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The effects of bycatch reduction devices on diamondback terrapin and blue crab catch in the North Carolina commercial crab fishery

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ABSTRACT

The diamondback terrapin (*Malaclemys terrapin*) is endemic to marshes, coves, and tidal creeks on the Atlantic and Gulf coasts of the United States. Currently, the terrapin is listed as a species of special concern in several states where one of the prominent threats to populations is the drowning of terrapins in commercial crab pots. Bycatch reduction devices (BRDs) that narrow the funnel opening on crab pots exclude terrapins, but BRDs face opposition from the fishing industry due to fears that they will decrease target species catch. The primary goals of this research were to examine the efficacy of two sizes of BRDs in excluding terrapins from crab pots and to assess the impact of BRDs on blue crab catch. Crab pots were deployed in paired and triplicate designs at estuarine sites along the central and southern coast of North Carolina in the summers of 2012 and 2013. A total of 4039 legal sized blue crabs and 14 terrapins were captured over the course of the study. Bycatch reduction devices did not have a statistically significant effect on catch rates or carapace width of legal-sized blue crabs. Thirteen of the 14 captured terrapins were in control pots, and one male terrapin was captured in a pot equipped with a large size BRD. An integrated approach that combines data on the spatial ecology and demography of terrapins with information on the most appropriate BRD dimensions for terrapin exclusion is most likely to succeed in addressing the issue of terrapin bycatch.

1. Introduction

Diamondback terrapins (*Malaclemys terrapin*) are native to the Atlantic and Gulf coasts of the United States, ranging from Massachusetts to Texas (Butler et al., 2004). They are typically found in coastal marshes, coves, and tidal creeks (Whitelaw and Zajac, 2002) and exhibit high site fidelity with small home ranges (Brennessel, 2006; Harden and Williard, 2012). Terrapins are designated as a species of special concern in several states, based on evidence of population declines and local extirpation (Seigel and Gibbons, 1995). Current factors contributing to the decline of the species include habitat degradation and pollution, motor vehicle mortalities, and nest predation (Brennessel, 2006; Butler et al., 2004; Feinberg and Burke, 2003; Wood and Herlands, 1997).

Among prominent threats facing terrapins is drowning in recreational and commercial crab pots (Brennessel, 2006; Roosenburg et al., 1997). The unintentional capture of terrapins in fishing gear has become a growing concern for fisheries managers and conservationists (Bishop, 1983; Butler, 2002; Crowder et al., 2000; Dorcas et al., 2007; Roosenburg, 1991). Terrapins enter crab pots out of curiosity, social behavior, and in search of food (Bishop, 1983; Butler, 2002). Once entrapped in a submerged crab pot, terrapins are not able to surface to breath and will drown in as little as 45 min (Crowder et al., 2000). Male and juvenile terrapins are more susceptible to being entrapped in crab pots, due to their smaller size, which may cause a demographic shift in populations towards older females (Roosenburg et al., 1997; Dorcas et al., 2007). Plastic and wire excluder devices, referred to as bycatch reduction devices (BRDs), that narrow the funnel opening on crab pots exclude terrapins (Morris et al., 2011; Rook et al., 2010). These devices face opposition from the fishing industry due to fears that they will decrease target species catch, however, several states including Maryland, Delaware, and New Jersey enforce BRDs in fisheries that overlap with terrapin habitats or areas that are close to the shoreline (Roosenburg, 2004). Specific BRD configurations must be assessed on a regional basis as terrapin demographics vary regionally and, therefore, the most effective BRD size for terrapin protection and maximum crab catch also varies by region (Roosenburg and Green, 2000; Roosenburg 2004).

Since 1950, North Carolina has ranked within the top three blue crab (*Callinectes sapidus*) producing states, and the blue crab commercial fishery is one of the most valuable in the state (NC DMF,

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2013). The issue of terrapin interactions with crab pots is addressed in the North Carolina Division of Marine Fisheries Blue Crab Fisheries Management Plan (NC DMF, 2013). Although the NC DMF currently does not require the use of BRDs in the state's blue crab fishery, the fisheries management plan recommends development of appropriate BRD specifications for use in North Carolina waters and the establishment of proclamation authority to implement BRDs in the fishery (NC DMF, 2013). Data regarding the efficacy of specific sizes of BRDs for terrapin exclusion and the impacts of BRDs on crab catch in North Carolina are critical for crafting a fair and effective management strategy for implementation of BRDs in the North Carolina blue crab fishery.

Hart and Crowder (2011) conducted terrapin bycatch research along the central coast of North Carolina from 2000 to 2004 using standard baited crab pots in a paired pot design to test 3 BRD configurations: 5.0 × 16.0 cm, 4.5 × 16.0 cm, and 4.0 × 16.0 cm (height × width). Their results indicated that larger BRD heights may be effective for excluding terrapins from crab pots without greatly impacting crab catch. A drawback to this study is that sampling occurred at only one location (Jarrett Bay, NC). Given that demographic characteristics of terrapin populations can vary regionally, additional data are needed to assess BRD configurations that will be most effective at reducing terrapin bycatch on a broader spatial scale.

The primary goal of our research was to examine the capacity of BRDs to exclude terrapins from crab pots without causing a reduction in blue crab catch or the size of legal crabs harvested. We assessed the efficacy of two sizes of BRDs (5.1 × 15.2 cm and 3.8 × 15.2 cm) at several locations along the coast of North Carolina, and incorporated a modified crab pot design (Rook et al., 2010) in order to reduce mortality of captured terrapins. The results of this research provide insight into the pros and cons of different BRD configurations and the overall utility of gear modification in preventing terrapin bycatch in the blue crab fishery.

2. Materials and methods

2.1. Modified crab pots and BRDs

Modified crab pots (Fig. 1A) were used to investigate the efficacy of two BRD configurations. Standard 2 ft commercial crab pots (61 cm × 61 cm × 61 cm) were fitted with a chimney (122 × 30.5 cm diameter) constructed from chicken wire to allow entrapped terrapins access to air during all phases of the tidal cycle. Square irons were fastened to the base of the pot for stabilization and a 180 cm length of 1.9 diameter PVC pipe was secured through the corner of the chimney and pot to reduce crumpling or folding of the chimney. Bycatch reduction devices were constructed from 12 gauge galvanized wire and 1.3 cm hog rings, assembled with hog ring pliers (Fig. 1B), into two dimensions, 2 × 6 in. (5.1 × 15.2 cm, "large") and 1.5 × 6 in. (3.8 × 15.2 cm, "small"). Sizes were based on size distribution of adult terrapins in North Carolina, regulations in other states, and commercially manufactured BRD dimensions (Harden et al., 2011; Hart and Crowder, 2011; Morris et al., 2011;

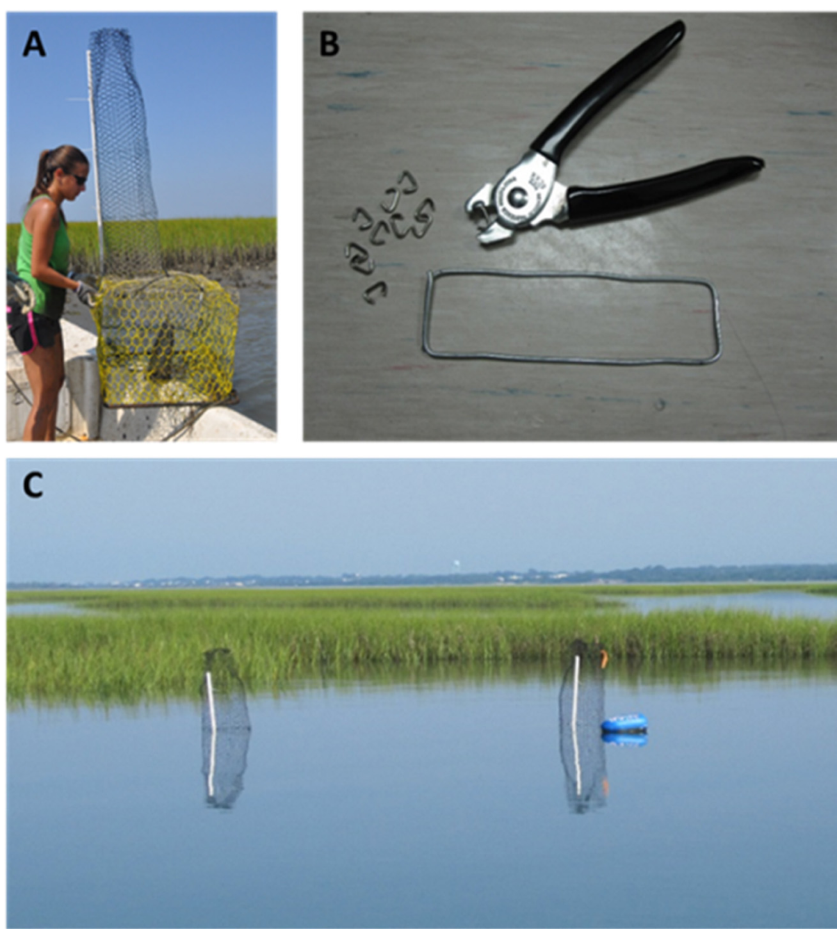

Fig. 1. Field deployments. A) Standard commercial crab pots (61 cm × 61 cm × 61 cm) were fitted with a chimney (122 cm × 30.5 cm diameter) constructed from chicken wire to allow entrapped terrapins access to air during all phases of the tidal cycle. B) Bycatch reduction devices constructed from 12 gauge galvanized wire, hog rings, and hog ring pliers. BRDs were two different dimensions, 5.1 cm × 15.2 cm(large) and 3.8 cm × 15.2 cm (small). C) Modified crab pots deployed in water in the paired pot design during the 2012 field season. A pot fixed with a BRD was always placed next to a control pot (not shown).

Rook et al., 2010; Wood, 1997). The width dimension was kept constant between treatments, as previous research has illustrated that the height dimension presents the primary obstacle to crab pot entry for both terrapins and crabs (Roosenburg and Green, 2000). We chose to use custom-built wire BRDs instead of commercially available plastic BRDS, as the plastic BRDs are usually brightly colored and fishers are more likely to use gear that is less visible. The BRDs were affixed to all four of the funnel openings of a crab pot using cable ties. Ten modified crab pots were fitted with large BRDs and ten modified crab pots were fitted with small BRDs. Twenty modified control pots were not fitted with either large or small BRDs.

2.2. Field procedures

In the summer of 2012, modified crab pots were deployed in waters in the vicinity of Beaufort, NC using a paired pot design. A pair of pots consisted of a BRD pot and a control pot placed side by side at a distance of approximately 2 m (Fig. 1C). Four sites were chosen within the Beaufort region (Fig. 2) and two sites were sampled simultaneously. Pots were deployed at Haystacks (34°44′15.61”N, 76°41′21.69”W) and Old House Slue (34°42′11.03”N, 76°38′17.60”W) from 7 June – 27 June 2012. Ten large BRD pots paired with ten control pots were placed at Haystacks, while ten small BRD pots paired with control pots were deployed at Old House Slue. The pots were processed and baited with menhaden (*Brevoortia tyrannus*) or croaker (*Leiostomus xanthurus*) every forty-eight hours. On 28 June 2012, the large BRD pots and their control pots were relocated to North River Marsh (34°43′1.41”N, 76°37′48.22” W), and the small BRD pots and their control pots were relocated to Middle Marsh (34°41′35.74”N, 76°36′43.43”W). Pots were processed and baited with menhaden or croaker on average every forty-eight hours at these two sites from 28 June–17 July 2012. Soak time was considered to be the time pots were deployed between each process, generally 48 h.

Captured terrapins were weighed on a balance scale with resolution of 0.1 g (Ohaus Scout Pro). The sex was determined by tail length and position of cloaca, and age was estimated by number of annuli on plastron scutes when possible. Straight carapace width (SCW, in cm) and straight carapace height (SCH, in cm) were recorded for each terrapin. Terrapins were externally marked using an 8 in general purpose mill file to make notches in their marginal scutes that corresponded to a letter coding system (Cagle, 1939). Crab carapace width (cm) was measured using calipers and sex was documented for all blue crabs that were captured. Water temperature at each study site was determined on processing days using a traceable waterproof thermometer (02-402-0, Fisher Scientific, Pittsburg, PA, USA) with accuracy of 0.2 °C, and water temperature data collected at a nearby water quality monitoring station within the Rachel Carson Reserve (34°41′35.74”N, 76°36′43.43”W) were downloaded from the National Estuarine Research Reserve (NERR) Centralized Data Management Office database (http://cdmo.baruch.sc.edu/). Water temperatures obtained from the NERR database were recorded every 15 min by a YSI 6600EDS data sonde with an accuracy of 0.15 °C and resolution of 0.01 °C. Correlation analyses were used to confirm that the NERR water temperature data reflected water temperatures recorded manually at each of the study sites. The NERR

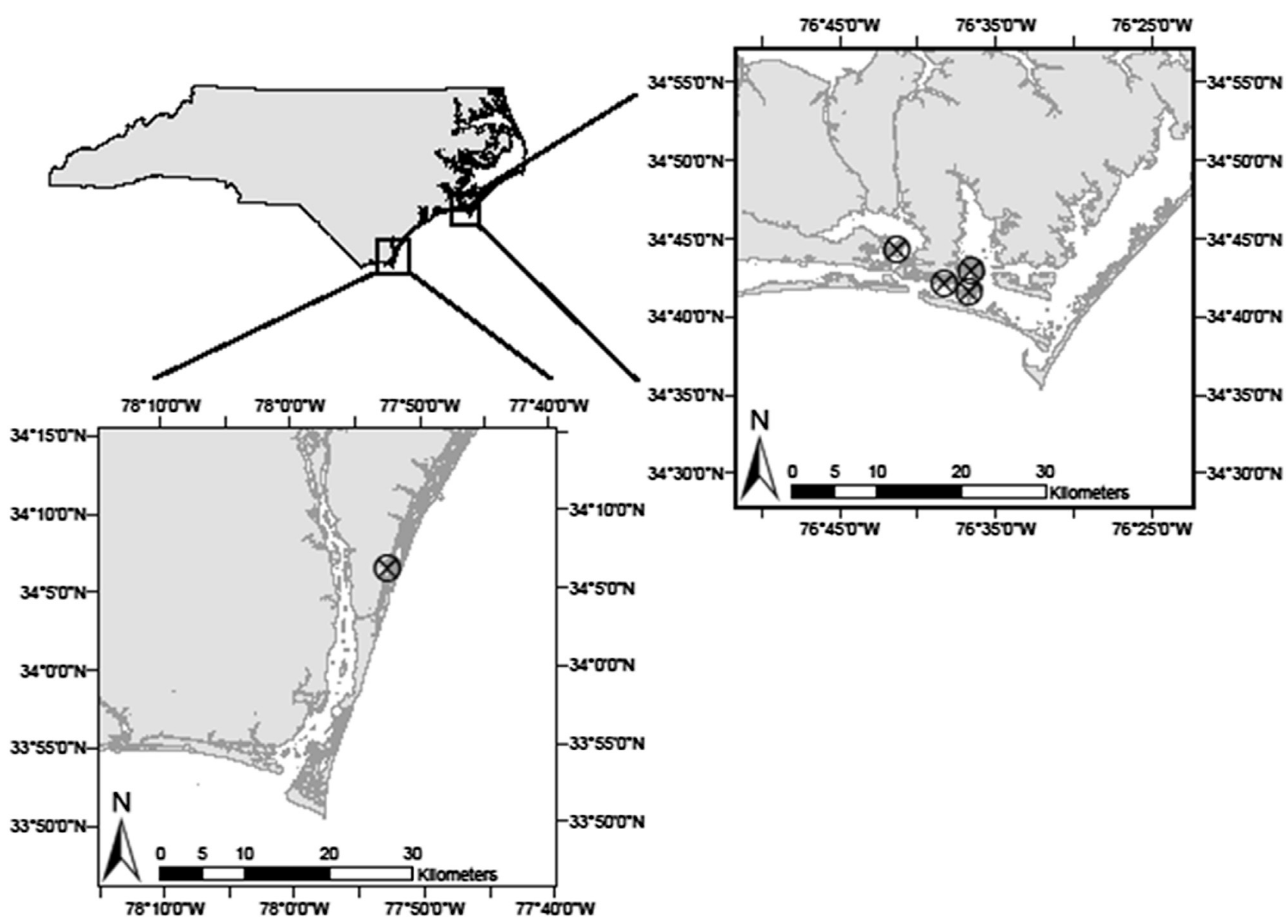

Fig. 2. Map of study sites along the coast of North Carolina. Modified crab pots were fished at four sites near Beaufort, North Carolina in 2012; from west to east, Haystacks, Old House Slue, North River Marsh, and Middle Marsh. Old House Slue and an additional site located in southeastern North Carolina (Masonboro) were fished in 2013.

water temperature data were used to calculate an average water temperature during each soak time.

Based on results obtained during the 2012 field season (see Section 3. Results) we modified field procedures such that triplicates of pots, rather than pairs, were deployed during the 2013 field season. A triplicate consists of a large BRD pot, a small BRD pot, and a control pot. Ten triplicates were deployed at Old House Slue (34°42′11.03"N, 76°38′17.60"W) from 4 June–24 June 2013. We also expanded the study to include a site in southern North Carolina, given the higher abundance of terrapins and higher potential for fisheries interactions in this region (Harden and Williard, 2012). The inclusion of this location also allowed for a comparison of sites at different latitudes. The triplicate pot design was used at a location along the Intracoastal Waterway opposite the Masonboro Island National Estuarine Research Reserve (34°6′18.40"N, 77°52′38.65"W, Fig. 2), from 15 June–6 July 2013. Processing procedures for terrapins and blue crabs and were the same as in the 2012 field season. Water temperature data collected at monitoring stations within the Rachel Carson Reserve and the Masonboro Island Reserve (34° 9′ 21.59"N, 77° 50′ 59.64"W) were downloaded from the NERR Centralized Data Management Office database, compared with water temperatures recorded manually at each study site, and used to calculate an average water temperature during each soak time. Research was approved by UNCW IACUC committee (protocol #A1213-014).

2.3. Statistical analysis

Statistical analyses were conducted on legal sized blue crab catch exclusively (minimum carapace width 12.7 cm). Two main analyses were performed, one to assess the effects of BRDs on crab catch and the other to assess the effects of BRDs on the carapace width (size) of legal crabs caught. To account for random effects and nonnormal count data, a generalized linear mixed model was used for crab catch. Catch is defined as the number of crabs caught per pot over the course of the soak time (crabs per pot per soak) and as such is considered count data. Individual pot was included as a random effect in the models, as each pot was sampled multiple times. Fixed factors in the model included *treatment* (control, large BRD, or small BRD), *site* (site of deployment), *time* (soak time), and *temp* (average water temperature during soak time). Data were fitted with a negative binomial distribution with a logarithmic link, to account for overdispersion in count data (Mazerolle, 2006; White and Bennetts, 1996), using the glmmADMB package in R. AIC corrected for small sample size (AICc), AIC differences (Δi) and evidence ratios were used to evaluate the models (Akaike, 1973). Models with Δi < 2 and evidence ratios < 2.7 were deemed best fit models. Precision of estimates for best fit models was assessed by calculating Highest Posterior Density (HPD) intervals (i.e. 95% credible interval) using Markov Chain Monte Carlo sampling (MCMC, n = 10,000). If the upper and lower bounds of the HPD interval for a given estimate excluded zero, then the factor had a significant effect on catch.

Size was measured as the width (cm) of the carapace of legal sized crabs and is therefore a continuous variable. A linear mixed model was used to assess the factors contributing to variations in size using the lmer routine in the lme4 package in R (3.1.0). Individual pot was included as a random effect in the models. Fixed factors in the model included *treatment*, *site*, *time*, and *temp*. The AICc, Δi and evidence ratios were used to evaluate best fit models, and HPD intervals were used to assess the strength of fixed effects as described above.

3. Results

3.1. Crab catch

A total of 4585 blue crabs were captured in 2012 and 1892 blue crabs in 2013. Out of all 6477 blue crabs captured, 4039 crabs were of legal size, of which 60% were female. Over the course of both field seasons, a mean of 3.43 ± 2.95 SD legal sized crabs were caught per pot per soak, with a minimum of zero crabs and a maximum of 20 crabs. Legal crab carapace width ranged from 12.7 cm to 16.6 cm with a mean of 13.9 ± 0.6 cm. Soak time varied between 24 h to 96 h and the average soak time was 48.2 ± 14.5 h. Correlation analysis showed that water temperatures recorded at NERR monitoring stations were a good proxy for temperatures recorded manually at each study site (OHS 2012 $P < 0.01$, $r^2 = 0.78$; HAY 2012 $P < 0.01$, $r^2 = 0.84$; NRM 2012 $P < 0.01$, $r^2 = 0.50$; MMR 2012 $P < 0.01$, $r^2 = 0.71$; OHS 2013 $P < 0.01$, $r^2 = 0.84$; MAS 2013 $P < 0.01$, $r^2 = 0.94$). The aver-

Table 1
Generalized linear mixed model results for crab catch during the 2012 and 2013 field season. Individual pot was included as a random effect in the models. Fixed factors in the full model included treatment (control, large BRD, or small BRD), site of deployment, soak time, and average temperature during soak time. Only best fit models (Δi < 2 and evidence ratios < 2.7) are presented.

Model	K	AICc	Δi	wi	Evidence Ratio
2012					
treatment + site	5	3486.456	0	0.2461	1.00
treatment + site + temp	6	3486.519	0.1000	0.2385	1.03
site	4	3486.804	0.3000	0.2068	1.20
2013					
site	4	1576.704	0	0.3182	1.00
site + time	5	1577.856	1.1524	0.1788	1.78
treatment + site	5	1578.656	1.9524	0.1199	2.65
site + temp	5	1578.656	1.9524	0.1199	2.65

Table 2
Highest Posterior Density (HPD) intervals constructed from a Markov Chain Monte-Carlo sample (MCMC, n = 10,000) from generalized mixed linear models for crab catch for the 2012 and 2013 field season. Significance was assessed based on the HPD interval excluding zero, and is denoted by *.

Model	Parameter	Estimate	HPDI (95%)
2012			
treatment + site	intercept	0.66	(0.39, 0.93)*
	treatment(large)	0.16	(−0.18, 0.49)
	treatment(small)	−0.27	(−0.59, 0.05)
	site(MMR)	0.51	(0.12, 0.88)*
	site(NRM)	0.17	(−0.13, 0.46)
	site(OHS)	1.07	(0.70, 1.43)*
treatment + site + temp	intercept	0.89	(−0.12, 1.91)
	treatment(large)	0.15	(−0.16, 0.47)
	treatment(small)	−0.28	(−0.59, 0.00)
	site(MMR)	0.53	(0.14, 0.90)*
	site(NRM)	0.19	(−0.16, 0.51)
	site(OHS)	1.06	(0.69, 1.43)*
	temp	−0.01	(−0.05, 0.03)
site	intercept	0.74	(0.52, 0.95)*
	site(MMR)	0.31	(−0.01, 0.65)
	site(NRM)	0.17	(−0.16, 0.47)
	site(OHS)	0.86	(0.54, 1.14)*
2013			
site	intercept	0.24	(−0.04, 0.52)
	site	1.02	(0.72, 1.36)*
site + time	intercept	0.41	(0.04, 0.77)*
	site(OHS)	1.04	(0.71, 1.35)*
	time	−0.00	(−0.01, 0.00)
treatment + site	intercept	0.34	(−0.03, 0.64)
	treatment(large)	−0.20	(−0.55, 0.12)
	treatment(small)	−0.16	(−0.49, 0.21)
	site(OHS)	1.04	(0.69, 1.34)*
site + temp	intercept	0.07	(−2.46, 2.67)
	site(OHS)	1.03	(0.67, 1.34)*
	temp	0.01	(−0.10, 0.10)

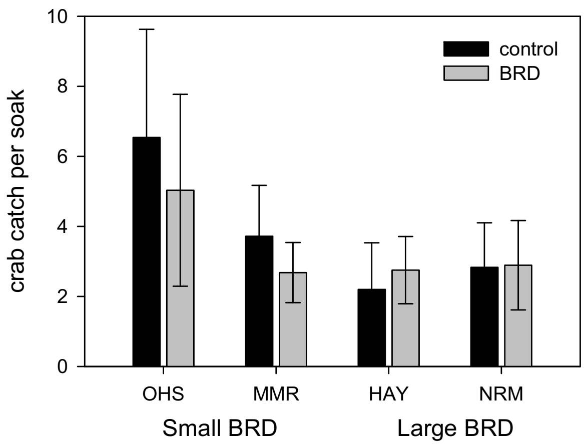

Fig. 3. Mean crab catch in control pots versus pots fitted with a large or small BRD during the 2012 field season. Pots were deployed in a paired design. Old House Slue (OHS) and Middle Marsh (MMR) contained pots with small BRDs versus control pots and Haystacks (HAY) and North River Marsh (NRM) contained pots with large BRDs versus control pots. BRDs do not have a statistically significant effect on crab catch. Models indicated that site had the strongest effect on crab catch.

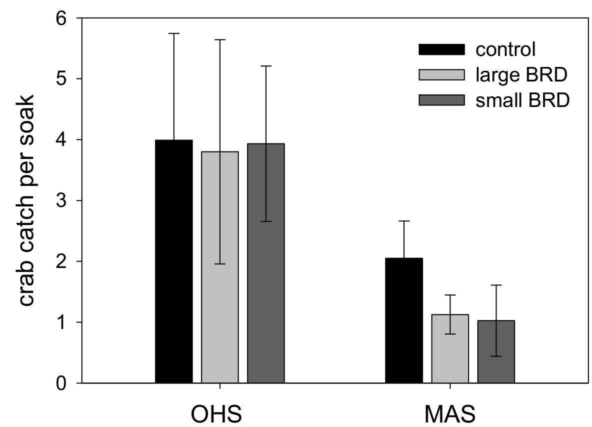

Fig. 4. Mean crab catch in control pots versus pots fitted with a large or small BRD during the 2013 field season at Old House Slue (OHS) and Masonboro Island (MAS). Pots were deployed in a triplicate design There was no statistically significant effect of BRDs on crab catch. Models indicated that site had the strongest effect on crab catch.

age water temperature during soak time ranged from 23.1–29.4 °C with a grand mean of 26.4 ± 1.7 °C.

Results of the generalized linear mixed models for the 2012 season showed the following three models best predicted crab catch; *treatment + site, treatment + site + temp,* and *site* (Table 1). The HPD intervals calculated from MCMC sampling indicated that *site* had the strongest effect on crab catch (Table 2). Pots deployed at Old House Slue caught the highest number crabs with 39% of the total crab catch. Pots deployed at Middle Marsh caught 23% of the total crab catch. The HPD intervals for *treatment* and *temp* encompassed zero, indicating no significant effect of these factors on crab catch. The mean crab catch in control pots was 2.5 ± 3.1, compared with 2.7 ± 2.1 in large BRD pots. The mean crab catch in control pots was 5.1 ± 3.8, compared with 3.9 ± 3.3 in small BRD pots. Although the models did not provide support for a significant effect of BRD size (*treatment*) on crab catch, there was a trend towards decreased crab catch with the smaller BRD compared with control pots (Fig. 3).

Results of the 2013 season indicated the models *treatment + site*, *site + time*, *site + temp*, and *site* were the best predictors of crab catch (Table 1). The HPD intervals for model estimates of *site* excluded zero (Table 2), which indicates this factor has a significant effect on crab catch. The HPD intervals for *treatment* included zero, indicating that BRDs did not significantly reduce crab catch (Table 2). At Old House Slue, the mean crab catch in control pots was 4.0 ± 2.7, compared with 3.8 ± 2.9 in large BRD pots and 3.9 ± 2.4 in small BRD pots (Fig. 4). At Masonboro the mean crab catch in control pots was 2.1 ± 1.5, compared with 1.1 ± 0.9 in large BRD pots and 1.0 ± 1.1 in small BRD pots (Fig. 4). The HPD intervals did not provide support for a significant effect of either *time* or *temp* on crab catch in 2013 (Table 2).

Results of the linear mixed models showed that models for the 2012 and 2013 field season including *treatment + site* and *treatment + site + temp* were the best predictors of crab size (Table 3). The HPD intervals for *site* did not include zero, indicating *site* had a significant effect on size of crabs captured (Table 4). The HPD intervals for *treatment* included zero indicating that BRDs did not have a significant effect on the size of crabs captured. The HPD intervals did not provide support for a significant effect of *temp* on crab size.

3.2. Terrapin catch

Over the course of the two field seasons 14 terrapins were captured, 12 females (mean mass 455.6 ± 146.2 g) and 2 males

Table 3
Model selection results for linear mixed model analysis of crab size during the 2012 and 2013 field season. Individual pot was included as a random effect in the models. Fixed factors in the full model included treatment (control, large BRD, or small BRD), site of deployment, soak time, and average temperature during soak time. Only best fit models (Δi < 2 and evidence ratios < 2.7) are presented.

Model	K	AICc	Δi	wi	Evidence Ratio
2012					
treatment + site	5	4637.356	0	0.5765	1.00
treatment + site + temp	6	4639.119	1.7631	0.2388	2.41
2013					
treatment + site	5	2318.756	0	0.3701	1.00
treatment + site + temp	6	2319.019	0.2631	0.3244	1.14

Table 4
Highest Posterior Density (HPD) intervals constructed from a Markov Chain Monte-Carlo sample (MCMC, *n* = 10,000) from linear mixed models for crab carapace width (size) for the 2012 and 2013 field season. Significance was assessed based on the HPD interval excluding zero, and is denoted by *.

Model	Parameter	Estimate	HPDI (95%)
2012			
treatment + site	intercept	10.59	(9.50, 11.67)*
	treatment(large)	0.46	(−0.7872, 1.68)
	treatment(small)	−0.66	(−1.92, 0.59)
	site(MMR)	2.43	(0.86, 3.95)*
	site(NRM)	0.70	(−0.54, 1.95)
	site(OHS)	2.87	(1.42, 4.47)*
treatment + site + temp	intercept	12.96	(6.04, 19.62)*
	treatment(large)	0.45	(−0.80, 1.72)
	treatment(small)	−0.67	(−1.90, 0.60)
	site(MMR)	2.65	(1.02, 4.28)*
	site(NRM)	0.95	(−0.52, 2.34)
	site(OHS)	2.79	(1.31, 4.35)*
	temp	−0.09	(−0.34, 0.18)
2013			
treatment + site	intercept	10.28	(8.91, 11.60)*
	treatment(large)	−0.19	(−1.59, 1.26)
	treatment(small)	−0.80	(−2.22, 0.58)
	site(OHS)	2.94	(1.62, 4.18)*
treatment + site + temp	intercept	9.45	(−9.72, 28.41)
	treatment(large)	−0.19	(−1.64, 1.20)
	treatment(small)	−0.80	(−2.23, 0.63)
	site(OHS)	2.96	(1.61, 4.30)*
	temp	0.03	(−0.70, 0.75)

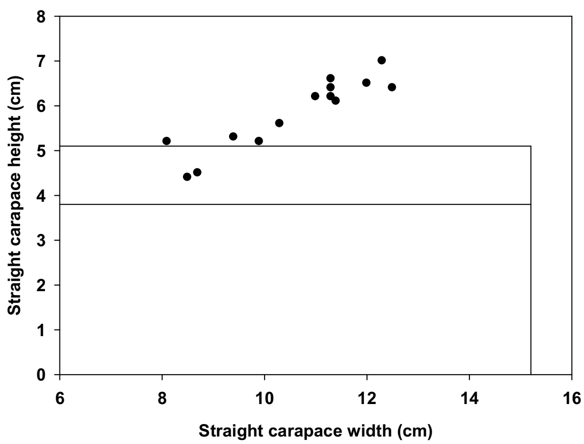

Fig. 5. Straight carapace width and height of captured diamondback terrapins plotted relative to the dimensions of the large and small BRDs. Two terrapins were small enough to fit into a pot fitted with a large BRD. Of these two, one was captured in a large BRD pot and the other was captured in a control pot.

(mean mass 208.0 ± 14.1 g). Mean SCW and SCH for females were 11.2 ± 1.4 cm and 6.2 ± 0.7 cm, respectively, and mean SCW and SCH for males were 8.6 ± 0.1 cm and 4.5 ± 0.1 cm, respectively. The SCW and SCH for all terrapins were plotted relative to the size of BRD configuration (Fig. 5). None of the terrapins captured were small enough to fit through the small BRD and consequently no terrapins were captured in small BRD pots. The two male terrapins were small enough to fit into pots with large BRDs (SCH of 4.4 cm and 4.5 cm) however, only one was found in a large BRD pot. The other male terrapin was captured in a control pot. Out of the 14 terrapins captured, there was 1 mortality. The mortality occurred in the 2013 field season and the terrapin was a small (335 g) female captured in a control pot. Masonboro had the highest rate of terrapin captures out of all of the sites with an average capture rate of 0.5 terrapins per pot per soak. Given the low number of terrapin captures, statistical comparisons were not performed with these data.

4. Discussion

Selection of appropriate BRD dimensions for use in blue crab fisheries has important implications for both terrapin conservation and the sustainability of blue crab harvest. Ideally, BRDs would be small enough to prevent all or most terrapins from entering a crab pot, but not so small that movement of blue crabs into the pot is impeded. Our study provides evidence that equipping crab pots with either 3.8 cm or 5.1 cm height BRDs does not significantly decrease the number or carapace width of legal-sized crabs captured in coastal North Carolina. While not considered statistically significant, the HPD intervals for the small, 3.8 cm height BRDs were marginal for crab catch in the 2012 field study (Table 2). The trend towards reduced crab catch in pots equipped with the small BRDs is in agreement with several other studies that have documented significant reductions in crab catch with BRD height dimension of less than 5.0 cm (Cole and Helser, 2001; Hart and Crowder, 2011; Roosenburg and Green, 2000; Upperman et al., 2014). BRDs with a slightly larger height of 4.5 cm may have less of an impact on crab catch rates (Cole and Helser, 2001; Butler and Heinrich, 2007; Roosenburg and Green, 2000), but conclusions regarding crab catch for this height dimension are equivocal (Upperman et al., 2014). Furthermore, the likelihood of capturing the smaller adult male and juvenile terrapins increases as the height dimension increases.

Based on SCH, none of the terrapins we captured were small enough to enter a pot equipped with small BRDs and, theoretically, 86% (12 out of 14) of the terrapins would be excluded from pots by the large, 5.1 cm height BRDs. Unfortunately, the two terrapins that were small enough to fit through the large BRDs were the only adult males captured during our study. This is a worrisome observation, given the evidence that entrapment in crab pots may selectively remove males from terrapin populations, thus skewing sex ratios over the long term (Dorcas et al., 2007). A study conducted in 2009 and 2010 (Harden et al., 2011) reported morphometric data for 34 terrapins at Bald Head Island, North Carolina, which is approximately 29 km from our Masonboro study site. The SCH of terrapins at Bald Head Island ranged from 4.2–7.3 cm with a mean SCH of 4.4 ± 0.2 cm for males and 6.4 ± 0.7 cm for females (Harden et al., 2011). When comparing these data to the dimensions of the BRDs tested in our study, small BRDs would have excluded 100% of the terrapins while large BRDs would have the potential to exclude only 47% of the terrapins at Bald Head Island. The largest male terrapin at Bald Head Island had a SCH of 4.8 mm, therefore all male terrapins sampled from that site were small enough to fit through the large BRDs. Observations from our study and Harden et al. (2011) suggest that use of large BRDs would not be effective at preventing directed capture of the adult male terrapins, which could lead to shifts in the demographic characteristics of terrapin populations (Dorcas et al., 2007). Given the potential for reduced crab catch with decreasing BRD height (Hart and Crowder, 2011; Roosenburg and Green, 2000), finding the optimal BRD dimensions for effectively preventing terrapin bycatch without negatively impacting crab catch rates remains a challenge. Based on morphometric data for terrapins sampled at various sites in North Carolina, we suggest additional testing of BRD dimensions with heights of 4.2–4.5 cm to ascertain whether a sufficient level of protection for adult male terrapins can be achieved while sustaining acceptable crab catch rates. Altering the orientation of the BRD in the entry funnel of the crab pot (i.e. vertical orientation instead of horizontal orientation) may also prove effective in excluding terrapins without impeding movement of crabs into the pot (Dorcas et al., 2007; Hart and Crowder, 2011). The efficacy of this simple modification should be further explored.

In our study, both crab catch and the carapace width of legal-sized crabs were most strongly affected by site (Tables 2 and 4), with crab pots fished at Old House Slue capturing more and larger crabs compared with the other sites. Rook et al. (2010) used generalized linear modelling and an information theoretic approach to evaluate the performance of crab pots equipped with 4.5 cm height BRDs in the Chesapeake Bay and, as in our study, found a strong effect of site but little to no effect of BRDs on crab catch or crab size. The site effect may reflect aspects of the natural history of blue crabs. Mating occurs in lower salinity estuarine areas from spring to late fall (Churchill, 1919; Millikin and Williams, 1984), and females travel to higher salinity areas to deposit eggs the following summer (Carr et al., 2004; Mense and Wenner, 1989). Of the five sites fished in our study, Old House Slue was the least sheltered and in close proximity to a major ocean inlet. The other three sites in 2012 were farther from inlets, and the additional site fished in 2013 was located on the Intracoastal Waterway. In both 2012 and 2013, crab pots fished at Old House Slue caught the most legal-sized crabs (Figs. 3 and 4) and 75% of these crabs were female. It is possible that Old House Slue is a spawning site for females and therefore a large number of crabs were present at the time of year (June) when we conducted our experiments.

The use of BRDs is often combined with spatial or temporal regulations to mitigate terrapin bycatch while causing minimal negative impacts on fishing operations. For example, the state of New York requires 5 cm height BRDs in specifically listed waters, and New Jersey requires 5 cm height BRDs in waters that are less than 45 m from the shoreline (Roosenburg, 2004; Upperman et al., 2014). Given the potential trade-off between terrapin exclusion and crab catch with decreasing BRD dimensions (Hart and Crowder, 2011; Roosenburg and Green, 2000; Upperman et al., 2014), a targeted approach to BRD regulations is more likely to be accepted by the fishing industry. Previous work has evaluated spatial overlap between diamondback terrapins and the blue crab fishery to determine the bycatch risk in southeastern North Carolina. Terrapins exhibit distinct seasonal trends in habitat utilization, such that the greatest degree of overlap with crabbing operations, and thus the greatest risk of bycatch, occurs in shallow (<3m), near-shore waters during the warm months when terrapins are most active (Harden and Williard, 2012). Terrapins appear to be particularly vulnerable to interactions with crab pots during the breeding months (April and May) when they are searching for mates and aggregating in breeding coves and creeks (Bishop, 1983; Hart and Crowder, 2011). Studies of terrapin distribution and abundance, habitat preferences, specific breeding sites, and seasonal activity patterns can provide fisheries managers with the data necessary to enact targeted BRD regulations, such as distance-to-shore and time-of-year restrictions (Hart and Crowder, 2011). A recent initiative by the North Carolina Coastal Reserve uses citizen science kayak surveys to document terrapin presence within the Masonboro Island Reserve boundaries. Expansion of this program to other regions could facilitate efforts to document terrapin presence and abundance, and provide information for managers to develop regional-specific strategies to reduce terrapin bycatch in commercial crab fisheries.

Overall, the capture rate for terrapins was low at all of our study sites, especially when compared to studies in other states. A similar study in the Chesapeake Bay recorded 71 terrapins from 30 unbaited modified crab pots over the course of 24 non-consecutive sampling days (Upperman et al., 2014). Rook et al. (2010) deployed 20 pots in a series of creeks in Virginia for 23 trapping days and captured 48 terrapins, 46 of which were found in control pots. As with our study, earlier work in North Carolina also found a low rate of terrapin capture (Hart and Crowder, 2011). Specific habitat characteristics and constraints on placement of modified crab pots may account for the low terrapin capture rates observed in North Carolina. Many of the tidal creeks and coves frequented by terrapins have narrow banks and high variation in water levels between low and high tide. To avoid mortality of terrapins captured in the course of our study, we placed crab pots in locations where a portion of the chimney would be exposed to air at all times (i.e. in water with a depth at high tide of less than 180 cm). It is also possible that the low terrapin capture rates simply reflect low terrapin abundance. Terrapin populations were severely impacted by commercial fisheries in the early 1900's (Carr, 1952; Gibbons et al., 2001) and we do not know the degree to which terrapin populations have recovered in coastal waters due to a lack of long-term monitoring.

5. Conclusions

Our data contribute to the growing body of evidence that BRDs are an effective tool for reducing terrapin bycatch, however, identification of a single BRD configuration that can sustain acceptable levels of crab harvest while effectively excluding all terrapins is difficult. We found that the large BRD configuration most likely to be accepted by fishers would not exclude adult male terrapins from crab pots in our region, which could contribute to changes in population demography over time. Gear modification via installation of BRDs as a stand-alone strategy is not likely to sufficiently address the issue of terrapin bycatch, particularly given the potential for reduced crab catch with the smaller BRD dimensions necessary to exclude adult male and juvenile terrapins. A multi-faceted approach that combines data on the spatial ecology and demography of terrapins with information on BRD efficacy may permit targeted mitigation strategies that accommodate regional differences in both terrapin and crab population characteristics. Incorporation of citizen science survey initiatives to document terrapin presence and abundance may facilitate development of management approaches to reduce bycatch and promote awareness and conservation of terrapins.

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