevo, the primary nesting site for this species (Shaver 1998; Shaver & Caillouet 1998). Since 1995, the number of nests found on Padre Island and surrounding beaches has increased from 4 to 38, although a portion of this observed increase may reflect improved detection efforts (D.J.S., personal observation). Over the same time period, there has also been an increase in the number of adult Kemp's ridley turtles stranded in the area during December–July, most likely as a result of increased adult activity associated with nesting. In 1999, 500 sea turtle biologists unanimously passed a resolution recommending that a no-take trawl area be established along Padre Island, Texas (Plotkin 1999). In response to these concerns and to enhance shrimp harvests, the TPWD proposed regulations to prohibit nearshore shrimp fishing within 5 miles of the southern Texas coast from 1 December through 15 July each year. This regulation went into effect in December 2000.

We evaluated the impact of these management actions—TEDs, the Texas closure, and the Padre Island closure—on turtle strandings. Sea turtle bycatch from trawl fisheries poses serious threats to populations in the United States and worldwide. Strandings are believed to be an indicator of trawler bycatch (National Research Council 1990; Crowder & Murawski 1998). Therefore, assessing the effect of TEDs and fisheries closures on turtle strandings is necessary to identify management strategies that effectively reduce turtle strandings and, ultimately, overall turtle bycatch.

Methods

The Sea Turtle Stranding and Salvage Network data set contains records of turtle strandings on Texas shores from 1980 to the present. For our analyses, we excluded (1) incidental captures of turtles by commercial or recreational fishing vessels, or turtles recovered from power-plant intakes; (2) strandings of captive-reared, or headstarted, turtles; and (3) strandings of post-hatchlings of <10 cm carapace length. The excluded data removed stranding records for captured, not stranded, turtles (case 1; $n = 47$), for captive-reared turtles that may not have been representative of the population (case 2; $n = 297$, but see Caillouet et al. 1995), and for size classes that were likely to be in water too shallow to interact with a trawler (case 3; $n = 127$). Although the stranding surveys on Texas beaches were initiated in 1980, we used data from 1986–2000 to minimize the effect of increased survey effort (beach survey effort for this area was standardized in 1986). This data set included 1795 and 1279 strandings of loggerhead and Kemp's ridley turtles, respectively.

We analyzed strandings separately for loggerheads and Kemp's ridleys. Because one goal of this analysis was to compare current trends to those previously reported (Royle & Crowder 1994; Crowder et al. 1995; Caillouet et al. 1996; TEWG 1998, 2000), we used statistical methods similar to those of previous analyses to facilitate comparisons. Analyses included identifying temporal and spatial trends in strandings, analyzing evidence of population changes, quantifying the effect of shrimping activity and closures on strandings, and the potential impact of TEDs. Strandings, as count data, were assumed to follow a Poisson distribution (Royle 2000). Stranding counts were transformed (log[strand + 1]) when necessary to conform to model assumptions of normality. We accounted for shrimping activity as effort (the number of 12-hour periods shrimped; Fisheries Statistics & Economics Division of NMFS), catch (pounds of shrimp landed; Fisheries Statistics & Economics Division of NMFS), and the number of TED violations (log[violations +1]) cited by the U.S. Coast Guard as an indicator of the level of TED compliance (National Oceanic and Atmospheric Administration, Southeast Enforcement Division). We also apportioned shrimping effort to broad categories of water depth and analyzed the relationship between shrimping effort at depth and the annual stranding patterns. For this analysis, we included shrimping effort at three depth regions: inshore (bays and sounds), nearshore (0–10 fm), and offshore (>10 fm).

We looked for evidence of population growth independent of nest counts by identifying changes in the size distribution of all stranded turtles. For this analysis, we divided loggerheads into three size classes based on straight carapace length (SCL): small, benthic, immature 40–69.9 cm; large, benthic, immature ≥70–91.9 cm; and adult ≥92 cm. Kemp's ridley turtles were divided into four SCL classes: posthatchling, >10–19.9 cm; small, benthic, immature, ≥20–50 cm; large, benthic, immature, >50–60 cm; and adult >60 cm. These size categories were based on size classes established by the Turtle Expert Working Group, of the NMFS (TEWG 2000).

In addition to the shrimping variables, we included turtle population size, number of nests, and number of nesting females as variables in some analyses. Population sizes and nest counts for both species were taken from estimates in NMFS reports (TEWG 1998, 2000). To estimate the number of nesting females, we divided the total nests counted by the estimated number of nests deposited per female annually, 4.1 and 2.5 for loggerhead and Kemp's ridley turtles, respectively (TEWG 1998, 2000).

To identify variables that were significantly related to strandings and to apportion observed variability in strandings to these variables, we used parametric and nonparametric analysis of variance (ANOVA) and regression general linear models (GLM). Best-subset regressions, based on adjusted r^2 values, identified variables that accounted for the highest proportion of stranding variation observed while also considering redundancy among predictor variables. After evaluation of the studentized residuals (Sokal & Rohlf 1995), models with population size as a predictor variable were fit to a polynomial (quadratic) regression.

We used the stranding data set to estimate the relative probability that a nesting female would strand in a given year, where the probability is defined as the product of the proportion of nesting females in the total population and the probability that an individual turtle will strand. For this calculation, we assume that all turtles have an equal likelihood of stranding, ignoring differences in vulnerability due to size or sex. These probabilities are based on extrapolated population estimates, so they cannot be used either as an accurate estimate of absolute threat for nesting females in either population or for comparisons between the populations.

Finally, we used our regression models to project future stranding levels at three levels of TED compliance, assuming a continued 4% population annual increase for the South Florida subpopulation of loggerheads and 11% increase for Kemp's ridley (TEWG 2000) and constant fishing effort. Compliance with regulations requiring turtle excluder devices was represented as complete compliance (zero violations), 50% improved compliance (50% reduction in violations from 2000 level), and current compliance (number of violations from 2000). For these projections, we assumed constant fishing effort and rates of population growth. All statistical analyses were performed with Statistica (Statsoft 1984).

Results

Annual Strandings

The number of annual strandings increased dramatically in 1994 (Fig. 1). The difference between annual strandings before and after the 1994 peak was significant (Kruskal-Wallis ANOVA, $H_{1,15} = 9.05, p = 0.002$), even when 1994 was excluded from the analysis ($H_{1,14} = 8.06, p = 0.005$). Average annual strandings of loggerhead and Kemp's ridley turtles increased by 51% and 22%, respectively, between 1986–1993 and 1994–2000, calculated with the harmonic means for these years.

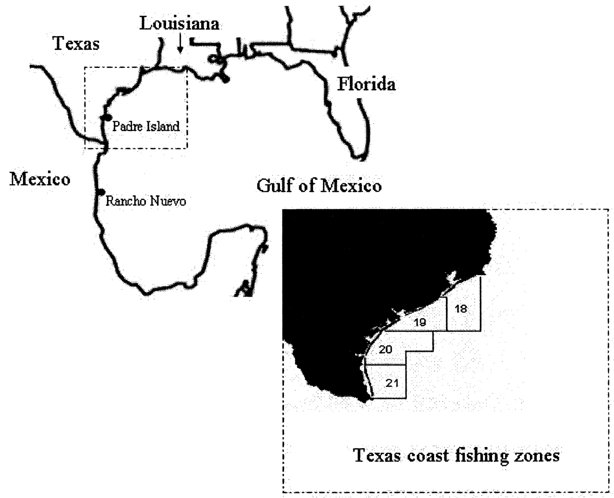


Figure 2. Location of Rancho Nuevo, Padre Island, and statistical fishing zones in the Texas Gulf of Mexico coastal waters.

Stranding Hotspots

Coastal waters of the Gulf of Mexico have been divided into 21 statistical subareas, or zones (Patella 1975) (Fig. 2). We detected significant differences in the number of loggerheads stranded among the Texas zones, with the highest number of strandings in zones 18 and 20 (Kruskal-Wallis ANOVA, $H_{3,56} = 13.96, p \leq 0.003$). The highest loggerhead lethal strandings occurred in zone 20 ($H_{3,56} = 14.06, p \leq 0.003$). For Kemp's ridleys, strandings and lethal strandings were highest in zone 18 ($H_{3,56} = 26.05, p \leq 0.001$), next highest in zone 20 ($H_{1,28} = 7.67, p \leq 0.010$), and evenly distributed at lower levels in zones 19 and 21. ($H_{1,28} = 0.968, p \geq 0.660$).

From 1986 to 2000, peak monthly strandings occurred consistently in March–May for loggerheads and Kemp's ridleys (Fig. 3). In 1994–2000, data for loggerheads indicated a second stranding pulse in July that was not found in prior years. The dramatic decline in strandings in June for both species corresponds to the 4- to 6-week Texas closure.

Evidence of Population Growth

Nest counts suggest that the South Florida loggerhead subpopulation, considered the primary source for tur-

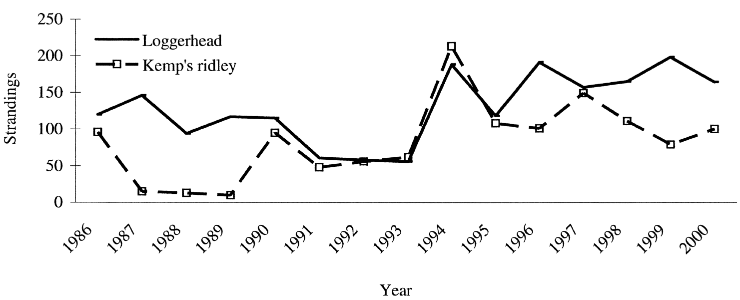


Figure 1. Annual strandings of loggerhead and Kemp's ridley turtles recorded by the Sea Turtle Stranding and Salvage Network on Texas shores of the Gulf of Mexico, 1986–2000.

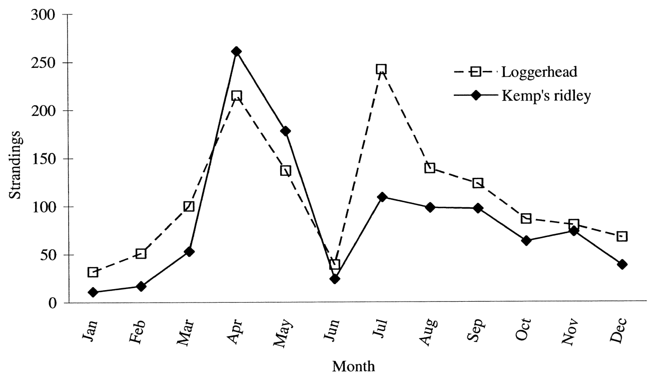


Figure 3. Average monthly strandings of loggerhead and Kemp's ridley turtles (1986–2000) recorded by the Sea Turtle Stranding and Salvage Network on Texas shores.

tles encountered by trawlers in the Gulf of Mexico (Francisco Pearce & Bowen 2001), is increasing; nest counts have risen 3–4% annually in recent years. The Kemp's ridley population also showed signs of growth; nest counts increased 11% per year (TEWG 2000; NMFS 2001).

We also looked for changes in the size distribution of stranded turtles. Between 1986 and 1990, the pre-TED period, and 1995 and 1999, a recent post-TED period of equal duration, the number of strandings of small and large benthic immature loggerhead turtles increased significantly (Kruskal-Wallis ANOVA, $H_{1,120} > 7.3$, $p \leq 0.01$). The proportion of stranded turtles from these size classes also increased, but not significantly ($p > 0.36$). For the same time period, the number and proportion of the smallest size class of Kemp's ridley increased ($H_{1,120} = 7.98$, $p = 0.001$; $H_{1,10} = 5.92$, $p = 0.02$). There were no significant changes in the number or proportion of small benthic immature Kemp's ridley turtles stranded ($p \geq 0.13$; $p = 0.60$), but the number of strandings of large benthic immature Kemp's ridley turtles increased significantly ($H_{1,120} = 12$, $p < 0.001$).

Shrimping Activity and Strandings

We looked at the relationship of shrimping activity—as measured by shrimping effort, catch, and TED violations (an indicator of TED compliance)—to strandings at two temporal scales. Data for all three variables of shrimping activity were available for 1990–2000.

MONTHLY SCALE

A GLM regression analysis on monthly stranding data revealed that TED compliance had a significant univariate effect for both species (GLM, $p < 0.03$, $r^2 \leq 0.12$), and effort had a significant effect for Kemp's ridleys (GLM, $F_{1,116} = 8.3$, $p = 0.003$, $r^2 = 0.10$). Shrimp catch, measured in pounds landed, had no significant effect for either species. Including month as a random effect, with TED compliance and shrimping effort in a mixed GLM model (random and fixed effects) increased the stranding variability accounted for by the model ($r^2 = 0.39$), but only the month effect was significant ($F_{1,105} = 5.7$, $p < 0.001$).

ANNUAL SCALE

Although the above analysis suggests that some shrimping activities have a statistically significant effect on strandings, these variables accounted for a relatively small proportion of the observed variation in monthly turtle strandings (adjusted r^2 approximately 0.12–0.40). Using annual stranding counts, we included population size and the three measures of shrimping activity—shrimping effort, catch, and TED violations—as predictor variables in a GLM polynomial regression. For loggerheads the regression model identified increasing population size and TED violations as the variables that account for a significant proportion of the variation in strandings (adjusted $r^2 = 0.65$, $p < 0.02$). Both population size (β coefficient = 0.30) and TED violations (β coefficient = 0.48) considered alone did not account for an equal proportion of stranding variation as found for the the variables together. These two variables accounted for 70% of variation observed in Kemp's ridley strandings (adjusted $r^2 = 0.70$; $p < 0.001$). However, Kemp's ridley strandings were more sensitive to population increases (β coefficient = 0.60) than to TED violations (β coefficient = 0.35). Shrimp catch had no significant effect for either species.

Among annual strandings and shrimping effort across depth regions, Kemp's ridley strandings between 1994 and 2000 were significantly related to inshore effort (β coefficient = 0.80, $p = 0.001$). For loggerheads, inshore and nearshore effort explained the greatest proportion of stranding variation (β coefficient = 0.64 and 0.50, $p = 0.03$). Across the entire time series, however, shrimping effort by depth category was not a significant factor.

IMPACT OF FISHERIES CLOSURES

To identify the association between shrimping and turtle strandings, we looked at stranding levels following the temporary trawling injunction introduced by the Texas closure. Biweekly strandings declined significantly in response to the Texas closure for both species (ANOVA, $F_{1,238} \geq 6.36$, $p < 0.01$). Although this closure was not implemented to reduce turtle-trawler interactions, it temporarily reduced strandings for the 6–8 weeks in which it was implemented. We projected a similar trend from the Padre Island closure. Using current levels of strandings in zone 21 as a baseline, we assumed that month and shrimping activity account for 39% of the variability in strandings (see Shrimping Activity and Strandings: Monthly Scale). With

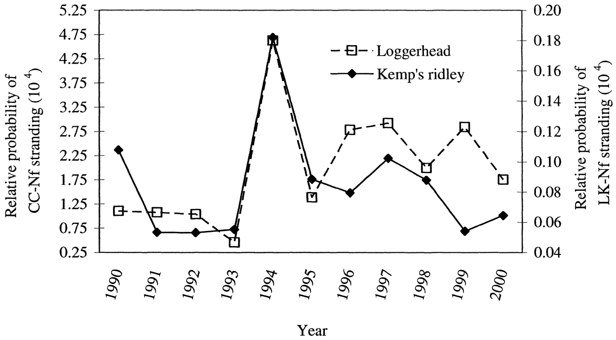
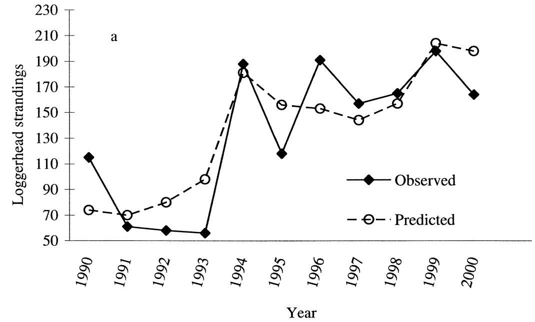


Figure 4. The relative stranding probability of a loggerhead (CC) and Kemp's ridley (LK) nesting female (Nf), calculated as the product of the proportion of nesting females in the population and the likelihood that an individual turtle will strand. Values represent relative risk across years within a population and cannot be used as an absolute risk estimate or as a comparison between populations.



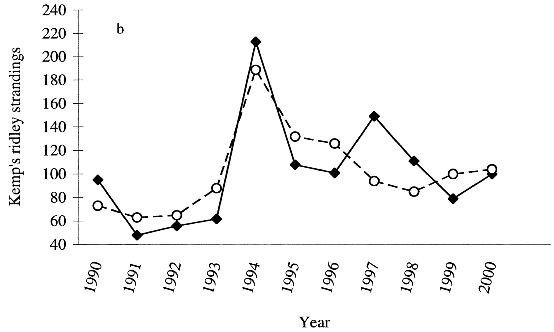


Figure 5. Observed and predicted turtle strandings (1990–2000) from a regression model, with TED compliance and population size as predictor variables for (a) loggerhead turtles and (b) Kemp's ridley turtles.

the seasonal Padre Island closure we would then expect, on average, a 39% reduction in the current strandings of adult Kemp's ridley turtles during December–July (Fig. 4). During the first closed season (December 2000–July 2001) there were 6 stranded Kemp's ridley turtles inside the closed area, down from 13 in the previous year (a 46% reduction). In the second year, there were 8 Kemp ridley strandings (a 38% reduction), also supporting our general stranding estimation (D.J.S., personal observation).

TED Effects

REDUCTIONS IN TURTLE MORTALITY

With the data set we used for this analysis, mortality could only be assessed as the proportion of stranded turtles found dead on the beach. We refer to these strandings as lethal strandings. The proportion of annual lethal strandings has declined since 1986, but not significantly, with declines ranging from 2% to 8% for loggerheads and Kemp's ridleys across the time period. Power analysis (two sample t test) suggests that to detect a 20% reduction in annual lethal strandings with 80% power, the sample size, in this case the number of years, would need to be two and five times longer than the existing time series for loggerheads and Kemp's ridleys, respectively. At a monthly time scale, there was a significant 7% reduction in lethal strandings for loggerheads between two time periods—1986 to 1990, a period before TED regulations, and 1995 to 1999, a post-TED regulation period of equal duration (Kolmogorov-Smirnov, $p = 0.025$). For loggerheads, there was sufficient power (0.80) to detect this difference. However, there was inadequate power to detect a similar change in mortality for Kemp's ridleys ($\beta = 0.20$).

PROPORTION OF NESTING FEMALES LIKELY TO STRAND

We calculated the relative change in the probability that a nesting female loggerhead or Kemp's ridley would strand each year. Whereas the probability of stranding for Kemp's ridley turtles declined, excluding the peak in 1994, the probability of a loggerhead nesting female stranding did not. (Fig. 5). Because the probability estimate takes into account total population size, the likelihood values indicate that stranding vulnerability fluctuated in response to other variables.

STRANDING PROJECTIONS ACROSS LEVELS OF TED COMPLIANCE

As indicated by the relatively high adjusted r^2 values in the regression models with population size and TED compliance, these models provide a good fit for the annual stranding data and capture the long-term trends (see "Shrimping Activity and Strandings: Annual Scale"). From 1990 to 2000, the models predicted on average ± 30 of the observed loggerhead strandings (Fig. 6a). Similarly, the model predicted Kemp's ridley strandings that were on average ± 25 of observed strandings (Fig. 6b).

Using these regression equations, we projected future

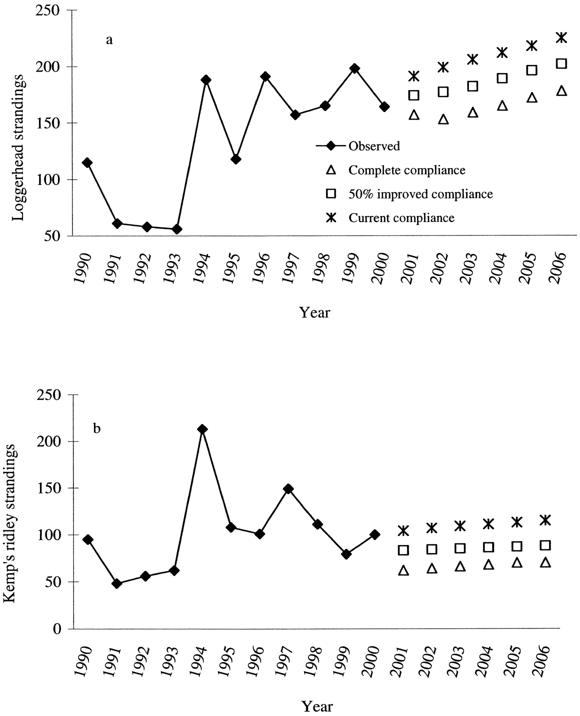


Figure 6. Projected annual strandings at three levels of TED compliance for (a) loggerhead turtles and (b) Kemp's ridley turtles. Compliance is represented by the number of TED violations: complete compliance (no violations), 50% improved compliance (half the violations from year 2000), and current compliance (level of violations from year 2000).

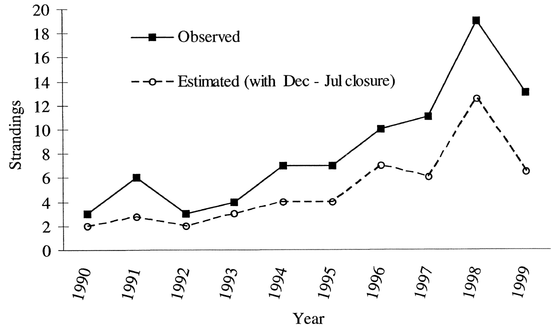


Figure 7. Observed and estimated annual strandings of Kemp's ridley adult turtles in zone 21 as a result of the December–July Padre Island closure. We assumed a 39% reduction in strandings for months during the closure.

strandings at three levels of TED compliance. Model projections suggest that at the current rate of population growth across the three levels of TED compliance, loggerhead strandings could increase as much as 37% over the next 5 years (Fig. 7a). Kemp's ridley strandings were also projected to increase, but only by 5% (Fig. 7b). For both species, high TED compliance would lead to fewer strandings. These projections are based on the assumptions of constant fishing effort and constant rates of population growth.

Discussion

Stranding levels of loggerhead and Kemp's ridley turtles have increased dramatically since 1994. This appears to be due, in part, to population growth in both species. Nest surveys of loggerheads in the South Florida subpopulation and Kemp's ridleys in Mexico and Padre Island suggest a growing number of nesting females since the early 1990s. Nest counts are only an index for population growth because nesting females account for a small percentage of the total population. However, the significant increase in strandings of young turtles provides some evidence of population growth, independent of nest counts. Given the increase in strandings and the putative population growth, it seems reasonable to ask whether (1) variation in shrimping activities accounts for observed variation in strandings and (2) whether TEDs, since their implementation in 1991, have reduced turtle strandings and/or mortality from trawl encounters.

Although shrimping activity measures (effort, catch, TED compliance) were poor predictors of turtle strandings at some temporal and spatial scales, there was sufficient evidence to support the hypothesis that shrimping activity does significantly affect stranding levels. The reduction of strandings during the Texas closure, which acts as an unintentional experimental treatment, points unequivocally to the positive relationship between trawling activity and strandings. Given the short duration of the closure and the continued shrimping in Louisiana waters, the Texas closure alone is insufficient to provide long-term protection from trawlers for these species. However, the significant drop in strandings during the closure does afford a short-term benefit to turtles in the western Gulf and provides clear evidence of the link between trawling and turtle strandings, a finding supported by other studies (National Research Council 1990; Crowder et al. 1995; Caillouet et al. 1996; Shaver 1998).

The Padre Island closure is also likely to reduce mortality of adult Kemp's ridley turtles, potentially as much as 39%. This figure may be optimistic because it (1) does not incorporate the potential effects of reallocated effort by shrimpers and (2) only accounts for nearshore interactions. Although the Padre Island closure prohibits shrimping in the nearshore area where nesting Kemp's ridleys are thought to aggregate, it is possible that adults leaving the nesting beach would move offshore and thus still be vulnerable to trawl nets. Our model may also underestimate the stranding reduction because the Padre

Island closure extends into a portion of zone 20. In the first and second year of the Padre Island closure, strandings in the closure area were down 46% and 38%, respectively, from previous years (D.J.S., personal observation).

The 1994 stranding pulse has also been linked indirectly to problems with TEDs or TED regulations: improper use or operational problems with legal TEDs, bycatch from trawl nets not required to use TEDs, inadequate size of TED openings, and poor TED compliance (Caillouet et al. 1996; Shaver 1998; Epperly & Teas 1999). We propose another putative cause that directly implicates shrimping activity: a spatial shift in shrimping effort. The stranding pulse observed during and after 1994 may be explained, in part, by an increase in inshore shrimping effort (i.e., in bays and sounds).

Our results suggest that TED regulations may have led to a modest decline in the proportion of stranded turtles that die (lethal strandings). Given the limitations of sample size and power, it seems notable that significant changes in lethal strandings could be detected. We found a significant 7% reduction in lethal, monthly strandings for loggerheads. However, an analysis of lethal strandings does not directly estimate how effective TEDs have been in reducing turtle mortality from trawl encounters. By nature of the measurement, lethal strandings are indicative of the number of turtles that were potentially harmed by trawl encounters, not of turtles that escaped from trawl nets unharmed. Previous estimations of mortality reductions as a result of the use of TEDs (Crowder et al. 1994) refer to the ratio of stranded turtles to healthy turtles that have encountered trawl nets in Gulf of Mexico waters. The stranding database provides only half the information needed to determine that ratio and thus limits our ability to estimate how effective TEDs have been in reducing turtle mortality from trawl encounters. To account for this lack of information, we calculated a relative probability that a nesting female of each species would strand. These values cannot be used as an estimation of absolute risk or as a comparison between populations. In relative changes over time, however, the probabilities are instructive within each population.

Evaluating the relative probability of stranding likelihood for these populations, we found that TEDs may have been more effective in reducing stranding likelihoods for Kemp's ridley turtles than for loggerheads, despite annual fluctuations. One potential cause for this may be the exit dimensions of TEDs. The National Marine Fisheries Service is considering a proposal to enlarge the opening by which a turtle escapes a trawl net (from 60–80 cm to 180 cm), following research on the inability of the largest size classes of loggerheads (and leatherbacks, *Dermochelys coriacea*) to escape from TED openings based on the original design (Epperly & Teas 1999).

Our analyses suggest that TED efficacy over time has more to do with the level of TED compliance than the onset of year-round TED regulations. Although stranding levels have increased for both species since 1994, TED compliance is a significant factor in annual stranding variability in our analyses. Thus, TED efficacy should be evaluated by how well TED technology is implemented, rather than by how many years TED regulations have been in place. Our projections of future strandings in response to changes in TED compliance suggest that high TED compliance is beneficial and necessary to minimize stranding levels.

The data we used have several limitations. Most are proxies, at best, of the measurement of interest. Most notably, strandings are only an index of total turtle mortality from shrimping activity. These data cannot directly identify the number of turtles that have encountered trawl nets and escaped unharmed through TEDs. The data also do not reflect the proportion of turtles that die as a result of trawling interactions, but do not strand. Even with effective TEDs, trawling may lead to cumulative sublethal effects if sea turtles are captured multiple times (Stabenau et al. 1991; Caillouet et al. 1996; Shaver 1998). In addition, stranding data are likely to be influenced by temporal and spatial variation in turtle abundance and water currents. Nest counts are also only an index for population growth, because nesting females generally account for $<1\%$ of the total populations (Crowder et al. 1994). Nest surveys may reflect varying survey effort (although both stranding and nest count surveys are standardized), and TED violations may reflect the varying effort of the enforcement agency.

Our results indicate that both increased population levels and shrimping activity account for the increase in strandings observed in recent years. Fisheries closures were effective in reducing strandings, whether intended to protect turtles or not. In particular, the seasonal Padre Island closure is likely to protect a second Kemp's ridley nesting beach to safeguard the population should a catastrophe affect the primary nesting beach in Rancho Nuevo, Mexico.

Our analyses suggest that TEDs can be effective in reducing strandings, depending on the level of TED compliance. Because stranding data cannot reflect the proportion of turtles that escape unharmed from TEDs, we were unable with this analysis to directly measure the reduction in mortality resulting from TED regulations and to verify mortality-reduction estimates from previous research (e.g., Crowder et al. 1994; Crowder et al. 1995; TEWG 2000). The TED regulations have not eliminated the possibility that a turtle will strand as a result of trawl encounters. Lack of compliance with existing TED regulations appears to contribute to stranding levels and mortality from shrimping. Cumulative sublethal effects from repeated TED encounters and inadequate TED openings may also lead to strandings and mortality. Because population growth, shrimping, other human activities, and underlying natural mortality all influence the number of strandings observed, complete TED compliance will not totally eliminate strandings for either of these sensitive turtle species. Our model projections suggest, however, that increased TED compliance, coupled with necessary closures, will reduce strandings to levels that enhance the probability of robust population recoveries.

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