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# Comparing In-Person versus Camera Monitoring of Shorebird Reproductive Success

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birds in research have been followed, including those presented in the Ornithological Council's "Guidelines to the Use of Wild Birds in Research" (Fair *et al.* 2010). We acknowledge that during this research, we lived and worked on the homeland of the Tutelo, Monacan, Pocomoke, Chincoteague, Occohannock, and Accomack People's homeland and we recognize their continued connection to the land, water, and resources of these areas.

**Abstract.** — Shorebird reproductive success monitoring often relies on surveys of nest and brood survival. However, conclusions may be inaccurate due to the challenges of gathering and interpreting evidence of nest and brood fate. We tested the efficacy of in-person versus camera-based monitoring to quantify productivity and evaluate threats to reproductive success of American Oystercatchers (*Haematopus palliatus*) and Piping Plovers (*Charadrius melodus*) at Metompkin Island, Virginia. We deployed 73 cameras using three set-ups: at nests, at brood sites, and along a transect. The same areas were also surveyed in-person approximately once per week. Camera monitoring confirmed nest fate where in-person monitors could not determine fate from field evidence and provided insight to the effectiveness of mammalian predator removal. However, cameras failed to capture causes of mortality for mobile chicks and did not consistently document chicks where in-person monitoring confirmed successful broods. Cameras produced large quantities of data requiring 63.5–315 hours to review, depending on camera set-up. We found cameras were useful for validating conclusions from in-person monitoring, highlighting threats that surveys missed, and characterizing the predator community. Managers should consider the tradeoff between potential benefits and required effort of camera monitoring when deciding which method would be effective for meeting management goals.

**Key words.** — American Oystercatcher, *Charadrius melodus*, *Haematopus palliatus*, Piping Plover, predation, productivity

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Monitoring is used to reduce uncertainty about a system and inform decisions regarding management actions (Lyons *et al.* 2008). In most locations, monitoring of beach-nesting shorebird reproductive success involves routine, in-person surveys for nests and broods during the breeding season. When integrated with an adaptive management framework, monitoring provides a useful way to evaluate the effectiveness of current management actions to address those threats and ensure management goals are met (Gibbs *et al.* 1999). This approach of continuous monitoring and re-evaluation of threats is important in dynamic landscapes such as coastal systems that vary spatiotemporally in response to short-term disturbances (e.g., tropical and extratropical storms; Robinson *et al.* 2019) and long-term changes (e.g., sea-level rise; Galbraith *et al.* 2014).

Estimating productivity and identifying factors that limit reproductive success of shorebirds from in-person surveys often is difficult, given that egg or chick loss events are rarely witnessed by in-person monitoring (Ivan and Murphy 2005). Many beach-nesting shorebird species breed in dry sand habitat where evidence of nest fate and causes of nest failure may be altered by abiotic conditions (e.g., high winds, heavy rainfall, tidal inundation). Moreover, visits from scavengers following nest failure may confuse the record by adding to or obscuring signs from the original nest failure event, such as predator tracks (Lariviere 1999). As a result, nest fate assignments and causes of nest failure may be erroneous, leading to inaccurate estimates of hatch rates and misidentification of threats to nest success (Hillman 2012; Ellis *et al.* 2018). Furthermore, shorebirds are semi- or fully precocial, meaning chicks leave the nest shortly after hatching, giving observers less than 48 hours after hatching to observe chicks in the nest (Andes *et al.* 2019). Once chicks leave the nest, they are challenging to re-locate, as they are highly mobile and cryptically colored, making it difficult to monitor chick survival (Whittier and Leslie, Jr. 2009; Lees *et al.* 2019).

Automatic cameras may provide an alternative method for estimating productivity and identifying threats to reproductive success, as they can provide near-continuous monitoring of a site (DeRose-Wilson *et al.* 2013; Hillman *et al.* 2015), increasing chances to determine nest fate and capture evidence of events affecting nest success that may otherwise be missed by investigators (Pietz and Granfors 2000; Liebezeit and Zack 2008; Ellis *et al.* 2018; Andes *et al.* 2019). Thus, cameras may reduce uncertainties about hatch success and threats to nest survival by capturing information missed by in-person surveys. Additionally, cameras may highlight threats to nest and chick survival by characterizing the predator community (Liebezeit and Zack 2008; McKinnon and Bêty 2009; Ellis *et al.* 2020; Brown *et al.* 2022) and the amount of disturbance from humans.

American Oystercatchers (*Haematopus palliatus*) and Piping Plovers (*Charadrius melodus*) are intensively monitored and managed on the Western Atlantic Flyway. Both are species of conservation concern under the U.S. Shorebird Conservation Plan due to population declines and habitat loss (Brown *et al.* 2001), and the Atlantic coast breeding population of the Piping Plover is federally threatened in the United States (U.S. Fish and Wildlife Service 1985). Range-wide studies of the population abundances and productivity (i.e., number of fledged chicks per pair) have identified threats to their reproductive success, namely loss of open sandy habitat due to vegetative succession and coastal development (Robinson *et al.* 2019; Kwon *et al.* 2021), disturbance from human activity (DeRose-Wilson *et al.* 2018; Kwon *et al.* 2021), and predation pressures (Erwin *et al.* 2001). These efforts have informed decision-making for management actions such as the implementation of seasonal beach closures and predator removal at breeding sites (Melvin *et al.* 1991; Schulte *et al.* 2010). Monitoring is used to evaluate the effectiveness of implemented actions (Brown *et al.* 2001).

We used cameras to remotely monitor the reproductive success of American Oystercatchers and Piping Plovers on Metompkin Island, Virginia. This site is an important breeding location, supporting an annual average of 92 American Oystercatcher pairs and 60 Piping Plover pairs from 2002–2018 (The Nature Conservancy in Virginia and Virginia Department of Wildlife Resources, unpubl. data). Managers have monitored the reproductive success of these species on Metompkin Island since 2002 using nest and brood surveys and noted that overall productivity has varied over time for both species at this site. However, as Metompkin Island is remote and only accessible by boat, monitoring intervals may be long (i.e., surveying approximately once per week), potentially biasing nest and chick survival estimates for the site. For these reasons, Metompkin Island provides an ideal study system to compare the methods of in-person versus camera monitoring. In addition to monitoring hatch success for both species, we also tested two novel camera set-ups (i.e., cameras located at brood-rearing sites and along a transect at the marsh edge) to monitor American Oystercatcher brood survival after chicks left the nest site. Our objectives were to 1) compare the efficacy of in-person versus camera-monitoring to quantify hatch and brood success, 2) test the utility of nest, brood, and transect-based cameras versus in-person monitoring to evaluate the importance of predation relative to other threats to reproductive success (e.g., abandonment, flooding, disturbance), 3) quantify any potential effects of camera monitoring on nest survival relative to in-person monitoring, and 4) evaluate the effort needed to process and review photos from camera monitoring to assist managers in making decisions about future use of technologies in their monitoring and management programs.

## METHODS

## Study Area

Metompkin Island, Virginia (37° 44' 27.04" N, 75° 33' 37.90" W) is a 10-km long, 107–831-m wide undeveloped barrier island located approximately 1.5–2.5 km from the mainland of the Delmarva Peninsula (Fig. 1). It is low-lying (mean elevation around 1.0 m asl), with a flat topography that is frequently overwashed (Stallins *et al.* 2020). As a result, the vegetative community on Metompkin Island is dominated by species such as Saltmeadow Cordgrass (*Spartina patens*) that exhibit rapid growth following frequent disturbances (Brantley *et al.* 2014; Brown and Zinnert 2020). The sandy beach used by breeding shorebirds varies around the mid-point of the island. The northern half of Metompkin Island has sparsely vegetated beach habitat and overwash areas backed by a salt marsh; in contrast, the southern half is dominated by a less erosional dune structure (Stallins *et al.* 2020) and a denser vegetative community composed of grasses and shrubs that terminates abruptly at the edge of the coastal bay.

Metompkin Island is part of a coastal system that provides crucial breeding, migration, and wintering habitat for shorebirds on the Western Atlantic Flyway (Wilke *et al.* 2005). Management priorities to benefit birds breeding on the island include year-round visitor use policies (e.g., no dogs, no camping), seasonal access restrictions (i.e., visitors are only permitted in the intertidal area and access is restricted to the inlets and roped corridors), and lethal management of mammalian predators (i.e., red fox *Vulpes vulpes*, and raccoon *Procyon lotor*). Managers also conduct seasonal weekly monitoring of the reproductive success of American Oystercatchers, Piping Plovers, and Wilson's Plovers (*Charadrius wilsonia*).

American Oystercatcher productivity rates on Metompkin Island are generally high relative to other locations along the Western Atlantic Flyway, making it one of the most important breeding sites for this species along the U.S. Atlantic and Gulf coasts (Atlantic Flyway Shorebird

Initiative [AFSI] 2020). However, oystercatcher productivity has declined on Metompkin Island from an average of 0.73 ± 0.08 (mean ± SE) fledged chicks/pair in 2002–2015 to 0.25 ± 0.06 fledged chicks/pair in 2016–2018 (The Nature Conservancy, unpubl. data). This decline resulted in a reproductive output below the estimated rate needed to maintain a stationary population on the Virginia barrier islands (0.42 fledged chicks/pair assuming observed immigration rates; Wilke *et al.* 2017). Piping Plover productivity averaged 1.29 ± 0.09 fledged/chicks per pair in 2002–2015 and 1.07 ± 0.04 in 2016 and 2018 (no data for 2017; Virginia Department of Wildlife Resources, unpubl. data), both of which are sufficient rates to maintain a stationary population (Hecht and Melvin 2009; Weithman *et al.* 2019).

## Field Methods

*In-person field monitoring of reproductive success.* We monitored the reproductive success of American Oystercatchers and Piping Plovers in-person by conducting walking surveys and observations of breeding bird behavior. We conducted in-person monitoring methods for all nests and broods from 1 April to 31 August 2019, even after cameras were placed. Due to the remoteness of the site, in-person surveys occurred approximately once per week, or as weather allowed. We located nests by observing breeding bird behavior and signs of nesting activity (e.g., dense tracks, scrapes) and through systematic searches of all suitable habitat on the island. For all nests, we used Collector for ArcGIS (ESRI, Redlands, California, USA) to record the GPS location and nest status (i.e., active or inactive) on each subsequent visit until the nest hatched or failed.

We identified nest fate and cause of clutch loss when possible, using field-gathered evidence (e.g., scat, tracks, yolk, eggshell fragments). For example, predation-caused nest failure could be inferred from the absence of eggs well before the expected hatch date coupled with the presence of predator tracks and egg yolk. Conversely, hatch success could be inferred from actual observations of broods, adult behavior (e.g., alarm calls), the presence of bivalve shells, and the presence of adult and chick tracks. Possible sources of clutch loss and associated evidence that we considered during in-person monitoring included, but was not limited to, nest predation (predator tracks and sign at nest site; Hunt *et al.* 2019), flooding (overwash sand texture and wet substrate), and abandonment (sand accumulation in nest).

We defined a successful nest as one that had at least one egg hatch. For successful nests, we monitored broods until chicks died or were considered fledged at 35 days for American Oystercatchers (American Oystercatcher Working Group [AMOYWG] *et al.* 2020) and 25 days for Piping Plovers (Elliott-Smith and Haig 2020). During site visits, we searched for broods from a distance using binoculars or spotting scopes to minimize disturbance and recorded the status of broods as alive or failed (i.e., all chicks were dead).

*Camera-based monitoring of reproductive success and threats to nests and broods.* We used three sets of cameras to provide near-continuous monitoring of shorebird activity at Metompkin Island (Fig. 1), which included cameras placed near active American Oystercatcher and Piping Plover nests (‘nest cameras’), at American Oystercatcher brood-rearing sites (‘brood cameras’), and along a transect adjacent to the marsh-beach interface to allow for a wide-angle view of the marsh edge (‘transect cameras’). A combination of solar panel kits and batteries powered the cameras. We checked cameras approximately once per week, replacing memory cards and batteries as needed. More detail on camera set-up is in AFSI (2020).

We deployed nest cameras (16 megapixel with ‘no-glow’ infrared 940 nm flash; Blaze Video, Irvine, California, USA) set with a 15 m motion detection range and a 20 m infrared flash range. These cameras operated 24 hr/day and captured three still images per trigger with a 5-sec pause between image sequences. We placed nest cameras on steel posts 0.3 m above the ground and 3–6 m from the nest. Cameras were placed by active nests with full clutches as site visits allowed, and thus they were not always deployed at the same number of days post-laying completion. After nest camera placement, we monitored the nest to ensure that adults resumed incubation within 30–45 min. This threshold was carefully evaluated for each deployment to ensure that existing conditions (e.g., weather, potential predators) would not pose a threat to active nesting attempts. If an incubating adult did not return within the set threshold, the camera was removed.

We mounted brood cameras (same model and specifications as nest cameras) on steel posts 1.0 m above the ground and positioned them to maximize their view of the marsh edge where brood survey observations from the current and prior years indicated American Oystercatcher brood activity. We focused this camera monitoring method on monitoring American Oystercatcher chicks, as American Oystercatcher broods often stay within a nesting or feeding territory, whereas Piping Plover broods have a more variable movement patterns and home range sizes that tend to increase as they approach fledging (AMOYWG *et al.* 2020; Weithman *et al.* 2020). Each brood camera was associated with a brood territory (i.e., the area where chick-rearing for one brood occurred) and we deployed cameras May through July 2019, as the nests of the broods using each territory hatched. We continued to conduct in-person monitoring as described above for all nests and broods monitored by cameras.

We placed seven cameras (PlotWatcher 6 Pro from Day 6 Outdoors, Columbus, Georgia, USA and MAC200DN from Brinno, Taipei City, Taiwan) facing the marsh edge and along a transect parallel to the marsh-beach interface, 40 m apart and 50–75 m from the marsh. We chose the transect location based on locations of observed American Oystercatcher brood activity in the previous year. Transect cameras operated from dawn to dusk (approximately 17 hr/day from 05:00 hr to 21:00 hr) on 24 May to 09 July 2019, and recorded images at 1-sec intervals, rather than using motion detection, to improve chances of capturing individuals beyond the cameras' motion detection range.

We reviewed photos from the nest and brood cameras for evidence of predation and other causes of productivity loss (e.g., partial or complete clutch or chick loss due to flooding, abandonment, and other non-predation events). As disturbance may reduce nest success by altering incubation patterns (McGowan and Simons 2006), we also recorded disturbance events, defined as any event that caused an incubating bird to leave the nest (e.g., another animal passing near the nest), using nest camera photos. To characterize the predator community at nest and chick rearing sites, we recorded the presence of all known or potential shorebird predators (Boettcher *et al.* 2007, Wilke *et al.* 2007) on all three camera set-ups, regardless of whether the predator interacted with a nest or brood.

## Analyses

*Estimating hatch and brood success.* We assigned nest and brood fates separately from field evidence from in-person monitoring, which began when a nest was found, and photographic evidence from cameras, which was collected from the time each camera was placed. We used only nests monitored with both methods, so that we could compare estimates of reproductive success (hatch success, i.e., proportion of successful nests, and productivity, i.e., number of fledged chicks per pair) produced by in-person versus camera monitoring. Comparing estimates of reproductive success from these methods allowed us to assess the accuracy of estimates of hatch success and productivity derived from in-person monitoring, which may be biased by long monitoring intervals (Etterson and Bennett 2005; Andes *et al.* 2019), against less biased estimates produced from camera monitoring.

To account for nests with unknown fate from in-person monitoring, we estimated upper and lower limits for hatch success where we assumed all nests with unknown fates hatched or failed, respectively. For camera-monitoring, we classified each nest attempt as hatched or failed from photos and assigned cause of failure when possible. We reviewed brood camera photos for brood presence by recording the maximum number of chicks seen on each camera twice per day, once for the morning (00:00 to 11:59 hr) and once in the evening (12:00 to 23:59 hr). We only estimated productivity for American Oystercatchers as camera monitoring of chick-rearing sites focused on only American Oystercatcher broods. We considered a chick to be fledged if it was observed at or after its expected fledge date during in-person surveys or on a camera.

*Determining threats during nest and chick-rearing stages.* We compared reasons for nest failure and chick loss recorded during in-person and camera monitoring to determine accuracy of fate assignment and threat identification for in-person monitoring. We reviewed footage from the transect cameras using programs provided by the manufacturer of each camera that allowed us to view still images in video format (Day 6 Outdoors GameFinder and Brinno Video Review). To characterize activity of non-shorebird species at the marsh edge, we recorded presence of all non-shorebird species. We also noted antagonistic interactions (e.g., attacking another species) between these species and adults tending broods. As cameras provided more continuous monitoring, we considered reasons for nest or chick loss determined from camera monitoring to be more accurate than data from in-person monitoring.

To quantify threats to nest survival, we calculated capture rates of disturbance and clutch loss events from nest camera photos. To quantify threats to chick survival, we calculated capture rates for all predator and non-shorebird species detected on transect camera photos. We chose to quantify capture rates for all non-shorebird species, rather than just known predators, because non-predators sometimes disturb broods (A. Wilke, pers. obs.) and there was potential for the cameras to highlight threats from species not typically considered to be shorebird predators. We calculated capture rates as the number of independent events (i.e., occurring > 30 min apart), divided by the total number of camera days and multiplied by 100 (i.e., event detections/100 camera days; Sollmann 2018). We recorded species observed from in-person and brood camera monitoring, but could not calculate capture rates, as these methods were not designed to collect data on independent capture events.

*Assessing camera effect on nest survival.* We used a logistic-exposure model (Shaffer 2004) to predict survival of nests using methods similar to Kwon *et al.* (2018) in the statistical computing environment R ver. 4.1.2 (R Core Development Team 2021). We first constructed a global model with presence or absence of nest cameras, shorebird species (American Oystercatcher or Piping Plover), location (northern or southern Metompkin), and nest age (days since the start of incubation, with the start of incubation as Day 1) as predictor variables. We could not estimate nest age from a known nest initiation date due to long in-person monitoring intervals (7–10 days). Instead, we backdated initiation dates according to the known laying sequence for the species (Colwell 2006) or from hatch dates. When possible, we were conservative with our estimate of nest age (i.e., we assumed earlier initiation dates when uncertain) and did not consider nests for which we could not estimate nest age because they were found in the incubation phase and did not hatch.

We evaluated the fit of the global model with a Hosmer and Lemeshow goodness-of-fit test (Hosmer *et al.* 2013). We then constructed 10 biologically plausible candidate models containing only additive effects of parameters from the global model, including a null (intercept-only) model, and used Akaike's Information Criterion corrected for the small sample sizes ($AIC_c$) to compare the models (Burnham and Anderson 2002). As our top-ranked model weight was < 0.9, we used model averaging (R package *AICcmodavg*; Mazerollem 2020) to provide parameter estimates using all candidate models (Johnson and Omland 2004; Arnold 2010). We report the conditional average of all candidate models and the corresponding 95% confidence intervals.

*Quantifying effort of monitoring techniques.* We reviewed all camera photos manually using built-in photo viewing applications on our computer systems or the manufacturer-provided photo review software described above. To understand the added effort spent reviewing the large amount of data collected by camera monitoring, we tracked the total number of hours required to review all photos from camera monitoring. We could not compare the total effort required for in-person monitoring versus camera monitoring because we conducted in-person surveys for all other American Oystercatcher and Piping Plover nests and broods on Metompkin Island simultaneously with in-person monitoring and camera trap deployment, maintenance, and removal for the subset of nests and broods included in this study. As a result, we cannot accurately estimate the field hours required for just this subset of nests alone or for camera set-up and maintenance versus in-person monitoring of these nests. For these reasons, we only report the time spent on camera data processing and review and do not report field hours.

## RESULTS

We monitored the success of 27 American Oystercatcher nests, 28 Piping Plover nests, and 11 American Oystercatcher broods with both in-person and camera monitoring methods. We deployed 73 cameras, including 55 nest cameras, 11 brood cameras, and seven transect cameras, which provided 1,800 cumulative camera days of monitoring (American Oystercatcher nests $n$ =

557 days; Piping Plover nests $n$ = 566; brood $n$ = 355; transect $n$ = 322). Set-up time for nest cameras averaged 7 ± 3 min (mean ± SE; range 2–18 min). Piping Plovers resumed incubation faster than American Oystercatchers (mean ± SE, 7 ± 7 min vs. 28 ± 18 min, respectively), excluding the seven attempts that we abandoned when adults did not resume incubation within the set threshold (American Oystercatcher $n$ = 6, Piping Plover $n$ = 1).

Of the 55 nest cameras deployed, 11 failed due to complications with solar panels (failure rate = 0.20; American Oystercatcher $n$ = 5, 18.5% of camera-monitored American Oystercatcher nests; Piping Plover $n$ = 6, 21.4% of camera-monitored Piping Plover nests). These nests were removed from estimates of hatch success as we could not document nest fate from those cameras for comparison with in-person observations, yielding 44 nests for analyses comparing in-person versus camera monitored fate. No brood cameras failed, so all 11 were used to characterize the predator threat during the chick-rearing stage; however, only eight cameras provided data on chick presence and survival. No transect cameras failed and all were used to quantify predator activity at the marsh edge.

### Estimates of Hatch and Brood Success from In-Person vs. Camera Monitoring

*Hatch success estimates.* Using in-person monitoring, we were able to assign a suspected nest fate for 82% of nests (American Oystercatcher $n$ = 20, 90.9% of American Oystercatcher nests used in analyses; Piping Plover $n$ = 16, 72.7% of Piping Plover nests used in analyses), but were unable to assign a fate for 18% of nests (American Oystercatcher $n$ = 2, 9.1% of nests; Piping Plover $n$ = 6, 27.3% of nests). Camera monitoring improved accuracy of nest fate assignment by confirming all nests with unknown fate from in-person monitoring as hatched or failed (Table 1). Hatch success estimates from camera monitoring were between the lower and upper limits of hatch success estimated from in-person monitoring for Piping Plovers and equivalent to the upper limit for American Oystercatchers (Table 2).

*Productivity estimates.* We estimated a higher productivity for American Oystercatchers from in-person monitoring than from brood camera monitoring (0.63 fledged chicks/pair via in-person surveys versus 0.25 fledged chicks/pair via brood cameras). Brood cameras recorded chick presence on eight of the 11 cameras, but only documented chicks at or after their estimated fledge dates for two broods. Observations from cameras and in-person monitoring agreed on the number of chicks that fledged from these two broods, but we noted fledged chicks from an additional two broods during in-person monitoring that were not detected by the brood cameras for a total of four fledged broods.

## Threats in Nest and Chick-rearing Stages: In-Person vs. Camera Monitoring

*Causes of Abandonment and Clutch Loss.* During in-person monitoring, we noted three nests as failed due to abandonment (American Oystercatcher $n = 1$, 4.5% of nests; Piping Plover $n = 2$, 9.1% of nests). Cameras confirmed all abandoned nests, but only provided insight to an obvious reason for abandonment for one American Oystercatcher nest, which was abandoned after the nest was flooded by a high tide.

We did not assign any sources of partial or complete clutch loss during in-person monitoring besides nest abandonment; as a result, we could not compare additional sources of clutch loss noted from in-person monitoring with camera observations. Cameras documented causes of partial or complete clutch loss for six nest attempts (American Oystercatcher $n = 1$, 4.5% of nests; Piping Plover $n = 5$, 22.7% of nests) where we assigned unknown causes of nest failure during in-person monitoring. For two of these attempts (American Oystercatcher $n = 1$, 4.5% of nests; Piping Plover $n = 1$, 4.5% of nests), we noted sign at the nest site during in-person monitoring but were still unable to assign a cause of failure. Camera-recorded causes of partial and complete clutch loss included predation by a Herring Gull (*Larus argentatus*), Laughing Gulls (*Leucophaeus atricilla*), and an Atlantic ghost crab (*Ocypode quadrata*); trampling by a Canada Goose (*Branta canadensis*); and nest abandonment.

*Causes of Brood Loss.* Nest cameras placed at two different Piping Plover nests captured one chick mortality event when an American Oystercatcher predated a newly hatched Piping Plover chick before it was mobile and one event when a Peregrine Falcon (*Falco peregrinus*) appeared to predate a Piping Plover chick. In-person monitoring noted that these nests had likely hatched but did not identify any cause of chick loss. Neither monitoring method noted causes of mortality for chicks of either species after chicks left the nest site.

*Identification of Other Threats.* American Oystercatchers were the most frequently captured species on all nest cameras (excluding pairs associated with nests on American Oystercatcher nest cameras; Table 3). The next most frequently captured species at nests were white-tailed deer (*Odocoileus virginianus*), grackles (*Quiscalus quiscalus* and *Q. major*), and human recreationists at American Oystercatcher nests, and Atlantic ghost crabs, Least Terns (*Sterna antillarum*), and Peregrine Falcons at Piping Plover nests. In-person monitoring noted the presence of these species on Metompkin Island and signs of some (e.g., grackles, humans, and Atlantic ghost crabs) at specific nest sites, but we could not calculate capture rates from in-person monitoring data.

Four wild mammal species were observed on the nest cameras, including red fox, white-tailed deer, muskrat (*Ondatra zibethicus*), and raccoon (combined 0.98 events/100 camera days; 4.54% of encounters on all cameras; Table 3). All four of these species were observed on cameras at American Oystercatcher nests and caused incubating adults to leave the nest;

however, none of these species were documented predating the monitored nests. Predator species that are targeted for removal on Metompkin Island (i.e., red fox and racoon) had a combined nest camera capture rate of 0.18 events/100 camera days (< 1% of all captures on nest cameras). Additionally, an off-leash dog (*Canis lupus familiaris*) was observed once near a Piping Plover nest.

Diamondback Terrapins (*Malaclemys terrapin*), grackles, and Atlantic ghost crabs were most frequently encountered on transect cameras (Table 3). Crows (*Corvus brachyrhynchos* and *C. ossifragus*), Herring Gulls, and Laughing Gulls were the only other known shorebird predators observed on transect cameras (all < 1% of encounters). There were no mammals captured on transect cameras.

Several known shorebird predators were observed in chick-rearing areas on the brood cameras, including 8 bird species (i.e., Laughing Gull, Herring Gull, Great Black-backed Gull *Larus marinus*, Black-crowned Night-heron *Nycticorax nycticorax*, Great Horned Owl *Bubo virginianus*, Peregrine Falcon, crows, and grackles), two mammal species (i.e., raccoon and dog), and Atlantic ghost crabs. Recreationists also were seen on the brood cameras with the dog.

## Effect of Cameras on Nest Survival

The global model to predict daily nest survival fit the data well ($\chi^2_8 = 13.64$, $p = 0.09$). The top model was the null model (Table 4). Four of the candidate models included camera presence, though we did not find strong evidence to suggest that camera presence had an effect on daily nest survival ($\beta = 0.38$, 95% CI = -0.57–1.32).

## Effort Required for In-Person vs Camera Monitoring

The nest, brood and transect cameras produced a total of 2.76 terabytes of data (i.e., 1.5 terabytes, 230 gigabytes, and 1.03 terabytes of data, respectively). We expended 11.5 hours processing images, which included time spent uploading and organizing data from the cameras. Nest camera review required 139 hours by one person to review photos encompassing 1,123 camera days. Two reviewers spent a combined 63.5 hours reviewing photos from brood cameras (355 camera days) for brood presence and chick mortality events. Two reviewers spent a combined 315 hours to review all the time-lapse footage recorded from the 322 camera days captured by transect cameras (approximately 5,152 hours of footage; 61,000 photos/camera/day). Thus, in total we spent 517.5 hours processing camera data.

## DISCUSSION

Camera monitoring was useful for validating the accuracy of nest fate assignments from in-person monitoring and for improving the accuracy of overall hatch success estimates for American Oystercatchers and Piping Plovers. Camera monitoring confirmed the fate of nests where signs of hatching or failure were recorded as unknown by in-person monitors and thus improved hatch success estimates. Our results were similar to other studies that found camera monitoring improved the accuracy of hatch success estimates for shorebirds (e.g., Ellis *et al.* 2018; Andes *et al.* 2019) and songbirds (e.g., Ball and Bayne 2012), despite our limited sample size and short (i.e., one-year) study duration.

We also tested the efficacy of using cameras to monitor American Oystercatcher chick survival once chicks had left the nest. We found that cameras were less useful for monitoring chick survival and fledging than in-person monitoring, as not all cameras consistently recorded chick presence. Only eight of the 11 brood cameras documented chick presence at least once and only two continued to record their presence until the chicks reached their expected fledge dates, whereas in-person monitoring confirmed that four of the camera-monitored broods fledged chicks. This suggests that camera monitoring underestimated productivity for American

Oystercatchers, possibly due to chicks remaining outside the detection range of cameras (e.g., hidden in the marsh grass).

Effective monitoring for species of conservation concern should not only focus on estimating population abundance and demographic rates, but also assist with threat identification (Campbell *et al.* 2002). Both in-person and camera monitoring methods aimed to identify sources of nest and chick loss and other potential threats. Observations from in-person and camera monitoring agreed on abandonment as a cause of nest failure, and cameras provided further insight into threats. Evidence collected by cameras confirmed predation by gull species and Atlantic ghost crabs, and in one case trampling by a Canada Goose, as sources of clutch loss, whereas field evidence found at these sites during in-person monitoring was challenging to interpret and inconclusive. In these instances, investigators correctly identified the presence of species that caused egg loss but failed to attribute them to that loss. Evidence of egg loss at a nest may be difficult to identify during in-person monitoring, as a nest site may become altered (e.g., presence of additional tracks) following the egg loss event by multiple predation attempts, scavengers visiting the nest site, or adult activity following the event (White *et al.* 2010). Investigators may also fail to consider previously unknown or underrealized species as threats, such as trampling by a non-predator species in our study, when assessing evidence around a failed nest or conducting predator surveys (Lariviere 1999; Liebezeit and Zack 2008). These reasons, as well as the ephemeral nature of field evidence on a sandy, sparsely vegetated beach exposed to wind, precipitation, and other abiotic factors that can obliterate sign (Ellis *et al.* 2018; Andes *et al.* 2019), may explain why in-person monitoring was inconclusive on the cause of egg loss.

Disturbance that is separate from predation and causes incubating adults to leave the nest is an important threat to consider as it may reduce productivity (McGowan and Simons 2006; Denmon *et al.* 2013; DeRose-Wilson *et al.* 2018). However, signs of disturbance to incubating adults or broods are not easy to identify with in-person monitoring for the same reasons as signs of predation, and behavioral changes due to frequent disturbance events are difficult to identify without routine behavioral surveys. Cameras at nests and brood-rearing areas identified events that caused incubating adults to leave the nest or elicited a defensive response from adults tending broods, such as recreationists or another animal passing closely to a nest or approaching a brood. While none of these events were direct sources of egg or chick loss, they may contribute to reduced nest and chick survival by altering adult behavior, such as time spent incubating a nest or tending to chicks (McGowan and Simons 2006; DeRose-Wilson et al. 2018). Thus, camera monitoring appeared to be useful in our study for identifying sources of disturbance that in-person monitoring may miss, but management of these sources (e.g., other animals passing nests or broods) may be limited except for management actions restricting recreational activities and visitor access to the site to reduce disturbance from recreationists and off-leash dogs.

Cameras were also useful for evaluating the effectiveness of current management actions. In-person monitoring prior to this study on Metompkin Island indicated that predation was the primary ongoing threat to the reproductive success of American Oystercatchers and Piping Plovers. Previous observations of red fox and raccoon predation of nests on Metompkin Island (R. Boettcher, Z, Poulton, and A. Wilke, pers. obs.) led to decisions to manage this threat through the lethal removal of mammalian predators. Both in-person and camera monitoring indicated mammalian predator management appears to be successful, as neither method noted signs of red fox or racoon predation events and cameras captured few mammalian predators.

In addition to using cameras for monitoring shorebird nest success, we were also interested in testing the utility of using cameras to monitor chicks once they left the nest. Assessments of threats to productivity must consider drivers of chick survival in addition to drivers of nest success, as chick survival is an equally important component of productivity (Cohen *et al.* 2009). Long intervals between site visits made it difficult to identify mortality in newly hatched chicks during in-person monitoring, as the period that American Oystercatcher and Piping Plover chicks are immobile is less than 48 hours (AMOYWG *et al.* 2020; Elliott-Smith and Haig 2020). Cameras recorded one predation event of a newly hatched Piping Plover chick by an American Oystercatcher that we failed to identify during in-person monitoring. However, we did not successfully identify sources of mortality for mobile chicks from either monitoring method, despite documenting chick loss (i.e., noting that there were fewer chicks in a brood over time).

Although cameras helped to characterize the predator community at brood sites and captured known shorebird predators at the marsh edge, they did not improve our ability to monitor survival of or to identify threats to mobile chicks over in-person monitoring in this study. Our methods for monitoring broods with cameras may not have been successful at our site due to the broods' access to the marsh and tidal flats during low tide, making them unavailable for detection on the cameras. It is possible that the brood and transect camera set-ups described in this study are viable methods at sites where broods' movements are more restricted by island topography and where broods are less likely to be hidden in vegetative cover. Additionally, a set-up with more cameras covering a broader view of brood rearing areas during day and night or using time-lapse versus motion-triggered settings on the cameras may increase chances of capturing chick presence and potential mortality events. However, the efficacy of these or different set-ups at other sites cannot be confirmed without further testing. Additionally, alternative methods such as tagging and tracking chicks using telemetry may aid with confirming threats to chick survival. These methods have been used in previous studies of shorebird chick survival, such as one study that relocated American Oystercatcher chick remains and conducted mortality investigations to identify causes of chick death (Schulte and Simons 2015).

In general, cameras seem unlikely to affect the daily survival rate of nests in our study and previous studies (e.g., McKinnon and Bêty 2009; Richardson *et al.* 2009; Ellis *et al.* 2018; Andes *et al.* 2019; McGuire *et al.* 2022). However, managers should still consider that cameras may have the potential to alter predator behavior, causing a change in nest predation rates by attracting predators (Hillman 2012; DeRose-Wilson *et al.* 2013) or deterring neophobic predators that avoid new and unusual objects (Herranz *et al.* 2002). In our study, a Peregrine Falcon appeared to use the camera equipment at one nest for perching and may have predated one chick. Managers that choose to use cameras for remote monitoring should be aware of this potential for perching and consider taking measures such as using perch deterrents and comparing nest survival for nests with and without cameras.

Managers also should consider the effort required for conducting camera monitoring versus in-person monitoring. As we continued to conduct in-person monitoring on Metompkin Island throughout the breeding season, we were able to conduct routine checks and maintenance on deployed cameras; however, such routine visits to cameras may not be necessary if memory card space and battery power are sufficient for longer deployments. If routine checks are not necessary, camera monitoring requires less overall time spent at the monitoring site than in-person monitoring, which may be beneficial when monitoring remote, difficult-to-access, or sensitive sites.

While camera monitoring may require less time in the field, some camera set-ups in our study produced large quantities of data that required more time for processing and review. Camera set-up (i.e., nest versus brood versus transect) and camera settings (e.g., motion-detection versus time-lapse) affected the type and quantity of data collected from camera monitoring, and thus also the amount of effort required to review the data. Camera photo review using methods for manually reviewing and recording data from photos for 73 cameras required over 500 hours, with the seven time-lapse transect cameras requiring the most hours for review (i.e., approximately 61% of the time spent on camera data). We found that motion-triggered nest cameras, which required 139 additional hours to review, were effective for improving accuracy of hatch success estimates and providing insight to true causes of egg loss. In contrast, brood and transect cameras, which required a combined 378.5 hours to review, were less useful for estimating fledge success and identifying causes of chick mortality. However, brood and transect cameras were useful for providing insight to the predator community active in and near brood-rearing territories.

We found that camera use may be beneficial for monitoring shorebird reproductive success at remote sites, where long monitoring intervals may lead to more inaccurate classifications of nest fate. Additionally, camera monitoring may reduce uncertainty in systems where little is known about the predator community or other local threats, though larger quantities of data from more cameras or time-lapse photography may be needed to collect this data, requiring more effort to review. Managers should consider these tradeoffs when deciding which method of monitoring would be most useful for answering their questions and meeting their management goals.

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FIGURE

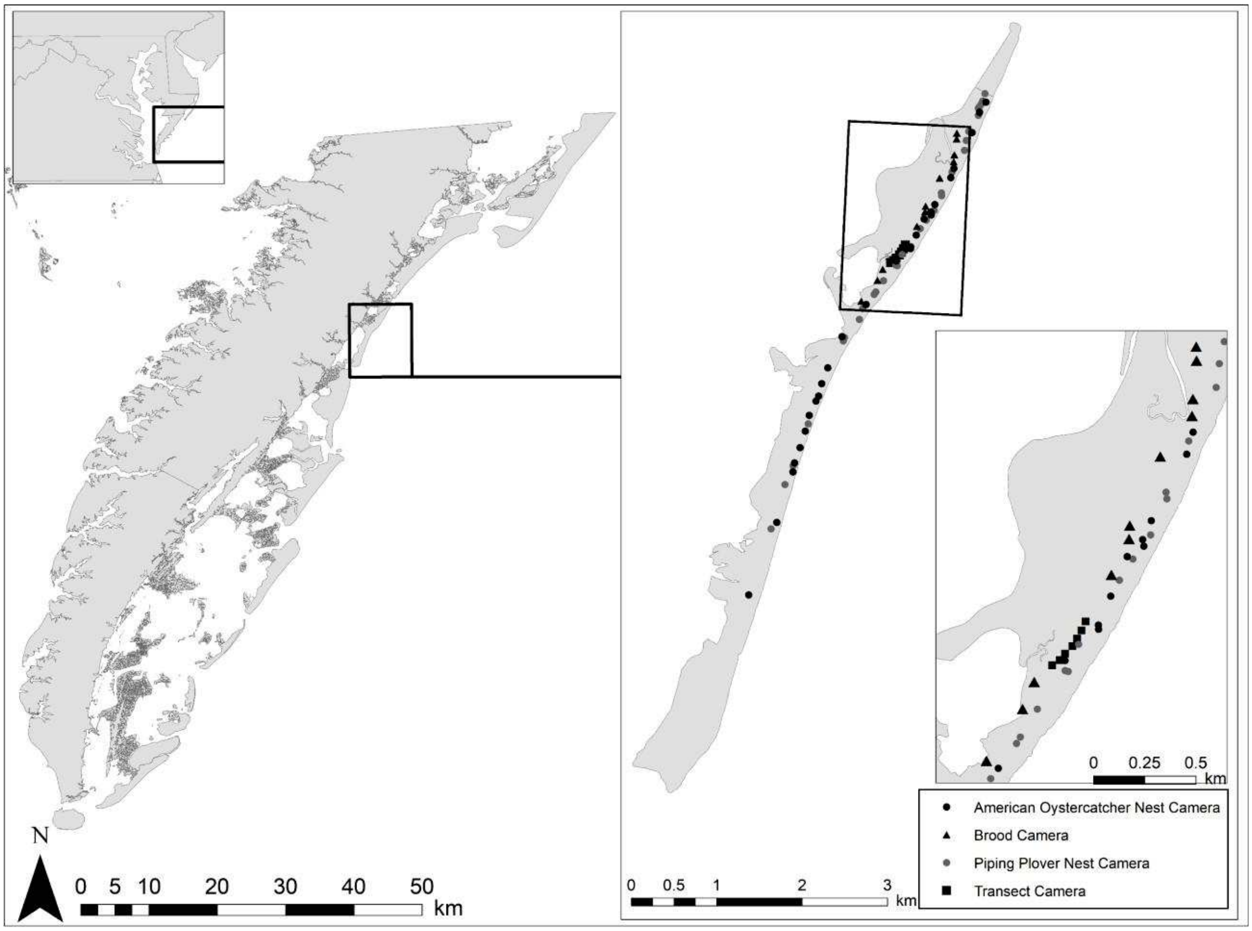

**Figure 1. Metompkin Island is within the Virginia barrier island system, on the seaward coast of the Delmarva Peninsula. Locations of nest (American Oystercatcher, *Haematopus palliatus, n* = 27; Piping Plover, *Charadrius melodus, n* = 28), brood (*n* = 11), and transect (*n* = 7) cameras deployed in 2019 are shown on the right plate. The inset on the right plate is a zoomed-in view of the brood and transect cameras.**

# TABLES

**Table 1. Number of nests with each possible fate assignment (success, failed, unknown) for American Oystercatchers (*Haematopus palliatus*, *n* = 22) and Piping Plover (*Charadrius melodus*, *n* = 22) nests monitored with both camera and in-person monitoring methods on Metompkin Island, Virginia, in 2019.** [1]

| | **American Oystercatcher** | **Piping Plover** |
|---|---|---|
| **Success** | | |
| **Camera** | 20 | 15 |
| **In-Person** | 18 | 11 |
| **Failed** | | |
| **Camera** | 2 | 7 |
| **In-Person** | 2 | 5 |
| **Unknown** | | |
| **Camera** | 0 | 0 |
| **In-Person** | 2 | 6 |

[1] Results are calculated from 44 nests; whereas 55 total were monitored, 11 cameras failed and thus those nests are excluded, as we could not document nest fate from those cameras for comparison with field observations.

**Table 2. Hatch success estimates (i.e., the proportion of nests estimated to have hatched at least one egg in the clutch) from camera and in-person monitoring methods on American Oystercatcher (*Haematopus palliatus*, *n* = 22) and Piping Plover (*Charadrius melodus*, *n* = 22) nests on Metompkin Island, Virginia, in 2019. Standard error is reported in parentheses. Lower and upper hatch success estimates from in-person monitoring assume that all nests with unknown fates failed or hatched, respectively. Only one hatch estimate is reported for camera monitoring, as there were no unknown nest fates from this method.**

| | **American Oystercatcher** | **Piping Plover** |
|---|---|---|
| **Camera** | 0.91 (0.06) | 0.68 (0.10) |
| **In-Person (Lower)** | 0.82 (0.08) | 0.50 (0.11) |
| **In-Person (Upper)** | 0.91 (0.06) | 0.77 (0.09) |

**Table 3. Number of events (individual detections ≥ 30 minutes apart; ‘*N*’), capture rate (*N*/100 camera days; ‘Rate’), and percent of total captures (‘%’) of species documented causing predation and disturbance on nest cameras (*n* = 27 American Oystercatcher and 28 Piping Plover; *n* = 55 combined; 1,123 camera days) and all species (excluding American Oystercatcher or Piping Plover) detected on transect cameras (*n* = 7; 322 camera days) at Metompkin Island, Virginia in April–August 2019. Several species could not be determined past genus, family, or order due to photo quality. Species are listed taxonomically following the American Ornithological Union Species Checklist (Chesser *et al.* 2021) for birds and North American Mammalian Species Checklist (Bradley *et al.* 2014) for mammals.**

| | **Oystercatcher Nest** | | | **Plover Nest** | | | **All Nests** | | | **Transect** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Species** | ***N*** | **Rate** | **%** | ***N*** | **Rate** | **%** | ***N*** | ***Rate*** | **%** | ***N*** | **Rate** | **%** |
| **Arthropoda** | | | | | | | | | | | | |
| Atlantic ghost crab (*Ocypode quadrata*) | 1 | 0.18 | 10.43 | 430 | 7.60 | 25.44 | 44 | 3.92 | 18.49 | 2 | 0.62 | 0.14 |
| **Class Reptilia** | | | | | | | | | | | | |
| Diamondback terrapin (*Malaclemys terrapin*) | 1 | 0.18 | 1.43 | 4 | 0.71 | 2.37 | 5 | 0.45 | 2.10 | 375 | 116.46 | 26.61 |

| **Species** | **Oystercatcher Nest** | | | **Plover Nest** | | | **All Nests** | | | **Transect** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***N*** | **Rate** | **%** | ***N*** | **Rate** | **%** | ***N*** | ***Rate*** | **%** | ***N*** | **Rate** | **%** |
| **Class Aves** | | | | | | | | | | | | |
| Canada Goose (*Branta canadensis*) | 3 | 0.54 | 4.29 | 4 | 0.71 | 2.37 | 7 | 0.62 | 2.94 | 84 | 26.09 | 5.96 |
| Rail sp. (*Rallus* spp.) | - | - | - | - | - | - | - | - | - | 1 | 0.31 | 0.07 |
| American Oystercatcher (*Haematopus palliatus*) | 24 | 4.31 | 34.29 | 52 | 9.19 | 30.77 | 76 | 6.77 | 31.93 | 252 | 78.26 | 17.89 |
| Black-bellied Plover (*Pluvialus squatarola*) | - | - | - | 1 | 0.18 | 0.59 | 1 | 0.09 | 0.42 | - | - | - |
| Willet (*Tringa semipalmata*) | 3 | 0.54 | 4.29 | 4 | 0.71 | 2.37 | 7 | 0.62 | 2.94 | 1 | 0.31 | 0.07 |
| Shorebird sp. (Charadriiformes sp.) | - | - | - | 1 | 0.18 | 0.59 | 1 | 0.09 | 0.42 | 68 | 21.12 | 4.83 |

| Species | Oystercatcher Nest | | | Plover Nest | | | All Nests | | | Transect | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***N*** | **Rate** | **%** | ***N*** | **Rate** | **%** | ***N*** | ***Rate*** | **%** | ***N*** | **Rate** | **%** |
| Laughing Gull (*Leucophaeus atricilla*) | 1 | 0.18 | 1.43 | 6 | 1.06 | 3.55 | 7 | 0.62 | 2.94 | 14 | 4.35 | 0.99 |
| Herring Gull (*Larus argentatus*) | 4 | 0.72 | 5.71 | 3 | 0.53 | 1.78 | 7 | 0.62 | 2.94 | 1 | 0.31 | 0.07 |
| Black-backed Gull sp. (*Larus marinus/fuscus*) | - | - | - | - | - | - | - | - | - | 4 | 1.24 | 0.28 |
| Gull sp. (Laridae sp.) | 1 | 0.18 | 1.43 | 2 | 0.35 | 1.18 | 3 | 0.27 | 1.26 | 12 | 3.73 | 0.85 |
| Black Skimmer (*Rynchops niger*) | - | - | - | - | - | - | - | - | - | 8 | 2.48 | 0.57 |
| Least Tern (*Sternula antillarum*) | 1 | 0.18 | 1.43 | 17 | 3.00 | 10.06 | 18 | 1.60 | 7.56 | 72 | 22.36 | 5.11 |
| Tern sp. (Sterninae sp.) | 1 | 0.18 | 1.43 | 1 | 0.18 | 0.59 | 1 | 0.09 | 0.42 | - | - | - |

| | Oystercatcher Nest | | | Plover Nest | | | All Nests | | | Transect | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Species** | ***N*** | **Rate** | **%** | ***N*** | **Rate** | **%** | ***N*** | ***Rate*** | **%** | ***N*** | **Rate** | **%** |
| Heron or Egret sp. (*Ardea* or *Egretta* sp.) | - | - | - | - | - | - | - | - | - | 88 | 27.33 | 6.25 |
| Osprey (*Pandion haliaetus*) | - | - | - | 1 | 0.18 | 0.59 | 1 | 0.09 | 0.42 | - | - | - |
| Bald Eagle (*Haliaeetus leucocephalus*) | 3 | 0.54 | 4.29 | 1 | 0.18 | 0.59 | 4 | 0.36 | 1.68 | - | - | - |
| Great Horned Owl (*Bubo virginianus*) | 1 | 0.18 | 1.43 | - | - | - | 1 | 0.09 | 0.42 | - | - | - |
| Peregrine Falcon (*Falco peregrinus*) | - | - | - | 12 | 2.12 | 7.10 | 12 | 1.07 | 5.04 | - | - | - |
| Hawk or Falcon sp. (*Buteo* or *Falco* sp.) | - | - | - | 2 | 0.35 | 1.18 | 2 | 0.18 | 0.84 | 2 | 0.62 | 0.14 |

| Species | Oystercatcher Nest | | | Plover Nest | | | All Nests | | | Transect | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *N* | **Rate** | **%** | *N* | **Rate** | **%** | *N* | ***Rate*** | **%** | *N* | **Rate** | **%** |
| Crow spp.<br>(*Corvus* spp.) | - | - | - | - | - | - | - | - | - | 14 | 4.35 | 0.99 |
| Eastern Meadowlark<br>(*Sturnella magna*) | - | - | - | - | - | - | - | - | - | 3 | 0.93 | 0.21 |
| Red-winged Blackbird<br>(*Agelaius phoeniceus*) | - | - | - | 1 | 0.18 | 0.59 | 1 | 0.09 | 0.42 | 95 | 29.50 | 6.74 |
| Grackle spp.<br>(*Quiscalus* spp.) | **7** | 1.26 | 10.00 | 9 | 1.59 | 5.33 | 16 | 1.42 | 6.72 | 311 | 96.58 | 22.07 |
| Human<br>(*Homo sapiens*) | 7 | 1.26 | 10.00 | 5 | 0.88 | 2.96 | 12 | 1.07 | 5.04 | - | - | - |
| Muskrat<br>(*Ondatra zibethicus*) | 1 | 0.18 | 1.43 | - | - | - | 1 | 0.09 | 0.42 | - | - | - |
| Domestic dog<br>(*Canis lupus familiarus*) | 1 | 0.18 | 1.43 | - | - | - | 1 | 0.09 | 0.42 | - | - | - |

| Species | Oystercatcher Nest | | | Plover Nest | | | All Nests | | | Transect | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***N*** | **Rate** | **%** | ***N*** | **Rate** | **%** | ***N*** | ***Rate*** | **%** | ***N*** | **Rate** | **%** |
| Red fox<br>(*Vulpes vulpes*) | 1 | 0.18 | 1.43 | - | - | - | 1 | 0.09 | 0.42 | - | - | - |
| Northern raccoon<br>(*Procyon lotor*) | 1 | 0.18 | 1.43 | - | - | - | 1 | 0.09 | 0.42 | - | - | - |
| White-tailed deer<br>(*Odocoileus virginianus*) | 8 | 1.44 | 11.43 | - | - | - | 8 | 0.71 | 3.36 | - | - | - |

**Table 4. Candidate models examining effect of predictor variables on nest survival of American Oystercatchers (*Haematopus palliatus*) and Piping Plovers (*Charadrius melodus*) at Metompkin Island, Virginia during the breeding season, April-August 2019. Models are ranked by ascending $\Delta AIC_c$, and the number of parameters (*K*), log likelihood, Akaike weight ($w_i$), and cumulative Akaike weight ($\sum w_i$) are given. $AIC_c$ for the top-ranked model was 203.01.**

| Candidate model[a] | *K* | Log likelihood | $\Delta AIC_c$ | $w_i$ | $\sum w_i$ |
|---|---|---|---|---|---|
| Null | 1 | -100.50 | 0.00 | 0.19 | 0.19 |
| Location | 2 | -99.55 | 0.13 | 0.18 | 0.36 |
| Species | 2 | -99.99 | 1.00 | 0.11 | 0.48 |
| Camera | 2 | -100.03 | 1.07 | 0.11 | 0.58 |
| Location + Species | 3 | -99.12 | 1.28 | 0.10 | 0.68 |
| Camera + Location | 3 | -99.30 | 1.64 | 0.08 | 0.77 |
| Age | 2 | -100.47 | 1.97 | 0.07 | 0.84 |
| Age + Location | 3 | -99.54 | 2.12 | 0.06 | 0.90 |
| Camera + Species | 3 | -99.65 | 2.34 | 0.06 | 0.96 |
| Camera + Location + Species | 4 | -98.96 | 3.00 | 0.04 | 1.00 |

[a] Variables in the model include species (American Oystercatcher or Piping Plover), location (northern or southern Metompkin Island), nest age measured as the number of days from the start of incubation, and camera presence or absence.