Potential Avian Predators of Piping Plover (*Charadrius melodus*): A Study at Fire Island, NY

by

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ABSTRACT

The Piping Plover (*Charadrius melodus*) is a federally-threatened shorebird that relies on nesting habitat along the Atlantic Coast, including in New York. A variety of management strategies to protect nesting plovers at Fire Island, NY, target mammalian predation, but the impact of avian predation remains largely unknown. During the summer of 2022, at Robert Moses State Park (RMSP) and the National Park Service (NPS) Lighthouse, I recorded abundance and behavior of raptors, gulls, corvids, blackbirds, and shorebirds of other species (*i.e.,* Ruddy Turnstone, *Arenaria interpres,* and American Oystercatcher, *Haematopus palliatus*) that are known or suspected to take (predate upon) Piping Plover adults, chicks, or eggs. This work was as part of the Virginia Tech Shorebird Program's annual monitoring of plovers on Fire Island. Before the chicks can fly at around 25 days of age and are considered fledged, they are especially vulnerable to predation.

During routine monitoring activities, I made instantaneous counts of potential avian predators while in plover nesting areas from early June to mid-August and recorded their habitat (*e.g.,* intertidal, wrack line, dry sand), behavior (*e.g.,* loafing, foraging), and flock size. Gulls were the most abundant potential avian predator and were observed daily (Great Black-backed Gull, *Larus marinus* = 122.1 birds/day; Herring Gull, *L. argentatus* = 58.0 birds/day; and Lesser Black-backed Gull, *L. fuscus* = 35.5 birds/day), though VTSP researchers and I detected little evidence of gulls taking plovers in 2022. Peregrine Falcons (*Falco peregrinus*) were seen infrequently (0.3 birds/day), but were observed hunting nesting shorebirds, including confirmed takes of plovers.

Based on my observations, I constructed a map of avian predator density across the area monitored in relation to locations of Piping Plover nests and broods for the months surveyed. Overall, the density of potential avian predators increased throughout July and August, likely as these species finished breeding and dispersed. To investigate the impact of avian predator abundance on chick survival before fledging, I modeled the probability of chick disappearance prior to fledge using avian predator abundance and hatch date as explanatory variables. I predicted that avian predators with more evidence of predation on plovers would have a larger negative effect on chick survival. This model should also aid our understanding of whether certain types of avian predators have a larger effect on chick mortality than others. In this study, I characterized the avian predator community present at Robert Moses SP and the NPS Lighthouse and begin to clarify the impact of these avian predators on chick survival. Understanding the species, numbers, and distribution of avian predators present can inform future management decisions.

INTRODUCTION

Across North America, as of 2019, bird populations have declined approximately 30% since 1970 (Rosenberg *et al.* 2019). Shorebirds are included in species declining world-wide, due to critical habitat changes along flyways as a result of climate change and development (Santos *et al.* 2023). Due to climate change dynamically altering coastal systems — for example, stronger and more frequent storms increasing threats during long distance migration, predation, and loss of habitats — shorebirds face many challenges throughout their lives. Consequently, the decline in shorebird species populations has resulted in many species requiring protection. The Piping Plover (*Charadrius melodus*) is one of those species, and therefore it is important to study the challenges they face and what measures might be employed to stabilize and increase their population sizes.

The Piping Plover is a federally-threatened shorebird that nests along the Atlantic Coast, as well as along the Great Lakes and across the Great Plains (U.S. Fish and Wildlife Service 1996). Adult Piping Plovers are small, stocky shorebirds weighing approximately 50 grams (about the same as 10 nickels) and are sandy-colored with dark markings and orange bills and legs in breeding plumage (Figure 1). The Atlantic population relies on nesting habitat along the coast, including in New York and on Fire Island. Piping Plovers nest on sandy substrate, with an average clutch size of four eggs (Wilcox 1959, Elliott-Smith and Haig 2020), which are sandy-colored with speckles (Figure 1). Once the clutch is complete, both sexes of adult plovers incubate the eggs for an average of 28 days in New York (Wilcox 1959). Soon after hatching, chicks are able to run and walk and can leave the nest but are unable to fly until fledging at around 25-30 days (Wilcox 1959). Fledglings look similar to adults but lack the dark markings of the adult breeding plumage and have entirely dark bills (Figure 1). Chicks are well-camouflaged for their sandy habitat, with their upper parts speckled brown and gray. In response to alarm calls from their parents, chicks often lie motionless, blending into the sand (Cairns 1982). Hiding and remaining motionless are the chicks' best defenses against predators, and, in locations with sparse vegetation, their coloration is important (Cairns 1982). The camouflage of both chicks and eggs minimizes detection by predators. Adult plovers also feign injury by performing broken-wing displays to distract potential predators from their nearby nest (Cairns 1982). While performing this display, the adult plover will hold one wing raised while flapping one or both wings against the ground and attempt to lure the predator away (Cairns 1982). Plovers also interact territorially with other plovers or individuals of different species, by assuming a crouched posture, erecting their feathers, and calling (Cairns 1982, Elliott-Smith and Haig 2020). However, if the use of exclosures (wire cages surrounding nests used as a federally-approved management strategy, Melvin *et al.* 1992) cues predators into plover nests, camouflaged eggs and the distraction displays of adults may not be as effective.

Figure 1. Piping Plover Identification. The Piping Plover (*Charadrius melodus*): (a.), (b.) eggs and nest bowl in the sand; (c.) adult on nest incubating eggs; (d.) chick; (e.) newly hatched chicks and eggs, green and black color bands can be seen on the back right chick; (f.) adult showing orange color band on right leg, and green alpha-numeric flag 799 on right leg. All photographs by K. E. Johnson.

Study Location

The Virginia Tech Shorebird Program (VTSP) has been monitoring Piping Plovers breeding on Fire Island since 2013 (DeRose-Wilson *et al.* 2013). In this study, I focus on the western end of Fire Island, which is located south of Long Island, at Robert Moses State Park (Robert Moses SP) and at the National Park Service (NPS) Lighthouse (Figure 2). Across this area of approximately 185 hectares, the amount of available habitat for nesting plovers varies, as does the amount of human activity (DeRose-Wilson *et al.* 2018, Walker *et al.* 2019, Walker 2020). The study area is separated into seven different subsites based on habitat characteristics (Figures 2, 3). Each subsite typically contains three different habitat types: the intertidal zone, dry vegetation, and dry sand. Democrat Point also has ephemeral pools, areas that flood with rain and very high tides from storms or spring tides (Figure 3). Robert Moses SP contains some of the most popular recreational beaches on Long Island (DeRose-Wilson *et al.* 2018). Consequently, some areas of the beach, such as Fields 4 and 5, are heavily used by humans, and there is reduced availability of plover nesting habitat. In contrast, the westernmost tip of the island, Democrat Point, has restricted recreational access, and the wide-open sandy space supports large, mixed-species breeding colonies of Common (*Sterna hirundo*) and Least Terns (*Sternula antillarum*) and a newly-established colony of Black Skimmers (*Rynchops niger*). American Oystercatchers (*Haematopus palliatus*), Willets (*Tringa semipalmata*), and many pairs of Piping Plovers also nest amongst these colonial breeders (Figures 3, 4).

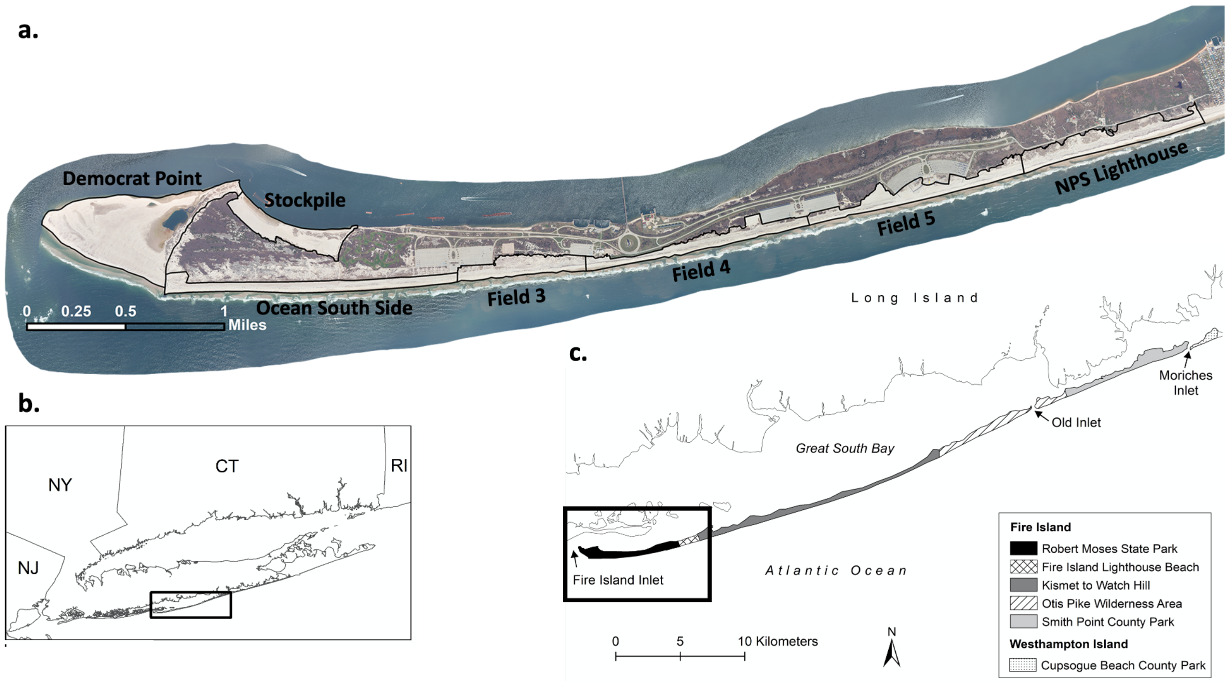


Figure 2. Location and subsites of the study site. The seven different subsites are shown on aerial imagery of the study site from April 2022 (a.). The study location is also shown in relation to the surrounding states (b.) and all of Fire Island (c.). Aerial imagery and maps courtesy of the Virginia Tech Shorebird Program 2022.

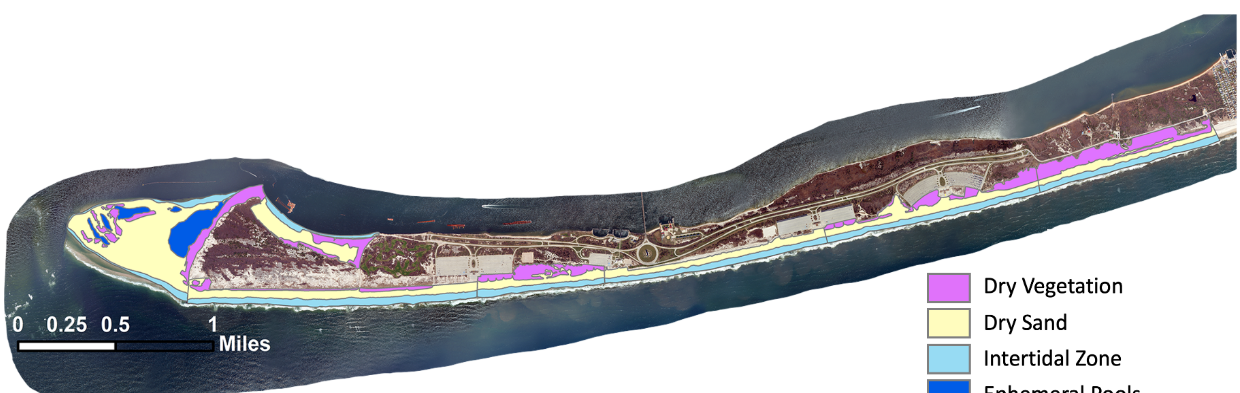


Figure 3. Habitat designations within the study site. Aerial imagery of Robert Moses SP and the NPS Lighthouse from summer 2022 showing locations of each habitat type within the seven different subsites. All subsites contain regions of dry vegetation, dry sand, and the intertidal zone, and only Democrat Point also has ephemeral pools. Constructed by K. E. Johnson with aerial imagery courtesy of the Virginia Tech Shorebird Program 2022.

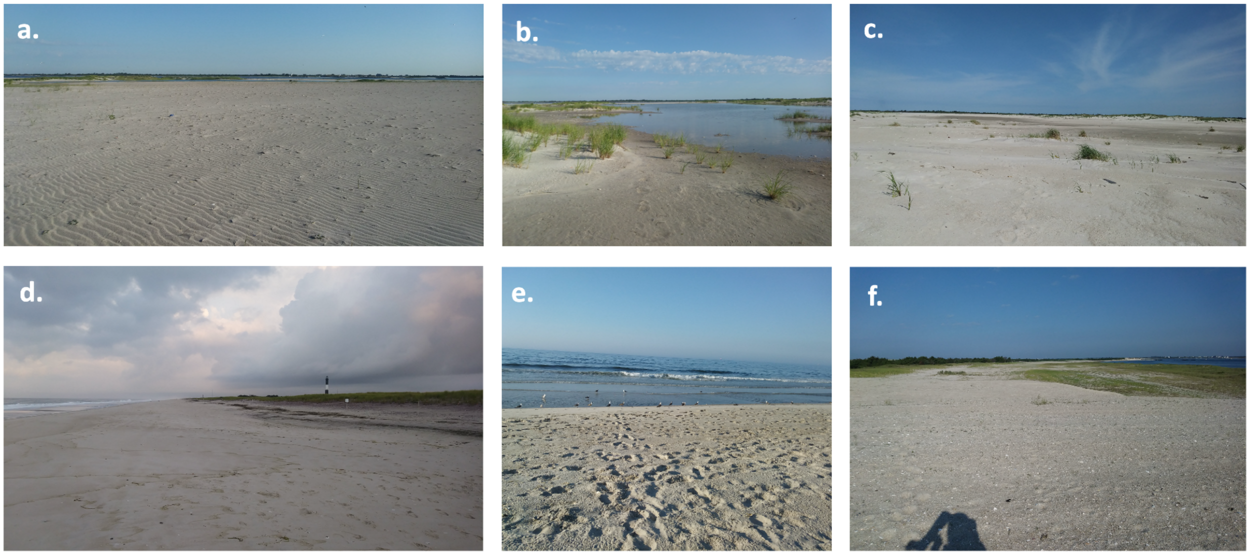


Figure 4. Imagery of the study site. Views from different areas within the study site from summer 2022. Democrat Point has wide-open, sandy areas (a.), and ephemeral pools which are flooded (b.) or dry (c.) for different parts of the breeding season. NPS Lighthouse has a wide intertidal zone and dunes (d.). The intertidal zone of Field 4 was heavily traveled by humans and often had many Lesser Black-backed Gulls (e.). The Stockpile has wide flat, sparsely vegetated areas (f.). All photographs by K. E. Johnson.

Factors Influencing Successful Breeding

During the breeding season, Piping Plovers' survival and breeding success are affected by many threats, including those posed by mammalian and avian predators. Historically, management has primarily focused on protecting nests from mammalian predation and human disturbance. At Fire Island, NY, the use of symbolic fencing closes portions of plover nesting habitat to the public, minimizing disturbances to nests. In addition, the use of nest exclosures - large wire cages enclosing the nest, designed to allow plovers to enter and exit - prevent most mammals from accessing nests (Burger 1987, Rimmer and Deblinger 1990, Melvin *et al.* 1992; Figure 5). Due to their design, exclosures also provide protection against predators unable to enter the exclosure (Kwon *et al.* 2018, Stantial *et al.* 2021), including larger avian predators; however, the exclosures may also increase visibility of the nest location to predators in general and create perches for avian predators. Consequently, it is important to consider both the advantages and disadvantages of erecting exclosures at specific locations, in order to maximize the benefit to nesting plovers (Murphy *et al.* 2003, Barber *et al.* 2010, Cohen *et al.* 2016, Anteau *et al.* 2022). Prior studies have found that the use of exclosures increases the likelihood of adult mortality from predators, despite also increasing nesting success (Murphy *et al.* 2003, Barber *et al.* 2010). As a result, the use of exclosures must be carefully monitored so breeding adults are not lost from the population in significant numbers. At Fire Island in 2022, 75% of all found active nests were exclosed, offering protection from large-bodied mammalian and avian predation at nests. Specifically at Robert Moses SP and the NPS Lighthouse, all found nests were exclosed in 2022 and there was only one instance where the nest of a brood had not been located. Thus, it is believed that egg predation is not a major concern for successful breeding (Wails *et al.* 2022).

Prior studies have also attempted to characterize the impact of avian predation in relation to mammalian predation. Ivan and Murphy (2005) found that avian predators account for more losses of chicks and adults. Roche *et al.* (2010) found mammalian predators account for more losses of eggs. Contrastingly, Cohen *et al.* (2009) found that exclosures increased nest survival, and mammal trapping increased chick survival. Anteau *et al.* (2012) attributed half of the losses of unexclosed nests to avian predators. Additionally, Kruse *et al.* (2001) found that predation on chicks may increase throughout the season due to changing predator abundances. Therefore, avian predation has an effect on the plover population throughout the breeding season, though it is hard to quantify that effect. Chick survival is important as juvenile birds face higher rates of mortality than adults (Robinson *et al.* 2023); therefore protecting this vulnerable stage of life is important. To help protect chicks from mortality, causes of mortality must be understood. I am further investigating the potential effect of avian predation starting by establishing the abundance and distribution of potential avian predator species at Fire Island, NY across three months of the Piping Plover summer nesting season.

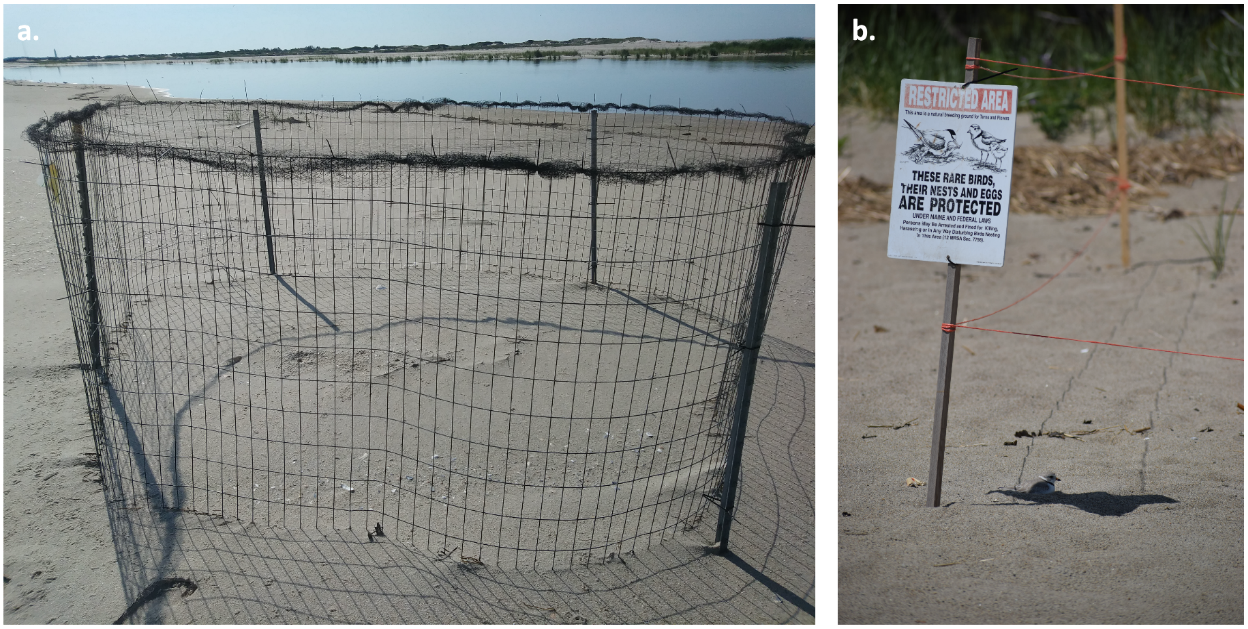


Figure 5. Predator exclosure protecting a plover nest; the wire allows plovers to visit the nest freely while excluding larger species of both avian and mammalian predators (a.). An example of symbolic fencing to keep humans from entering plover nesting areas (b.). All photographs by K. E. Johnson.

While mammalian predators likely have a strong impact on plover populations (Stantial *et al.* 2020, Black *et al.* 2022), the presence of avian predators may be tied to management activities such as fencing and exclosures providing perches for avian predators. Therefore, it is important to gain an understanding of the effects of avian predators on the plover population. Known mammalian predators of both nests, chicks and adult plovers are red foxes (*Vulpes vulpes*), feral cats (*Felis catus*), striped skunks (*Mephitis mephitis*), and American minks (*Neovison vison*) (Cohen *et al.* 2009, Barber *et al.* 2010, Stantial *et al.* 2020, Black *et al.* 2022, Wails *et al.* 2022). In addition, it is important to consider all the threats to the successful breeding of plovers, in order to have the greatest management success. Each individual has an impact on the overall population on Fire Island, and successful breeding should help the population increase. Since predation can vary at each location, site-specific studies can provide additional information on how to approach management in specific areas. Investigating the avian predator community at Robert Moses SP and the NPS Lighthouse can inform management decisions made in future breeding seasons. Additionally, this study can be used as a model to expand the knowledge of the effect of avian predators on other portions of Fire Island and other breeding grounds of this Federally-threatened species, and determine directions for future studies on avian predation of Piping Plovers.

Known Predators of Piping Plover

To determine which avian species to monitor and consider as potential predators, I conducted a literature review to identify known and suspected species of Piping Plovers. Since avian predators of plovers vary geographically, I considered predators reported in the literature that could also occur on Fire Island. Throughout the literature, I found 15 confirmed or suspected avian predators of Piping Plovers that are also present along the Atlantic Coast (Table 1, 2, p. 8-11). When collecting data in the field, I also included predators in the same family as known predators, or species with evidence of predation for other species of shorebirds. These predators are shown along with Piping Plovers and their comparative size, using mass in grams and wingspan in centimeters, in Figure 6.

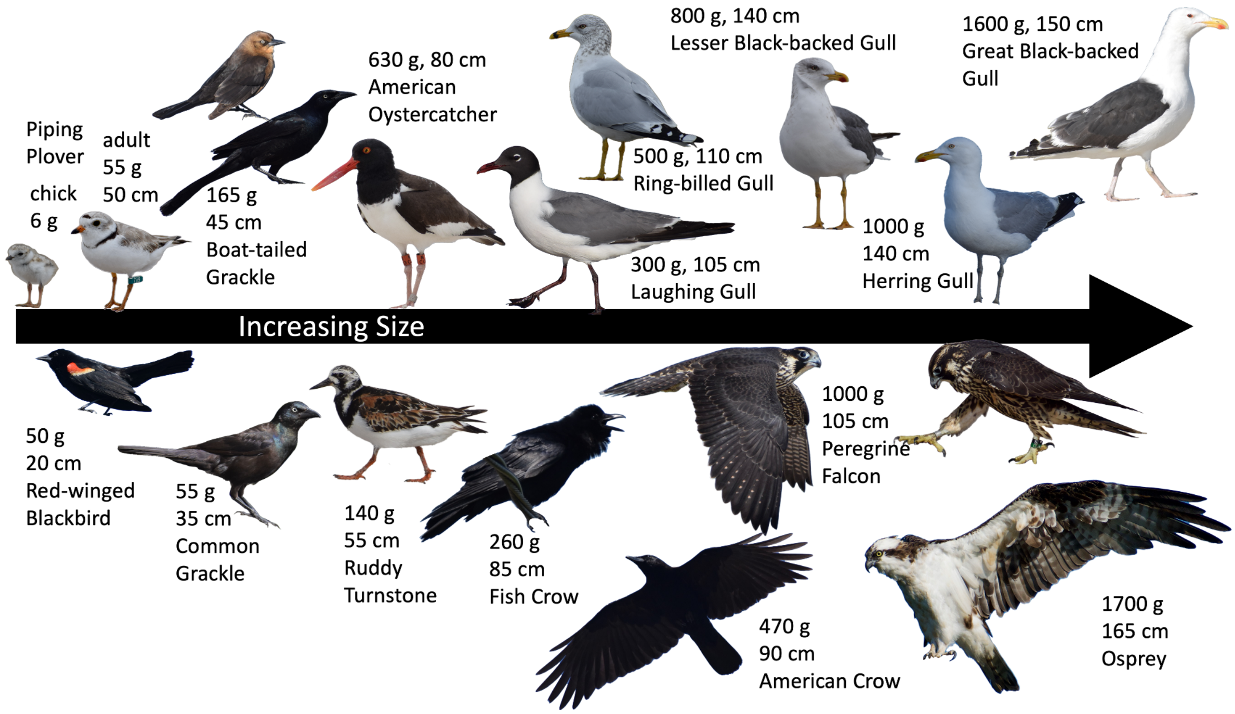


Figure 6. Size comparison of potential avian predators. A comparison of the potential avian predators of Piping Plover using mass, in grams, and wingspan, in centimeters. All photos by K. E. Johnson. Mass and wingspan data from All About Birds (Cornell Lab) and The Sibley Guide to Birds.

Gulls are often considered as a family and are known to take chicks; therefore, I considered all species of gulls as predators. Lesser Black-backed Gulls (*Larus fuscus*) are not specifically mentioned in prior studies considering the predation of gulls on plovers; however, they often form mixed-species flocks with other species of gulls (pers. obs.). The lack of specific mentions may be because Lesser Black-backed Gulls are an uncommon species on the Atlantic Coast, although their numbers have been increasing in recent years (Burger *et al.* 2020). There are no confirmed breeding records of Lesser Black-backed Gulls from within the United States, and they are more common in the non-breeding season (Burger *et al.* 2020). Similarly, Peregrine Falcons (*Falco peregrinus*) are known to depredate several species of shorebirds (*e.g.,* Beauchamp 2008, Watts and Truitt 2021). Although they are raptors, Osprey (*Pandion haliaetus*) are unlikely to take plovers, but the plovers may perceive them as a predator (Weithman *et al.*

2020). Boat-tailed Grackles (*Quiscalus major*) have been documented taking eggs of American Oystercatchers (*Haematopus palliatus*), a much larger species of shorebird (Watts *et al.* 2006) and therefore could depredate plover nests. Likewise, Ruddy Turnstones (*Arenaria interpres*) are known egg predators and could therefore take plover eggs (Parkes *et al.* 1971). American Oystercatchers (*Haematopus palliatus*) nesting in proximity to plovers present a territorial threat to plover eggs and chicks as they protect the area around their nests. However, large flocks of oystercatchers are not defending nesting territory, and are, therefore, not aggressive towards plovers. Overall, these known and suspected species of avian predators of plovers can be divided into five main groups: shorebirds, gulls, raptors, corvids and grackles. I considered all species with known evidence of direct predation along with others in these taxonomic categories as the potential avian predators of Piping Plovers in Fire Island, NY.

Lauro and Tanacredi (2002) considered crows (corvids) the most serious egg predator and gulls the most serious chick predator (of all types of predation, including mammalian) at Breezy Point in Queens, NY (approximately 35 miles west of Robert Moses SP). Consequently, gulls and crows are often targeted for predator removal when locations are actively managing predators (Struthers and Ryan 2005). Additionally, both Merlin and American Kestrels, two other species of falcons, have been known to use exclosures as perches and depredate adults (Murphy *et al.* 2003, Barber *et al.* 2010, pers. obs. 2020).

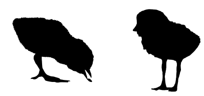
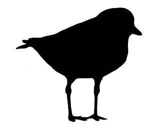
Table 1. Avian predators on the Atlantic Coast reported in the published literature that are known or suspected to predate Piping Plover eggs, chicks, and adults. Avian predators known or suspected to depredate plovers but do not occur on the Atlantic Coast (*e.g.,* Swainson's hawk, *Buteo swainsoni*; Murphy *et al.* 2003) were not included. Avian predators are listed in taxonomic order according to the 2022 eBird/Clements Checklist (Clements *et al.* 2022). Specific references have been annotated to indicate study populations: a = US Atlantic Coast, b = Great Plains, c = Great Lakes, d = Canadian Maritimes/Canadian Atlantic Coast. Table continues on the next page.

Avian predator	**Egg predation**	**Chick predation**	**Adult predation**	**Unspecified or suspected**
American Oystercatcher (*Haematopus palliatus*)	Wilke and Denmon (2014)[a]	Call *et al.* (In Press)[a]		
Laughing Gull (*Leucophaeus atricilla*)				Lauro and Tanacredi (2002)[a]
Ring-billed Gull (*Larus delawarensis*)	Ivan and Murphy (2005)[b]	Ivan and Murphy (2005)[b] Saunders *et al.* (2018)[c]	Saunders *et al.* (2018)[c]	Whyte (1985)[b]
Herring Gull (*L. argentatus*)		Saunders *et al.* (2018)[c]	Saunders *et al.* (2018)[c]	Rimmer and Deblinger (1990)[a] Lauro and Tanacredi (2002)[a]
Great Black-backed Gull (*L. marinus*)				Rimmer and Deblinger (1990)[a] Lauro and Tanacredi (2002)[a]
Northern Harrier (*Circus Hudsonius*)		Ivan and Murphy (2005)[b]		Whyte (1985)[b] Murphy *et al.* (2003)[b]
Bald Eagle (*Haliaeetus leucocephalus*)	Andes *et al.* (2019)[b]			
Great-horned Owl (*Bubo virginianus*)	Andes *et al.* (2019)[b]	Kruse *et al.* (2001)[b] Catlin *et al.* (2011)[b]		Rimmer and Deblinger (1990)[a] Murphy *et al.* (2003)[b]
Red-tailed Hawk (*Buteo jamaicensis*)				Kruse *et al.* (2001)[b]

Table 1. (continued)

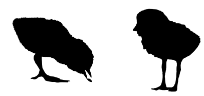
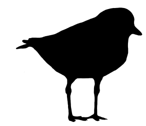
Avian predator	Egg predation	Chick predation	Adult predation	Unspecified or suspected
American Kestrel (*Falco sparverius*)		Kruse *et al.* (2001)[b]		
Merlin (*F. columbarius*)			Murphy *et al.* (2003)[b] Roche *et al.* (2010)[c] Saunders *et al.* (2018)[c]	Barber *et al.* (2010)[d]
American Crow (*Corvus brachyrhynchos*)	Barber *et al.* (2010)[d] Cohen *et al.* (2009)[a]	Ivan and Murphy (2005)[b] Saunders *et al.* (2018)[c]		Whyte (1985)[b] Rimmer and Deblinger (1990)[a] Lauro and Tanacredi (2002)[a] Murphy *et al.* (2003)[b] Ivan and Murphy (2005)[b]
Fish Crow (*C. ossifragus*)				Lauro and Tanacredi (2002)[a]
Common Raven (*C. corvax*)	Barber *et al.* (2010)[d]	Saunders *et al.* (2018)[c]	Saunders *et al.* (2018)[c]	
Red-winged Blackbird (*Agelaius phoeniceus*)	Deblinger *et al.* (1992)[a,d]			Lauro and Tanacredi (2002)[a]
Common Grackle (*Quiscalus quisculua*)	Deblinger *et al.* (1992)[a,d]	Ivan and Murphy (2005)[b]		Rimmer and Deblinger (1990)[a]

Table 2. Pictorial representation of avian predators on the Atlantic Coast reported in the published literature that are known or suspected to depredate Piping Plover eggs, chicks, and adults. Avian predators that do not occur on the Atlantic Coast were not included even if they are known or suspected to depredate plovers (*e.g.,* Swainson's hawk, *Buteo swainsoni*; Murphy *et al.* 2003) were not included. Avian predators are listed in taxonomic order according to the 2022 eBird/Clements Checklist (Clements *et al.* 2022). Table continues on the next page.

Avian Predator Species	**Eggs** 	**Chicks** 	**Adults** 
American Oystercatcher (*Haematopus palliatus*)	■	■	
Ruddy Turnstone (*Arenaria interpres*)	□ known for eggs of other shorebird species		
Laughing Gull (*Leucophaeus atricilla*)	□	□	
Ring-billed Gull (*Larus delawarensis*)	■	□	
Herring Gull (*L. argentatus*)	■	□	
Great Black-backed Gull (*L. marinus*)	□	□	
Northern Harrier (*Circus Hudsonius*)		■	
Bald Eagle (*Haliaeetus leucocephalus*)	■		
Great-horned Owl (*Bubo virginianus*)	■	□ known predator of tern chicks	■
Red-tailed Hawk (*Buteo jamaicensis*)			
American Kestrel (*Falco sparverius*)		□	■
Merlin (*F. columbarius*)		□	■

■ Published evidence of predation   □ Suspected predator

Table 2. (continued)

Species	Eggs 	Chicks 	Adults 
American Crow (*Corvus brachyrhynchos*)	■	■	
Fish Crow (*C. ossifragus*)	■	▒	
Common Raven (*C. corvax*)	■	■	■
Red-winged Blackbird (*Agelaius phoeniceus*)	■		
Common Grackle (*Quiscalus quisculua*)	■	■	
Boat-tailed Grackle (*Quiscalus major*)	▒ known for eggs of American Oystercatcher	■	

■ Published evidence of predation ▒ Suspected predator

Purpose

At Fire Island, the impact of avian predation remains largely unknown; therefore, I sought to characterize the avian predator community, and the abundance and distribution of predators at Robert Moses SP and the NPS Lighthouse. In addition to characterizing the avian predator community, I was also interested in how the distribution of predators compared to the locations of plover nests and broods. Plover eggs and chicks have different predators; therefore, it is important to note how the distribution of potential predators changes over the breeding season and to consider the presence of species in relation to their expected impact. I expected to observe more species of potential avian predators at Democrat Point, due to the abundance of alternative prey from a large tern colony. I predicted the distribution of potential avian predators would change over the course of the breeding season, as newly-fledged juveniles and adults of many species dispersed from their breeding territories to nearby areas with minimized human disturbance, such as Democrat Point. Additionally, I summarized my and VTSP's anecdotal observations of interactions between potential avian predators and Piping Plovers. These behavioral interactions support the classification of these species as predators of plovers. This study represents the first step towards understanding how Piping Plover mortality from avian causes compares to other sources of mortality and can be used as a model to expand the knowledge of the effect of avian predators on other portions of Fire Island to inform management practices.

METHODS

Field Methods

All fieldwork was conducted under Virginia Tech Institutional Animal Care and Use Committee protocols (22-190), a United States Geological Survey Federal bird Banding permit (21446), a USFWS Endangered Species permit (ESPER0033920), US NPS Research permit (FIIS-2002-SCI-0005), NY State DEC Endangered Species license (314), and NY State Office of Parks, Recreation and Historic Preservation permits (22-0040). All permitting and funding was administered by the Virginia Tech Shorebird Program.

Monitoring of Piping Plovers was conducted as part of an ongoing study by the Virginia Tech Shorebird Program. In order to determine nesting and fledging success of the Piping Plovers nesting on Fire Island, nests were located and routinely monitored until hatching or failure, typically at least every three days, between the hours of 06:00 and 16:00. Date of hatching was predicted either from locating or monitoring the nests as eggs were laid, or by using egg flotation to predict hatch of nests that were found with an already complete clutch (usually four eggs). Individual eggs were floated in ambient-temperature water; the angle and height of the egg in the water column corresponds to the embryo's developmental stage (Alberico 1995, Liebezeit *et al.* 2007). Predicting hatch date allowed for increased monitoring of the nests immediately prior to hatch, which aided in timing the banding of chicks soon after hatch. Broods were routinely monitored (typically every 1-3 days, weather permitting) until the chicks fledged. The location of chicks were recorded using coordinates, as broods often move away from their nest location to better foraging habitat. Nest locations were marked using Trimble GPS units (Trimble Navigation, Sunnyvale, CA); brood locations were also collected similarly, or by using an offset from the observer's location using a compass bearing and distance estimated using a Nikon 8397 Aculon Laser Rangefinder (Nikon, Tokyo, Japan) (Robinson *et al.* 2020). Most adult and chick Piping Plovers were banded, with alphanumeric flags (adults) or color band combinations (chicks), to facilitate identification of individuals in the field. These alphanumeric flags and color bands allowed for resighting of plovers with spotting scopes; chicks were banded as close to hatch as possible, ensuring individuals could be consistently identified throughout their development.

During the summer of 2022 from early June to mid-August, I made instantaneous counts (Altmann 1974), recording numbers of potential avian predators while traveling through subsites, of potential avian predators while in plover nesting areas. During routine monitoring activities, I made observations in plover nesting areas and recorded the species of each avian predator, their habitat (intertidal, ephemeral pool, wrack line, dry sand, dry vegetation, or other), behavior (loafing, foraging, roosting, courtship, parental, incubating, flying, disturbed, or other), and flock size. I recorded abundance and behavior for raptors, gulls, corvids, blackbirds, and other shorebird species (*i.e.,* Ruddy Turnstone and American Oystercatcher) that are known or suspected to take Piping Plovers or their eggs (Kruse *et al.* 2001, Lauro and Tanacredi 2002, Wilke 2014; Tables 1 and 2).

Photography

Using a Nikon D3300 (Nikon, Tokyo, Japan) equipped with a 70-300 mm zoom lens, I documented both Piping Plovers as well as the other species of Avian Predators present at Robert Moses SP and the NPS Lighthouse.

Data Processing

I conducted all statistical analyses in R ver. 4.1.3 (R Core Team 2021) and geospatial processing in ArcGIS (ver. 10.8.2; ERSI, West Redlands, CA).

From the collected avian predator data, I eliminated certain observations based on the published evidence of plover predation by specific species. For example, Ruddy Turnstones are only potential egg predators; therefore I only considered observations of Ruddy Turnstones for dates with unhatched eggs in a subsite. American Oystercatchers were often observed in both large roosting flocks and as nesting individuals; only the nesting individuals (flock size recorded as six or fewer) were kept for the analyses, as these were the individuals defending their nesting territories with potential impacts on the plovers. Though plovers could view Osprey as predators, Osprey primarily consume fish, and there is no evidence in the literature that Osprey are predators of shorebirds; therefore they were eliminated from the analyses. The remaining taxonomic groups considered in analyses were corvids, falcons, grackles, gulls, and shorebirds.

I considered the density of avian predators, calculated as the number of potential avian predators per subsite (total hectares in subsite), and distribution of avian predators at Robert Moses SP and NPS Lighthouse. The number of days with observations in each subsite varied (range: 8 - 31 days) depending on the abundance of plovers nesting in each area, and likewise, the total time spent in a subsite also varied (range: 7.6 - 99.4 hr, Table 3). However, the time spent in each subsite varied both due to the size of the subsite (range: 18.33 - 64.86 ha), and the monitoring activities done in each subsite on any given day (Table 3). Since chick monitoring was a subset of the overall summer monitoring efforts, it was impossible to standardize time with each brood or within each subsite. Thus, I standardized counts by day and survey area (predator abundance in one day per subsite hectare) and compared predator community composition between months. This approach normalizes by area and as a result also takes into account observational hours, as it took longer to survey larger subsites. For subsites that were visited multiple times in the same day, each visit was then averaged to create one value for the day, so individuals were not double-counted. Averages were then calculated across visits for each day when there were multiple visits to the same subsite.

Table 3. Summary of subsite size in hectares, and observational effort in each subsite, with the number of visits and the number of observational hours. Subsites are listed west to east from left to right in the table.

Subsite	Democrat Point	Stockpile	Ocean South Side	Field 3	Field 4	Field 5	NPS Lighthouse
Area (hectares)	64.86	18.33	21.82	14.98	18.15	21.24	24.35
Number of visits	24	8	64	14	13	16	17
Number of days with observations	24	8	31	10	12	11	17
Observational hours	99.42	12.00	14.08	5.83	7.60	9.53	27.32

I overlaid the density and distribution of avian predators with nest and brood locations to visualize the relative locations of plovers and the density of avian predators. I calculated the average daily abundance of predators recorded in each subsite. To visualize predator density for each subsite, I summed the average daily predator abundance across all predator species in June, July, and August and divided by the number of days with observations and the subsite area (ha). This process was also repeated for each month but with averages at the habitat level within each subsite resulting in the average number of predators in each habitat for visualization. For this map, any observations of avian predators within the wrack line were treated as part of the intertidal zone, as the location of the wrack line changes frequently and it is not large enough to visualize in aerial imagery. The wrack line is made up of material washed up with the tides, so it is similar to intertidal habitat and often at the border of intertidal zone and dry sand. The different habitat types were mapped as polygons using ArcGIS; aerial photography from April

2022 (VTSP unpubl. data) allowed for appropriate distinction between habitat types. This allowed for the calculation of the area habitat types in order to graph the average number of predators per hectare.

Statistical Analyses and Models

I visualized avian predator counts each month using principal component analysis (Jolliffe and Cadima 2016) and tested for significant changes in the PCA centroid means and spread using PERMANOVA and PERMADISP (Anderson 2001) in the R package *vegan* (Oksanen *et al.* 2022).

I tested whether maximum avian predator density (observed in July) explained the number of plover fledglings per brood. I fit a logistic regression predicting brood success (the y variable represented the frequency of chicks fledging [1] and chicks failing to fledge [0]) per brood and included avian density (average daily predator count per ha in a subsite) in July using the R package *glmmTMB* (Brooks *et al.* 2017) and examined significance of avian density (α = 0.05).

I then tested whether the abundance of avian predators present in a subsite explained chick disappearance. Since not all broods or subsites were visited every single day, I summarized the maximum number of chicks per brood seen in 5 day intervals from hatching (day 0) to fledging (day 25), similar to previous studies on Fire Island considering the impact of mammalian predation and human influence (DeRose-Wilson *et al.* 2018, Robinson *et al.* 2022, Wails *et al.* 2022). Ordinal dates were used for the hatch date and start of each interval, and I included a quadratic effect of ordinal date, to simplify analyses with date as a variable. Each brood (n = 32) had a corresponding number of chicks present within each interval, and, based on the chicks observed in the previous interval, a number of chicks missing. If a chick was not directly observed in one interval, but subsequently observed, it was still recorded as present. I analyzed chick disappearance in two ways using logistic regression, as y represented the chicks missing (1) and absent (0) using the R package *glmmTMB* (Brooks *et al.* 2017). In the first analysis, I calculated the avian density during each interval as an average of any observations within that interval (mean daily avian predators per ha) and included ordinal date as possible explanatory variables. In the second analysis, I calculated average gull and other avian predator abundance for each monitoring period. Because Peregrine falcons were observed infrequently, I included this variable as a binary predictor (0 when no peregrines were observed, 1 when at least one peregrine was observed) and also included ordinal date. For all models, I included brood ID as a random effect to account for repeat measures. All predictor variables were scaled by 2 SD (Gelman 2008). After confirming the global model containing all possible predictor variables could meet standard model assumptions using the R package *DHARMa* (Hartig 2022), I then used an information-theoretic approach to assess candidate models (Akaike 1974 and Burnham and Anderson 2002). In the first analysis, I considered six candidate models (a global model containing all predictor variables, four single-term models, and a null intercept-only model). I ranked candidate models by Akaike's information criterion corrected for small sample size (AIC_c, Akaike 1974, Hurvich and Tsai 1989). I used model weight to evaluate model fit. Since there were multiple equally informative models, I performed model averaging across all candidate models (Johnson and Omland 2004). I then visualized the results of the parameters included in the averaged model using prediction plots.

RESULTS

Overall, I collected data on 20 different species of birds across the study location that could potentially be considered predators of Piping Plovers. This study involved spending 175.8 hours across seven subsites on 40 different days. After reviewing the behaviors and known predation of these species, 11 different species of potential avian predators were considered in my analyses. Due to the different habitats of each subsite, the numbers and species of avian predators varied across subsites; though the subsites also vary in size, the average number of predators in one visit provides a sense of how many of each species were observed (Table 4). Gulls were the most abundant potential avian predator, with five species: Laughing, Ring-billed, Herring, Lesser Black-backed, and Great Black-backed observed daily, though VTSP researchers and I detected no evidence of gulls taking plover chicks. Egg predation was not possible because of exclosures protecting nests. The number of gulls increased in the latter half of the breeding season and is consistent with an increasing number of juvenile gulls and accompanying adults in August. Peregrine Falcons were seen infrequently (11 observations) but were observed hunting nesting shorebirds, including two confirmed takes of plovers (described in greater detail in *Field Observations of Avian Interactions*). Ruddy Turnstones are a potential predator of plover nests; however I only observed turnstones in subsites after all nests had hatched. Red-winged Blackbirds are also a potential predator of plover nests, and there were scattered observations of Red-winged Blackbirds throughout the breeding season, including before nests had hatched. Over the entire breeding season there were no instances of nest failure (defined as loss of all eggs) that we could attribute to avian causes.

Plover Distribution Across Space and Time

At Robert Moses SP and the NPS Lighthouse, VTSP and I monitored 46 different plover nests of about 40 pairs of plovers over the course of the 2022 breeding season (Figure 8). Thirty-two of these nests successfully hatched at least two chicks; therefore my analyses consider 32 broods and 108 total chicks. The hatch dates of nests ranged from June 3rd through July 21st, with a mean of June 24th (ordinal hatch range: 154-202, mean: 175; Figure 7). Nineteen of the nests monitored that successfully hatched were in Democrat Point, with 13 nests across the other subsites (Figure 7). Fifty-seven of these chicks were confirmed as fledged, based on observing them in sustained flight or alive after 25 days of age; though the fate is not confidently known for all of the other 51 chicks, my analysis considers them to have died within the breeding season and before 25 days of age. Once hatched, chicks may move away from their nests with their parents, so the nests and broods may be in different locations for one set of chicks. For analysis, each brood was assigned to the appropriate subsite where they were located before fledging; in all but one case, where plovers nested in Ocean South Side but moved their brood to Democrat Point, this was the same subsite as the nest location. Twenty broods were located in Democrat Point, six located in the NPS Lighthouse and the remaining six broods scattered across the other subsites (Figure 8).

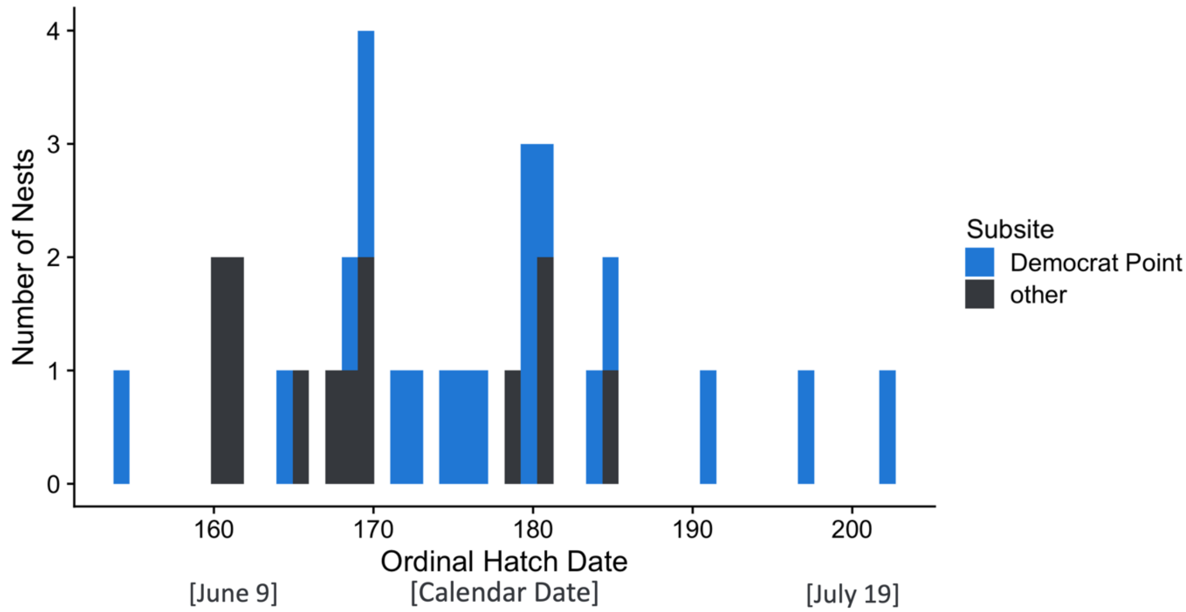


Figure 7. Hatch date range at study site. Range of hatch dates of Piping Plover nests at Robert Moses SP and the NPS Lighthouse. Nests in the subsite Democrat Point are colored blue, whereas nests in other subsites are dark gray.

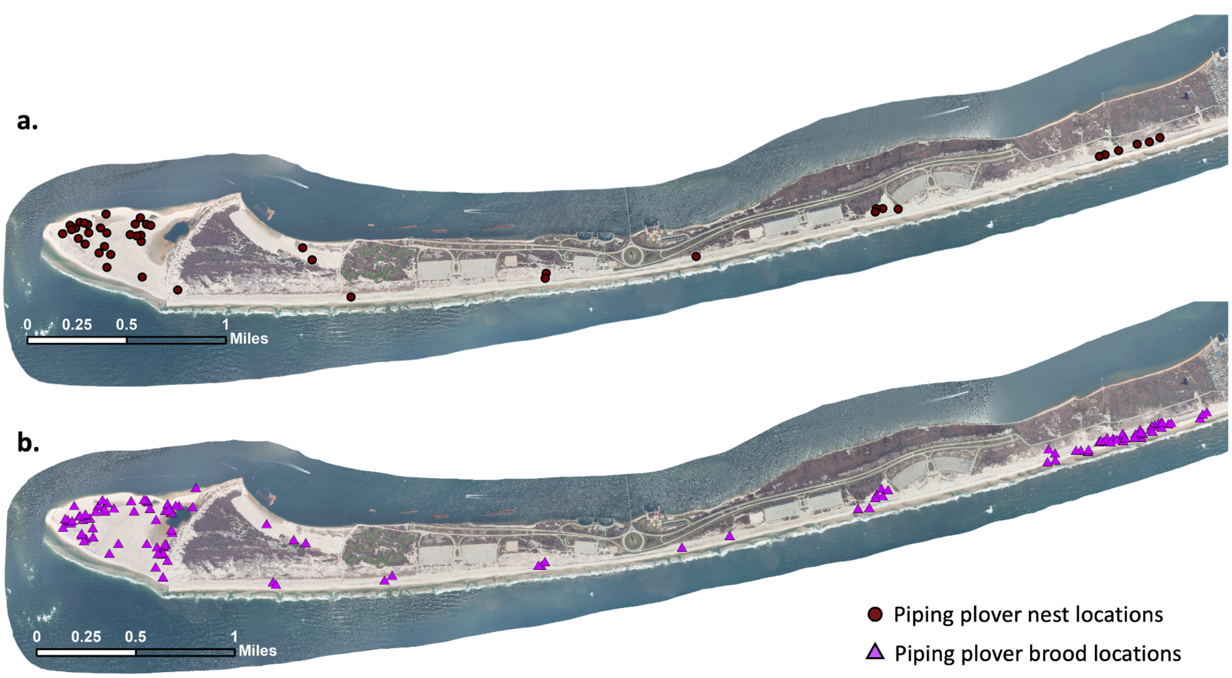


Figure 8. Nest and brood locations at the study site. Aerial imagery of Robert Moses SP and the NPS Lighthouse from April 2022, showing nest locations (red circles, a.) and brood locations (pink triangles, b.) for all monitored Piping Plovers in the 2022 breeding season. Constructed by K. E. Johnson with aerial imagery courtesy of the Virginia Tech Shorebird Program 2022.

Avian Predator Distribution Across Time

Principal Component Analysis (PCA) of chick predators, with predators sorted into five taxonomic groups: gulls, falcons, shorebirds, corvids and grackles, revealed that the potential avian predator community varied significantly across the three months surveyed (PERMANOVA $F = 6.93$, df = 2, 37, $P < 0.01$; PERMADISP $F = 6.75$, df = 2, 37, $P < 0.01$; Figure 9a). The principal components accounted for 99.9% of the variance in the data, with the most influential principal component, approximately corresponding to gulls, driving the majority (99.7%) of that influence. In early June, the predator community was consistent across areas I surveyed (Figure 9a). As the summer progressed, I saw greater abundances of shorebirds, influencing the July community, and gulls which largely characterized the July and August communities (Figure 9a).

PCA repeated at the species level, to visualize how specific species influence the predator community, revealed that the potential avian predator community varied significantly across the three months surveyed (PERMANOVA $F = 6.78$, df = 2, 37, $P < 0.01$; PERMADISP $F = 8.13$, df = 2, 37, $P < 0.01$; Figure 9b). Principal component 1 accounted for 66.5% of the variance, and Principal component 2 accounted for 28.2% of the variance; overall, the principal components accounted for 94.7% of the variance in the data. The July community was particularly influenced by numbers of Great Black-backed Gulls, whereas the August community was particularly influenced by numbers of Lesser Black-backed Gulls (Figure 9b).

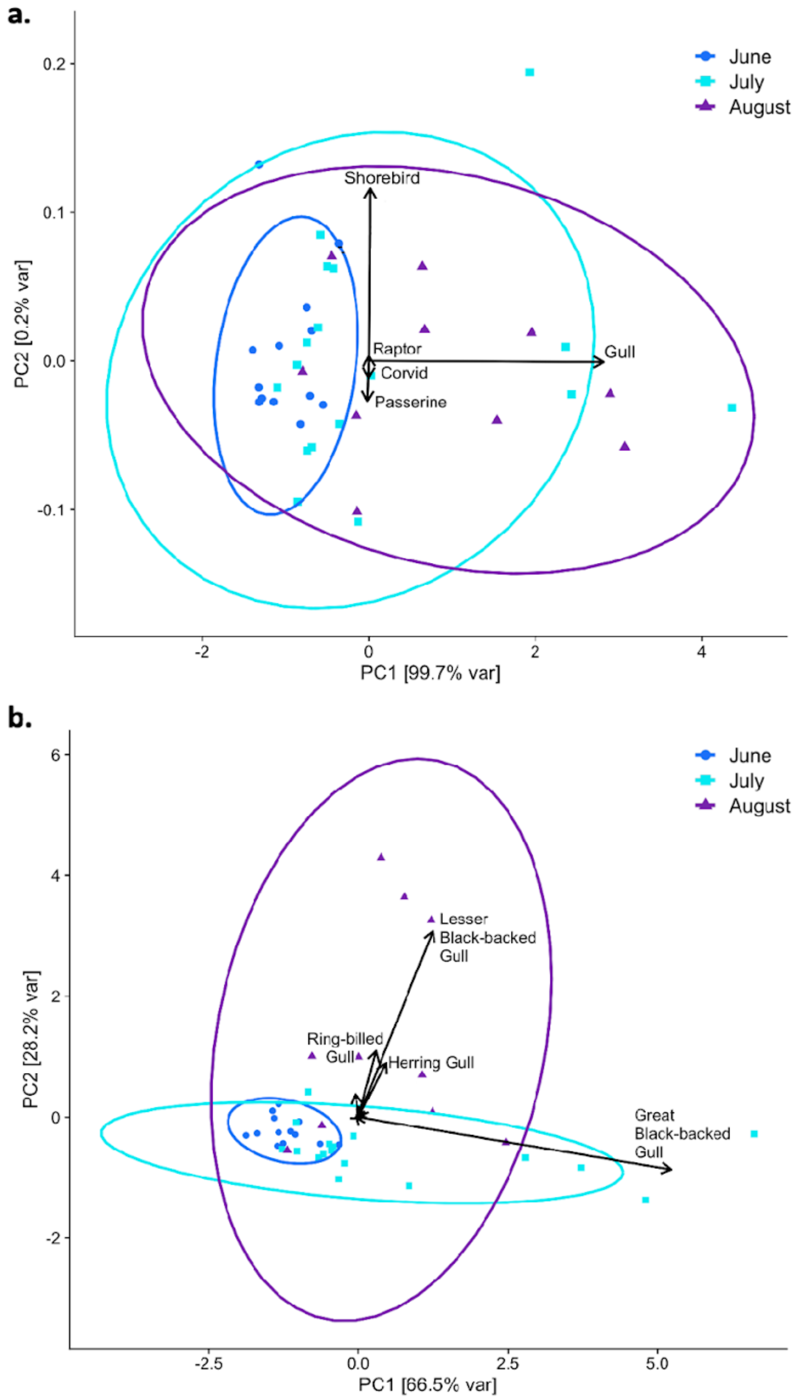


Figure 9. Principal Component Analysis of the potential avian community across June, July, and August, the three months surveyed. Each point, color-coded by the month, represents an observation at a survey area on a given date. Points closer together are similar in their avian predator community composition while points farther apart are different. Ellipses illustrate the 95% confidence interval for the avian predator community composition for a given month. The vectors show which taxonomic group (a.) or species (b.) are driving changes in the avian predator community. The labels of short vectors close to the origin have been omitted for visual clarity.

Avian Predator Distribution Across Space

Considering the distribution and density of avian predators across taxa within the subsites at Robert Moses SP and the NPS Lighthouse, we found differences between June, the early part of the breeding season, July, and August (Figure 10). In August especially, among the most heavily human-used beaches — Fields 2-5 and the off-road vehicle area (in Ocean South Side) — there were more avian predators present (Figure 10). Each month shows the corresponding nests that had yet to hatch, and any brood locations of broods that had not fledged; in August, only Democrat Point still had unfledged chicks. (Figure 10).

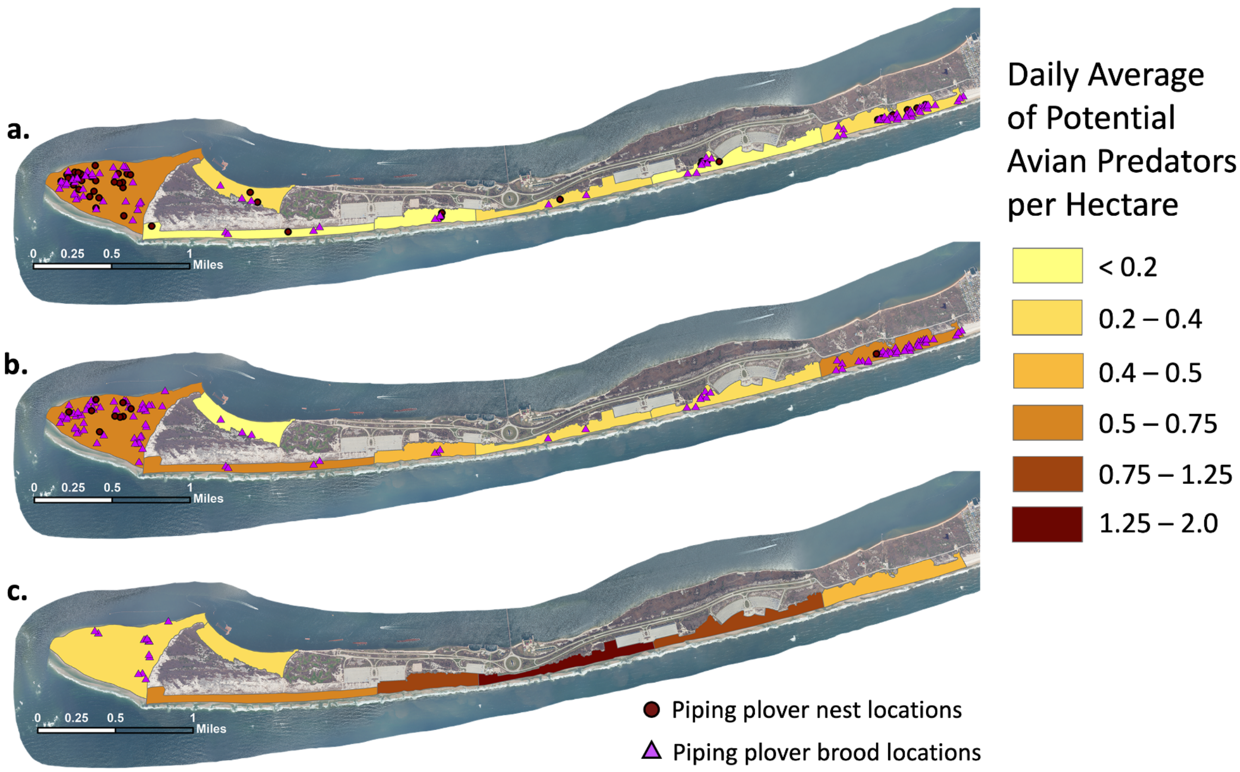


Figure 10. Potential avian predator densities (calculated as the daily average of potential avian predators per hectare) between June (a.), the early part of the breeding season, July (b.), and August (c.), late in the breeding season, with aerial imagery of Robert Moses SP and the NPS Lighthouse from April 2022. Each map also shows locations of nests (red circles) that were still present (unhatched) for at least some time within that month, and brood locations (pink triangles) of any broods that were unfledged for any point in that month. Constructed by K. E. Johnson with aerial imagery courtesy of the Virginia Tech Shorebird Program 2022.

Across the entire breeding season, most of the avian predators were present on either dry sand or in the intertidal zone (Figures 11, 12a). Since gulls comprise most of the total numbers of avian predators observed, I looked specifically at what percentage of the total number of gulls across species was observed in each habitat. Gulls were most commonly observed in either the intertidal zone (45.7% of all gulls) or on dry sand (41.3% of all gulls). Only 12.6% of all gulls were observed in ephemeral pools, and gulls were observed even less frequently (< 1%) in dry vegetation, wrack or other. The other avian predators were distributed across suitable habitats for the species; for example, American Oystercatchers were not observed in dry vegetation but were commonly seen in dry sand, ephemeral pools, or the intertidal zone (Figure 12a).

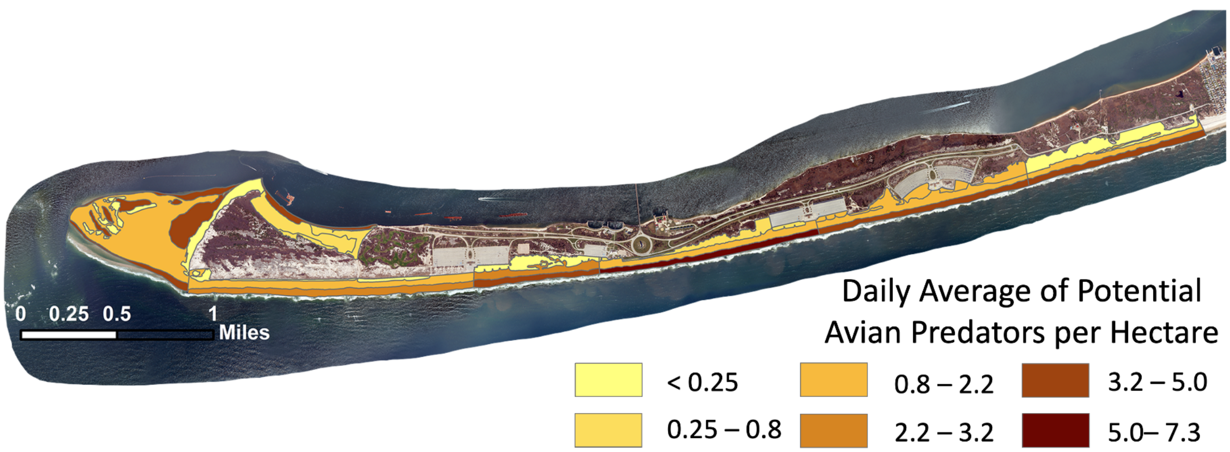


Figure 11. Potential avian predator densities by habitat. Potential avian predator densities (calculated as the daily average of potential avian predators per hectare) across the entire breeding season (June - August) with aerial imagery of Robert Moses SP and the NPS Lighthouse from April 2022. Constructed by K. E. Johnson with aerial imagery courtesy of the Virginia Tech Shorebird Program 2022.

Similar to the distribution of different habitat types, I looked at the percentage of the total number of gulls observed for each behavior. The majority, 82.6%, of all gulls were observed loafing, 13.5% of all gulls were observed foraging, and less than 3% were observed roosting, flying or disturbed by human presence. For the other avian predators, various behaviors were observed in similar percentages; for example, American Oystercatchers (shorebird) were observed roosting, exhibiting territorial behavior, loafing, incubating, foraging, flying, disturbed by human presence or participating in courtship (Figure 12b).

As gulls were the most abundant avian predator, I also considered how the abundance of gulls changed over the course of the breeding season (Figure 13). Great Black-backed Gulls were the most abundant, though numbers of Lesser Black-backed Gulls increased dramatically in the latter half of July and August (Figure 13). Overall there were fewer Herring, Ring-billed, and Laughing Gulls present, though these species also increased in August (Figure 13). The changes in gull abundance across time showed a clearer trend than other avian predator species (Figure 13). However, Ruddy Turnstones were mainly observed towards the end of July and in August during shorebird migration.

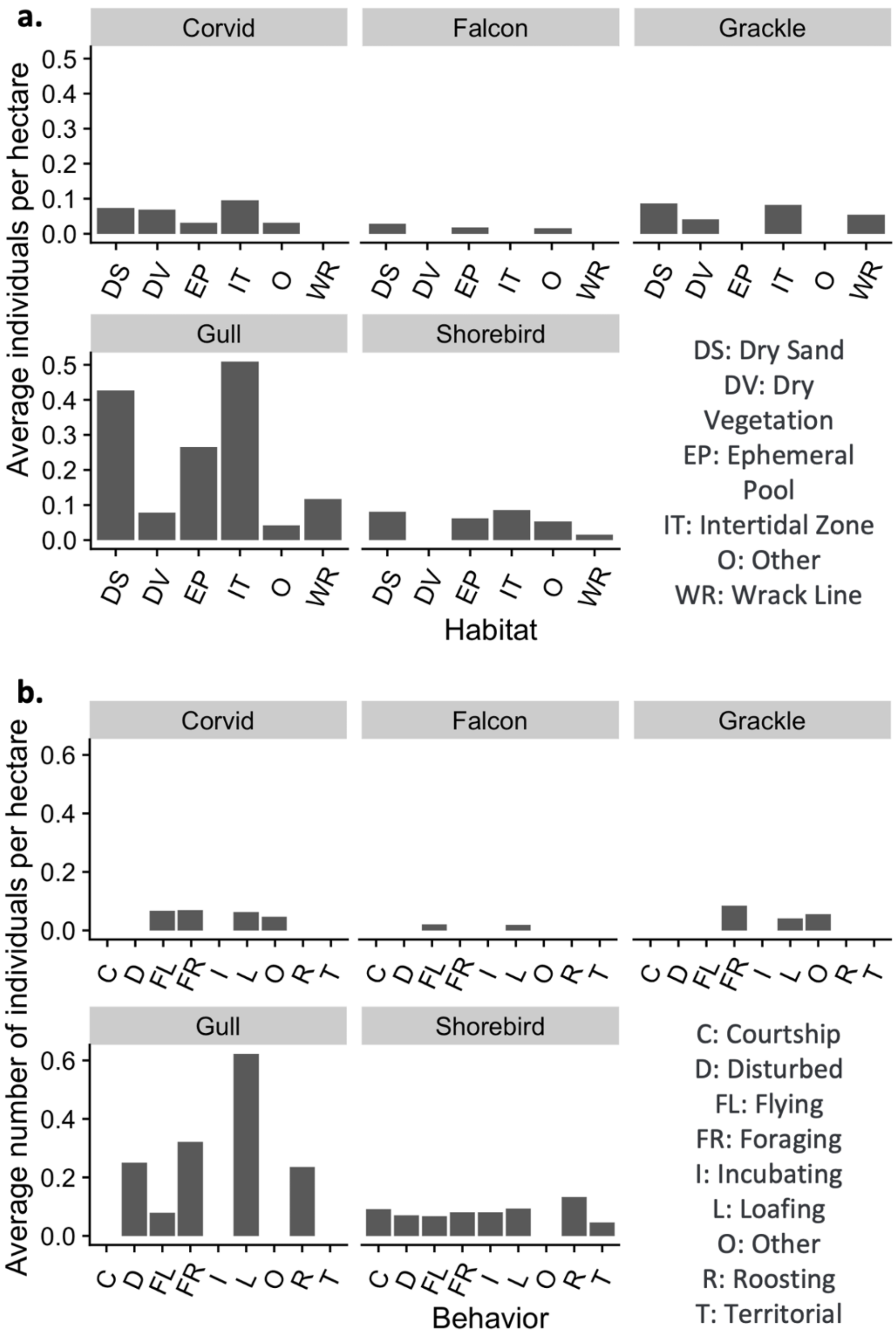


Figure 12. Distribution of different habitats and behaviors. Distribution, using the average number of individuals per hectare of each subsite in one day of different behaviors (a.) and habitat types (b.) of the five major taxonomic groups of avian predators considered. Species of predators in taxonomic groups are corvid: American and Fish Crow; falcon: Peregrine Falcon; grackle: Common and Boat-tailed Grackle; gull: Great Black-backed, Herring, Laughing, Lesser Black-backed, and Ring-billed Gulls; shorebird: American Oystercatcher.

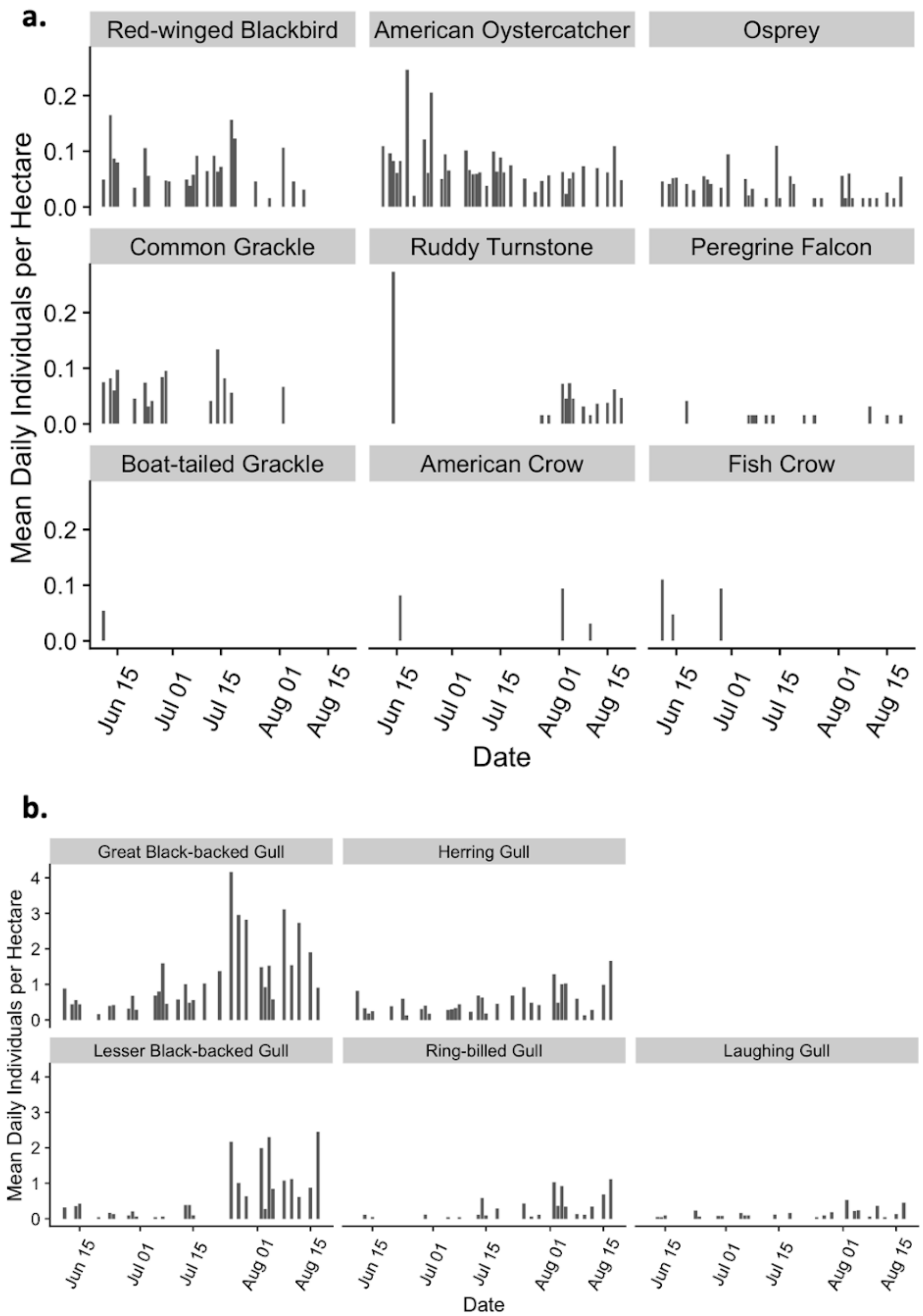


Figure 13. Changes in potential avian predator abundance (mean daily individuals per hectare) of observed gull species (b.) and all other observed species (a.) at Robert Moses SP and the NPS Lighthouse across months. The number of all gull species increased in the latter half of the breeding season.

Table 4. Potential avian predators of chicks observed at Robert Moses SP and NPS Lighthouse subsites in the summer of 2022. Avian predators are listed in taxonomic order according to the 2022 eBird/Clements Checklist (Clements *et al.* 2022). Numbers were calculated as the average number of individuals seen per day in the subsite. Though this table contains numbers of all Red-winged Blackbirds observed, in further analyses Red-winged Blackbirds were only considered as an egg predator. Subsites are listed, left to right, from west to east across the study area. Table continues on the next page.

	Subsite						
Avian predator	**Democrat Point**	**Stockpile**	**Ocean South Side**	**Field 3**	**Field 4**	**Field 5**	**NPS Lighthouse**
American Oystercatcher (*Haematopus palliatus*)	9.50	1.75	0.64	0.21	1.23	1.75	1.71
Laughing Gull (*Leucophaeus atricilla*)	1.75	7.00	1.22	1.50	1.85	8.88	1.24
Ring-billed Gull (*Larus delawarensis*)	1.50	0.00	3.47	9.29	5.92	13.94	0.88
Herring Gull (*L. argentatus*)	35.42	4.88	10.39	12.71	22.61	10.63	7.18
Lesser Black-backed Gull (*L. fuscus*)	1.92	0.00	6.94	7.57	49.92	3.38	7.18
Great Black-backed Gull (*L. marinus*)	86.46	3.75	25.70	7.14	26.08	16.38	25.41
Peregrine Falcon (*Falco peregrinus*)	0.46	0.00	0.00	0.00	0.00	0.00	0.06

Table 4 (continued)

	Subsite						
Avian predator	**Democrat Point**	**Stockpile**	**Ocean South Side**	**Field 3**	**Field 4**	**Field 5**	**NPS Lighthouse**
American Crow (*Corvus brachyrhynchos*)	0.08	0.00	0.00	0.00	0.00	0.13	0.12
Fish Crow (*C. ossifragus*)	0.00	0.00	0.00	0.00	0.15	0.19	0.00
Red-winged Blackbird (*Agelaius phoeniceus*)	0.58	1.50	0.75	0.43	0.77	0.31	0.18
Common Grackle (*Quiscalus quisculua*)	0.13	0.38	0.45	0.71	0.15	0.38	0.88
Boat-tailed Grackle (*Q. major*)	0.00	0.25	0.00	0.00	0.00	0.00	0.00

Field Observations of Avian Interactions

While monitoring plovers and observing species of potential predators, I observed some direct interactions between avian predator species and the plovers. Though VTSP researchers and I rarely observed avian predators taking plovers or their eggs, avian species were observed using exclosures as perches (two instances of Willet, one instance of a Red-winged Blackbird, and numerous Common Terns). At Democrat Point, avian predators were often harassed by Common and Least Terns. Peregrine Falcons were dive-bombed in flight at the ephemeral pools if spotted by the terns, whereas other predators such as gulls and oystercatchers were only harassed when close to tern nests. Fish Crows and American Oystercatchers were also dive-bombed by the small Least Tern colony in Field 5.

At Democrat Point, one plover nest was found due to watching one of the adult plovers exhibiting broken-winging behavior in front of an American Oystercatcher near its nest. The oystercatcher had two chicks in the area and was walking by the plover nest when the adult started broken-winging to lead it away. The oystercatcher did not seem disturbed by the plover, nor did it seem interested in the nest; after it moved further away, the plover stopped its broken-wing display. A different adult plover, with a brood of four chicks nearby, showed an oblique threat posture, a type of territorial behavior, to an adult American Oystercatcher with one chick. Also at Democrat Point, a group of six Great Black-backed Gulls and two Herring Gulls in close proximity to an exclosure were chased by two plovers. Common Terns often perched on exclosures in Democrat Point.

At the NPS Lighthouse, a Herring Gull was observed eating near an enclosure and one of the adult plovers was broken-winging. Also at the Lighthouse, two plovers with a brood of chicks in the area chased two Herring Gulls consuming a crab. At the Stockpile, a Herring Gull was chased in flight by an adult plover after it took off from where it was loafing in the dry sand. Also at the Stockpile, an Osprey flew through the dry sand to pick up a stick and was chased by an adult plover. Fish Crows and Herring Gulls were observed using signs as perches within plover nesting habitat. Least Terns were also observed multiple times chasing plovers in Democrat Point.

A Peregrine Falcon was observed once at the NPS Lighthouse, and was seen repeatedly diving towards the dune; the plovers in the vicinity were alarmed. At Democrat Point, one adult peregrine was observed on various days throughout July, and up to two juveniles were observed in August; a total of 10 out of 24 days throughout the breeding season had peregrine sightings. One of the juvenile peregrines observed in August had a field-readable leg band and was banded at the MetLife building in New York City in May, a distance of about 58 km away from Democrat Point. The peregrines frequently flushed all terns, skimmers and shorebirds as they flew over the area. Peregrine pellets were recovered after seeing the falcon depart from its roost of logs at the edge of an ephemeral pool. Many Least Tern legs, feathers, carcass and mandibles were found, both of chicks and adults, and on two occasions plover legs were found as well; tern legs can be distinguished from plover legs by the presence of webbing between the toes. Confirmed by the size of the tarsus, two plover chick legs were found with the remains and pellets on July 8th. On July 16th, two color bands from a plover chick were found inside a pellet. Therefore it is clear that the peregrines, on at least two occasions, were consuming plover chicks.

Fitted Models to Explain Chick Loss Over the Breeding Season

Overall maximum avian predator density did not explain brood success ($Z = -1.27$, df = 5, $P = 0.21$), which was assessed using the logistic regression predicting brood success (the y variable represented the frequency of chicks fledging [1] and chicks failing to fledge [0]) per brood and included avian density (average daily predator count per ha in a subsite) in July as the explanatory variable. More specifically, looking at the fledging success of 32 broods monitored using five-day intervals, considering the density of all avian predators and hatch date to predict chick disappearance, hatch date had a quadratic effect. This model met standard assumptions and found only the linear term of hatch date to be a significant parameter (Table 5).

Table 5. Parameter estimates for the model predicting brood success using hatch date (as a quadratic) and avian predator density, [1] Avian predator density was scaled to have a mean of 0 and a SD of 1.

Parameter	**Parameter estimate (β)**	**SE**	**Lower 95% CI**	**Upper 95% CI**
Intercept	-0.41	0.24	-0.87	0.06
Avian predator density[1]	0.18	0.12	-0.05	0.42
Ordinal hatch (Linear)	6.84	3.13	0.71	12.98
Ordinal hatch (Quadratic)	-4.95	3.02	-10.86	0.96

I also considered the density of avian predators split into three main categories: gulls, falcons and all other avian predators; this model, including hatch date, met standard assumptions and therefore this was used as the global, full model (containing all four possible explanatory variables) for further analysis. Aikaike's Information Criterion (AIC_c) values for all models were very similar; the top model with only falcon density and the global model were only 3.2 AIC_c units apart (Table 6). Using this average (conditional) model and considering the 95% confidence intervals for each parameter, I found the falcon density was the only informative parameter for predicting chick disappearance before fledging. Additionally, this average model was used to generate prediction plots for how changing parameter values impact plover brood success (Figure 14). Running the model with just the first four intervals, to see if the assumed fledging age of 25 days had an effect, did not change which model parameters were informative.

Table 6. Model comparison results for models assessing the fledging success of 30 broods monitored using five-day intervals considering the density of various types of avian predators and hatch date. Generalized linear mixed-effects models ranked by Akaike's information criterion corrected for small sample size (AIC_c) using ordinal hatch, and predator abundances in five-day intervals, for chick disappearance at the brood level n = 32) observed during the 2022 breeding season (June–August). *k* is the number of parameters associated with each model, including the intercept. AIC_c values are Akaike's Information Criterion corrected for small sample size. ω_i is the model weight.

[1] Variables used in the model: Falcon = scaled falcon presence in each five day interval, Gull = scaled gull densities in each five day interval, Other = scaled other avian (non-falcon, non-gull) predator densities in each five day interval, Ordinal hatch = the hatch date for each nest. All models also contained a field nest variable, which associates the five five-day intervals with their corresponding brood.

Model[1]	k	Log likelihood	AIC_c	ω_i
Falcon	3	-192.88	391.91	0.72
Falcon + Gull + Other + Ordinal hatch	6	-190.66	393.88	0.27
Ordinal hatch	3	-199.56	405.29	< 0.01
Null (intercept-only model)	2	-201.35	406.78	< 0.01
Gull	3	-201.27	408.69	< 0.01
Other	3	-201.32	408.80	< 0.01

Table 7. Parameter estimates in the conditional average model, using all of the models compared above in Table 6. [1]Falcon, Gull and Other have been scaled to have a mean of 0 and a SD of 2.

Parameter	Model-averaged parameter estimate	SE	Lower 95% CI	Upper 95% CI
Intercept	-2.05	3.44	-8.79	4.69
Falcon[1]	1.19	0.29	0.62	1.77
Gull[1]	0.44	0.28	-0.10	0.98
Other[1]	-0.02	0.29	-0.59	0.54
Ordinal hatch	0.03	0.03	-0.02	0.08

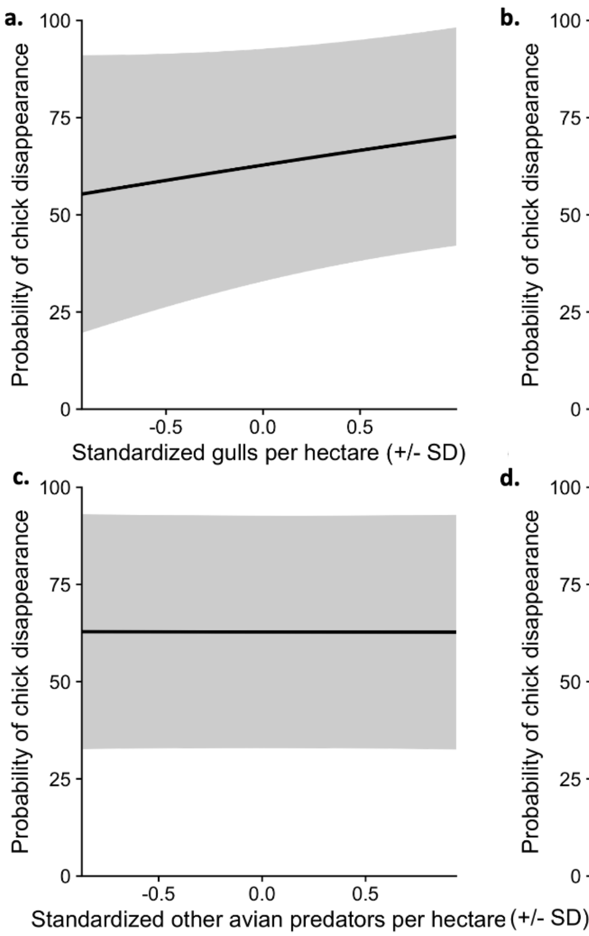


Figure 14. Prediction plots using the average model outlined in Table 7, showing how the probability of chick disappearance is impacted by a change in one variable at a time: the standardized number of gulls per hectare (before standardizing, mean = 0.56, sd = 0.27) (a.), the falcon presence per hectare (absence = 0, presence = 1) (b.), the standardized number of other avian predators per hectare (before standardizing, mean = 0.13, sd = 0.08) (c.), or the ordinal hatch date (160 = June 9th, 200 = July 11th)(d.).

DISCUSSION

Across the plover breeding season in summer 2022, the diversity and abundance of avian predators varied, reflecting avian predators that breed on or around Long Island (gulls, Peregrine Falcons) fledging and dispersing, and migratory patterns (other shorebirds). While overall I did not find evidence that changing densities of all avian predators impacted plover brood success, I did find evidence suggesting that changing falcon densities are important. Instances of observed take of Piping Plover by avian predators were infrequent in the study area on Fire Island. However, with just over 50% of hatched chicks fledging, chick mortality is consequential to successful plover breeding (Wails *et al.* 2022). Careful consideration of all contributors to mortality at this young age, such as avian predation, is critical for a comprehensive understanding of plover survival.

Plover Distribution Across Space and Time

In the 2022 breeding season, about 40 pairs of Piping Plovers nested at Robert Moses SP and the NPS Lighthouse, which is an increase from prior years (Walker *et al.* 2019, 2020, Wails *et al.* 2022, Robinson *et al.* 2023). The majority of plover nests were located in Democrat Point, with only a few additional nests distributed across the other subsites in this study. Democrat Point underwent a recent restoration that has increased suitable nesting habitat, as well as likely better locations for plover chicks to forage at ephemeral pools (Wails *et al.* 2022). Nests at Democrat Point also hatched much later into the breeding season, likely with more pairs renesting; we know one male renested with a different female at Democrat Point after his first nest failed at the nearby Heckscher State Park (VTSP unpubl. data, Figure 7). Consequently, the broods in Democrat Point are impacted by the set of avian predators at that point, which does change over time and therefore may affect broods differently across the breeding season.

Avian Predator Distribution Across Space and Time

Across subsites, the avian predator distribution was different, with Democrat Point having more avian predators in June and July, whereas in August more avian predators were located along Fields 2-5 (Figure 10). Since gulls represent the majority of the avian predator community, especially in August, the increase in predator density can be attributed to the increasing number of gulls. It seems that gulls are likely attracted by human presence and refuse, since the numbers of gulls increased at the more popular portions of Robert Moses SP and the NPS Lighthouse where there is human infrastructure with refuse collection. The subsites with the greatest increase in human activity throughout the summer also had the fewest plover nests (Figure 8), a pattern that has persisted through VTSP's long-term monitoring (DeRose-Wilson *et al.* 2018, Wails *et al.* 2022). Therefore, it seems that gull predation on plovers may be limited and opportunistic on Fire Island. At the same time, all of the avian predators I considered can easily move between subsites, so it is possible the avian predator community has extreme temporal variation. This is one difficulty in monitoring avian predation, and is why I decided to consider the location of predators at the subsite level instead of in relation to the location of specific broods.

If human presence attracts avian predators, such as gulls, to the popular recreational beach, the avian predation risk to the plovers may increase at all portions of the study site. Despite the apparent separation of high human presence and high gull abundances from nesting plovers, this view is a snapshot in time. Knowing how avian predator species change across time, my specific observations provide context for how these different species should be grouped when considering how the avian predator distributions can be connected to the plover distributions.

Though the increased gull numbers are found mainly on the recreational beaches, the gulls may additionally go elsewhere to forage, leading to an increased risk of predation at other sites. The risks associated not only with human presence, but also with the concomitant factors that change in response to that presence, (*e.g.,* an increased number of avian predators attracted to the area) are important to consider. Further study can investigate this link between human and avian predator abundance, which would allow for insights into the many factors influencing nesting plovers.

At Democrat Point, across June, July, and August, the highest density of avian predators was located at the ephemeral pools, whereas in the other subsites the intertidal zone had the highest density of avian predators (Figure 11). In all sites, dry sand had a medium density of avian predators. Since plover broods often forage at ephemeral pools, the intertidal zone or in dry sand, there is overlap in their habitat use. However, the behavior of predators varied, especially for gulls which were most often loafing (Figure 11). Though a flock of loafing gulls likely does not have an instantaneous effect on the plovers, gulls do move around and will forage at some point. However, perhaps the presence of gulls is not a huge concern, if the gulls are mainly present loafing instead of actively foraging. Since the activity of species is likely tied to the tidal cycle, it would be interesting to consider avian predator abundance in proximity to either high or low tide in future research.

Insights into Avian Species with Unclear Predator Status

Additionally, though three of the subsites — Democrat Point, Stockpile, and Field 5 — had nesting American Oystercatchers, these subsites and others also had flocks of oystercatchers present. Although plovers are not a food source for oystercatchers, oystercatchers are a potential predator of plovers through aggression, protecting and defending their own nests and young

(Wilke and Denmon 2014). My decision to include only oystercatcher observations of six individuals or fewer (corresponding to breeding individuals) seems reasonable because larger flocks of oystercatchers were most commonly seen roosting in ephemeral pools at Democrat Point and would not be expected to interact negatively with breeding plovers. Nevertheless, it may be worth considering a different cut-off density based on further observations of plover and oystercatcher interactions.

I also decided to exclude Osprey in my analyses, since there is no evidence that Osprey prey on shorebirds. Nonetheless, it is possible that plovers might view these raptors as a threat due to their size and manner of flight (Weithman *et al.* 2020). In fact, I did observe an adult plover chasing an Osprey; perhaps in future analyses of how avian predator abundances relate to plover survival, predator species such as this could be included, as well. Considering other species such as Osprey that plovers might react to as predators, whether or not these species actually take plovers or their young, could be important as an increased number of potential predator species may indirectly reduce plover survival by being present and affecting behaviors including decreasing foraging time, rather than directly taking plovers. Therefore, in future studies, it would be beneficial to consider species viewed as threats as a separate group as separate from those that are confirmed predators when considering potential predator densities.

A behavioral analysis could be used to identify which species are viewed as threats by the Piping Plover. Analyzing responses of plovers to potential threatening species and known predators could categorize the impact of each on plover fitness. Observations of the response of adults and broods to avian predators, such as the frequency of alarm calls, whether the chicks drop motionless onto the sand, and how long their behavior is impacted after the perceived threat would show the magnitude of the risk as perceived by the plover. For an avian predator that frequently takes plovers, it is likely that the plovers would respond at a greater distance from the predator, and their behavior would be impacted for longer. However, for an avian threat of a species not known to predate plover, the plover's behavior might be less severely impacted. Though there is a balance between the energy expenditure of constantly reacting to perceived threats and survival, looking in depth at specific interactions between plovers and potential predators could characterize their perceived predation risk. This is an important area for future research.

In addition to the interactions between the plovers and their avian predators, it is also important to consider the impact of the different predator species on each other. In the case of the predator species I observed at Fire Island, this is mainly a consideration for the Peregrine Falcon, as the other predator species likely have less of an impact on each other. For example, gulls may consume the eggs or chicks of other shorebird species considered as potential predators, but they are unlikely to prey upon adults. In contrast, Peregrine Falcon frequently prey upon other species of shorebirds, even larger species such as adult American Oystercatchers and gulls. Therefore the presence of the peregrine could reduce the abundance of other species of avian predators, however that might also increase the likelihood of plover predation by the falcons. Further considering these interactions between avian predators will also help understand the many factors that play a role in the fluctuating predator densities.

Confirmed Predation

VTSP and I confirmed Peregrine Falcons as a predator of Piping Plovers by recovering both plover chick bands and legs from inside peregrine pellets. Therefore it is clear that the peregrines, on at least two occasions, were consuming plover chicks, though it is hard to know how frequently without additional monitoring. Furthermore, these observations demonstrate there is avian predation of plovers at Fire Island, and therefore avian predation is something important to consider in management. VTSP and I first observed a peregrine at Democrat Point on July 6th, and at least one peregrine was present on 10 of the 19 visits to Democrat Point from July 6th to August 19th. Throughout this time, it was often difficult to locate broods of plovers in the area; it is quite likely that, due to the presence of a peregrine, chicks spent more time hiding in vegetation, and therefore it was harder to track their survival. Although it provides challenges for monitoring, adjacent vegetation is beneficial for the chicks as vegetative cover may make it harder for predators to locate plover chicks. Consequently, investigating whether there are ways to increase the vegetation cover at a site to provide protection from predators could become an important management strategy. Simple changes such as modifying potential perches for avian predators and vegetation control in order to provide locations for chicks to hide from predators could lead to enhanced plover survival.

Observing two juvenile peregrines, one of which was banded at the MetLife Building in New York City, suggests that we may need to consider a wide area to encompass all potential predators. Though the observed juvenile Peregrine Falcons did not come from the same nest, as only one was banded, it is possible that the adult seen periodically at Democrat Point was hunting at Fire Island to feed its young. In Colorado, some Peregrine Falcons are known to travel 79 km when foraging (Enderson and Craig 1997), and the distance to NYC is within this range. While this is just one of the observed potential predators, it demonstrates that there is avian predation of Piping Plovers at the study site, and the potential use of Fire Island as a foraging site for breeding falcons in New York City may make management imperative.

Contextualizing Observed Predation

Although elsewhere (Breezy Point, Queens, NY and Dimmick's Point, Lake Michigan, MI), gulls and crows are considered to be the primary avian predators of plover nests (Lauro and Tanacredi 2002, Struthers and Ryan 2005) the same is unlikely to be true at Fire Island. Since most plover nests at Robert Moses and the NPS Lighthouse are exclosed (in summer 2022, all found nests were exclosed by land managers), the potential for nest depredation by most of the avian predators I considered is limited. Additionally, I seldom observed other birds using nest exclosures as perches, and the few species seen perched directly on exclosures (Willets, Red-winged Blackbirds) were not associated with any cause of nest failure in the study area. Before this study, the effect of exclosures in relation to avian predators on Fire Island was previously unknown; however I conclude that exclosures are providing useful protection from avian predators.

Despite gulls being the most abundant potential avian predators, no VT Shorebirds researchers observed any takes of chicks or adults by gulls at Robert Moses SP or the NPS Lighthouse in 2022. However, the abundance of gulls observed in the study area was less than at other locations where gulls are recognized as primary predators, for example at Monomoy National Wildlife Refuge (Chatham, MA) which supported >19,000 pairs of Herring and Great Black-backed Gulls (Melvin *et al.* 1992, Keane *et al.* 2002). Fire Island does not currently support large colonies of breeding gulls, and based on locations where gulls were most frequently observed, I believe gulls were likely attracted by, and perhaps consuming, human food detritus on recreational beaches (ORV area, Fields 2-5 at Robert Moses SP). It may be that gull predation at Fire Island is rare and opportunistic. Nonetheless, chick bands were recovered from gull bolus by VTSP researchers in 2021 (Wails *et al*. 2021), the potential for gull predation of chicks should not be ignored.

Although I did observe species with known evidence of prior predation at Fire Island, direct interactions between plovers and avian predators were observed fewer than 10 times. Consequently, only one species, Peregrine Falcon, was known to take plover chicks over the three months I monitored in the 2022 breeding season. Because peregrines are not documented in the literature as known predators of plovers, these observations are valuable information. Although I did not observe takes by other species of avian predators, avian predation can still be a significant factor contributing to plover chick mortality. If avian predation is contributing significantly to chick mortality, it would be occurring over a large enough window of time, from hatch until fledging, that it is difficult to observe. Overall, though only the effect of the Peregrine Falcon presence is significant in the model prediction brood fledging success, this could result from the peregrine having a larger effect than other species. While the model suggests the peregrines are an important factor in chick survival, it does not rule out the possibility of other avian predation. With only seven subsites and 32 broods, the sample size is limited and it is difficult to observe avian predation events. Expanding to include data from other sites in the future would increase the ability to detect effects of different predator species.

Fitted Models to Explain Chick Loss Over the Breeding Season

In my analyses to determine whether the avian predator densities can predict chick survival, I considered avian predators based on prior evidence of predation of plovers at other locations. As these final decisions on potential avian predators were made post-data collection, I did collect data for a few species that were not considered in the analyses. For example, Red-winged Blackbirds are known nest and egg predators but are not likely to take chicks, although they are blackbirds like grackles. In addition, this allowed me to collect data on a variety of species throughout the breeding season, to ensure consistent observations of any species I might later have wanted to consider as an avian predator in analyses.

I did not detect strong evidence that the abundance of potential avian predators in July explained plover brood success. Perhaps avian predation risk for plover chicks is diluted in later months, as the increase in other migratory shorebirds (especially those larger in size and forming larger flocks) may be at greater risk of depredation. Similar to the benefit of living in a tern colony, there is safety in numbers, and a greater abundance of alternative prey may mitigate the risks for individuals of prey species.

Predicting chick survival using the predator density of gulls, falcons, and all other avian predators as well as hatch date, showed that the falcon density is an important explanatory variable in chick disappearance. This also supports our observations in the field of only observing Peregrine Falcon predation during the 2022 breeding season. In this global model, falcon density is the only significant parameter. When considering model fit, the AIC_c values were quite close for all of the models, and it is interesting that the top model and the global model were so close, since the global model has three extra parameters. Consequently, an average model was evaluated as there is no evidence for a single best model.

Overall, the model, whose parameters are limited to avian predator densities (as gull, falcon and other) and hatch date, predicts chick disappearance of over 60%. This predicted disappearance of between 60% and 70% is higher than the observed disappearance of 47.2% in 2022, as 52.8% of chicks were recorded as fledged. Consequently, this model is overpredicting chick disappearance, likely as it is missing other factors that influence chick disappearance.

However, the model does show that avian predators are an important factor of chick disappearance and are consequently an important target for future research.

Additionally, though only falcon density was found to be significant, the parameter values for the other densities and ordinal hatch are consistent with what might be expected (Figure 14). Gull density and ordinal hatch were positively related to chick disappearance, but these were not informative parameters in the model (Table 7). Since gulls are a chick predator, even if at a low frequency on Fire Island, it is expected that larger numbers of gulls would decrease chick survival. Similarly, the hatch date of nests has been found to impact survival; nests hatching later in the season are often less successful (Brudney *et al.* 2013). Contrastingly, the mean density of other, non-gull and non-falcon predators was not an informative parameter, though the parameter estimate was negative (Table 7). Therefore, an increased density of other predators such as grackles and shorebirds that can be prey for species such as Peregrine Falcons might increase chick survival. This fits my predictions: the presence of alternative species that are also prey for important avian predators of plovers is similar to the protection provided by living in a large colony of nesting individuals.

Conclusion

At Robert Moses SP and the NPS Lighthouse in summer 2022, I identified 11 different species as potential avian predators of Piping Plover: American Oystercatcher, Laughing, Ring-billed, Herring, Lesser Black-backed and Great Black-backed Gulls, Peregrine Falcon, American and Fish Crows, and Common and Boat-tailed Grackles. The distribution of these predators varied across the study area and breeding season, with higher avian predator densities at Democrat Point in June and July, and higher avian predator densities at sites with high human impact in August. Five species of gulls comprised the majority of the avian predator community, and the numbers of gulls increased considerably in the end of July and August. VTSP researchers and I observed two separate takes of plover chicks by Peregrine Falcon, confirming peregrines are a predator of Piping Plover. Furthermore, I considered the impact of avian predators on chick disappearance and found Peregrine Falcons were an important explanatory variable.

Understanding the specific types of avian predators of Piping Plovers present at Fire Island informs management decisions to improve plover breeding success. My data suggests that gulls are attracted more to popular recreational areas of the beach with human refuse; therefore, minimizing this attraction to gulls might reduce the number of gulls present in neighboring plover breeding habitat. Additionally, exclosures and fencing create extra perches that are often used by raptors, and minimizing the impact of these measures used for protection of the plovers is beneficial. Since exclosures no longer provide protection for plovers once the nest has hatched, removing them promptly would remove the potential for predators to perch on exclosures and prey upon plovers. Increasing vegetation cover in portions of plover nesting habitat may also provide protection from predators by allowing plover chicks to hide in vegetation reducing their visibility to predators.

My results provide insight into the role of avian predators at Fire Island in plover breeding success, although there is more information to be gained from future studies. My results describe the potential avian predator community composition and how it changed over most of the breeding season, and provide a starting point for future research aiming to characterize avian predator communities elsewhere. Standardizing predator counts and effort across subsites, by using another method such as point counts, would aid in comparisons across the study area, as my data may have a bias towards sites with more observational hours having more predators. However, by considering predator numbers in terms of the number observed per visit across the total area of the subsite in hectares, I was able to take into consideration both the varying sizes and observer hours. For larger sites, it is necessary to spend more time traversing the area. Also, because the avian predator observations were collected at the same time as routine monitoring activities, more time in a subsite does not necessarily mean more predators were observed. I recorded groups of avian predators only once on each visit, and this reduced the potential for double-counting individuals, especially larger flocks that often stayed in the same location the entire time VTSP researchers and I were in the subsite. However, in the future it would be beneficial to standardize effort to make sure effort hours are not influencing results.

For the most part, I cannot specifically attribute the presence of potential predators to unsuccessful chick fledging and presumed mortality. Moreover, accurately documenting mortality is challenging as it requires an individual to either directly observe the mortality event or find evidence post-mortality. In both scenarios, evidence is ephemeral and easily missed. Plover chicks are small compared to the area of each subsite, and it is easy to miss resighting chicks, especially as they easily hide in the vegetation. In addition, the presence of avian predators such as Peregrine Falcons results in most bird species hiding or remaining inconspicuous to protect themselves from the threat, and therefore difficult to resight. There were chicks confirmed as fledging that went undetected for a week, so it is possible that some chicks were alive after 25 days, but not observed. However, when considering the survival and growth of a population, it is better to be conservative rather than exaggerate population growth and abundance. Additionally, not all chicks that died are expected to be from avian predation; therefore considering other factors besides predator abundance would likely better explain chick mortality. Overall, my results lead towards an increased understanding of how the presence of potential predators might influence chick fledgling, though we cannot specifically attribute the presence of these predators to the presumed mortality.

It is likely that both avian predators and other external factors not considered here are working in congruence to drive plover chick disappearance, which are ultimately reflected in chick survival rates. In either case, further monitoring can help to answer these questions more comprehensively. Because many factors influence both successful plover breeding and the presence and number of predators, it would be especially informative to characterize the avian predator community across breeding seasons to understand yearly variation, how that might affect the plovers, and correlations with multiyear nesting success. Examples of these factors could be weather, human presence and prey availability. For example, my data suggest that perhaps the abundance of gulls is related to the human presence on the beach; determining whether this is a correlation could allow for insight into how gull numbers might influence plovers. Furthermore, having comprehensive data for the entire breeding season would also allow for conclusions about egg and nest predators, something that could potentially impact where plovers decide to nest. Using nest cameras would also offer information on whether avian predators are visiting nests. Whether or not they consume eggs or chicks, the predation pressure could influence survival in other ways, such as impacting the adults' ability to care for their young. In the case of chick survival, an increased number of predators may result in decreased foraging time for the chick, potentially decreasing health and growth. Therefore, the presence of avian predators may be detrimental to chick survival even if the predators are not directly taking the chicks, and might also put adults at risk.

I was able to characterize the potential avian predator community present at Robert Moses State Park and the NPS Lighthouse in the summer of 2022. Throughout the breeding season, the number of avian predators increased, especially all five observed species of gulls. I was also able to make comparisons of the avian predator community across the breeding season, for the three months surveyed; however, the potential for annual changes to the avian predator community is not yet fully understood. This is the first step towards understanding how avian predators impact breeding Piping Plovers over their lifetimes.

I will be returning again this summer to work with the Virginia Tech Shorebird Program and consider the presence of avian predators across a second breeding season. Knowing the species present at the study location can inform focal species for future research, for example understanding the interactions between Peregrine Falcons and Piping Plovers. This study has revealed that merely the presence of these potential predators does not guarantee an impact on plovers. Further studies, such as considering how often these avian predators are visiting nests, which could be quantified through the use of nest cameras, is needed. Though our current understanding of the distribution and types of potential avian predators is incomplete, it does increase our knowledge of the avian predator community at Fire Island and can inform future management decisions to improve Piping Plover breeding success.

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