NOTE

**Intertidal rack-and-bag oyster farms have limited interaction with horseshoe crab activity in New Jersey, USA**

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**ABSTRACT:** Concern has been raised about the ability of horseshoe crabs *Limulus polyphemus* to traverse intertidal rack-and-bag oyster farms, and how farms may change shorebird foraging activity. During the 2016 horseshoe crab spawning season, experiments conducted in Delaware Bay (New Jersey, USA) assessed the ability of crabs to move among oyster farms and access landward nesting grounds, and surveyed the distribution of dislodged eggs upon which many shorebirds feed. Experiments included testing (1) for impairment of crab passage by oyster racks, (2) for differences in crab abundance among paired farm/control transects, (3) whether farms affect crab stranding rates on nesting beaches, and (4) assessing the spatial distribution of dislodged eggs along the wrack zone among farm and non-farm areas. All crabs, regardless of size, passed beneath racks \( \geq 10 \) cm tall, indicating that the regulated rack height of 30.5 cm is abundantly precautionary to allow crab movement beneath racks. Farm/control census observed 853 crabs in total, with no evidence of differing crab numbers among farmed and control transects. Only 2 of 853 (<0.5%) crabs were obstructed by farm gear, and more crabs were present on nesting beaches inshore of farms compared to adjacent farm-free areas. The proportion of crabs flipped (stranded) at low tide within nesting habitats was constant regardless of farm presence. Dislodged eggs in the wrack zone were observed most frequently in the center of the survey area, and were not concentrated near farms, suggesting that in 2016, shorebird foraging opportunities were not coincident with farm locations.

**KEY WORDS:** Oyster aquaculture · *Crassostrea virginica* · Rack-and-bag · *Limulus polyphemus* · Ecological interactions · Shorebird foraging

**INTRODUCTION**

For the first time since records have been kept, the contribution of aquaculture to global seafood supply has exceeded that of wild capture fisheries (FAO 2016). Although shellfish culture is largely viewed as an environmentally and ecologically sound industry (Shumway et al. 2003), as global production expands, the industry is faced with key challenges to ensure ecological sustainability and social acceptance. The ways in which molluscan aquaculture interacts with fundamental ecosystem processes such as particle depletion, nutrient cycling, and benthic–pelagic coupling has been relatively well studied (Newell 2004, Dumbauld et al. 2009, Rose et al. 2015); however, central to sustainability and acceptance is also understanding the nature of the interaction among farms and wildlife such as birds and mammals that may use habitat near to or occupied by farms. Studies that have examined the ways that molluscan farms inter-
act with local avian populations provide examples of mixed interactions (Roycroft et al. 2004, Godet et al. 2009, Žydelis et al. 2009), leaving the question unable to be generalized broadly across species, habitats, and culture practices.

Shellfish aquaculture in the Cape Shore region of New Jersey (USA) has a long history as a local food production system (Ford 1997). Eastern oyster *Crassostrea virginica* production declined sharply following the appearance of Multinucleated Sphere X, more commonly known as MSX disease (caused by *Haplosporidium nelsoni*) in 1957 and the more recent establishment of Perkinsosis (caused by *Perkinsus marinus*) (Ford 1997). Advances in hatchery and production methods as well as the development of disease-resistant stocks and triploid technology (Dégremond et al. 2015) have revived the industry. Today, an annual production of approximately 1.8 million market-sized aquacultured oysters is primarily carried out on intertidal farms in the Cape Shore, encompassing 10 acres (~4.05 ha) of actively farmed bottom (Calvo 2017).

Horseshoe crabs *Limulus polyphemus* are an iconic and ecologically important species in the Delaware Bay area. Hundreds of thousands come ashore during spring to mate and lay eggs along sandy beaches of the New Jersey and Delaware coastline (Smith et al. 2002, 2017). Approximately 5% of the total shoreline baywide that has been categorized as suitable for crab spawning (Lathrop et al. 2006) is also home to rack-and-bag oyster farming. These activities occur in the Cape Shore region, where farmers grow oysters in specialized cultivation bags on top of short metal racks. Recently, horseshoe crab biologists with a history of studying this region have indicated that most of this area is no longer suitable habitat due to shoreline erosion following recent changes in sea level (Loveland & Botton 2015). Variations of this cultivation method have occurred along this region for more than a century (Ford 1997). An important migratory food source for red knots are lipid-rich horseshoe crab eggs (Haramis et al. 2007) that are deposited on beaches along the migratory route by mating crabs during the birds’ spring northward migration, typically in May of each year (Castro & Myers 1993, Botton et al. 1994). The eggs become available to the transitory bird flocks when they are exhumed from nests by sediment disturbance such as crab burrowing and wave action (Kraeuter & Fegley 1994, Smith 2007) and become concentrated in the

![Fig. 1. (A) Study area in Delaware Bay, USA, with the Cape Shore region noted in black. Zoomed-in panels show the distributions of washed up horseshoe crab *Limulus polyphemus* eggs on (B) 8 May and (C) 30 May 2016 within the Cape Shore region relative to farm locations; arrows denote farm locations, and arrow size scales with the relative farm footprint.](image-url)
upper intertidal zone by wave action in the swash zone as the tide rises (Nordstrom et al. 2006).

The rufa subspecies of the red knot Calidris canutus is a medium-bodied shorebird that breeds in the Canadian Arctic and winters in parts of the southern USA, the Caribbean, and South America (Morrison & Hobson 2004). Red knots migrate between wintering and breeding grounds using stopover areas along the Atlantic coast of the USA, one of which is the shore of the Delaware Bay (Clark et al. 1993, Botton et al. 1994; Fig. 1A). Effective 12 January 2015, the red knot was designated under the US Endangered Species Act as ‘Threatened’ in the USA by the US Fish and Wildlife Service; Canada listed it as Endangered in 2007.

Concern has recently been raised about the ability of horseshoe crabs to traverse intertidal rack-and-bag oyster farms, and how farms may change shorebird foraging activity leading to the implementation of precautionary risk-averse conservation measures until additional information is obtained (Walsh et al. 2016). During the spawning season in 2016, we conducted a series of experiments to assess the ecological interactions among intertidal rack-and-bag oyster farms and horseshoe crabs and shorebird feeding opportunities. These included tests of whether horseshoe crabs are impinged by farm gear or alter their movement in, around, and among the oyster farms as they make their way to mate and spawn on nesting beaches, and a census of the spatial distribution of washed up eggs upon which red knots feed.

**MATERIALS AND METHODS**

All experiments were conducted in the Cape Shore region along the New Jersey side of the southern Delaware Bay (Fig. 1A) during late spring through early summer of 2016 (mid-April through late June). The study region is characterized by extensive mudflats that are exposed at low tide, and sloping sand beaches bordered by salt marsh at the upper intertidal. Tides in the Delaware Bay are semidiurnal, with a mean range of 1.6 m.

**Testing rack heights for impairment of crab passage**

During a daytime low tide, oyster racks were set at 4 heights above the surface of the sand: 7.5, 10.2, 15.2, and 30.5 cm. A range of 10 to 20 male horseshoe crabs ranging in prosoma width from 17.5 to 23.0 cm were collected from adjacent/nearby sloughs and placed right side up approximately 1 m from and facing toward the rack, then observed as they walked beneath the rack. The prosoma width and success or failure of each crab to pass beneath the rack was recorded. Crabs that arrested movement as they physically came into contact with the racks were scored as having impaired movement.

**Repeated transects to test if crabs avoid farms**

Paired farm/control transects were established at each of 2 active oyster farms on the Cape Shore (n = 4 transects total). Each pair included 1 transect that intersected the farm, and 1 parallel control transect 20 m from the farm that passed through adjacent unfarmed intertidal habitat (Fig. 2). Each transect spanned a 1 m wide area perpendicular to the high tide line, and covered a zone inshore of the farm area (Zone 1) and through the farm (Zone 2) (Fig. 2). Transect lengths at each of the farms were unequal due to the nature of the mudflats on which they were located; they measured 190 and 138 m in total length (Farm A and B, respectively), with Zone 1 spanning the inshore 128 and 93 m of each (Farm A and B, respectively). The paired transects were surveyed a
total of 10 times during daytime low tides between 29 April and 15 June 2016. Location and activity of all crabs encountered (observed visually) along each transect were recorded, and all crabs whose mobility was impaired by a rack (e.g. crabs that were trapped, caught, or impinged) were noted.

Data were non-normally distributed, thus a non-parametric Wilcoxon signed rank test was performed to test for differences in the abundance of crabs observed on control versus farm transects. Absolute values of crab observations varied greatly over the course of the study due to seasonal spawning immigration and emigration; therefore, standardization of each survey was performed by summing paired transect counts for each survey and then calculating the fraction of the total that was observed on the farm. The fraction observed on the farm transect was then analyzed using a mixed model analysis of variance in which zone was nested within farm site to assess the influence of zone.

**Nesting beach census**

Three adjacent upper beach segments spanning approximately 91 m (150 yards) parallel to the shoreline were surveyed on 16 nights bracketing horseshoe crab spawning peaks around full and new moons between 22 April and 22 June 2016. The central segment was inshore of an active oyster farm, whereas the 2 segments on either side were not. Surveys were conducted at night 3 h after high tide to enumerate stranded crabs. All live crabs in the upper beach spawning habitat were counted and recorded along with their condition: flipped on their back (stranded) or right side up. The fractions of crabs flipped at farm and non-farm segments were compared using repeated measures analysis of variance.

**Spatial survey of washed up egg distribution**

Two photographic censuses were performed overnight on 8 and 30 May 2016, to document the distribution of horseshoe crab eggs washed up near the high tide line where red knot foraging is concentrated (Burger et al. 1977, 1997, Botton et al. 1994). The upper intertidal along the Cape Shore region (Fig. 1A) was divided evenly into 150 segments (approximately 91 m of shoreline per segment), and photographic samples documented a 0.5 m wide (alongshore) by 1 m (downbeach) quadrat perpendicular to the high tide line and crossing the wrack line, located randomly alongshore near the center of each segment. Each photographic quadrat was assessed for the presence of horseshoe crab eggs that had been washed up at the surface, and each quadrat was coded as having no eggs, few eggs (defined as ≤5% of the quadrat containing eggs), and many eggs (defined as >5% of the quadrat containing eggs).

**RESULTS**

All crabs, regardless of prosoma width, were able to pass beneath racks ≥10 cm above the bottom (Fig. 3). Of the total 48 observations, 42 crabs passed beneath the racks, whilst 6 failed to transit the rack. Those 6 were among a total of 10 crabs tested at a rack height of 7.5 cm; the other 4 were able to pass the rack at a height of 7.5 cm. All of the 6 crabs that were unable to pass buried the front of their prosoma beneath the rack edge and stopped, but were not irreversibly stuck.

In total, we observed 853 crabs during the repeated transect surveys, with a relatively even distribution of crabs between farm and control transects (46 farm and 39 control transects at Site A, and 369 farm and 399 control transects at Site B, Table 1), both inshore...
of farm activities (Zone 1) and within the farms (Zone 2). In total, 2 out of 853 (<0.5%) crabs were observed to be obstructed by racks.

The first 2 and final farm transect surveys were removed from statistical analyses because very few crabs were observed at the beginning and end of the study (i.e. many 0 counts). We found no significant difference in the number of crabs among farm and control transects \( (V = 76.5, p = 0.3) \), paired Wilcoxon signed rank test). Likewise, the fraction of crabs observed on the farm transects approximated 0.5, and zone \( (F = 0.94, p = 0.51) \) did not significantly affect the fraction of crabs observed on the farm transects.

In total, 3527 live crabs were counted on the 3 nesting beach segments during overnight censuses, with nearly half of those \( (48\%) \) observed in the central segment inshore of the oyster farm. Segment 2 (inshore of the farm) tended to have more crabs observed during each census (Fig. 4), with the highest numbers of crabs on all 3 segments associated with full and new moons in the middle of the spawning season (Fig. 4). The fraction of flipped (stranded) crabs varied greatly among censuses; however, there was no significant difference in the fraction of flipped (stranded) crabs among farmed and nonfarmed segments (Fig. 5; \( F = 15.2, p = 0.16) \).

The amount of washed up eggs observed in the survey was relatively lower in early May, before the majority of crabs returned to spawn. Densities of crab eggs washed up at the high tide line were distributed unevenly throughout the region surveyed (Fig. 1B,C). Washed up eggs were observed most frequently in the central portion of the survey area, and were not highly concentrated in the area of farms.

### DISCUSSION

Complementary experiments and surveys were conducted during the 2016 horseshoe crab spawning season to assess the ecological interactions among intertidal rack-and-bag oyster farms and horseshoe crabs and shorebird feeding opportunities. These included tests of whether horseshoe crabs become trapped by gear or alter their movement in, around, and among the oyster farms as they make their way to mate on nesting beaches, and a census of the spatial distribution of washed up eggs upon which red knots feed. All crabs, regardless of size, passed easily beneath racks positioned \( \geq 10 \) cm above the bottom. This rack height corresponds with prosoma heights measured across a random selection of spawning male and female crabs \( (7.5 \) and \( 10.0 \) cm, respectively) from this same region (Kraeuter & Fegley 1994). Thus, the regulated rack height of \( 30.5 \) cm should be sufficiently precautionous to allow crab movement beneath racks.

Repeated surveys of paired farm–control transects showed no evidence that crabs avoid or are trapped by farms as they come ashore to mate and lay eggs. The 2 farms used in this study showed a large difference in the number of crabs observed during transect surveys, with Site A being a longer transect with fewer crabs. The Cape Shore shoreline is somewhat
heterogeneous in the quality of crab habitat, with high-quality habitat, erosional areas, and some bulk-headed sections; the 2 farms also differed in the quality of the crab habitat near the upper intertidal. At Site A, the upper intertidal had been eroded with exposed peat, which has been shown to lead to fewer crabs returning to spawn (Botton et al. 1988). Site B was located within a section of higher quality, predominantly sandy crab habitat.

Farm gear did not alter the number of horseshoe crabs onshore on nesting beaches (Fig. 4). In fact, the trend was for more crabs to be present on nesting beaches inshore of where farming was occurring. The fraction of crabs on nesting beaches that were flipped over (stranded) varied greatly among the census walks, with a tendency for a greater fraction flipped on nights when wind and waves were greater (data not presented), which is consistent with previous studies (Botton & Loveland 1989). Importantly, the fraction of stranded crabs was not higher on nesting habitat inshore of farm gear (Fig. 5).

The density of crab eggs washed up in the wrack zone was unevenly distributed throughout the surveyed region of the Cape Shore. Washed up eggs were observed most frequently in the central portion of the survey area, and were not highly concentrated in the area of farms. Once eggs are resuspended from nests by wave action or other means, they are passively dispersed on waves and wind-driven currents (Smith et al. 2002) and tend to accumulate at concentrating features such as sand spits and jetties (Botton et al. 1994). Thus, the spatial pattern of egg concentration in the wrack line observed here does not necessarily reflect where concentrations of spawning females are coming ashore. Considering that 20% of the surficial eggs on the entire beach are found in the uppermost wrack line (Nordstrom et al. 2006), the spatial patterns of eggs in the wrack line should be a good relative predictor of the best shorebird foraging habitat within the survey region.

In general, more eggs are available to birds in the swash zone on a rising tide than are available remaining on the beach; therefore, active foraging in the swash zone during high, rising tides may provide the best foraging opportunities, and counts of eggs remaining on the beach may underestimate the absolute foraging opportunities (Nordstrom et al. 2006). Likewise, the distribution of available eggs baywide varies, with the highest densities of resuspended eggs found upbay in the areas of Sea Breeze on the New Jersey side of the bay, and Kitts Hummock and North Bowers on the Delaware side (Smith et al. 2002). Our surveys showed no evidence that farms interfere with the ability of spawning crabs to reach nest sites, and that optimal horseshoe crab egg-foraging opportunities for shorebirds are not coincident with farm locations.

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