Research Article

Mitigating By-Catch of Diamondback Terrapins in Crab Pots

KRISTEN M. HART,[1] *U.S. Geological Survey, Southeast Ecological Science Center, 3205 College Avenue, Davie, FL 33314, USA*

LARRY B. CROWDER, *Duke Center for Marine Conservation, Nicholas School of the Environment Marine Laboratory, 135 Duke Marine Lab Road, Beaufort, NC 28516, USA*

ABSTRACT Chronic by-catch of diamondback terrapins (*Malaclemys terrapin*) in blue crab (*Callinectes sapidus*) pots is a concern for terrapin conservation along the United States Atlantic and Gulf of Mexico coasts. Despite the availability of by-catch reduction devices (BRDs) for crab pots, adoption of BRDs has not been mandated and by-catch of terrapins continues. We conducted experimental fishing studies in North Carolina's year-round blue crab fishery from 2000 to 2004 to evaluate the ability of various BRDs to reduce terrapin by-catch without a concomitant reduction in the catch of blue crabs. In 4,822 crab pot days fished, we recorded only 21 terrapin captures. Estimated capture rates were 0.003 terrapins/pot per day in hard crab experimental fishing and 0.008 terrapins/pot per day in peeler experimental fishing. All terrapin captures occurred from April to mid-May within 321.4 m of the shoreline. Longer soak times produced more dead terrapins, with 4 live and 4 dead during hard crab experimental fishing and 11 live and 2 dead during peeler experimental fishing. The 4.0-cm BRDs in fall and 4.5-cm and 5.0-cm BRDs in spring reduced the catch of legal-sized male hard crabs by 26.6%, 21.2%, and 5.7%, respectively. Only the 5.0-cm BRDs did not significantly affect the catch of legal-sized hard male crabs. However, BRDs had no measurable effect on catch of target crabs in the peeler crab fishery. Our results identify 3 complementary and economically feasible tools for blue crab fishery managers to exclude terrapins from commercially fished crab pots in North Carolina: 1) gear modifications (e.g., BRDs); 2) distance-to-shore restrictions; and 3) time-of-year regulations. These measures combined could provide a reduction in terrapin by-catch of up to 95% without a significant reduction in target crab catch.

KEY WORDS blue crab, by-catch, fisheries, North Carolina, terrapin, turtle.

Incidental catch of non-target species (by-catch) in fisheries is a serious conservation problem (Alverson and Hughes 1996, Hall 1996, Lewison et al. 2004). Researchers and managers have tried to reduce by-catch by modifying fishing gear (e.g., turtle excluder devices [TEDs] in trawls), changing fishing practices (e.g., reducing tow times or restricting the timing of fishing; Melvin et al. 1999), or reducing overlap between fisheries and the habitat of protected species by establishing no-fishing zones (Henwood and Stuntz 1987, Dayton et al. 1995, Ruckleshaus and Hayes 1998). A particular by-catch issue along the Atlantic and Gulf of Mexico coastlines involves diamondback terrapins (*Malaclemys terrapin*), estuarine turtles that occupy habitats heavily fished for Atlantic blue crabs (*Callinectes sapidus*; Davis 1942, Bishop 1983, Seigel and Gibbons 1995, Roosenburg et al. 1997). Crab pots frequently capture and drown terrapins, which are currently a species of special concern in many regional states and is listed as threatened in Massachusetts and endangered in Rhode Island. Terrapins have also been Category 2 candidates for listing under the Endangered Species Act (Seigel and Gibbons 1995), but quantitative data on their risk of extinction remains insufficient to support federal listing.

Received: 2 November 2009; Accepted: 7 May 2010

[1]*E-mail: kristen_hart@usgs.gov*

Terrapin by-catch in crab pots constitutes a major threat for the species (Seigel and Gibbons 1995, Gibbons et al. 2001, Butler et al. 2006, Dorcas et al. 2007). The mortality rate for diamondback terrapins in crab pots ranges from 10% to 78%, depending on time of year and body size of individuals (Bishop 1983, Roosenburg et al. 1997, Roosenburg 2004). Crab pots set near resident terrapin populations may directly threaten those populations. Considerable mortality may also stem from terrapin capture in abandoned or "ghost" pots, which are common in this fishery. Grosse et al. (2009) recently reported 94 dead terrapins in one ghost pot in Georgia, and earlier Bishop (1983) reported 29 terrapin carcasses in 1 ghost pot in South Carolina, highlighting the potential negative impacts of such fishing gear on by-caught species. For terrapins, juvenile females and juvenile and adult males are at greatest risk because they can easily fit through crab pot funnel openings (Roosenburg et al. 1997). Adult male terrapins are especially vulnerable because none are too large to enter crab pots and they may be attracted to traps that contain females. Other size classes of terrapins are either too large (e.g., adult females with carapace height dimensions greater than that of a crab pot opening) or too small (e.g., hatchlings that will fit through crab pot mesh and cull rings) to be affected. Terrapins, like other turtles, are long-lived with delayed sexual maturity (Ernst et al. 1994). These life history characteristics make population growth highly sensitive to small changes in adult mortality as may be caused by by-catch in fishing gear (Heppell 1998, Hart 2005).

Diamondback terrapins can, however, be excluded from crab pots. Wood (R. C. Wood, Wetlands Institute, unpublished data) developed a simple, inexpensive by-catch reduction device (BRD) that consists of a rectangular wire that can be affixed to each funnel entrance of a crab pot. The device works to exclude terrapins with straight carapace heights (SCHs) greater than the height dimension of the BRD. Ideal-sized BRDs would exclude terrapins of high reproductive value (i.e., mature females) and juveniles to ensure continued recruitment, but simultaneously retain commercially valuable blue crabs (i.e., large male crabs, peeler, and soft shell crabs). Since BRDs were introduced to scientists in 1992, many short-term field tests of these devices have been conducted (see Roosenburg 2004 for a review). Whereas many of these previous studies have shown a marked decrease in terrapin captures in BRD-equipped versus control pots, the effects of BRDs on crab catch rates were not as clear. Some researchers quantified an increase in target crab catch (Guillory and Prejean 1998), others measured a decrease (Cole and Helser 2001), whereas still others detected no effect (Roosenburg and Green 2000, Butler and Heinrich 2007) or even a combination of no effect on size of crabs captured with a coincident increase in number of crabs caught (A. D. Mazzarella, New Jersey Department of Environmental Protection Agency, unpublished report). In general, no effects on blue crab catches were seen with larger (i.e., 5.0 cm) BRDs. Overall, increased catch rates of blue crabs in traps with BRDs may have been due to fewer crabs escaping through the entrance funnel (Guillory and Prejean 1998), whereas decreased catch rates of crabs might have been because the crabs could not enter through the restrictive BRD opening.

Despite the available data, it is difficult to translate previous estimates of terrapin by-catch/crab pot per day to a number of terrapins that might be captured in active commercial crabbing operations, especially because terrapins are patchily distributed and their activity varies with time of year. To date none of the previous BRD evaluations have been performed throughout the duration of a commercial fishing season, and few have been conducted in areas of overlap between terrapins and active commercial blue crab fishing. Still others were performed at a time when at least female terrapins would be likely to be spatially separated from crab pots (i.e., summer months of nesting; see Roosenburg 2004). Thus, to quantify the effect of BRDs on catch rates of blue crabs and terrapins in the North Carolina commercial blue crab fishery, we designed a fishing experiment across seasons and years in direct collaboration with 2 commercial fishers.

Blue crabs support extremely valuable commercial and recreational fisheries in the southeast United States and the species is the base of the most valuable commercial fishery in North Carolina. Average commercial landings for hard crabs (defined as valuable male crabs with hard shells and carapace width >127 mm) and peeler or soft crabs for the 10-yr period 1996–2006 was 19,555,630 kg, valued at US $30,582,230 (North Carolina Division of Marine Fisheries [NCDMF] 2008). Annually, male hard crabs account for 97% of the total blue crab harvest in North Carolina, and 95% of the total hard crab harvest since 1994 has been taken in crab pots (North Carolina Division of Environment and Natural Resources [NCDENR] 2004). Peak months for crab pot landings are May through October (NCDENR 2004). Reported crab pot use increased from 1,200 in 1953 when the first reported landings from crab pots in North Carolina were registered, to >3.5 million in 1996, and in recent years has remained at about one million pots annually. The large number of hard crab pots fished each year indicates that potential terrapin by-catch and mortality in North Carolina may be high, especially for populations severely reduced from historical levels (Seigel and Gibbons 1995). Although the terrapin by-catch issue was recognized as one of several "principal issues" in the North Carolina 2004 Division of Marine Fisheries Blue Crab Management Plan (BCMP), the extent of terrapin mortality in actively fished crab pots is unknown in North Carolina.

In 2000, the International Union for the Conservation of Nature (IUCN) listed the diamondback terrapin as at low risk. This assessment was based on the broad geographic distribution of the species and an estimated abundance of >10,000 individuals across their range. Although this ranking may reflect the viability of the species at a coarse-scale (Mitro 2003), it does not capture the status or viability at the local- or regional-population level. But, based on expert opinion, populations of terrapins in >75% of the states they occupy are either declining or of unknown status (Seigel and Gibbons 1995); in North Carolina, terrapins are thought to be declining. One current blue crab fishery management goal in North Carolina is to encourage the coexistence of the lucrative fishery and viable diamondback terrapin populations (NCDENR 2004). Terrapins are also recognized in North Carolina as a species of special concern, so quantitatively assessing BRD effects on target catch is necessary to evaluate management strategies that could reduce terrapin by-catch without compromising crab catches. Thus, our specific objectives were to 1) test crab pot designs that included BRDs of various sizes to examine their efficacy in excluding terrapins and their effects on catch rates and sizes of blue crabs retained, and 2) characterize the temporal and spatial extent of overlap of terrapins with commercial crab fisheries by mapping locations where terrapins were captured in our study site to examine trends in captures by distance from shore. We explicitly tested the hypothesis that various sizes of BRDs had no effect on crab catch rates.

STUDY AREA

We performed experimental fishing studies in Jarrett Bay, off central Core Sound, North Carolina, adjacent to the Cape Lookout National Seashore (Fig. 1). Core Sound (Carteret County, NC) connects with the Atlantic Ocean through Barden and Drum Inlets. Core Sound adjoins Pamlico Sound to the north and Back Sound to the south (Fig. 1), covering an area of approximately 2,270 ha. Average depth was approximately 2 m (Dudley and Judy 1973), and salinity averaged about 30 parts per thousand (ppt), seldom dropping

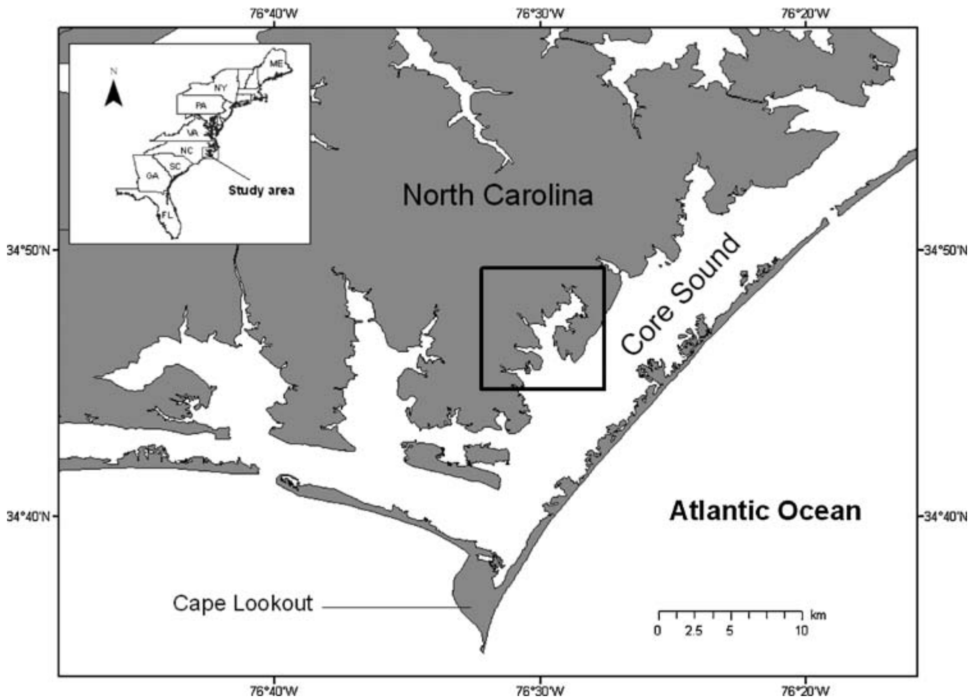

Figure 1. Study area in eastern North Carolina (inset box around Jarrett Bay) where we conducted experimental fishing work with blue crabs and diamondback terrapins, 2000–2004. For reference, Jarrett Bay is 1,625 m across at its widest point. Approximate coordinates for the mouth of Jarrett Bay are latitude 34.75261°N, longitude −76.48340°W.

below 20 ppt. Annual water temperature range was about 8–28°C, and mean tide range was about 30 cm (Dudley and Judy 1973).

METHODS

Using SigmaStat 2.03 (SPSS Incorporated, Chicago, IL) we calculated the number of replicates necessary for 0.80 statistical power and targeted hard crabs and peeler crabs. Sampling dates included April, May, June, September, October, and November; hard crab fishing experiment dates were 2 May to 9 June 2000, 8 September to 18 November 2000, and 9 May to 22 June 2001 and peeler crab fishing experiment dates were 4 April to 6 May 2004. These periods coincided with commercial fishing seasons in this region. All sampling activities followed approved Duke University Institutional Animal Care and Use Committee Protocols (Protocols no. A120-02-01 and A120-05-04).

Experimental Fishing

During the 3 hard crab fishing seasons during spring 2000, fall 2000, and spring 2001, we fished standard crab pots (60 cm × 60 cm × 60 cm) with and without BRDs. We deployed paired hard crab study pots throughout Jarrett Bay from a commercial fishing vessel. For the hard crab study, 2 paired pots made up a block: 1) a control or standard hard crab pot (Fig. 2A); 2) a BRD-outfitted hard crab pot that had BRDs affixed to the inside each of 4 crab pot entrance funnels (Fig. 2B). We arranged paired blocks along shore, and we set successive blocks in line with each other, following the shoreline of Jarrett Bay. We fished 21 blocks each day, for a total of 42 pots/day. We fished pots either daily or every other day and baited all pots with menhaden (*Brevoortia tyrannus*), the common bait used by crab fishers in the area.

In the hard crab portion of the study, we tested one size BRD per season, which was a strategy acceptable to the commercial fisherman (despite the limitations it poses for statistically comparing among seasons objectively). In spring of 2000, fall 2000, and spring 2001, we tested 5.0-cm (ht dimension) BRDs, 4.0-cm BRDs, and 4.5-cm BRDs, respectively. We handcrafted all BRDs used in the hard crab experiment from 14-gauge galvanized fencing and secured each one to the crab pots with galvanized metal rings to the back of the entrance funnels; we believe this placement mimics previous BRD experiments conducted by Roosenburg and Green (2000) and Cole and Helser (2001) and others (see Roosenburg 2004). We constructed all BRDs to be the same width as the crab pot entrance funnels (16.0 cm wide), as Roosenburg and Green (2000) found that terrapins were not excluded based on their width.

We measured all captured crabs from carapace tip-to-tip on a measuring board to the nearest mm (following Roosenburg and Green 2000, Cole and Helser 2001, Radzio and Roosenburg 2005) and determined gender. We recorded daily crab catch information and a Global Positioning System (GPS) location for each pot. We normalized data for effort (i.e., soak time [duration of time the pot is in the water]) and used a Kruskal–Wallis 1-way analysis of variance (ANOVA) on ranks (Zar 1984) on each seasonal data set to determine if there were differences between control and BRD pots for catch of legally sized (>127 mm) hard male crabs. We calculated statistical

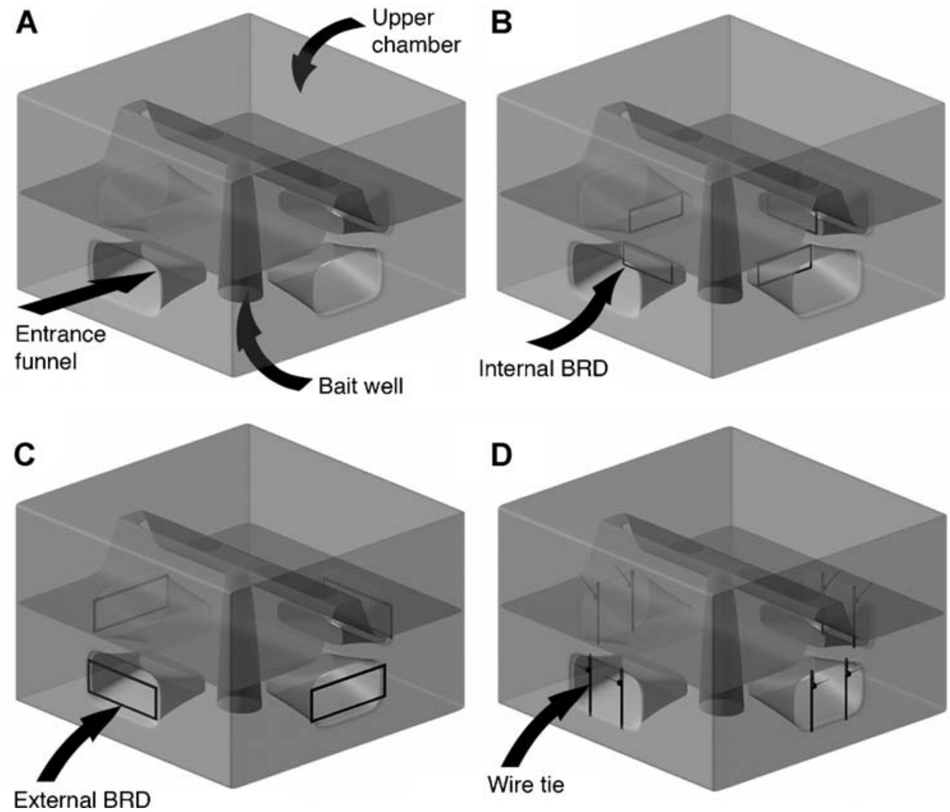

Figure 2. Scale illustration of a standard blue crab pot with by-catch reduction devices (BRDs) of various sizes and configurations tested during experimental fishing studies on diamondback terrapins in North Carolina, 2000–2004. Panel (A) represents a standard hard or peeler crab pot; panel (B) shows internal BRD placement on all entrance funnels; panel (C) shows external BRD placement on entrance funnels (used only in the peeler pot experiment), and panel (D) shows the wire tie configuration (used only in the peeler pot experiment).

significance using SigmaStat 2.03 and we set significance levels to reject our null hypothesis at $P < 0.05$.

For the peeler experiment, we tested several different BRDs simultaneously because of the short duration (i.e., 4–6 weeks; Apr–May) of the peeler season. We deployed peeler pots in blocks throughout Jarrett Bay, again in an area where the fishers usually set their pots. In the peeler experiment, 4 pots constituted a block: 1) a control or standard peeler pot (Fig. 2A); 2) a peeler pot with BRD1 (handcrafted 4.3 cm × 16 cm galvanized, 14-gauge excluders) on all funnel entrances (Fig. 2B); 3) a peeler pot with BRD2 (commercially available orange plastic 5.1 cm × 15.2 cm excluder [TOP-ME Products, Topsham, Maine]) on all external funnel entrances (Fig. 2C), and 4) a pot with BRD3 (2 wire ties 7.8 cm apart, vertically arranged) on all funnel entrances (Fig. 2D). We arranged and deployed blocks of pots along the shoreline, with successive blocks set in line with each other, from a different commercial fishing vessel. Based on power analysis in SigmaStat 2.03 (0.80 power, 0.5 difference in means, 0.5 SD, $\alpha = 0.05$), we fished 22 blocks or samples each day, for a total of 88 pots/day. We fished pots either daily or every other day, and we did not bait peeler pots with fish, consistent with standard practice in the North Carolina commercial peeler fishery.

We measured all peeler crabs as above and again recorded daily crab catch information and a GPS location for each pot. We normalized data for effort (i.e., soak time) and analyzed variance (ANOVA) in the peeler data. We performed all statistical tests using SigmaStat 2.03 and set significance levels to reject the null hypothesis at $P < 0.05$.

Terrapin Captures

For each terrapin captured, we assessed condition (live or dead), determined gender when possible (i.e., when condition of the terrapin allowed) by examining the position of the cloaca relative to the edge of the carapace (Carr 1952, Lovich and Gibbons 1990), and measured both straight and curved carapace and plastron dimensions with calipers and a flexible measuring tape, respectively, to the nearest millimeter. We recorded all information along with capture location for each terrapin. For live terrapins, we marked marginal scutes with notches (Cagle 1939) and injected a passive induced transponder (PIT) tag, photographed, and released each animal at the point of capture. For dead terrapins, we measured the same carapace and plastron dimensions as above, determined gender when possible, and stored terrapins for later analysis in a freezer at Duke University Marine Lab. We mapped locations for all captures in ArcView 3.2 Geographic Information System (GIS) software and calculated distance to shore using National Oceanic and Atmospheric Administration (NOAA) high-resolution shoreline data (NOAA 2007). We created a derived, distance to shore layer and evaluated the distance value for each terrapin capture location using the Animal Movement and

Table 1. No. of legal male blue crabs (e.g., >127 mm) caught during experimental fishing by-catch reduction device (BRD) studies in North Carolina, 2000–2004.

Hard crab fishing experiment			Peeler crab fishing experiment		
BRD size (in cm)	Control	BRD	BRD size (in cm)	Control[a]	BRD
5.0	386	365	5.0	374	372
4.5	625	459	4.3	374	376
4.0	1,270	1,002	Wire tie	374	372

[a] We simultaneously tested all BRDs during the peeler experiment, so all control numbers are equivalent.

Analysis Extension (AMAE) in ArcView (Hooge and Eichenlaub 1997).

RESULTS

Experimental Fishing

We fished hard crab pots for 75 days or 75 × 42 = 3,150 crab pot days from 2 May–9 June 2000 (20 days), 8 September–18 November 2000 (27 days), and 9 May–22 June 2001 (28 days). Soak time averaged 1.5 days in summer 2000, 1.6 days in summer 2001, and 2.6 days in fall 2000. Mean distance to shore for hard crab pots was 208.8 m (SD = 118.2 m). Similarly, we fished peeler pots for a 19 days or 19 × 88 = 1,672 crab pot days from 4 April–6 May 2004. During the peeler experimental fishing study, pots had 1–2 day soak times in 17 out of 19 (89.5%) total study days, one period with a 3-day soak time, and one period of a 5-day soak time. Mean distance to shore for peeler pots was 121.7 m (SD = 78.4 m). Total fishing effort equaled 4,822 crab pot days for hard crab and peeler experiments. There was no difference in mean distance to shore for hard versus peeler pots (t-test; $t_1 = 0.907$, $P = 0.531$).

In hard crab experimental fishing, we consistently caught a slightly (though not significantly) higher absolute number of hard male crabs in control pots than in BRD pots (Table 1); fall experimental fishing produced the highest absolute number of crabs. Catch of legally sized male hard crabs in each season was reduced by 5.7% with 5.0-cm BRDs, 21.2% with 4.5-cm BRDs, and 26.6% with 4.0-cm BRDs. A Kruskal–Wallis 1-way ANOVA on ranks with Dunn's method for each seasonal data set revealed that the difference in median values between the 2 types of crab pots was greater than would be expected by chance for 2 of 3 seasons; crab pots fitted with 4.0- and 4.5-cm BRDs caught fewer male hard crabs than did control pots (4.0-cm BRD: $H_1 = 18.141$, $P < 0.001$; 4.5-cm BRD: $H_1 = 29.153$, $P < 0.001$). In contrast, the number of male hard crabs caught did not differ between control pots and those outfitted with 5.0-cm BRDs (5.0-cm BRD: $H_1 = 0.368$, $P = 0.544$).

We captured only 8 diamondback terrapins in 3,150 trap days during the 3-season hard crab experimental fishing study for a capture rate of 0.003 terrapins/crab pot per day, and all captures occurred in the first half of May (2000 and 2001; Table 2). Further, we captured terrapins only in control pots. All terrapins were small with respect to length (straight carapace length [SCL] = 10.5–13.2 cm) and height (SCH = 4.7–5.9 cm; Table 2). Locations of terrapin captures varied in the hard crab study, but we caught

Table 2. Capture details for female and male diamondback terrapins captured in hard and peeler blue crab experimental fishing studies in North Carolina, 2000–2004.

Terrapin no.	Terrapin capture date	Crab pot type and design	Terrapin status and sex	Terrapin straight carapace height (cm)	Terrapin straight carapace length (cm)
1	2 May 2000	H, C	Live, F	5.9	13.2
2	3 May 2000	H, C	Live, F	5.5	12.8
3	4 May 2000	H, C	Live, M	4.9	10.8
4	4 May 2000	H, C	Live, M	4.7	10.5
5	6 May 2000	H, C	Dead, F	5.1	11.4
6	6 May 2000	H, C	Dead, F	4.9	11.2
7	8 May 2000	H, C	Dead, M	5.1	11.0
8	14 May 2001	H, C	Dead, F	4.9	11.3
9	6 Apr 2004	P, C	Live, M	4.5	11.2
10	10 Apr 2004	P, 5.0-cm BRD	Live, M	4.3	10.5
11	17 Apr 2004	P, C	Live, M	NE	NE
12	23 Apr 2004	P, C	Live, M	4.6	11.1
13	23 Apr 2004	P, wire tie BRD	Live, M	4.8	11.0
14	25 Apr 2004	P, C	Live, M	4.1	10.0
15	25 Apr 2004	P, 5.0-cm BRD	Live, F	4.8	11.0
16	26 Apr 2004	P, C	Live, F	5.2	11.7
17	29 Apr 2004	P, wire tie BRD	Live, M	4.7	11.7
18	29 Apr 2004	P, C	Live, F	4.7	10.7
19	29 Apr 2004	P, C	Live, M	4.4	11.1
20	4 May 2004	P, C	Dead, M	NE	NE
21	4 May 2004	P, wire tie BRD	Dead, F	NE	NE

C, control; H, hard crab pot; *P*, peeler pot; BRD, by-catch reduction device; NE, not estimable due to poor condition.

all terrapins within 321.4 m of the shoreline. However, mean distance to shore for hard crab pots that captured terrapins was 143.2 m (SD = 121.4 m).

We detected no difference in peeler crab catch per pot type (Table 1; ANOVA results: $F_3 = 0.364$, $P = 0.779$) over all days of the peeler experimental fishing study. Intriguing, but not statistically significant, was that pots with the wire tie BRD caught 4.4% more peeler crabs than did control pots (Table 1). We observed the highest catch of peelers during the week of 19–26 April, when we recorded >100 peelers/day.

We captured 13 terrapins over 19 days of the peeler study (Table 2), for a capture rate of 0.008 terrapins/crab pot per day. Two terrapin mortalities occurred during the peeler season, however, both were in pots with the longest soak times (i.e., 5 days). Notably, we captured no terrapins in pots outfitted with the smallest BRDs (i.e., 4.3-cm BRD), whereas we captured 2 terrapins in pots outfitted with the largest BRDs (i.e., 5.0-cm BRD) and 3 terrapins in pots outfitted with the vertically arranged wire tie BRD. Size of captured terrapins ranged from 10.0 cm to 11.7 cm SCL and 4.1 cm to 5.2 cm SCH (Table 2). We captured all terrapins in the peeler experiment in the upper portion of Jarrett Bay in shallow water and between 20.0 m and 220.0 m ($\bar{x} = 121.1$ m, SD = 60.6 m) from the closest shoreline.

All terrapin captures combined showed an effect of soak time on the likelihood of terrapin survival (Correlation: adjusted $r^2 = 0.79$); longer soak times of 5 days during 2 periods in the peeler experiment produced 2 dead terrapins. Moreover, mean distance to shore for all 21 terrapin captures in both hard and peeler pots was 129.5 m (range = 0.0–321.4 m, SD = 86.5 m). We detected no difference in means of distances to nearest shoreline for terrapins captured in hard versus peeler pots (t-test: $t_{18} = 0.321$, $P = 0.376$). In our study, avoiding crab pot sets within 321.4 m of the shoreline could have eliminated 100% of terrapin captures, avoiding crab pot sets within 250 m of the shoreline could have eliminated 90% of terrapin captures, and similarly avoiding crab pot sets within 150 m of the shoreline could have eliminated 76% of terrapin captures (Fig. 3).

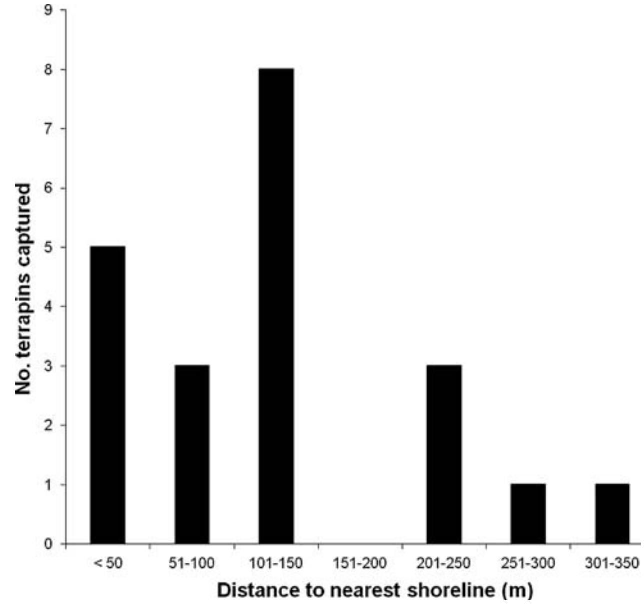

Figure 3. Distance to shoreline (m) for each diamondback terrapin we captured in either hard or peeler crab pots during experimental fishing studies in North Carolina, 2000–2004. We measured distance in ArcView from Global Positioning System (GPS) locations collected for each capture.

DISCUSSION

Previously, several researchers recommended requiring 4.5-cm BRDs on crab pots because this size would theoretically exclude most terrapins encountered and not decrease crab catch (Grant 1997, Roosenburg and Green 2000, Cole and Helser 2001, Butler and Heinrich 2007). However, Roosenburg (2004) discussed that the geographic variation in both terrapin and crab size may warrant studies to determine appropriate-sized BRDs on a state-by-state basis. Thus, we conducted the first study in conjunction with commercial crabbers in North Carolina to specifically quantify the effect of various BRDs on catch of target male hard crabs and peeler crabs, as well as characterize the timing, location, and magnitude of terrapin captures in actively fished commercial crab pots. Our results generally support those in previously published BRD studies, but whereas our data agrees that most (77%) terrapins we captured would have been excluded with the 4.5-cm BRD, we found a decrease (−26.6%; $P < 0.001$) in catch of the target legal-sized male blue crabs with the 4.5-cm BRD in our North Carolina study. In contrast, the 5.0-cm BRD did not have a significant effect on catch of either large male blue crabs or peelers and 28% of terrapins we captured could have been excluded with the 5.0-cm BRD. Still, a decline in hard crab catch, may be expected with use of the 5.0-cm BRD during the hard crab season in our study site.

Similar to other previous BRD studies that captured terrapins, we observed a low overall terrapin capture rate across both hard crab and peeler experiments. This low capture rate of terrapins precluded making strong inferences on BRD effects on terrapin catch, as it is impossible to know how many terrapins were excluded from pots because of BRDs. However, a small by-catch rate can be sufficient, particularly if biased to particular seasons, age classes, sexes, or habitats, to cause negative population growth. Here, our low catch rates of terrapins in actively fished crab pots do not imply no net effect on the terrapin population. For example, in North Carolina, if each of the approximately 7,500 crab fishers who participate in the fishery for hard blue crabs catches a number of terrapins similar to that in our study and removes ~50% of that catch from the population due to mortality in crab pots (as we observed), then tens of thousands of terrapins could be removed each year. Thus, terrapin capture and mortality in actively fished commercial crab pots may represent an extremely large collective impact on the local terrapin population. This a concern because life history requirements for terrapins and other long-lived turtles necessitate high survivorship (Congdon et al. 1993, Heppell 1998), thus increased mortality in juvenile or adult stages (as is possible in crab pots) will generally cause populations to decline.

Our data are valuable for characterizing the problem of incidental terrapin capture and mortality in commercially fished hard and peeler crab pots. Our results are biased to reflect the intensity and behavior of the 2 fishing operations with which we worked, yet they are representative of the 4–5 active fishing operations in Jarrett Bay. One of the 2 fishers with whom we cooperated regularly fishes up to 500 pots/day, whereas the other regularly fishes up to 150 pots/day. Thus, by working with these 2 fishers we believe we captured the range of fishing pressure and resulting terrapin mortality that might be expected for other fishers actively operating in this study site. However, future work incorporating a simultaneous test of currently available BRDs, including the wire tie BRD that we investigated, should be conducted to more clearly quantify the crab catch differences among pots outfitted with BRDs in one hard crab fishing season.

In addition to our quantified catch rate data for hard crabs and peelers in pots with and without BRDs, we obtained key results about the status of terrapins captured as well as trends in the timing and location of these captures in active commercial crabbing operations; these results may be of specific interest to managers of blue crab fisheries in North Carolina and other states in the Southeast United States. First, of the 8 terrapins we captured in the experimental hard crab pots, upon capture 50% were dead and 50% were live. Soak time also had an effect on the likelihood of terrapin mortality—longer soak times of 5 days during 2 periods in the peeler experiment produced both of the dead terrapins we obtained during experimental peeler fishing. Currently, North Carolina law requires that all pots be checked every 5 days (North Carolina Administrative Code 2008), but consistent regulations for the southeast region are lacking. Managers could improve enforcement of such existing regulations or change the requirement to a fewer number of days between checks to alleviate additional terrapin by-catch due to long soak times on pots.

Second, based on SCH of both live and dead terrapins captured in experimental hard crab pots, these terrapins theoretically would have been excluded entirely (100%, or 8/8) by 4.5-cm BRDs and partially excluded (50%, or 4/8) by 5.0-cm BRDs. Similarly, based on SCH of both live and dead terrapins we captured in experimental peeler pots, 53.8% (7/13) theoretically would have been excluded by 4.5-cm BRDs. Conversely, only one of the terrapins we captured in the peeler experiment (1/13 or 7.7%) would have been excluded by 5.0-cm BRDs. Managers can use these data to help rank management options according to their potential benefit for species protection or recovery and cost-effectiveness (Heppell 1998). However, the most cost-effective option may not always benefit recovery of the target species as much as a less cost-effective option. This is the case with terrapins and BRDs, as the least costly alternative (economically) for crabbers is the 5.0-cm BRD because it does not appear to cause a statistically significant decrease in crab catch, whereas the best option for terrapins is the smallest BRD (i.e., because it would exclude a larger proportion of size classes; Wood 1997, Roosenburg and Green 2000). The BRDs themselves are inexpensive per unit (approx. 10% the cost of a $20 crab pot). Thus our results should be useful for managers to evaluate currently available crab pot and BRD designs to decide on the optimal strategy for protecting terrapins while still allowing capture of valuable blue crabs.

Third, although we captured only 21 terrapins in our study pots and thus have a low overall terrapin capture rate, we captured all terrapins in the hard crab study during early to mid-May and all terrapins in the peeler study in April and May. Previously, Bishop (1983) found that 55% of the total number of terrapins captured in his landmark study ($n = 281$) were captured in April and another 32% were captured in May. Twenty years later, our work confirms that terrapin captures in crab pots occur primarily early in the crabbing season, at a time of year that coincides with terrapin mating activity when terrapins may disperse to find mates (Ernst et al. 1994). We found that the critical time period for overlap of terrapins with activity of the hard crab fishery in our study site in North Carolina was in the early spring season, for several months of the commercial fishing season. Similarly, the critical time period of overlap of terrapin activity with that of the peeler fishery was also in spring, but throughout the entire peeler fishing season. This overlap does not appear to extend into summer or fall (i.e., into the peak of the hard crab fishery activity) in our study area. Unless fishers move their pots close to shore to escape interaction with shrimpers (R. Cahoon, C & S Seafood, personal communication) or sea turtles that damage pots (Avissar et al. 2009), terrapin by-catch in this region of coastal North Carolina should be minimal after June. However, because mean distance to shore for peeler and hard crab pots fished was 121.7 m and 208.8 m, respectively, managers must realize that a spatial restriction on fishing pots at a certain distance to shore would more likely affect a greater percentage of peeler pot locations rather than hard crab pot locations. In our experimental fishing studies, 78% of hard crab pots were located $\leq$250 m from shore and the remaining 22% of hard crab pots were situated $>$250 m from shore. In contrast, 98% of peeler pots were located $\leq$250 m from the nearest shoreline, and the remaining 2% of peeler pots were situated $>$250 m from shore. Considering how such spatial distances-to-shore restrictions could affect catch rates of peeler crabs may be a valuable follow-up study before regulations are adopted by blue crab fishery managers.

Fourth, related to our findings regarding time-of-year for terrapin captures in active crabbing operations, we captured terrapins in pots fished close to shore. This result suggests that incidental capture of terrapins might be substantially reduced if pots are set further from the shoreline, especially in early spring (i.e., Mar, Apr, May); in fact, in this study we captured 100% of terrapins within 321.4 m from shore in April and May. Such information on distances of terrapin captures to shore could be used by blue crab fishery managers to delineate and prioritize no-fishing areas at times of year when crab fishers are likely to encounter and trap terrapins, such as in spring (Mar–May). However, there is likely to be considerable regional variation in where most terrapins occur (i.e., in small creeks vs. in larger water bodies), so assessments of appropriate distances-to-shore limits for crab pots that may capture terrapins in different areas might be warranted, even within one region. For example, results from a separate yet related study in our area produced 109 terrapin captures in salt marsh ditches adjacent to the Jarrett Bay study site from 2 May 2000 through 20 June 2001 (Crowder et al. 2000). Thus, terrapins are present in the marsh and creek habitat of this study site in higher numbers than out in the slightly deeper waters of Jarrett Bay where crab fishing primarily occurs.

Finally, our terrapin capture rates lie within the bounds of values calculated for terrapin catch rates in previous studies (Bishop 1983, Roosenburg et al. 1997, Roosenburg and Green 2000; see Roosenburg 2004). But these relatively small per capita effects or low overall terrapin capture rates in individual studies, when multiplied by a large number of fishers, can produce a cumulatively large effect. Thus, low but consistent rates of by-catch should not be ignored, especially for a species with special concern and state-listed status in >75% of the states it occupies. As well, it is difficult, at best, to extrapolate the rates of terrapin captures to a number of terrapins that would be caught in other active commercial crabbing operations because the number of commercial hard crab pots fished varies across fishers and seasonally, regionally, and annually. Additional work is needed to quantify terrapin by-catch in other active crabbing operations in this and other regions of North Carolina, as terrapins do not necessarily occupy all available habitat where fishers may place their pots (i.e., in deeper water), and densities of terrapins may vary seasonally within a given habitat. In our own study site, we may have a low density of terrapins due to fishing pressure over the past 5 decades, despite high densities of terrapin captures in nearby marsh habitat (Crowder et al. 2000). If terrapin population abundance at our site is low, then crab pots placed in the vicinity of terrapin habitat may catch fewer turtles than if population abundance was high. Thus, our low terrapin catch rate may simply reflect low abundance of terrapins, especially compared to historic precrabbing periods. A study by Dorcas et al. (2007) in South Carolina suggested a 50% decline in terrapin abundance over the past 30 yr in an area with crabbing, implying a smaller catch rate could be expected for terrapins in a study conducted today versus one conducted when abundances were higher. Further, Grosse (2009) showed that terrapin densities in commercially crabbed creeks in Georgia were much lower than that in creeks not commercially crabbed. Thus, interpretation of low terrapin by-catch rates is complex, as in some habitats terrapin by-catch in single crab pots can be extreme (Grosse et al. 2009).

MANAGEMENT IMPLICATIONS

Our results identify 3 complementary tools to exclude terrapins from commercially fished crab pots: 1) gear modifications (BRDs); 2) distance-to-shore restrictions; and 3) time-of-year regulations—for a possible significant reduction in terrapin by-catch without a significant reduction in target crab catch. These tools could protect terrapins from interactions with active crab operations. We suggest a strategy for North Carolina blue crab fishery managers whereby no-fishing zones established nearshore for the period with the highest recorded by-catch (i.e., spring) and enforced in combination with the widespread use of BRDs on all pots that fisher have set (e.g., blue crab pots and traps to catch American eels [*Anguilla rostrata*]; Radzio and Roosenburg 2005) may be the best currently available option for mitigating terrapin by-catch in crab pots. Although these 3 management strategies will have to take local conditions into consideration and target catch and by-catch will vary among years and locations, all strategies should be exportable to other coastal blue crab fisheries along the Atlantic and Gulf coasts where terrapins are present.

In addition, we suggest that managers focus on improving recording of fishery participation as this may help to further characterize the potential effects of terrapin by-catch on the local terrapin population. Currently an unknown number of fishers participate in the early season peeler fishery in North Carolina because the NCDMF currently collects only hard crab landings data through their Trip Ticket program. Having more accurate counts of fishers participating in the peeler fishery, along with number of pots fished, would facilitate making valid extrapolations from our data on terrapin catch rates across the fishery. We also encourage further testing of innovative BRD and crab pot designs, as neither the ideal crab pot nor the optimal BRD has yet emerged. Given our observation of a slight increase in peeler catch with the vertically arranged wire tie BRD, we promote tests of different configurations of crab pot entrance funnels and alternative crab pot designs. For example, Roosenburg et al. (1997) encouraged use of a tall crab pot, but with double the cost and bulk, this novel gear has not been successfully used in the commercial blue crab fishery. Finally, we recognize that economic tradeoffs are a large part of conservation decisions, and we expect that terrapin conservation plans that involve requiring BRDs of various sizes on commercially fished blue crab pots will be no exception.

ACKNOWLEDGMENTS

Funding for experimental fishing studies was provided by the North Carolina Sea Grant Fishery Resource Grant Program (00-FEG-23 and 03-FEG-18). Part of this work was completed as part of the doctoral work of K. Hart at Duke University. We thank our fishing collaborators M. Hooper and the Cahoon family and our Sea Grant Monitor B. Hines. We acknowledge the field assistance of P. Gillikin, L. Thorne, E. McLaughlin, and J. Kelley. We thank T. Ziegler and K. Craig for assistance with statistical analysis, C. Good and J. Gannon for help with calculations of distance to shore, L. Avens and Y. Escribano for the map of our study site, and B. Boynton for crafting the crab pot figure. J. Krebs, T. Smith, III, and E. Larrivee provided helpful comments on an earlier draft of this manuscript. Use of trade or product names does not imply endorsement by the United States Government.

LITERATURE CITED

Alverson, D. L., and S. E. Hughes. 1996. By-catch: from emotion to effective natural resource management. Reviews of Fish Biology and Fisheries 6:443–462.

Avissar, N. A., K. M. Hart, L. B. Crowder, J. Marsh, and J. Gannon. 2009. At loggerheads: evidence of Loggerhead sea turtle damage to gear used in the blue crab (*Callinectes sapidus*) fishery. North American Journal of Fisheries Management 29:163–169.

Bishop, J. M. 1983. Incidental capture of diamondback terrapin by crab pots. Estuaries 6:426–430.

Butler, J. A., and G. L. Heinrich. 2007. The effectiveness of by-catch reduction devices on crab pots at reducing capture and mortality of diamondback terrapins (*Malaclemys terrapin*) in Florida. Estuaries and Coasts 30:179–185.

Butler, J. A., G. L. Heinrich, and R. A. Seigel. 2006. Third workshop on the ecology, status and conservation of diamondback terrapins (*Malaclemys terrapin*): results and recommendations. Chelonian Conservation and Biology 5:331–334.

Cagle, F. R. 1939. A system for marking turtles for future identification. Copeia 1939:170–173.

Carr, A. 1952. Handbook of turtles: the turtles of the United States, Canada, and Baja California. Cornell University Press, Ithaca, New York, USA.

Cole, R. V., and T. E. Helser. 2001. Effect of four by-catch reduction devices on diamondback terrapin (*Malaclemys terrapin*) capture and blue crab (*Callinectes sapidus*) harvest in the Delaware estuary. North American Journal of Fisheries Management 21:825–833.

Congdon, J. D., A. E. Dunham, and R. C. van Loben Sels. 1993. Delayed sexual maturity and demographics of Blandings turtles (*Emydoidea blandingii*): implications for conservation and management of long-lived organisms. Conservation Biology 7:826–833.

Crowder, L. B., K. M. Hart, and M. Hooper. 2000. Trying to solve a by-catch mortality problem: can we exclude diamondback terrapins (*Malaclemys terrapin*) from crab pots without compromising blue crab (*Callinectes sapidus*) catch? Final report 00-FG-23. North Carolina Fishery Resource Grant, North Carolina, Sea Grant, Morehead City, North Carolina, USA.

Davis, C. C. 1942. A study of the crab pot as a fishing gear. Chesapeake Biological Laboratory Publication No. 53, Solomons, Maryland, USA.

Dayton, P. K., S. F. Thrush, M. T. Agardy, and R. J. Hofman. 1995. Environmental effects of marine fishing. Aquatic Conservation of Marine and Freshwater Ecosystems 5:205–232.

Dorcas, M. E., J. D. Wilson, and J. W. Gibbons. 2007. Crab trapping causes population decline and demographic changes in diamondback terrapin over two decades. Biological Conservation 137:334–340.

Dudley, D. L., and M. H. Judy. 1973. Seasonal abundance and distribution of juvenile blue crabs in Core Sound, N.C. 1965–68. Chesapeake Science 14:51–55.

Ernst, C. H., J. E. Lovich, and R. W. Barbour. 1994. Turtles of the United States and Canada. Smithsonian Institution Press, Washington, D.C., USA.

Gibbons, J. W., J. E. Lovich, A. D. Tucker, N. N. Fitzsimmons, and J. L. Greene. 2001. Demographic and ecological factors affecting conservation and management of diamondback terrapins (*Malaclemys terrapin*) in South Carolina. Chelonian Conservation and Biology 4:66–74.

Grant, G. S. 1997. Impact of crab pot excluder devices on diamondback terrapin mortality and commercial crab catch. University of North Carolina, Wilmington, USA.

Grosse, A. M. 2009. Assessment of the effects of roads and crabbing pressures on diamondback terrapin populations. Thesis, University of Georgia, Athens, USA.

Grosse, A. M., J. D. VanDijk, K. L. Holcomb, and J. C. Maerz. 2009. Diamondback terrapin mortality in crab pots in a Georgia tidal marsh. Chelonian Conservation and Biology 8:98–100.

Guillory, V., and P. Prejean. 1998. Effect of a terrapin excluder device on blue crab, *Callinectes sapidus*, trap catches. Marine Fisheries Review 60:38.

Hall, M. A. 1996. On by-catches. Reviews in Fish Biology and Fisheries 6:319–352.

Hart, K. M. 2005. Population biology of Diamondback terrapins (*Malaclemys terrapin*): defining and reducing threats across their geographic range. Dissertation, Duke University, Durham, North Carolina, USA.

Henwood, T. A., and W. E. Stuntz. 1987. Analysis of sea turtle captures and mortality during commercial shrimp trawling. Fisheries Bulletin 85:813–817.

Heppell, S. S. 1998. Application of life-history theory and population model analysis to turtle conservation. Copeia 1998:367–375.

Hooge, P. N., and B. Eichenlaub. 1997. Animal movement extension to Arcview. ver. 1.1. Alaska Science Center—Biological Science Office, U.S. Geological Survey, Anchorage, Alaska, USA.

Lewison, R. L., L. B. Crowder, A. J. Read, and S. A. Freeman. 2004. Understanding the impacts of fisheries by-catch on marine megafauna. Trends in Ecology and Evolution 19:598–604.

Lovich, J. E., and J. W. Gibbons. 1990. Age at maturity influences adult sex ratio in the turtle *Malaclemys terrapin*. Oikos 59:126–134.

Melvin, E. F., J. K. Parrish, and L. L. Conquest. 1999. Novel tools to reduce seabird by-catch in coastal gillnet fisheries. Conservation Biology 13:1386–1397.

Mitro, M. G. 2003. Demography and viability analyses of a diamondback terrapin population. Canadian Journal of Zoology 81:716–726.

North Carolina Department of Environment and Natural Resources [NCDENR], Division of Marine Fisheries. 2004. North Carolina fishery management plan: draft blue crab. December 2004. North Caroline Marine Fisheries Commission, Morehead City, North Carolina, USA.

North Carolina Division of Marine Fisheries [NCDMF]. 2008. Commercial landings statistics. <http://www.ncfisheries.net/statistics/comstat/>. Accessed 2 Jan 2008.

National Oceanic and Atmospheric Administration [NOAA]. 2007. National Geophysical Data Center. <http://www.ngdc.noaa.gov/mgg/bathymetry/relief.html>. Accessed 10 Jul 2007.

North Carolina Administrative Code. 2008. Department of Environmental and Natural Resources, Leaving devices unattended. Chapter 3, subchapter 03I, section 0105b.

Radzio, T. A., and W. M. Roosenburg. 2005. Diamondback terrapin mortality in the American eel pot fishery and evaluation of a by-catch reduction device. Estuaries 28:620–626.

Roosenburg, W. M. 2004. The impact of crab pot fisheries on terrapin (*Malaclemys terrapin*) populations: where are we and where do we need to go? Pages 23–30 *in* C. Swarth, W. M. Roosenburg, and E. Kiviat, editors. Conservation and ecology of turtles of the mid-Atlantic region: a symposium. Bibliomania, Salt Lake City, Utah, USA.

Roosenburg, W. M., and J. P. Green. 2000. Impact of a by-catch reduction device on terrapin (*Malaclemys terrapin*) and crab (*Callinectes sapidus*) capture in pots. Ecological Applications 10:882–889.

Roosenburg, W. M., W. Cresko, M. Modesitte, and M. B. Robbins. 1997. Diamondback terrapin (*Malaclemys terrapin*) mortality in crab tots. Conservation Biology 11:1166–1172.

Ruckleshaus, M., and G. C. Hayes. 1998. Conservation and management of species in the sea. Pages 112–156. *in* P. E. Fiedler and P. M. Kareiva, editors. Conservation biology for the coming decade. Second Edition. Chapman and Hall, New York City, New York, USA.

Seigel, R. A., and J. W. Gibbons. 1995. Workshop on the ecology, status, and management of the diamondback terrapin (*Malaclemys terrapin*), Savannah River Ecology Laboratory, 2 August 1994: final results and recommendations. Chelonian Conservation and Biology 1:240–243.

Wood, R. C. 1997. The impact of commercial crab traps on northern diamondback terrapins, *Malaclemys terrapin terrapin*. Pages 21–27 *in* J. Van Abbema, editor. Proceedings: conservation, restoration, and management of tortoises and turtles—an international conference. New York Turtle and Tortoise Society, New York City, New York, USA.

Zar, J. H. 1984. Biostatistical analysis. Prentice-Hall, Englewood Cliffs, New Jersey, USA.

Associate Editor: John C. Maerz.