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Lethal and sublethal effects of simulated dredged sediment deposition on overwintering blue crabs *Callinectes sapidus*

Gabrielle G. Saluta*, **Gina M. Ralph, Kathleen E. Knick, Michael S. Seebo, Romuald N. Lipcius**

Virginia Institute of Marine Science, William & Mary, Gloucester Point, Virginia 23062, USA

ABSTRACT: Regular maintenance of waterways and ports requires dredging and disposal of accumulated sediment, which can injure or kill infaunal and epifaunal species. Our understanding of the lethal and sublethal effects of dredged sediment deposition in marine communities is based predominantly on benthic infaunal species, whereas knowledge of the effects of these additions on mobile macrofauna is limited. We explored lethal and sublethal effects of simulated dredged sediment (hereafter, sediment) on blue crabs *Callinectes sapidus*. Twenty mature female crabs were allocated into 4 treatments: no sand, no sediment; sand, no sediment; sand + 2.5 cm sediment; and sand + 10.0 cm sediment. Accounting for size, mortality in the 10 cm sediment treatment was immediate and 10- to 20-fold higher than that in other treatments. Crabs that eventually died also experienced sublethal effects as evidenced by a reduced behavioral repertoire. These results suggest that in winter, all mature female crabs will suffer high mortality under 10 cm of dredged sediment deposition, while smaller crabs may suffer substantial mortality and sublethal effects at even lower levels. As blue crab activity is temperature dependent, the detrimental effects can be minimized by disposing of dredged sediment either where crabs are not abundant or when water temperatures are higher and blue crabs can avoid burial.

KEY WORDS: Anthropogenic sedimentation · Sediment disposal · Disturbance · Chesapeake Bay · Benthos

1. INTRODUCTION

Coastal communities and economies rely on the regular maintenance of waterways to ensure safe navigation. The dredging of these waterways requires the disposal of significant volumes of accumulated sediment, with limited large-scale estimates of total dredged sediment available. Estimates at regional, country, and local scales are highly variable. For example, in Europe, 200 million m^3 of sediment are estimated to be dredged annually (Renella 2021), while estimates from the OSPAR region (including 15 governments along Europe's northeast Atlantic coast) range from 140 to 152 million m^3. In the USA, over 152 million m^3 of sediment was dredged annually between 2008 and 2012 (USACE 2015). The disposal of this sediment must include cost, environmental, and technical feasibility considerations (RMC Pty Ltd 2014, USACE 2015). Uncontaminated sediments can help stabilize shorelines, serve as a habitat restoration resource (e.g. underwater grasses, wetlands), and serve as a suitable alternative material for reuse on land, such as landfill cover (MDE 2017).

In addition to these accepted land-based uses, substantial volumes of dredged sediment are deposited

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*Corresponding author: gsaluta@vims.edu

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at uncontained, open-water placement sites in diverse aquatic environments, from rivers to offshore (RMC Pty Ltd 2014, USACE 2015). The most obvious effect of non-toxic dredged sediment disposal is burial of benthic infaunal and epifaunal species. Recovery time of a population from localized 100% mortality is variable; in previously stressed environments harboring opportunistic species, full recovery can occur after 9 to 24 mo, while in unspoiled areas where long-lived species occur, it can take up to 4 yr (Bolam & Rees 2003). For example, recovery based on single-species and community data occurred within a year in Corpus Christi Bay, USA, compared with benchmarks relative to pre-disturbance conditions and nearby undisturbed areas (Wilber et al. 2008). Relatively rapid recovery of benthic communities after dredged sediment deposition events have also been documented in other dynamic or disturbed locations, such as near Itajaí Harbour, Brazil (Vivan et al. 2009); Emilia-Romagna, Italy (Simonini et al. 2005); and Port Nelson, New Zealand (Roberts & Forrest 1999). However, while some components, such as specific species or suites of species, may recover rapidly, full recovery of ecosystem functioning in areas with historically persistent high degradation can take a minimum of 15 to 25 yr (Borja et al. 2010). The temporal scale and quantity of material deposited also contribute to recovery potential: large, annual deposits may not allow a system to recover, whereas smaller, less frequent deposits may not prevent quick recovery (Bolam 2012).

The thickness of accumulated dredged sediment and mobility of species are major factors in overall recovery; e.g. some species can avoid burial by moving vertically through the sediment during a deposition event (Roberts et al. 1998). Thus, distributing dredged sediment in thin layers, typically no more than 15–30 cm thick, was proposed to minimize negative consequences to most species in the benthic community (USEPA & USACE 2004). Recovery from (i.e. resilience) this type of dredged sediment disposal can be quicker; e.g. 3–10 mo (Wilber et al. 2007). However, species-specific responses are a function of burial depth, sediment bulk density, and intrinsic characteristics, such as motility and position in the benthos (Kukert & Smith 1992, Hinchey et al. 2006, Schaffner 2010).

Knowledge of the effects of dredged sediment deposition on more mobile fauna, however, is limited, as these species may simply leave the area. For example, based on field observations, thin-layer disposal (2.5–25 cm) only temporarily displaced active Dungeness crabs *Metacarcinus magister*, which returned to the deposition site within 20 min (Roegner et al. 2021) to 55 min (Fields 2016). Model-based estimates of the physical forces associated with sediment disposal on Dungeness crabs suggest that the crabs are unlikely to be severely impacted by compression forces or surge currents (Pearson et al. 2006). Instead, at high disposal overburdens, buried crabs may be unable to maintain respiratory currents that bring oxygenated waters to the gills and subsequently suffer mortality (Chang & Levings 1978, Pearson et al. 2006). In laboratory experiments, Dungeness crab mortality occurred at deeper burial depths, with nuanced responses dependent on crab size and gender (Chang & Levings 1978, Vavrinec et al. 2007).

In Chesapeake Bay, USA, with its naval installations and major shipping ports, dredging and dredged sediment disposal are crucial. In lower Chesapeake Bay, at least 5 sites have been used historically for open-water dredged sediment deposition (Thimble Shoal, Naval Channel, Wolf Trap, Rappahannock Shoal, and York River; depths of approximately 6–22 m); 2 additional nearby sites (Wolf Trap alternate and Rappahannock Shoal alternate; average depths of approximately 12 m) were designated in the mid-1980s based on environmental and biological considerations (Zappi et al. 1990, Palermo et al. 1993). Environmental windows, when dredging and dredged sediment deposition activities are limited to specific times of the year, are often requested as part of the permitting process to minimize environmental impacts. The result of multiple window restrictions often limits dredging activities to winter months, when biological activity is lower (Reine et al. 1998).

The commercially and ecologically important blue crab *Callinectes sapidus* is widely distributed in benthic habitats throughout Chesapeake Bay, from shallow waters to deeper channels (Hines 2007). Unlike the Dungeness crab, the blue crab reduces movement, feeding, and growth at cold water temperatures (Van Engel 1958, Brylawski & Miller 2006, Smith & Chang 2007). In Chesapeake Bay, growth is inhibited at temperatures below 9.8–10.8°C (Smith 1997, Brylawski & Miller 2006); locomotor activity is reduced below this threshold and ceases by about 5.5°C (Van Heukelem & Sulkin 1990). Thus, dredged sediment deposition in Chesapeake Bay when temperatures are below these thresholds may increase mortality of overwintering blue crabs. However, the effects of dredged sediment deposition on blue crab survival have not been documented anywhere along its range, and only a few studies have been conducted on other decapod crustaceans (Reine et al.

1998). Therefore, we conducted a mesocosm experiment to evaluate lethal and sublethal effects of simulated dredged sediment deposition (i.e. sediment) on overwintering blue crabs.

2. MATERIALS AND METHODS

2.1. Sediment and blue crab collection

We collected sediment by hand from the York River, at approximately 0.5 m depth, adjacent to the Virginia Institute of Marine Science (VIMS), Gloucester Point, Virginia, USA. This area is characterized by a high percentage of sand (>90%; J. Patel unpubl. data). As blue crabs bury with only eyestalks visible in the field (Hay 1905), 3.5 cm of base-layer muddy sand (hereafter, sand) was added to both sediment treatments and one of the control treatments. Newly exposed muddy sand is subject to microbial decomposition of organic material, increasing oxygen demand and resulting in hypoxic conditions; thus, the base layer was allowed to settle for 6 d, ensuring the return of ambient dissolved oxygen (DO) levels (8–10 mg l^{-1}). The remaining sediment sat in open containers to simulate barge storage during the settlement period, and then served as a surrogate for dredged sediment.

Mature female blue crabs (non-ovigerous) measuring 127 to 159 mm carapace width (CW) were collected on 9 February 2017 from the mainstem of Chesapeake Bay from Poquoson Flats to Wolf Trap Lighthouse (37.2–37.4° N) as part of the annual blue crab winter dredge survey (WDS); for further details on the survey methodology, see Sharov et al. (2003). The study was limited to mature female crabs because they compose over 90% of all crabs residing in the dredge spoil disposal sites in winter (Lipcius & Stockhausen 2002, Sharov et al. 2003). Crabs were aerated during transport to VIMS and acclimated in a large outdoor, flow-through holding tank.

2.2. Experimental design

To evaluate the effects of dredged sediment deposition, we developed 4 treatments: 2 experimental treatments (sand + 2.5 cm sediment, and sand + 10.0 cm sediment) and 2 control treatments (no sand, no sediment; and sand, no sediment). The 2 sediment treatments were based on the midpoints of previous low- and medium-deposition treatments (Schaffner 2010) and are below the threshold (sediment depth <15 cm) for thin-layer disposal (Wilber et al. 2007). Both sediment treatments had a base sand layer to mimic ambient conditions (i.e. sand + 2.5 cm sediment and sand + 10.0 cm sediment). Our expectations were that crabs in the 10.0 cm treatment would not survive well due to smothering by sediment deposition, whereas crabs in the 2.5 cm sediment treatment would have intermediate mortality. In addition, 2 control treatments were not exposed to any simulated dredged sediment deposition. The first control, consisting of just the base layer (i.e. sand, no sediment), was intended to reflect background levels of mortality (e.g. natural mortality and caging artifacts), and was expected to have high survival. The second control, consisting of an empty tank without a base layer or any sediment addition (i.e. no sand, no sediment) was intended as a warning of potential acute effects due to problems with the sediment itself (e.g. toxicity). If significant mortality or abnormal behavior had occurred in the crabs assigned to the 3 treatments with a base layer during the 24 h acclimation period, the experiment would have been terminated. However, given that this treatment does not mimic natural conditions, we expected crabs unable to bury into a base layer would be stressed over the course of the full experiment, potentially resulting in a relatively high mortality.

One week prior to blue crab collection, 20 experimental plexiglass tanks (0.20 × 0.40 × 0.25 m) were prepared for the 4 treatments (5 replicate tanks, with a single crab, for each of the 4 treatments), and arranged randomly within 1 large, outdoor flow-through fiberglass tank (Fig. 1). Crabs were acclimated for 24 h, during which time they were presented with food (partially crushed hard clams), but no feeding was observed. After acclimation, 1 crab was randomly allocated to each of the experimental tanks. Cable tie rulers, previously affixed to the tops of their carapaces (Fig. 2), allowed observers to estimate crab movements (horizontally and vertically) during the simulated dredge spoil deposition events and determine burial depths. After another 24 h of acclimation within the experimental tanks, temperature (7.5°C), DO in the large tank (10.5 mg l^{-1}), DO in a representative experimental tank (10.1 mg l^{-1}), condition (live or dead), buried state (unburied, partially buried, buried with depth measurement), and activity were recorded. Water flow into the large tank was halted and the water was drained to a level below the top of the experimental tanks, so that the addition of sediment to one tank would not affect adjacent tanks. We then simulated 10 independent

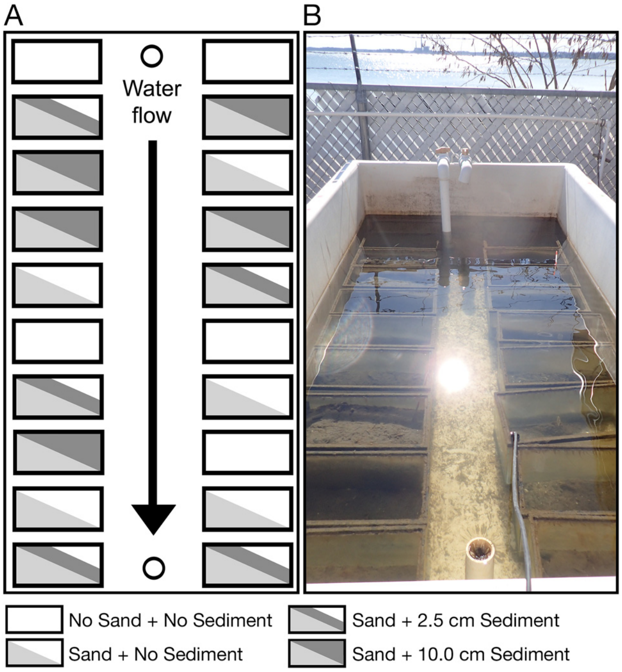

Fig. 1. (A) Schematic and (B) photo of the randomly allocated treatment tanks within the flow-through holding tank. There were 5 replicate tanks, each with a single crab, for each of the 4 treatments. The 2 experimental treatments (sand + 2.5 cm sediment and sand + 10.0 cm sediment) and one of the control treatments (sand, no sediment) included a base layer of sand to mimic ambient conditions; the second control (no sand, no sediment) was intended to warn of potential acute effects due to problems with the sediment itself

dredged sediment deposition events by adding sediment to depths of 2.5 and 10.0 cm above the base layer. Sediment was evenly distributed within the experimental tanks over approximately 1 min (2.5 cm treatment) and 4 min (10.0 cm treatment). After approximately 15 min, the majority of the sediment had settled; experimental tanks were covered with a mesh screen and the water level in the large, flow-through tank was raised to 50 mm above the tanks. Once the experimental tanks had been flushed clear (approximately 15 min), the mesh screens were removed and crabs were again allowed to move freely.

In addition to crab condition (dead or alive), temperature in the large tank and DO in both the large tank and an individual tank were recorded every morning and afternoon from the initiation of the study until 2 wk had passed with no mortality (32 d total). We also recorded a suite of behaviors as evidence for sublethal effects, as previous work has documented increased lethargy as a sublethal response to various triggers (Burnett et al. 2006, Thibodeaux et al. 2009, Schroeder-Spain et al. 2018, Schroeder-Spain & Smee 2019). For all crabs in the 2 control treatments and those that emerged from the initial sediment addition, we noted which crabs had escaped from their individual tanks into the large flow-through tank or into other individual tanks, and returned them to their original tanks. Three measures of behavior were also recorded twice per day for the surviving crabs until they died. If the crab moved when a probe was waved above it, it was noted as active; otherwise, it was considered inactive. If the condition was not immediately apparent, reflex actions were induced in the following order: (1) eye retraction, (2) antennule retraction, (3) mouth defense, and (4) movement after full removal from the water. Finally, the crab was noted as buried if at least the swimming legs were buried.

Throughout the course of the experiment, DO ranged from 6 to 12 mg l^{-1} both inside individual tanks and in the holding tank (Fig. A1 in the Appen-

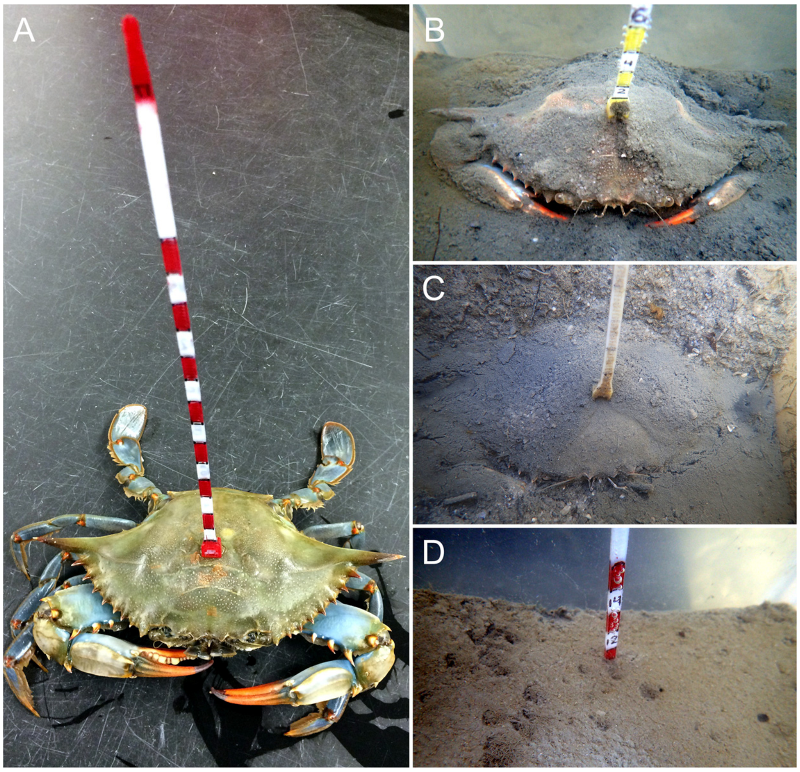

Fig. 2. Representative blue crabs with cable tie rulers affixed to the carapace: (A) prior to simulated dredged sediment deposition disposal event; (B) partially buried; (C) buried; (D) buried in 10 cm of sediment

dix). As oxygen levels below 4 mg l^{-1} affect blue crab behavior (Brill et al. 2015), oxygen limitation was unlikely to be a source of mortality and was therefore excluded from analyses. Similarly, temperature ranged from 7.5 to 13.6°C (Fig. A2) and was unlikely to be a source of mortality under natural conditions, as crabs do not experience significant mortality until water temperature drops below 3°C (Rome et al. 2005).

2.3. Analysis

All statistical analyses were executed in the statistical program R, version 3.3.0 (R Core Team 2016) using RStudio (RStudio Team 2015). For the purpose of this analysis, we differentiate between acute mortality (i.e. crabs that were unable to emerge from the sediment overburden) and cumulative mortality (i.e. all mortalities that occurred from the time of the sediment addition to the conclusion of the experiment). Kaplan-Meier survival curves for each treatment were compared using the Tarone-Ware test, which determines whether the survival distributions across the entire experiment in the 4 treatments are different. A semiparametric Cox proportional hazards test with exact calculation for ties assessed the relative influence of crab size and each treatment on survival. Both of these analyses were completed using the 'survival' package (Therneau 2015). We used an ANOVA to test for an effect of size on cumulative and prolonged mortalities. Observed behaviors were compared using a radar plot conducted in the 'fmsb' package (Nakazawa 2015). We used $\alpha = 0.05$ for evaluating the statistical significance of the results.

2.4. Distribution of overwintering females

To explore potential effects of dredged sediment deposition at the population level, we used the long-term monitoring survey of overwintering blue crabs in Chesapeake Bay (2009–2022; R. N. Lipcius unpubl. data) to map the distribution of adult females. The WDS is a stratified random survey that samples 1500 stations throughout the bay using a crab dredge in waters >1.5 m (Sharov et al. 2003). Although the survey began in 1990, we excluded data collected prior to 2009 to avoid any confounding effects of the crab dredge fishery, which occurred in Virginia waters of Chesapeake Bay during the winter until 2008. Spatial analysis and the map of overwintering adult female distribution were completed in ArcGIS Pro, version 2.9.2.

3. RESULTS

3.1. Survival

Survival times differed significantly among treatments (Tarone-Ware test, = 8.5, df = 3, p = 0.03). Specifically, acute mortality of crabs was immediate and significantly higher in the sand + 10.0 cm sediment treatment (80%) than in the other 3 treatments, whereas the other 3 treatments did not differ significantly from each other (Fig. 3, Tables 1 & 2). Across all crabs included in the experiment (n = 20), crabs that survived to the end of the experiment were larger than those that died (ANOVA, $F_{18,1} = 4.36$, p = 0.051). Even when excluding 4 crabs that experi-

Table 1. Treatment-specific mortalities and survival. Acute mortality reflects crabs that were unable to emerge from the sediment overburden. Cumulative mortality indicates all mortalities that occurred from the time of the sediment addition to the conclusion of the experiment. Total survival reflects the crabs that survived to the end of the experiment. NA: not applicable

Treatment/Factor	Acute mortality	Cumulative mortality	Total survival
No sand, no sediment	NA	3	2
Sand, no sediment	NA	1	4
Sand + 2.5 cm sediment	0	3	2
Sand + 10.0 cm sediment	4	4	1

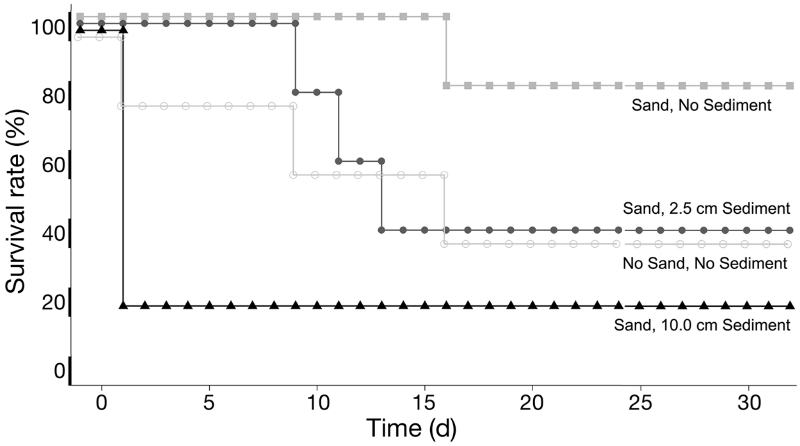

Fig. 3. Proportional survival by treatment group through time; study was terminated after 2 wk of no mortality. Lines are jigged for easier comparison between groups

Table 2. Coefficient, standard error (SE), $e^{coefficient}$, and significance (p) of the treatments and factor (Size) from the Cox proportional hazards model. Each value of $e^{coefficient}$ estimates the proportional increase ($e^{cooefficient} > 1$) or reduction ($e^{coefficient} < 1$) in cumulative mortality per unit change in the covariate or factor relative to the baseline treatment (sand, no sediment; or sand + 10.0 cm sediment). For example, cumulative mortality in the sand + 10.0 cm sediment treatment was 12.6-fold higher than cumulative mortality in the sand, no sediment control, while cumulative mortality decreased by 15% ($1 - e^{-0.165} = 0.15$) for a unit increase in crab size. Note that coefficients are multiplicative, not additive; e.g. a 2-unit increase in crab size reduces cumulative mortality by $1 - e^{-0.165 \times 2} = 28\%$

Treatment/Factor	Coefficient	SE	$e^{coefficient}$	p
Baseline = Sand, no sediment				
Size	−0.165	0.070	0.85	0.018
Sand + 10.0 cm sediment	2.534	1.249	12.60	0.042
Sand + 2.5 cm sediment	−0.404	1.476	0.67	0.784
No sand, no sediment	0.181	1.347	1.20	0.893
Baseline = Sand + 10.0 cm sediment				
Sand + 2.5 cm sediment	−2.94	1.311	0.05	0.025
No sand, no sediment	−2.35	1.154	0.10	0.042

enced acute mortality in the sand + 10.0 cm sediment treatment, surviving crabs were significantly larger than those that died (ANOVA, n = 16, $F_{14,1} = 6.88$, p = 0.020). Mortality was also inversely correlated with crab size, decreasing by 15% for a unit (mm CW) increase in crab size (Table 2). The effect of crab size on mortality was evident from the average sizes of crabs that survived and died in the experiment (Fig. 4), which was 152.4 mm CW for surviving crabs and 7% larger than that of crabs that died (142.2 mm CW). Using the estimated size coefficient (Table 2), mortality of a 152.4 mm CW crab is expected to be $e^{-0.165 \times (152.4-142.2)} = 0.186$ that of a 142.2 mm CW crab, reflecting a reduction in mortality of 1 − 0.186 = 81.4% for the larger crab.

After accounting for female size, mortality in the sand + 10.0 cm sediment treatment was 10- to 20-fold higher than that in the other treatments (Table 2). The 4 mortalities in the sand + 10.0 cm sediment treatment were immediate. Mortality rates in the sand + 2.5 cm sediment treatment and no sand, no sediment control were higher (60%) than in the sand, no sediment control (Fig. 3), but these rates did not differ significantly after accounting for the effect of crab size (Table 2). The 3 mortalities each from the sand + 2.5 cm sediment treatment and no sand, no sediment control were spread out over 16 d post-disposal. In contrast, only 1 crab (20%) died in the sand, no sediment control treatment (Fig. 3).

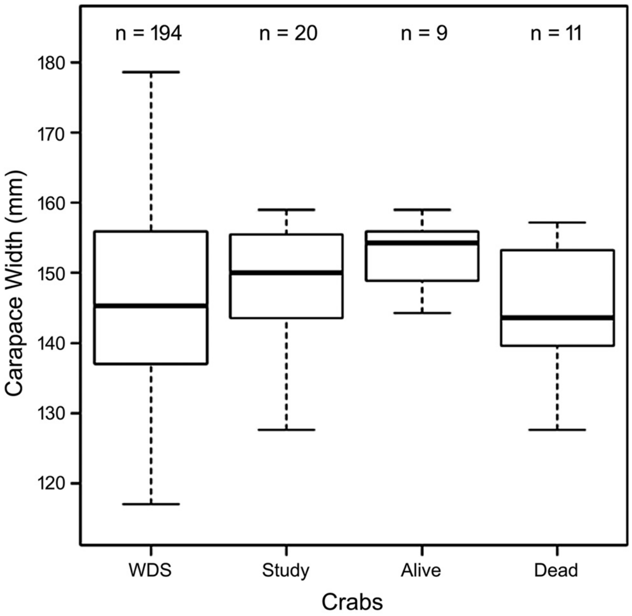

Fig. 4. Crab sizes. 'WDS' (Winter Dredge Survey) includes all crabs found within the collection area (mainstem Chesapeake Bay between Poquoson Flats and Wolf Trap Lighthouse) for the entire dredge season (December to March). 'Study' refers to the subset of adult female crabs that were used in the experiment. 'Alive' and 'Dead' indicate the subsets from the crabs used in this experiment that were alive and dead, respectively, at the conclusion of the study. The bold line denotes the median, the box indicates the interquartile range and whiskers indicate the full range of values. No values were considered outliers (i.e. greater than 1.5 times the interquartile range)

3.2. Behavior

Within 1 h of sediment addition, 6 of the 10 crabs experiencing sediment addition (all from the 2.5 cm sediment treatment and 1 from the 10.0 cm sediment treatment) had resurfaced from the plume of sediment. Throughout the course of the study, the 9 crabs across all 4 treatments that survived to the end of the experiment exhibited all 3 behavior measures. On average, these crabs responded to stimuli 32% of the time, were buried 52% of the time, and had escaped their tank 14% of the time. The 2 crabs in the no sand, no sediment treatment that survived to the end of the experiment would frequently escape and bury in neighboring tanks with sediment. Conversely, the 7 crabs across all 4 treatments that survived to the first observation period (10 h) but died prior to the end of the study typically exhibited fewer of the behavior measures, with only 1 crab exhibiting all 3 behaviors, responding to stimuli 65% of the time, burying 39% of the time and escaping 61% of the time. Five crabs responded to stimuli or buried (or both), and 1 crab exhibited none of the behaviors (Fig. 5).

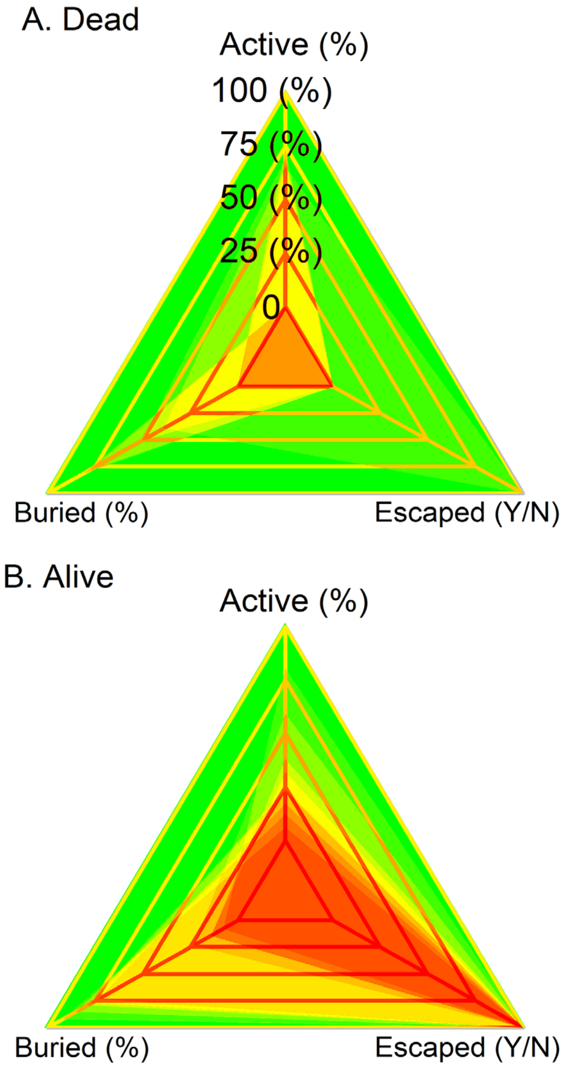

Fig. 5. Radar plots of 3 measures of behavior for crabs that by the end of the study were (A) dead, excluding the 4 crabs experiencing instantaneous mortality after dredge spoil addition (n = 7), and (B) alive (n = 9). The behavior configuration includes active, buried and escape. Axes for active and buried signify proportions whereas the escape axis signifies whether a crab escaped at least once for the duration of the study. Gradient color indicates the number of crabs exhibiting the behavior from none (green) to all (red). Adobe Photoshop CC v19.1.6 was used to add gradient color to plot

4. DISCUSSION

4.1. Effects of dredge spoil addition

Most of the crabs exposed to the medium (10.0 cm sediment) treatment were unable to emerge from the sediment during deposition, resulting in acute mortality, whereas all crabs in the lower (2.5 cm sediment) treatment were able to return to the surface. Thus, dredged sediment deposition will likely cause acute mortality of overwintering blue crabs even when deposited in layers thinner than the 15 to 30 cm typically recommended (USEPA & USACE 2004). The sediment overburden that overwintering crabs can survive may be a function of the bottom temperature at which the dredged sediment deposition occurs, as activity and ability to emerge from the dredged sediment increases with temperature (Lewis & Roer 1988, Brill et al. 2015). Similar results have been reported for the mud crab *Dyspanopeus sayi* (previously *Neopanope sayi*), with mortality a function of sediment depth and type, burial time, and water temperature (Maurer et al. 1981).

Mortality rate of crabs in the sand + 2.5 cm sediment treatment was similar to that of crabs in the no sand, no sediment treatment. This suggests that an overburden of 2.5 cm is as stressful to a crab as being prevented from burying in sediment, and that these stresses resulted in mortalities. Starvation and environmental conditions were unlikely to have directly caused these mortalities, as temperatures were below typical thresholds for feeding (Leffler 1972) yet above minimum lethal temperatures (Rome et al. 2005, Molina et al. 2021). However, the only mortalities of crabs exposed to this treatment occurred more than 1 wk after the addition of sediment. It is possible that the sediment addition may have progressively affected survival of a small proportion of crabs if the experiment was continued for a longer period. Although limited research has been published on the effects of suspended sediments on crustaceans, there is some evidence that high concentrations of suspended sediments result in less than 25% mortality during short-term experiments and progressively higher mortality as the length of the experiment increases (Wilber & Clarke 2001).

4.2. Caveats

To conduct a well-designed experiment with individual crabs as independent replicates, our study was limited to 20 experimental tanks and crabs. Contrary to survival, the relatively low sample size of 20 limited our ability to generate precise estimates for and detect sublethal effects of dredged sediment deposition. Furthermore, the use of 2 overburden treatments (sand + 2.5 cm sediment and sand + 10.0 cm sediment) limited our ability to determine the threshold for acute mortality effects of sediment overburden on overwintering blue crabs, which likely occurs between 2.5 and 10.0 cm. However, our findings demonstrate that current accepted sediment overburdens <15 cm for benthic infauna may result in significant mortalities for epibenthic species such as the blue crab in winter.

4.3. Implications for the blue crab population

The effects of dredged sediment deposition on the Chesapeake Bay blue crab population depends on various factors, including the extent of the sediment overburden, bottom temperature during deposition, and the density of blue crabs within the deposition site. The Wolf Trap site tends to be a hotspot for adult female blue crabs during the winter (Fig. 6), which may result in significant population-level mortality.

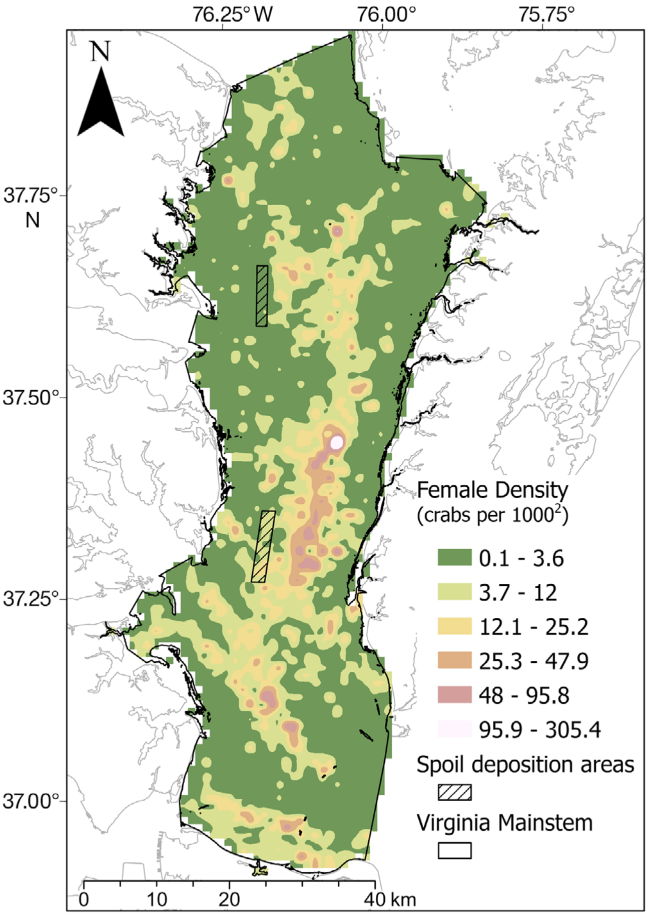

Fig. 6. Adult female blue crab density in the Virginia mainstem based on the annual Blue Crab Winter Dredge Survey (R. N. Lipcius et al. unpubl. data) from 2009 to 2022 (inverse distance weighted interpolation). Data breakpoints were determined using Jenks Natural Breaks, which maximize differences between and minimize differences within groups. Dredged sediment deposition areas are Rappahanock Shoals alternate (in the north) and Wolf Trap alternate (in the south)

To limit negative effects on blue crabs, changes in dredged sediment management are warranted. For example, temporal restrictions on dredged sediment spoil deposition at the Norfolk Disposal Site (Atlantic Ocean, approximately 17 n miles offshore) were recommended based on potential impacts to blue crab larvae and megalopae (Devonald & Ausubel 1984). Spatially, the southern disposal site (Wolf Trap) contained an average of 10.5 female crabs per 1000 m^2 (n = 29 stations) whereas the northern disposal site (Rappahannock Shoals) contained only 0.6 crabs per 1000 m^2 (n = 23 stations) on average over the past 14 yr. These 2 sites also differ substantially in sediment type, with Rappahannock Shoals consisting of muddier sediments that are not preferred by overwintering females (Lipcius & Knick 2016). The resulting 18-fold difference in density of overwintering adult female blue crabs suggests that Rappahannock Shoals is a better location than Wolf Trap for dredged sediment deposition during the winter to lower mortality of overwintering female blue crabs. Alternatively, dredged sediment deposition could be limited temporally to avoid disposal when bottom water temperatures are less than 10°C, below which crabs are less active (Leffler 1972, Brylawski & Miller 2006). Managers could also consider restricting deposition to <10.0 cm, and potentially <2.5 cm; however, as this study only considered 2 levels of sediment deposition, further work is needed to more precisely determine threshold levels of deposition to minimize negative effects on overwintering blue crabs.

The effects of dredged sediment deposition were size-dependent. Smaller crabs were more likely to experience lethal or sublethal effects, as the crabs that died during the experiment were smaller than those that survived. While a mechanism driving size-dependent survival is not obvious, it is possible that larger mass provides benefits such as improved motility, buffering from stressful temperatures, or greater energy reserves (Brill et al. 2015) that would enhance survival of larger crabs. Size-dependent responses in blue crabs have been documented previously. For example, large crabs (>60 mm CW) suffered higher overwintering mortality than smaller crabs (<60 mm CW) in upper Chesapeake Bay, and mature females experienced lower survival than juveniles in the laboratory (Rome et al. 2005). Several other studies have examined effects of temperature and salinity on survival of overwintering blue crabs but none included crabs >130 mm CW (Molina et al. 2021). However, as all but one of the crabs used in our experiment were larger than this size, trends for smaller size classes may not be relevant for our study.

4.4. Implications for natural disturbances

Estuaries are hubs of primary productivity and critical habitats for commercially important marine species that use these areas for feeding and spawning and as nurseries (Cloern et al. 2014). Sediment resuspension is a natural process in estuaries involving large volumes of sediment spread over large areas on a continuous time scale (Hsu 2016). In contrast, while dredged sediment deposition events also involve large sediment volumes, sediment resuspension generally occurs in a short time period over a small area, and is perhaps the clearest and most direct example of human-mediated sedimentation in coastal environments. However, climatological sources of large-scale sedimentation have increased in the Atlantic basin over the past few decades, such as tropical cyclones, extreme events, and winter storms (Melillo et al. 2014, Walsh et al. 2016). These events increase sedimentation along coasts (Melillo et al. 2014). For example, Hurricanes Katrina and Rita deposited an estimated 281 million t of offshore sediment in coastal waters of Louisiana (Turner et al. 2006), while an estimated 16 million t were deposited after Hurricane Ike (Williams 2012). While our results can directly inform strategies for dredge spoil disposal to minimize adverse effects, in light of projected increases in sedimentation due to climate change, broader examination of species-specific sedimentation tolerances may prove valuable.

In Chesapeake Bay, the effects of sedimentation due to tropical storms depend on season and location. For example, flooding due to Tropical Storm Lee (September 2011) deposited sediment in layers <4 cm deep (Palinkas et al. 2014) to 4–10 cm deep (Cheng et al. 2013) in the upper Bay, with limited deposition in the lower Bay. In contrast, sedimentation after Tropical Storm Agnes in 1972 was substantial and caused mortality of epibenthic and benthic fauna baywide (Cory & Redding 1976, Schubel 1976).

5. CONCLUSIONS

Our findings validate the proposition that life history characteristics are critical when determining effects of dredged sediment deposition (Hinchey et al. 2006, Schaffner 2010) to a mobile crustacean when activity is reduced by low water temperatures. Unless major changes to our global transportation systems occur, dredging channels will continually increase, as will our need for disposal sites. Thus, minimizing long-term negative consequences of dredged sediment deposition to marine biodiversity by accounting for the behavior and characteristics of the impacted species is essential.

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Appendix. Dissolved oxygen and temperature data during experiment

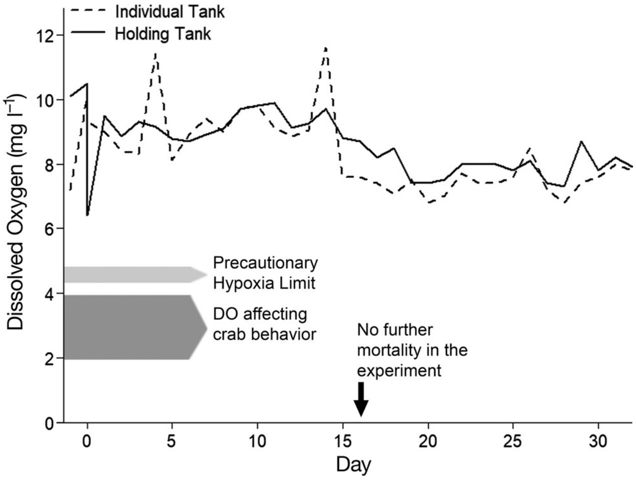

Fig. A1. Dissolved oxygen (DO) levels in holding tank and representative individual tank during the study. Precautionary hypoxia limit (4.6 mg l^{-1}) is based on Vaquer-Sunyer & Duarte (2008). The blue crab behavior limit (2.0–4.0 mg l^{-1}) is based on Brill et al. (2015)

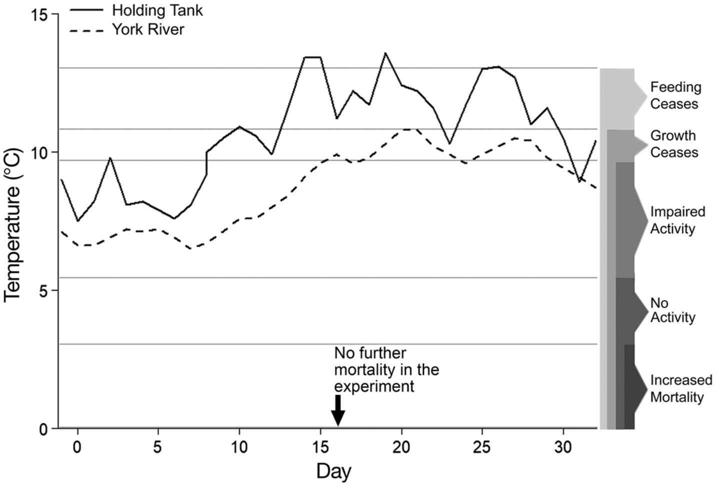

Fig. A2. Afternoon temperature in holding tank and average daily temperature in York River during the study. Temperature ranges at which crabs exhibit decreasing activity are based on Leffler (1972), Rome et al. (2005), and Brylawski & Miller (2006)

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