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Experiments with By-Catch Reduction Devices to Exclude Diamondback Terrapins and Retain Blue Crabs

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Abstract Experiments were completed in SE Virginia during June–July 2014 and 2015 to examine the responses of blue crabs (*Callinectes sapidus*) and diamondback terrapins (*Malaclemys terrapin*) to commercial-style crab pots modified in visual and other ways that might attract and retain crabs while excluding terrapins as by-catch. In a seawater tank, far fewer crabs entered crab pots fitted with red plastic by-catch reduction devices (BRDs), relative to pots without BRDs. Crab retention times, however, were significantly longer in pots fitted with red BRDs. In a second experiment, fewer terrapins entered crab pots with funnels painted red relative to black. From a field pilot study, the legal crab catch from pots with red BRDs was similar to pots without BRDs, and terrapin by-catch was reduced. Relative to those treatments, fewer crabs and more terrapins were captured in pots with orange BRDs and blue BRDs, and in pots with a magnetic field directed into the funnel openings. Based on these results, a final field trial yielded comparable crab catch from 15 pots without BRDs and 15 pots fitted with red plastic BRDs. Of a by-catch of 68 terrapins, 58 were from pots without BRDs. The structure and color of BRDs can exclude most terrapins; because crab retention rates are high, the net effect of BRDs on crab catch is relatively minor, even though fewer crabs may enter pots fitted with BRDs.

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Introduction

The Atlantic and Gulf Coast blue crab (*Callinectes sapidus*) fishery in recent years has yielded over 60,000 t annually (https://www.st.nmfs.noaa.gov/commercial-fisheries/index), and this crab harvest poses a substantial risk to diamondback terrapin populations (Roosenburg 2004). Although most of the commercial crab catch is taken in open water away from shore, a portion of commercial crabbing activity and a majority of additional, recreational crabbing take place in shallow water close to shore (Hoyle and Gibbons 2000). This subset of the crab fishery deploys commercial-style crab pots near marshes, in tidal creeks, or from private or public docks. Diamondback terrapins (*Malaclemys terrapin*) live in near-shore estuarine habitats, and frequently drown as by-catch, trapped in the pots set in these habitats (Butler et al. 2006). In just a single year, crabbing had the potential to reduce local terrapin populations in two tidal systems studied in Maryland and Virginia by an estimated 15–78% (Roosenburg et al. 1997; Upperman et al. 2014). Unchecked and lost or abandoned (derelict) pots may be particularly troublesome for terrapins (Havens et al. 2008), as ~20% of commercial pots are lost by commercial crabbers each year (Bilkovic et al. 2014), and Grosse et al. (2009) found a single unchecked crab pot in a Georgia marsh creek that contained 94 dead terrapins. Terrapin populations are vulnerable or imperiled in eight states with significant blue crab fisheries (Bishop 1983; Wood 1997; Hoyle and Gibbons 2000; Roosenburg 2004; Butler and Heinrich 2007; Dorcas et al. 2007; Rook et al. 2010).

Conservation efforts to reduce the drowning of terrapins in crab pots have included the development of different versions

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of by-catch reduction devices (BRDs) (Hart and Crowder 2011; for a general description of BRDs, see http://www.vims.edu/research/units/projects/terrapin_brds/_docs/terrapin_bdr_brochure.pdf). These exclusion-type devices (Wood 1997) are simple wire or orange plastic inserts that narrow the funnel openings into crab pots, thereby preventing terrapins from entering the pots (Roosenburg and Green 2000). Crabs, which have a smaller dorso-ventral dimension than most juvenile and adult terrapins are still able to enter pots. To date, two slightly different BRD sizes have been incorporated into by-catch regulations in New York and New Jersey (5.1 × 15.2 cm) and Maryland, Delaware, and Virginia (4.5 × 12.0 cm). The results from a number of published studies investigating crab catch and terrapin by-catch in pots with and without BRDs have been equivocal: terrapin by-catch generally is reduced with BRDs, but the impact of BRDs on crab catch (both number and size) varies for reasons that may include different behavioral responses of crabs and terrapins throughout the range of the studies completed (New York to Texas; summarized by Chambers and Maerz 2017). In terms of size, most crabs are capable of easily passing through BRDs, but some studies have documented fewer crabs are captured in pots fitted with BRDs (e.g., Coleman et al. 2011; Hart and Crowder 2011; Upperman et al. 2014), suggesting a negative behavioral response by crabs to BRDs.

Both blue crabs and terrapins are able to detect color, so their behaviors around crab pots could be influenced by funnel or BRD color and perhaps other factors in addition to the physical narrowing of the funnel opening caused by BRDs. For example, blue crabs have a dichromatic visual system, with photoreceptors peaking in the blue (440 nm) and green (508 nm) portions of the electromagnetic spectrum (Baldwin and Johnsen 2012). Male blue crabs respond positively to the color red over orange, perhaps a sexually selected trait for mating because female crab claws are colored red (Baldwin and Johnsen 2009, 2012). Likewise, terrapins have a tetrachromatic visual system with photoreceptor peaks in the UV (356 nm), blue (427 nm), green (572 nm), and red (630 nm) portions of the electromagnetic spectrum (Dominy 2015). Visual cues used by crabs or terrapins around crab pots, however, have not been considered important, since chemical attractants (from bait or pubertal-molt female "peeler" crabs) and physical structures (funnels with and without BRDs) seem the more obvious factors influencing crab catch and terrapin by-catch. Another unstudied cue could be magnetic fields, as some sea turtles use the Earth's electromagnetic field for long-distance navigation to their natal beaches (Brothers and Lohmann 2015). If terrapins can detect magnetic fields, then a magnetic cue might trigger a deterrent response. No one has investigated, however, whether magnetism affects small-scale terrapin movements around crab pots.

For the current study, we investigated responses of blue crabs and terrapins to different modifications of commercial-style crab pots to determine what features are associated with enhanced crab catch and terrapin exclusion. In a seawater tank experiment to test crab retention, we compared crab movements into and out of unbaited crab pots fitted with and without red plastic BRDs. We also completed a short laboratory study monitoring terrapin behavior around crab pots with different funnel modifications (color and magnetic field), to determine whether terrapins could be behaviorally excluded from pots without the use of an inserted BRD to physically impede their entrance. We then conducted a pilot study of crab catch and terrapin by-catch in the field, comparing pots without BRDs with pots fitted with different colored BRDs and other modifications including magnets and BRD material (wire or plastic) that might affect the catch. Based on those outcomes, we then completed a more directed field study comparing crab catch and terrapin by-catch in pots without BRDs and pots fitted with red plastic BRDs.

Methods

Study Areas

All seawater tank experiments were conducted in an indoor tank at the Virginia Institute of Marine Science (VIMS) Seawater Research Laboratory in Gloucester Point, VA. The tank was 1.2 m deep by 4.5 m in diameter and filled with 10 μm filtered brackish water (salinity ~22 at 18 °C) from the York River. The tank received indoor lighting daily from 6:00 to 20:00 averaging 380 ± 142 lx.

For field experiments, most crab pots were deployed at Indian Field Creek and Felgates Creek in the Yorktown Naval Weapons Station, VA (37.2667 N, −76.5850 W). Indian Field and Felgates Creek are both tidal marsh tributaries of the York River. Additional crab pots for field experiments were deployed in Assawoman Creek in a polyhaline tidal marsh on the Eastern Shore of VA (37.816467 N, −75.510047 W).

Crab Response to BRDs

Sixty male and female crabs (carapace width ≥ 12.7 cm, the legal size of marketable crabs) were captured from the York River and brought to the VIMS seawater tank from 1 to 17 June 2015. The crabs were numerically tagged for identification and kept in the tank for no longer than a week. We filmed the movements of crabs into and out of unbaited pots fitted with or without red BRDs, to test whether the decreased size of the funnel opening caused by the BRDs would influence crab entry and exit. Unbaited pots were used to avoid confounding effects of chemical cues from the bait. For the experiment, four identical, galvanized wire crab pots were placed in the tank; two were fitted with red plastic BRDs placed horizontally in each of the four funnel openings and two non-BRD pots were left unmodified. Holes in the tops of all pots allowed crabs to exit if they did not move back out through the funnel openings. This arrangement allowed crabs to make repeated entries into pots. Crab activities were filmed during daylight hours via four cameras mounted above each pot over the tank. Video reviewers recorded each time a crab entered a pot as a capture and measured the total amount of time each crab spent in the trap once captured. The average time crabs spent in pots prior to exiting via a funnel opening in the BRD or non-BRD pots was compared using a *t* test.

Terrapin Response to Funnel Modification

To test whether terrapins might use visual cues and would be excluded from pots without the use of a size restricting BRD, we filmed the behavior of terrapins with respect to different colors of entry funnels in crab pots and to a magnetic field placed around the funnels. For this experiment, two galvanized wire crab pots were placed in the VIMS seawater tank. The "control" pot had funnels painted black. The "experimental" pot had funnels painted red, orange, green, or blue (sprayed on with Performix Plasti-Dip©). We also modified an experimental pot with black funnels by placing a ring of ceramic magnets around each of the four funnels, creating a magnetic field directed into the funnel opening (magnetic flux = 50G). Holes were cut into the tops of all pots to allow trapped terrapins to exit the pots if they did not move back out the funnel openings.

For each of 3 weeks, groups of two, four, or five male terrapins were captured in the field, numerically tagged for identification and added to the VIMS seawater tank with the control and experimental pots. Male terrapins are smaller than female terrapins and thus are more susceptible as by-catch. On consecutive days each week, terrapins were exposed to each of the five experimental treatments selected in random sequence (four colors of funnels plus the magnetic field funnels). Terrapins were filmed for 24 h in each treatment via two cameras mounted above each pot over the tank. After 5 days of exposure to each of the five experimental treatments, the terrapins were released at the point of capture. The per-terrapin entry rates into experimental pots were compared with entries into control pots using a *t* test.

Pilot Field Experiment

The pilot field experiment was conducted on 12 June–2 July 2014. To test responses to funnel modifications, we compared crab catch and terrapin by-catch in baited pots grouped with the following six treatments: pots with orange, red, or blue plastic BRDs (the 5.1 × 15.2 cm TopME Products© BRDs are orange; red and blue BRDs were created by dipping the orange BRDs in Performix Plasti-Dip©); pots with wire BRDs (5.1 × 15.2 cm, 11-gauge copper wire); pots with magnetic field funnels; and pots with unmodified funnels. Holes cut in the top corners of all pots were fitted with 120-cm-tall chicken wire "chimneys" to prevent any trapped terrapins from drowning. Pots with attached chimneys were tied to tall wooden stakes for stabilization in flowing tidal water. Within groups, pots were separated by at least 5 m. At Felgates Creek, three groups of the six treatment types were deployed at least 50 m from each other at different locations along the creek. At Indian Field Creek, two groups were deployed, one with the six treatment types and another with only five treatment types (lacking the magnetic field treatment).

Crab pots were deployed at an approximate depth of ~180 cm at MHW, which is representative of the shallow depth of most recreational and some commercial crabbing in tidal creeks (Rook et al. 2010; Morris et al. 2011). Light penetration, measured by Secchi depth, was always <200 cm. All pots were baited with Atlantic menhaden (*Brevoortia tyrannus*) or Atlantic croaker (*Micropogonias undulates*) each Monday and Wednesday during the experiment. The traps were cleared of crab catch and by-catch Tuesday–Friday of each week (pots were left open and unbaited on weekends). All captured crabs were sexed and their carapace widths (point-to-point) were measured. Captured terrapins were sexed, and the dorso-ventral thickness was measured prior to release.

Directed Field Experiment

The second field experiment took place from 5 June to 10 July 2015. We compared crab catch and terrapin by-catch using a funnel modification based on the results of the pilot field experiment. Fifteen pots were fitted with red plastic BRDs (painted with marine grade Rustoleum© Topside Paint). An additional 15 crab pots with unmodified funnel openings served as non-BRD pots. All pots were fitted with chimneys to prevent any trapped terrapins from drowning. We deployed six pairs of red BRD and non-BRD pots at Felgates Creek, six pairs at Indian Field Creek, and three pairs at Assawoman Creek. All pots were tethered, baited, and data were collected using the same methods as for the pilot field experiment.

Results

Crab Response to BRDs

We watched over 100 h of video and monitored the movements of crabs into and out of pots through unmodified funnels (non-BRD) or through funnels fitted with red BRDs. With equal access, more crabs were recorded entering non-BRD pots (131) than BRD pots (73) (*t* test, $df = 6$, $t = 2.42$,

$p = 0.026$). On average, however, crabs entering pots with BRDs remained in the pots for almost 8 h compared to <2 h for crabs entering pots without BRDs. For non-BRD pots, 35 of 131 entries led to rapid exit back out a funnel opening within 2 min, whereas no crabs entering BRD pots exited within 2 min. Some crabs that entered pots stayed throughout the day of recording (7.6% of crabs entering non-BRD pots; 34% of crabs entering BRD pots). To satisfy the Kolmogorov-Smirnov goodness-of-fit test for normality ($p > 0.05$), these extremes in retention time (i.e., < 2 min or >13.45 h) were removed from the dataset and the remaining data were log-transformed. With this smaller, more conservative dataset, the average time spent in BRD pots (4.3 ± 0.9 h; $N = 45$) was still significantly longer than time in non-BRD pots (1.3 ± 0.4 h; $N = 76$) (t test, $df = 119$, $t = 4.34$, $p < 0.01$).

Terrapin Response to Funnel Modification

After reviewing 24-h videos of terrapin activity around pots with different funnel modifications, we documented strong variation in day-night behavior. From 271 h of daytime video, we recorded 520 terrapin movements into crab pots; from 139 h of nighttime video, we recorded only 65 terrapin movements into crab pots. Terrapins were much more active by day, suggesting that terrapins might respond to visual cues such as color.

From the review of daytime activity, terrapins exhibited some response to funnel modification, relative to pots without modification (Fig. 1). On average, the “capture rate” of terrapins (i.e., movement into pots, normalized terrapin^{-1} h^{-1}) was lowest for red funnels relative to unmodified black funnels (paired t test, $df = 5$, $t = 2.68$, $p = 0.04$). The highest rate of terrapin capture was in pots with green funnels, although none of the other modifications (orange, green, or blue color; magnetic field) yielded capture rates significantly different from unmodified black funnels.

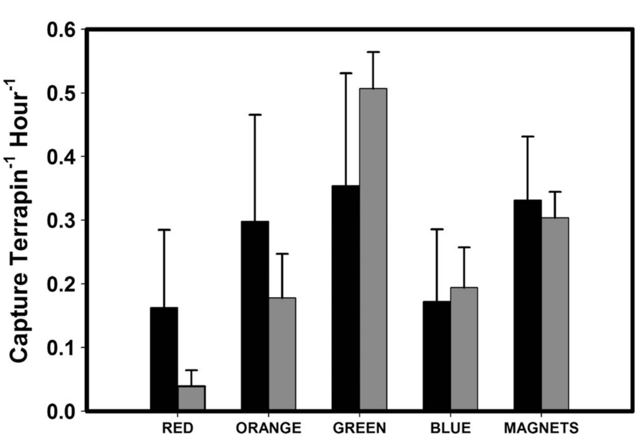

Fig. 1 Paired comparisons of terrapin capture rates (average number of entries terrapin^{-1} h^{-1} ± SD) in pots without modification (*black bars*) and pots with modified funnels (*gray bars*: colors or magnetic field)

Pilot Field Experiment

From the groupings of six crab pot treatment types in the field, a total of 327 trap days were recorded, with the capture of 1020 blue crabs. Of these, 19 were legal-sized female crabs and 445 were legal-sized male crabs ≥12.7 cm. In addition, 82 terrapins were caught as by-catch, with the most in pots without BRDs (20) and in pots fitted with wire BRDs (22). We found that the 11-gauge wire used to make the BRDs was not sufficiently rigid to maintain shape and was pressed outward by terrapins passing through the funnels. The average shell height of terrapins entering wire BRD pots was 5.5 ± 1.1 cm ($N = 22$), significantly greater than 4.8 ± 0.2 cm for pots fitted with plastic BRDs ($N = 25$) (t test, $df = 45$, $t = 3.47$, $p < 0.01$). Among the other treatments, the lowest by-catch of terrapins was from pots fitted with red BRDs (3), with greater terrapin by-catch in orange BRD (9), blue BRD (13), and magnetic field (15) pots. Owing to the large daily variation in by-catch within each of the six treatment groups, however, these differences were not significant (ANOVA, $F_5 = 0.864$, $p = 0.53$).

From the summary of legal crab catch and terrapin by-catch per unit effort (CPUE, catch pot^{-1} day^{-1}), pots fitted with red plastic BRDs had a lower terrapin by-catch without affecting crab catch, relative to pots without BRDs (Fig. 2). No differences in crab CPUE among treatment groups were significant (ANOVA, $F_5 = 1.819$, $p = 0.11$).

Directed Field Experiment

Over the 5 weeks of directed study comprising a total of 588 trap days, we captured 1164 crabs in pots with red plastic BRDs and1140 crabs in pots without BRDs. The size distribution of captured crabs was similar, 7.1–18.7 cm, in non-BRD pots and 6.0–17.5 cm in red BRD pots (Fig. 3; Kolmogorov-Smirnov two-sample test, $Z = 0.958$, $p = 0.188$). In all three creeks where the study was conducted, the male/female crab ratio was higher in pots with red BRDs (Table 1). The number of legal crabs (carapace width ≥ 12.7 cm) was almost identical in BRD pots and non-BRD pots (622 vs 630, respectively). The average carapace width of marketable crabs captured in non-BRD pots, however, was 1 mm larger, relative to pots fitted with red BRDs (14.0 ± 1.0 vs 13.9 ± 0.9 cm, respectively, t test, $df = 1250$, $t = 2.07$, $p = 0.04$; Fig. 4). The four largest crabs captured were from pots without BRDs. Of 68 terrapins caught as by-catch during the study, 58 were from pots without BRDs.

Discussion

By-catch reduction devices on commercial-style crab pots, irrespective of color, appear to have a singular effect on crab movements by altering traffic flow. Pots without BRDs in the funnel openings allow for somewhat unrestricted movements

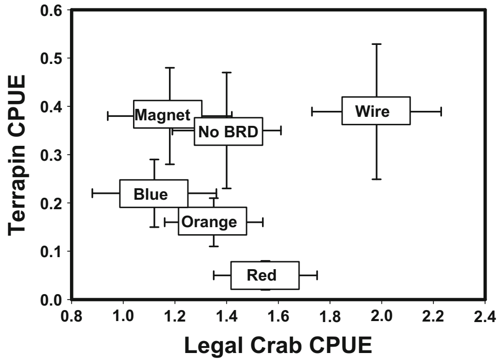

Fig. 2 Comparison of average legal crab catch and terrapin by-catch per unit effort (catch pot^{-1} day^{-1} ± SD). Results from pots without modification (no BRD) were compared with pots with wire BRDs, pots with magnetic field funnels, and pots with blue, orange, or red plastic BRDs

of crabs in and out of pots. In our tank experiment, a larger number of crabs moved into unbaited pots without BRDs but then moved back out again fairly quickly. From a prior study in the Chesapeake Bay estuary, blue crabs moved relatively freely into and out of the lower chamber of standard baited crab pots without BRDs (Sturdivant and Clark 2011). For our unbaited pots fitted with BRDs, a smaller number of crabs moved into the pots, but an even smaller number of crabs moved back out over time. The increased crab retention time in pots with BRDs was significant even based on a reduced sample size, i.e., for the statistical comparison, we removed the short retention times of crabs from pots without BRDs and the long retention times

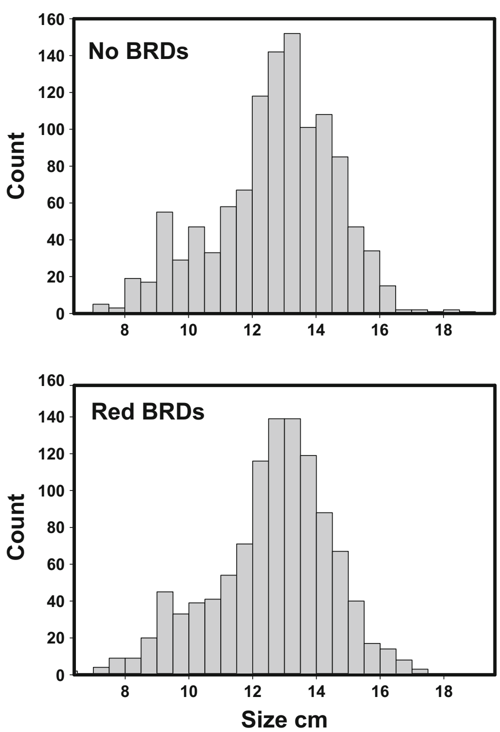

Fig. 3 Size-frequency distribution of all crabs captured in the directed field experiment comparing pots with no BRDs (N = 1140) and pots with red plastic BRDs (N = 1164)

Table 1 Male/female sex ratios of all crabs captured during the directed field experiment in Virginia tidal creeks comparing pots fitted with red plastic BRDs and pots with no BRDs

Sampling creek	Red BRDs	No BRDs
Felgates (N = 696)	9.7	8.1
Indian field (N = 1354)	8.5	5.9
Assawoman (N = 254)	10.5	6.4

of crabs from pots with BRDs. We would expect increased traffic flow into both BRD and non-BRD pots and even longer retention times if the pots were baited.

With crab bait used in our directed field experiment, the net effect of “fewer in—even fewer out” caused by BRDs was that about equal numbers and sizes of crabs were caught and retained by pots with and without red BRDs (Fig. 3). From a catch of over 1200 legal-sized crabs in our study, the four largest were from pots without BRDs (Fig. 4). These crabs may be the most valuable economically but the fishery cannot be managed effectively with a focus on the few crabs that make up <0.5% of the total catch, especially if the external costs of pots without BRDs include the drowning of so many terrapins. The effect of red plastic BRDs on crab catch was minimal, relative to their conservation value in reducing terrapin by-catch.

Results from the pilot field study, however, caution that BRDs made of wire instead of plastic must be of a heavy enough gauge to maintain sufficient rigidity to exclude most terrapins (Fig. 2; see http://www.vims.edu/research/units/projects/terrapin_brds/_docs/terrapin_bdr_brochure.pdf). Our wire BRDs allowed many larger terrapins into pots, although the crab catch from pots with wire BRDs was higher than without BRDs, a result also seen by Guillory and Prejean (1998) in Louisiana.

In the pilot field study, crab catch was not reduced in pots fitted with red BRDs (Fig. 2). In the directed field study, legal crab catch was almost identical numerically, but crabs had a significantly smaller carapace width, albeit by just 1 mm, in pots with red BRDs. Using the equation by Miller et al. (2011) to calculate the wet weight of male crabs based on size, this 1-

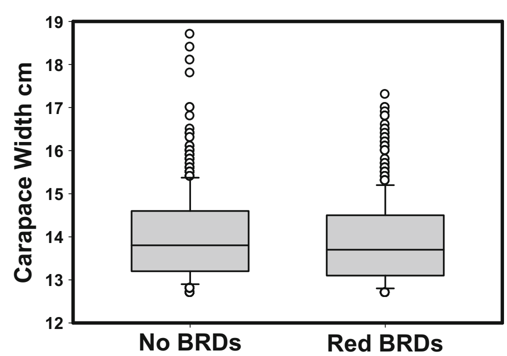

Fig. 4 Box plots of legal crab sizes for captures from pots with no BRDs (N = 630) and pots with red plastic BRDs (N = 622)

mm difference translates into crabs that are on average 3 g lighter (~ 2% of total crab weight). For a bushel of crabs (~72) with an average carapace width of 13.9 cm, the bushel wet weight would be 216 g lighter than a bushel of crabs at 140 mm average width. We conclude that red plastic BRDs do not strongly impact the crab catch.

Male crabs may be attracted to red (Baldwin and Johnsen 2009), so that even though fewer crabs might physically enter pots fitted with red BRDs relative to pots without BRDs, they did enter at a higher frequency than with blue or orange BRDs (Fig. 2), perhaps in search of females. Supporting this conclusion, the ratio of total male/female captures from all three creeks in the directed study was higher in pots with red BRDs, relative to pots without BRDs (Table 1).

Do terrapins respond to color? Terrapins may have some aversion to red, but we did not test this specifically. We demonstrated that terrapins are visual, are more active by day, and did not pass through red funnels in crab pots as much as through black funnels. Terrapins tended to enter pots with green funnels more frequently—a potentially poor choice for pot color in terrapin habitat (Fig. 1). Additionally, in the pilot study in the field, fewer terrapins were caught in pots fitted with red BRDs (Fig. 2), which is in part why the directed field study focused on comparing pots with and without red plastic BRDs. Dominy (2015) suggested that the ability of terrapins to detect color contrasts between shell and skin may lead to nonrandom mating, and that other terrapin behaviors could be influenced by other visual signals in the light environment of the estuarine water column. We suggest that red BRDs might exclude more terrapins than other colors of BRDs. All of our experiments were completed with BRDs placed horizontally in crab pots, though McKee et al. (2015) suggest that BRDs should be oriented vertically in the funnel openings to reduce terrapin by-catch without affecting crab catch.

Despite our results suggesting that male crabs are attracted to red BRDs and terrapins might avoid red BRDs, we know that there are certain caveats to these recommendations. Red light is absorbed quickly in water, so that what appears red to organisms in shallow, nonturbid water may not be perceived as red in deeper water or in the typically turbid waters of estuaries. We have not investigated what crabs and terrapins “see” at different depths and in different turbidity conditions. Further, both crab pots and their attached BRDs become biofouled within days of deployment. In our field studies, all pots were scrubbed at regular intervals to remove bio-deposits, expose the BRD colors, and maintain experimental conditions. Thus, although we documented an effect of color in our tank experiments and field studies, we suspect the greater effect of BRDs on crab retention and terrapin exclusion is related to the restricted size of the funnel opening created by the BRDs and its impact on ingress and egress (Guillory and Prejean 1998). Additional work is needed to determine the perception of and response to colors by crabs and terrapins.

Our study argues for the use of red BRDs to assist with management of the blue crab fishery and conservation of the diamondback terrapin. By-catch reduction devices clearly reduce terrapin by-catch, and in many studies, legal crab catch is not affected (Chambers and Maerz 2017). The cost of the terrapin conservation benefits ($0.50 per BRD or $2 per pot) are borne by the crabber who purchases and installs BRDs or who buys pots with BRDs preinstalled. For recreational crabbing, which typically occurs in shallow tidal creeks and embayments where terrapins live, BRDs should be compulsory. Commercial crabbers, who may seasonally follow crabs into these same shallow systems (Harden and Williard 2012), should likewise be required to have BRDs on their pots. Pots with BRDs installed will have less by-catch of terrapins, whether the pots are active, abandoned, or derelict. Given the amount of derelict crabbing gear in estuaries (Havens et al. 2011; Bilkovic et al. 2014), this would be a great benefit. Because crabs are more likely to be retained in pots with BRDs, however, the inclusion of biodegradable panels on pots (Bilkovic et al. 2012) would ensure that caught crabs eventually would have an escape from derelict crabbing gear.

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