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Importance of Stewards and Other Protection Efforts for Conservation of Red Knots (*Calidris canutus rufa*) and Other Shorebirds on Delaware Bay, New Jersey

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ABSTRACT

Understanding the factors that contribute to population stability in long-distance migrant birds is increasingly important, particularly given global climate change, sea level rise, and loss or disturbance at essential habitats. While the populations of most shorebirds are declining worldwide, those that migrate through Delaware Bay, New Jersey and Delaware, are declining at the most rapid rate despite conservation efforts. In this paper, we 1) provide background information on population declines of red knots (*Calidris canutus rufa*) using Delaware Bay, threats to their foraging, and efforts to reduce threats, 2) summarize briefly our studies of the effects of human activities on knots and other shorebirds, 3) present data on management efforts to protect knots and other shorebirds from the activities of people, and 4) discuss the efficacy of such efforts (usually referred to as "decreasing the effect of human disturbances"). The Shorebird Project on Delaware Bay is over 25 years old and provides long-term data to help assess the status of shorebird numbers, particularly for red knot, as well as the density of horseshoe crabs (*Limulus polyphemus*) and their eggs. Red knots have continued to decline even more precipitously in the last few years, presenting cause for concern. Protective efforts have been successful in reducing human disruption on the N.J. Delaware Bay beaches, but the lack of uniformity in implementation across the New Jersey side, and across the whole Bay have hampered further improvements. Implementation of signs, fencing, and stewards on some beaches significantly enhanced the use of these beaches by red knots, determined by examining the use of beaches pre- and post-implementation. Implementation of fencing and stewards had the greatest effect. From 1986 to 2018, there was a significant shift in the percent of Delaware Bay red knots using the NJ side, where protection efforts had been implemented

on many of the beaches. Merely restricting access (without fencing or other efforts) did not result in more knots using the beaches post-restriction. This is the first paper that clearly shows the protective effects of having beach stewards. We discuss the long-term needs for continued management of Delaware Bay beaches, and other beaches coastwide, and of determining the causes of population declines of red knots.

1. INTRODUCTION

Understanding the factors that contribute to survival and reproduction in coastal species is key to maintaining healthy coastal ecosystems. Shorebirds are one of the most endangered groups of birds in the world, exhibit some of the longest migration routes, and make some of the longest non-stop flights known [1-5]. Many shorebird species are threatened or endangered, and more species are heading in that direction [5]. The causes of declines relate to human disturbance, habitat loss, prey depletion, predation pressures, severe weather events, sea level rise, and climate change acting at breeding, stopover, and wintering sites [6-12]. Whether the threats act most severely at breeding areas, wintering areas, or during migration is unclear, but identifying the stressors shorebirds face on different nodes of their yearly cycle is a necessary step for conservation [13, 14]. The connectivity between breeding and wintering areas is clearly important for evaluating the stressors shorebirds face during migration, including the key stopover sites [15-17]. Understanding the stressors and threats faced by red knots (*Calidris canutus rufa*) and other shorebirds at stopover sites is important to protect existing populations, but it is equally important to document the extent and efficacy of different protection efforts employed at stopover sites. This information is critical to designing a hemisphere-wide conservation strategy and business plan for protecting shorebirds.

In this paper, we: 1) document changes in the number and distribution of red knots using Delaware Bay, New Jersey from 1986 to 2018, 2) briefly describe studies on effects of human disturbance on shorebirds, and 3) examine the effect of conservation (protection) efforts of the NJ Department of Environmental Protection and others to reduce the impact of disturbance resulting from human activities, including their efficacy. The time period for surveys was used because it is the time period when efficacy of stewards can be examined in a similar pre- and post-steward case study. We suggest that several studies with knots and other shorebirds in NJ and elsewhere indicate that some human activities disrupt shorebird foraging, and that knots are particularly sensitive to human activities, and we test the hypothesis that conservation protection efforts contribute to increased red knot use of particular beaches in New Jersey. The latter is difficult to prove because environmental conditions vary among beaches, which in turn results in differences in numbers of spawning horseshoe crabs (*Limulus polyphemus*), available crab eggs, and foraging opportunities. However, we employ a weight of evidence approach to show that conservation efforts are successful. Such efforts need not be successful every year, nor on every beach, but they need to be sufficient to increase use overall.

Red knot is listed as Endangered in Canada and Threatened in the United States (USFWS 2014 a,b), but the Western Hemisphere population of knots continues to decline. Listing is necessary but not sufficient to protect these birds. The southern South America wintering cohort, particularly dependent on Delaware Bay for refueling, has declined more precipitously [18] (R.I.G. Morrison, pers. comm.). Because of their listed status, we concentrate on the *rufa* subspecies of red knot. Other shorebird species that migrate through Delaware Bay show declines [19], although in this paper they are discussed only in passing. *Rufa* red knots breed in low-Arctic and Arctic Canada, and winter from Texas and the southern United States [20-22], to northern Brazil, and southern South America [23-27]. It is unlikely that declines in red knot populations are due to limited breeding habitat because nesting knots are scattered across the Canadian Arctic on sparsely vegetated tundra in numbers below the estimated carrying capacity [28]. While they could experience inclement weather, preventing successful breeding in some years, presumably, knots have evolved with these conditions. Thus, the difficulties may well lie either on the wintering grounds or during migration. Global warming and sea level rise are threats that are increasing in importance as intertidal habitats are lost at

stopover areas [6, 7, 10, 11] and on the breeding grounds. Some studies indicate that shifts in predator-prey relationships may cause higher nest depredation [29]. In recent field studies environmental variables (e.g., temperature, snow melt) had a larger effect on nesting outcomes, and predator impact (e.g., Arctic fox, *Vulpes lagopus)* was limited to few species [30]. Red knots nest at low densities in higher-elevation, barren habitats inland from coastal wetlands [28]. Study areas on southern Southampton Island, Nunavut, where red knots are known to breed, anecdotally have infrequent predators (mammalian and avian), lemmings are scarce, and when present, predators are limited to isolated freshwater sedge wetlands (A. Dey, pers. comm.).

The Atlantic flyway red knots exhibit two migration patterns: long distance migration routes with few stops, and short distance migrations with frequent stops and a longer total migration period [20, 24, 25, 31]. Two decades of intense study have identified degraded conditions on Delaware Bay as a major cause of declines, which provides a greater threat to the long-distance migrants from Tierra del Fuego. The decline of red knots has been attributed to foraging difficulties on Delaware Bay [32-34] where they feed primarily on the eggs of horseshoe crabs [35-37]. Overharvesting of horseshoe crabs resulted in a scarcity of eggs (documented by systematic egg counts), and several species of shorebirds declined, including red knots [1, 5, 38, 39]. Delaware Bay is particularly important for all the species of shorebirds migrating north through the Bay because they must store enough fat for a long non-stop flight to breeding grounds and must reach the Arctic in a healthy condition to start breeding immediately on arrival, constrained by the short Arctic season. Time and undisturbed feeding opportunities are critical. For example, knots must nearly double their weight to reach the Arctic in good breeding condition [40, 41]. There are clear links between crab spawning abundance and mass gain of red knots, knot mass on departure, and apparent annual survival, and between knot mass and reproductive success [32, 42]. Since Delaware Bay is important to the survival of red knots, and their success on Delaware Bay depends upon egg availability and foraging efficiency, we note that there are two ways to increase the availability of eggs: 1) increase the number of crabs (and thus of crab eggs), and 2) increase the disturbance-free foraging time.

The overall goal of the Delaware Bay Project is to study the ecology, behavior, habitat use, migration, and connectivity of migratory shorebirds, particularly the red knot, to contribute to understanding how species survive in an ever-changing environment, and to provide the basis for sound, science-informed conservation and management. The data can help managers and researchers understand the relative importance of the Delaware Bay stopover compared to other stopovers, its relative importance in the flyway, and the efficacy of conservation efforts that can contribute to preserving populations of shorebirds and other long-distance migrants [43]. One of the main objectives of this paper is to address this issue in two ways: 1) document the effects of human activities on foraging shorebirds, and 2) analyze the available data on red knot use of New Jersey beaches as a function of the management actions (protective actions, including restrictions, fencing, signs, and stewards). Our intent in this paper is to demonstrate the efficacy of having beach stewards and other protection efforts to reduce disturbance to the shorebirds within the context of other conservation efforts. Conserving shorebirds is a hemispheric-wide problem of connectivity and the availability of suitable stopover habitats (foraging opportunities and prey availability).

2. METHODS

Protecting shorebirds on Delaware Bay is a multi-agency, multi-non-governmental Agency, multi-university, and stakeholder driven and implemented program to protect and enhance not only shorebirds, but the ecology of the Bay overall. The Delaware Bay Shorebird Project was initiated by New Jersey's Endangered and Nongame Species Program in 1986, and has been aided by New Jersey Audubon, Rutgers University, and scientists from all over the world, as well as citizens and volunteers from Citizens United to Protect the Maurice River, American Littoral Society, New Jersey Audubon Society, and others who volunteered for a wide range of projects. The State of Delaware has a program to monitor and assess shorebird use of Mispillion Harbor. The overall methods for the Project are: 1) scientific ones to examine the biology, ecology and population changes of the red knots and other shorebirds, 2) conservation methods to protect the foraging shorebirds and their habitats, 3) legal ones to ensure compliance (e.g. federal and State laws and regulations,

conservation officers), and 4) social science ones to educate and engage the public.

The first management goal of the Project was to assess how many migrating red knots and other shorebirds use the Delaware Bay stopover in May and early June, and thus yearly aerial surveys of the entire Bay were initiated and continue currently. Initially, weekly surveys were conducted in May, but after 2009, only one or two aerial/surveys per year were conducted during the peak period of shorebird abundance on the bay (determined using the previous data when 4 surveys/year were conducted). Overall, 48 beaches were surveyed along the New Jersey side of the Bay, and 33 were surveyed along the Delaware side during the annual census. Each beach was designated by roads, creeks, forest patches, other discontinuities, or traditional names (census methods can be found in Clark *et al.* 1993 [44]).

During this period, several studies were conducted to examine the effect of human activities on foraging shorebirds, both observational and experimental, and these are reviewed here. We then describe the actions taken to protect and conserve shorebirds that migrate through Delaware Bay each spring and test the efficacy of these actions. The specific methods are described in that section. In the following sections, we 1) present data on temporal patterns of red knot populations on Delaware Bay from 1986 to 2018, and potential reasons for these declines, 2) summarize data on the effects of human activities on shorebirds on New Jersey beaches, and 3) describe the actions taken to protect shorebirds from disturbance and test the efficacy of these actions.

3. POPULATION LEVELS OF RED KNOT ON DELAWARE BAY

Estimates of peak stopover populations of shorebirds using Delaware Bay are critical to understanding whether declines have continued, and whether conservation efforts have been successful. Aerial counts for red knots were conducted each year from 1986 to 2018 [45], and are continuing. Although ground counts were made since 2009, they do not provide a long-enough time series to assess the efficacy of protection efforts. **Figure 1** shows the number of red knots counted each year from 1986 to 2018 on an aerial survey conducted at the peak migration period (May 20-28). There are two trends: variation of the short term (increases and decreases like a wide inverted U), and also an apparent long-term decline. Although the numbers vary from year to year, numbers of red knots generally declined from 1986 to 2003, remained relatively stable until 2012, and appear to have increased slightly since then (knots had already experienced a decline in the early 1980s [33, 34]). Although elaborate models for population levels of the Atlantic coast populations

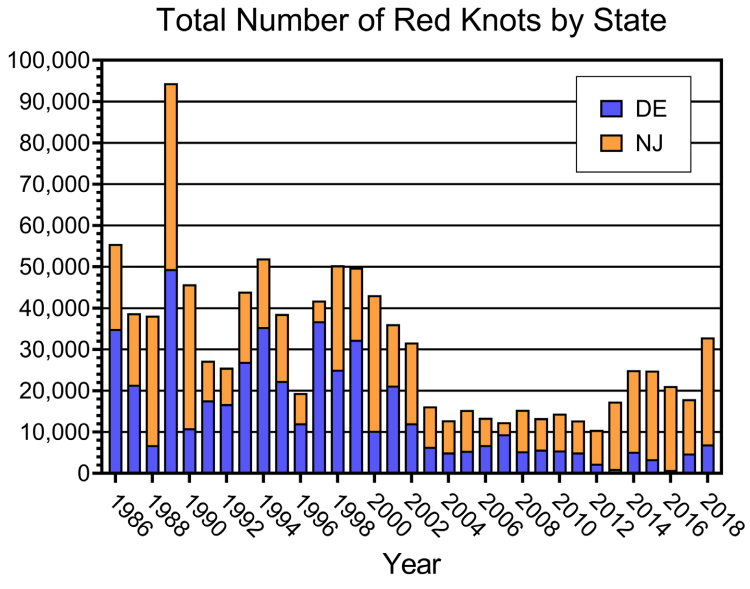

Figure 1. Aerial counts of the red knots on Delaware Bay (high tide) from 1986 to 2018 [45]. Counts are conducted when peak numbers are on the Bay.

of *rufa* red knot have been developed [39, 46], in this paper, we use the aerial counts conducted by the NJ DEP (after Dey *et al.* 2020 [45]). Further, we note that population numbers using Delaware Bay have continued to fluctuate but were especially low in 2021 following a year of low crab egg numbers in 2020 (L. Niles, Unpubl data).

The major threats faced by shorebirds at the Delaware Bay stopover are: 1) decline in the number of spawning horseshoe crabs due to overharvest [38], 2) inclement weather events that reduces horseshoe crab spawning (and thus foraging opportunities, 3) severe storms that wash away spawning habitat [47], 4) habitat loss due to on-shore development or intertidal development from aquaculture [12, 48-50], 5) predation by gulls or raptors [51-53], 6) competitors (other shorebirds, gulls) [49], and 7) sea level rise that can eliminate spawning and foraging habitat [7, 11]. Understanding the threats shorebirds face allows scientists, conservationists, and the public to design protection efforts aimed at reducing the stressors faced during migration.

Laws and regulations have been implemented to protect red knots, including its Federal and State listing, and regulations dealing with habitat loss and the expansion of aquaculture [38, 54-56]. Increasing the availability of eggs requires increasing and managing populations of horseshoe crabs. There are two ways to increase spawning crabs: 1) decrease the removal of crabs from the population (especially females) for the bait industry and the biomedical industry, and 2) providing more optimal spawning habitat to ensure that all females can spawn successfully. The Atlantic States Marine Fisheries Commission [38] manages the take of horseshoe crabs. Unfortunately, female horseshoe crabs, which lay eggs eaten by shorebirds, have not increased despite regulations and restrictions [57, 58].

Loss of habitat, especially due to sand removal during hurricanes or other severe storms is being addressed by science-based beach nourishment on selected, high-use spawning beaches [34, 59]. Over 30% of Delaware Bay shore is experiencing an erosion rate of over 1.5 m/year, leading to a decrease in habitat suitability for spawning in the period, from 2002 to 2010, although spawning habitat conditions improved somewhat by 2015 from restoration efforts post Hurricane Sandy.

Gulls and shorebirds are native foraging assemblages on the Bay, and the solution to competition is to increase the available prey base (horseshoe crab eggs) and space for foraging to reduce competition [49, 60]. Prey depletion (and competition with other species) is managed partly by management of horseshoe crab populations, under the purview of the Atlantic States Marine Fisheries Commission [38]. Direct predation on shorebirds has been addressed elsewhere but has not yet been addressed in Delaware Bay, where introduced breeding peregrine falcons (*Falco peregrinus*) depredate migrant shorebirds and can preclude use of several high-quality foraging sites. This is particularly harmful in years when horseshoe crab eggs are scarce (e.g., 2017, A. Dey, pers. comm.). Efforts to protect red knots and other shorebirds from human activities are the main subject of this paper, and our studies are described in detail below.

4. EFFECTS OF HUMAN ACTIVITIES ON KNOTS AND SHOREBIRDS IN COASTAL NEW JERSEY

Humans have many uses of coastal environments, including residential, recreational, commercial, and other activities, which often lead to habitat loss. Clearly, habitat loss can have a severe effect on shorebirds, particularly migratory shorebirds, because they have less suitable habitat in which to forage. We make the point that humans engage in a range of activities along coasts, some cause a disturbance, and some do not. Not all human activities cause a severe disturbance, while others may have a positive effect. Further, we make a distinction between available and suitable habitat. Habitat may be present (e.g., available), but not suitable because there is some form of development nearby that causes disturbance (e.g., noise, bright lights at night), or because the presence of people in these environments makes them no longer suitable. Human populations along the New Jersey shore increased markedly starting in the 1980s in coastal areas generally [61, 62], and will continue to do so.

There was a growing recognition of the decline of shorebirds, especially red knots in the early 1980s [63, 64]. Migrant shorebirds spend 1 - 3 weeks at the Delaware Bay stopover each spring and try to optimize

energy intake and fattening by concentrating on beaches where food is abundant. Any disturbance that results in their moving and searching for another foraging area may impose a cost in terms of feeding time and resource quantity. Recognition of these constraints resulted in a number of studies in the early 1980s and 1990s of the foraging behavior of different species in relation to habitat and people. In this section, we briefly summarize some of the studies conducted with shorebirds in NJ to demonstrate that the activities of people can adversely affect shorebirds.

In the 1980s and early 1990s, there were few restrictions on beaches, without the realization of the severity of potential effects of human activities on foraging shorebirds. There were no restrictions on the use of beaches, and people (and their dogs) regularly walked on beaches, and fishermen drove along the shore, with little regard for the shorebirds. This also was true of the beaches along Delaware Bay because the awareness of the plight of shorebirds was not recognized. People were walking, jogging, fishing, digging clams, and driving off-road vehicles. Most of these human activities caused a disturbance. Herein, we define disturbance as any activity that causes a change in behavior of the shorebirds that could have an adverse effect on their survival and/or reproduction, in this case, causing the birds to fly. It is not the act of flying in response to people that is the problem, it is the frequency with which this happens. Shorebirds that are forced to fly very often because of the activities of people cannot spend that time foraging, and they have to seek another place to forage with less disturbance.

Observations in 1986 showed that as the shorebird migration season progressed, both the number of shorebirds and people using the beach increased, and the percent of birds that flew in response to people increased (Norbury's, Reed's Beach, Moore's Beach; data from Burger [65]) (**Table 1**). In other words, the shorebirds did not habituate to the increase in the number of people. At this time, only 2% of the people on the beach were birdwatchers (with no photographers), and most people were local. The two factors that were most highly associated with shorebirds flying away were the duration of the disturbance and the distance between the shorebirds and the disturbance [65].

Table 1. Presence of people and shorebirds and effect on the shorebirds of approaching people (adapted from Burger [65]).

Date	Mean number of shorebirds/beach	Mean number of people	% that flew in response to people approaching
Last week in April	260	11	60
1 - 7 May	244	12	67
8 - 14 May	560	23	69
15 - 22 May	600	24	70
23 - 31 May	2000	38	72
1 - 7 June	1090	40	75

The phenomena of the shorebird migration through Delaware Bay was only discovered in the early 1980s, bringing bird watchers who wanted to see the masses of birds and to look for rarities for their lists. Previously the bay beaches were used by local people, mainly who lived along the shore in small beach communities. With the media attention, casual and hard-core birdwatchers and photographers descended on the bay. By 2002-2003, NJDEP Endangered and Nongame Program recognized the disruptions that human activities were causing the shorebirds on the beaches and began protecting beaches and enforcing beach restrictions [48].

The effect of management at Reed's Beach is shown in **Table 2**. Signs and enforcement reduced the number of birdwatchers and photographers by 2002. Some people continued to walk or fish on the beach

(which accounts for the disturbances in 2002). Other beaches were not similarly protected in 2002. Thereafter, the state implemented stronger restrictions (see below).

Table 2. Effect of management of human activities on Reed's Beach (after Burger *et al.* [48]).

	1982	1987	1992	2002
Restrictions	None	Signs only	Signs Viewing platform	Signs Viewing platform Enforcement Patrols
Mean number of disturbances by people/hr[a]	4.7	5.6	4.5	0.4
Percent of disruptions caused by birdwatchers	2	30	44	0
Percent of disruptions caused by fisherman	18	15	32	29
Mean minutes disturbed/hr	32.9	53.0	42.0	3.6

[a]Resulted in shorebirds flying.

Clearly the mean number of human disturbances declined with greater protection measures (2002). Although birdwatchers responded to the signs, fishermen often did not. Partly this is because birdwatchers came to see the shorebirds and appreciated that they may have an effect. Still, some people continued to walk on the beach. Fisherman, since they did not intend to walk directly toward the shorebirds (as birdwatchers did), explained that they were not "bothering" the birds. Managers provided the platform so that birdwatchers could see the birds, but it proved to be too close to the foraging shorebirds during high tide (and was eventually removed after 2003). The State initiated a shorebird steward program, where volunteers were stationed at entry points. The addition of stewards at Reed's beach access points decreased human activity at this beach, but steward presence was sporadic in 2002. After 2003 ropes and fences were used to prevent access except along the rocky jetty, which provides an opportunity for shorebird viewing, fishing, and walking. These measures reduced human disturbance to foraging shorebirds considerably.

Studies in the mid-2000s showed that 5 species of shorebirds selected foraging habitats where aggression among shorebirds was minimized, and foraging rates were highest [49]. Then, horseshoe crab eggs were available along the high tide line, upper beach, creeks, mudflats, and sandbars, often forming a green sheen of eggs (Burger, pers. obs). When there are dense flocks of shorebirds foraging on the beach, there are usually laughing gulls (*Leucophaeus atricilla*, formerly *Larus atricilla*), as well. The problem arose with a human disturbance. With the approach of people or dogs, shorebirds flew, and often did not return. Laughing gulls returned immediately, leaving little room for the shorebirds to land at the high tide line because of the densely packed gulls. Ten minutes after being disrupted by people, only 47% of red knots were foraging on the beach, whereas 60% of ruddy turnstones (*Arenaria interpres*), and 89% of sanderlings (*Calidris alba*) had returned, and twice as many laughing gulls were present [49]. If a dog caused the disturbance, no knots or sanderlings returned, but about a third of turnstones returned and twice as many laughing gulls returned to the beach. Still, some managers, conservationists and the public needed convincing that shorebirds were foraging at all times of the day (indicating a need to do so), and in 2015 and 2016 we surveyed the presence of 4 shorebirds species on 5 NJ beaches as a function of tide, time and distance [60]. Surveys were conducted from dawn to dusk and required several assistants. In general, shorebirds fed at the tide line during high tide, and moved out on the tidal flats as the tide receded, as far as 300 m. Knots were present in the intertidal on 67% of the surveys (other species were present on 77% - 86%) [60].

The data clearly show that the activities of people affect the behavior of shorebirds foraging along the coastal beaches of New Jersey that was particularly critical during spring migration of shorebirds through

Delaware Bay. With time, the importance of the Atlantic coastal beaches during the fall migration was also recognized. This resulted in addressing the question, are people disrupting the activities of shorebirds during fall migration? Two experiments were conducted to determine the efficacy of restricting human access to beaches during critical fall migration: 1) voluntary restricted access (Avalon Beach, 2011), and 2) enforced restricted access (Brigantine Beach, 2010). The town of Brigantine allowed us to close a section of a popular beach (Brigantine Natural Area), enforced by conservation and town law officers [66, 67]. Data were collected when the beach was open and when it was closed. In November 2011, we closed a section of Avalon beach voluntarily (people were asked NOT to disturb the birds). Data were collected during the closure period, and when the beach was open to recreationists. We collected data on the responses of people and shorebirds (species presence and numbers, percent flew, use of beach sections) [66-68]. In both studies, a strong fence and signs said the area was closed because of shorebird protection. Observers were located well away from the closed area and observed the shorebirds and people using telescopes.

Table 3. Differences in shorebird behavior on beaches where human access was experimentally completely restricted (with law enforcement patrols) and voluntarily restricted (after Burger and Niles [66-68]).

Characteristic	Brigantine: complete restriction (police patrols)[d]	Avalon: voluntary restriction
Compliance by dog-walkers[a]	98%	63%
Bird response		
Size of mixed-species flocks[b]	986 + 173	612 + 201
Size on monospecific Red knot flocks	169 + 66	655 + 505
% mixed species flocks that flew when people arrived (disturbed)[b,c]	70	99
% mixed flocks that returned[a]	82	40
% all-knot flocks that flew	87	100
% of all-knot flocks that returned	65	8

[a]There was 100% compliance by walkers without dogs and by birdwatchers and photographers; [b]Flocks with Red knots; [c]At both beaches, some people managed to get onto the beach even when access was restricted, and of course, people were on the beach when it was open; [d]Although there were frequent patrols and it was irregular, some people got on the beach.

The recreationists using the two beaches were similar in age and were mainly Caucasian (99% and 96%). Compliance was higher when it was mandated than when it was voluntary (**Table 3**). Birdwatchers, photographers, and anglers were 100% compliant regardless of whether it was enforced or not. However, dog walkers were less compliant when they were not required to keep off the beach. Several conclusions can be drawn: 1) a higher percentage of monospecific knots flocks flew when approached by people than did mixed species flocks. 2) a lower percentage of monospecific knot flocks returned following the disturbance than mixed species flocks, and 3) spatial use of beaches by shorebirds was dependent upon whether the beach was open or access was restricted. In the experiment at Brigantine (no police patrols), red knots only foraged at the end of the sand spit which was still fenced off from the public (fencing remained from piping plover (*Charadrius melodus*) protection [66]. When beach access was restricted by police patrols, red knots

occupied all the linear segments of the beach (regardless of tide stage). The latter suggests that restricted beach access increases foraging time and space for shorebirds (and red knots), and that determining the amount of protected space necessary to provide sufficient foraging opportunities for shorebirds is an important management question. The experiment at Avalon clearly showed that people (particularly dog walkers) were not compliant when it was voluntary (and they did not see anyone watching them).

5. STEWARDS, PROTECTION MANAGEMENT EFFORTS, AND THEIR EFFICACY

There are several available methods to protect shorebirds, including restricting human activities on foraging beaches during critical shorebird migration periods, developing protected areas that are completely off-limits during shorebird migration, and managing and protecting these areas (e.g., signs, ropes, fencing, and stewards, and other restrictions). New Jersey has employed all of these techniques to protect foraging shorebirds during migration (mainly during spring, but also for nesting shorebirds). Further, some beaches are accessible, while others are not easily accessible (e.g., no roads); some have housing developments along them, others do not. Aerial surveys began in 1986 (**Figure 1**), and restricting access began shortly thereafter. However, these initially involved a few signs and building a viewing platform at Reed's Beach North. These were somewhat ineffective without having some methods of enforcing the restriction of people on Reed's and other key beaches. Further, national attention devoted to the spectacle of shorebirds on Delaware Bay increased the number of eco-tourists, including some photographers who wanted to get a photograph of massive shorebirds taking flight, and deliberately flushed feeding flocks time after time. After 2003, concerted efforts were employed to protect key beaches where shorebirds were thought to concentrate; personnel and other costs prohibited the use of these protective efforts on all key beaches, or on a number of other beaches that were used by foraging shorebirds. People who come to Delaware Bay do so for a number of reasons, including bird-watching, horseshoe crab watching, fishing, and the aesthetics and beauty of the Bay [69]. The objective of this section is to describe the main protection efforts and examine their efficacy. This analysis has not been previously attempted.

5.1. Methods

We examined the efficacy of conservation methods using the annual aerial survey counts of red knots on all the beaches on the New Jersey and Delaware side of Delaware Bay. We developed two methods of assessing the efficacy of conservation methods: 1) development of a hierarchy of conservation conditions and protection efforts, and 2) assignment of beaches to different protection methods. In both cases, we determined the percent of red knots/beach/year as our measurement endpoint. Since the total number of knots on Delaware Bay varied each year (and decreased and increased over short periods of time), we provide percentages for beach use to account for these variations.

We identified a hierarchy of conditions and protection efforts for red knots and other shorebirds on Delaware Bay beaches, which began in 2003 on some beaches. Methods included: 1) signs and postings, 2) ropes or fencing across access areas, 3) stewards (often volunteers), and 4) deployment of conservation police, especially on weekends from mid-May through Memorial Day. Not all beaches had all protective efforts. This allowed us to develop a "management score", from 0 to 4, that included whether access was restricted and whether there was signage and postings, fencing, stewards, and conservation officer patrols. While law enforcement and patrols are critical, we did not have access to quantitative or qualitative data on police visits (although they always came when called by stewards). We developed the "management score" based on accessibility, development, restrictions, fencing/signs and stewards (**Table 4**). Using **Table 4**, we provide the following examples: 1) a beach that is accessible and developed, but has no management received a score of 0; 2) a beach that is accessible, undeveloped, restricted, and has fencing and stewards received a score of 4; and 3) a beach that is accessible, undeveloped, and restricted with fencing (but no stewards) received a score of 3.

Conditions varied among the beaches where conservation efforts were implemented; some had houses adjacent to the beach (others did not), and some had easy access, while others were difficult to access. The State of Delaware has restricted access on only one of 33 beaches, 20 are accessible, and 17 are adjacent to

housing and development. On the New Jersey side of the Bay, we had aerial counts from 1986 to 2018, and intensive management from 2003 to 2018. We had designated 48 beaches from the aerial counts. This made it possible to compare Red Knot use of the beaches before 2003, and after 2003, and to examine the red knot use of beaches with no conservation protection methods to those with protection after 2003. An examination of population levels from 1986 to 2018 allows us to examine the percentage of knots using each side of the Bay (NJ, Delaware).

Table 4. Management Score based on whether a beach was accessible, developed (housing), restricted (access designated as restricted on maps), had fencing and signs, or had beach stewards. The total number of 1s equals the score. However, a beach that is accessible, but is restricted gets only 1 point, + the other points for management if it had them (fencing or stewards).

Characteristic	Yes score	No score	Definition
Accessible	0	1	Is there a road leading to the site?
Developed	0	1	Is there development along the coast (near the site)?
Restricted	1	0	Is the site designated as restricted access?
Fencing/signs	1	0	Does the site have string and post fencing, and signs? from May 7 to June 7 (migration period)?
Stewards	1	0	Is the beach staffed by shorebird stewards?

In this paper, we concentrated on the two periods because the management actions in the second period could be compared to the earlier period without them, the time frames were the same, and conditions varied after 2018. The second period was followed by COVID and a disruption of the stewardship program in general. It is important to analyze the effectiveness of the program at this time to move forward with future planning for a stewardship program and the potential for roving stewards who would shift their locations daily to be where the shorebirds were foraging in large numbers rather than monitoring a given beach. Determining how to provide information to the public and encouraging multi-directional communication is an important aspect of conservation.

5.2. Results

Use of particular beaches by red knots in different years:

The total number of shorebirds on the Bay varied from year to year. Also, beaches were not used the same way or for the same amount of time each year. Red knot use of beaches clearly depends upon the availability of Horseshoe Crab eggs, but it also depends upon foraging conditions, weather (they avoid high winds, seeking shelter in coves or protected areas), and any disruptions (e.g., presence of peregrines, people). The beaches monitored are wide enough (with enough slope) that there is room for knots and other shorebirds to feed or roost during normal high tides. Based on the bay-wide aerial survey covering New Jersey and Delaware beaches (e.g., all knots counted for the entire Bay), we computed the average percent of the total knots that occurred on each beach for each year from 1986 to 2018 (**Figure 2**). For example, in 1986, 9% of the total knots on Delaware Bay were located on Reed's Beach. Conclusions from the data indicate: 1) knots were not present on each beach every year during the aerial count, 2) the maximum percent on any beach varied over the years, 3) the variation indicates that a number of different beaches are used every year, and this diversity may be essential to providing adequate foraging opportunities, and 4) even beaches that are generally favored over time, may have little use in some years.

Hierarchy of conditions and protection efforts:

We compared data on accessibility, development, and conservation efforts for all 48 NJ beaches (scores

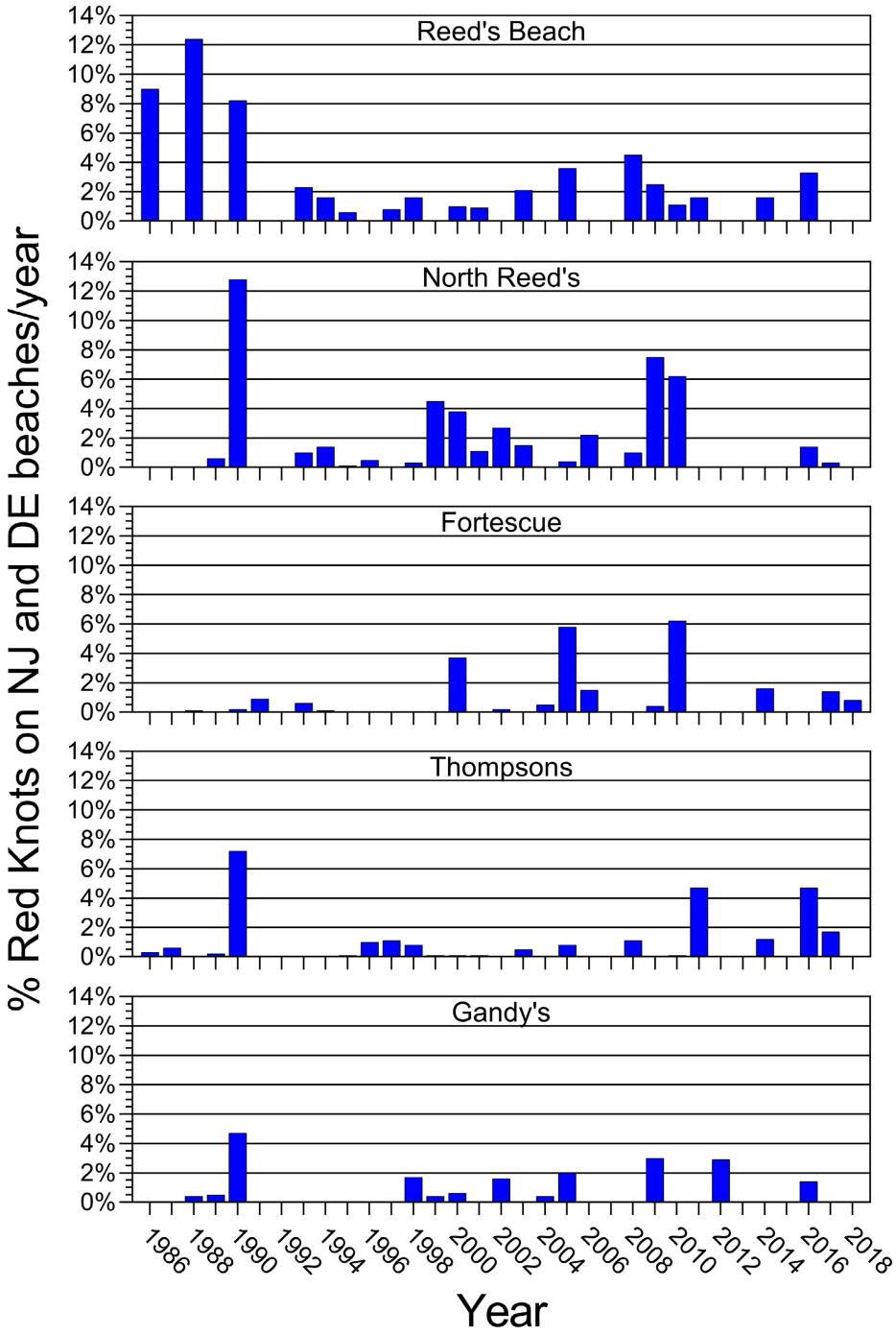

Figure 2. Temporal use of five New Jersey beaches by red knots. Given is the percentage of knots on each beach/year during the aerial counts (includes population counts from both sides of the bay).

of 0 - 4). This allowed us to examine the mean percent of knots present/beach as a function of the management scores (data: aerial counts of knots on the entire bay, both NJ and Del). All beaches were designated based on the score they received when management was implemented (2003), even though management was not implemented until 2003. This allowed us to compare pre- and post-conservation efforts. A number of beaches were accessible (roads leading to them) and developed (houses along the beach) and had no conservation efforts (score = 0). There was no difference in the mean percent of birds present before and

after treatment (institution of protection efforts) (Figure 3). For beaches with the maximum protection (no development, restricted, fences/signs and stewards) there was the greatest difference between the pre-treatment (1986-2003) and post treatment (2004-2018, restrictions, signs/fencing, stewards) periods. Figure 3 is based on the aerial counts for the entire bay and indicates an effect of conservation efforts ($X^2 = 121$, df = 4, $p < 0.001$).

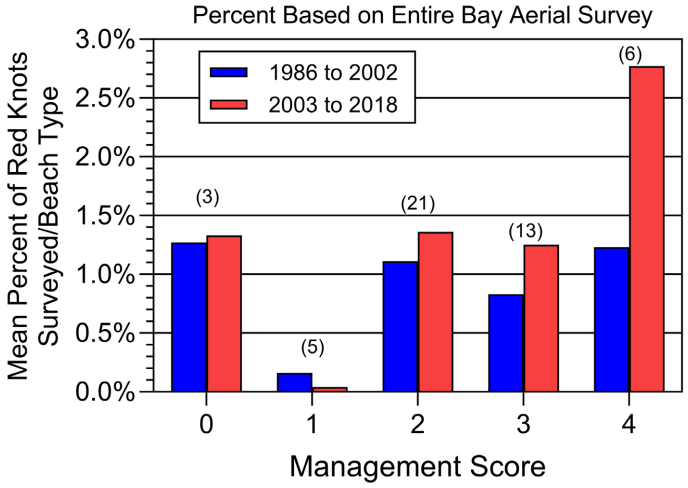

Figure 3. Mean percentage of red knots surveyed/beach for each management type along the New Jersey shore. The data given are for the percent of red knots surveyed for the entire bay as a function of management score (0 to 4). The blue refers to the mean percent/beach prior to management, and red is after management.

In the period from 1986-2003, a significant proportion of the birds were concentrated on the beaches that were road-accessible and developed (and had no restricted access or other protections, Figure 3). During the period from 2003-2018, the knots concentrated on beaches that had restrictions (even if they were accessible), particularly if there were also fences/signs and stewards. The results are similar whether one considers the entire census counts, or only those knots counted along NJ beaches.

Assignment of beaches to different protection methods:

We also examined the percent of red knots present/beach/year as a function of protection categories (e.g. no restriction, restricted, restricted/fences, restricted/fences/stewards) for the New Jersey beaches (Figure 4). Figure 4 shows the mean percent of knots/beach on New Jersey side as a function of protection efforts (restricted, fences, stewards) for the period 2003-2018, compared to the period prior to 2003 when no efforts were generally implemented. For any given year the percentages add up to 100%. By inspection, there were more knots, on average, on the beaches with management efforts after implementation, than before. This figure also shows the mean percentage of knots/beach on New Jersey beaches with no restrictions, and on the combined beaches on the Delaware side of the Bay (this graph includes all the knots on the bay/yearly survey). Although the mean percentage of knots/beach varied over the time period.

The variation in both the number of knots on the Bay (Figure 1), and the percent of knots on beaches with different protection efforts makes it difficult to see patterns when examined on a yearly basis (e.g. Figure 4), although on inspection, beaches with stewards did better than those without. Thus, we analyzed the data to examine the overall mean percentage (averaged over the two 16-year periods) of red knots/beach by management category (e.g. no restrictions, restrictions but no management, fences (and signs), and stewards) (Figure 5). The graph includes all the knots counted on the Bay-wide aerial survey. This graph summarizes the efficacy of management actions. Since the presence of conservation officers was episodic, we could not include this in our analysis.

This graph indicates the following: 1) on NJ beaches with no restrictions, there was no significant

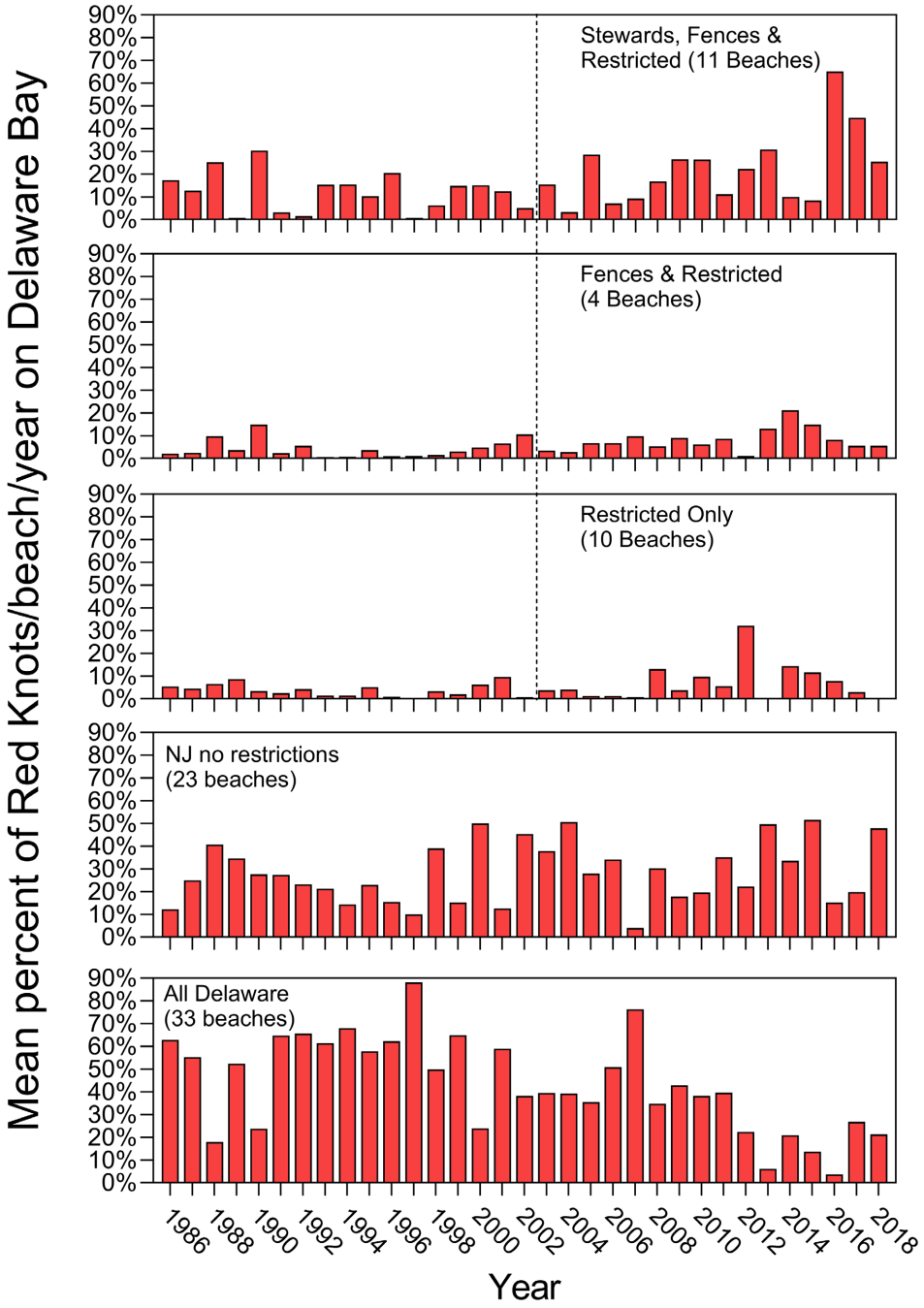

Figure 4. Variation in the percent of red knots/beach on Delaware Bay as a function of side of the bay (e.g., NJ or Delaware side), and conservation efforts (NJ only). Protection efforts include restricted, fences and signs, and stewards, and began in 2003 (the vertical line on the top three panels).

increase in the percent of knots using these beaches in the 2003-2018 period (compared to prior to 2003), 2) on NJ beaches there was a difference in the percent of knots using these beaches when fences were employed, 3) the greatest increase in percentage of knots using NJ beaches occurred for beaches that were fenced and had stewards, and 4) the Delaware beaches (with these conservation efforts on only one beach) lost a significant percentage of knots from the pre- to post-management era (Figure 5). Given the variability in knot use as a function of year and beach section, it is remarkable that these differences are significant.

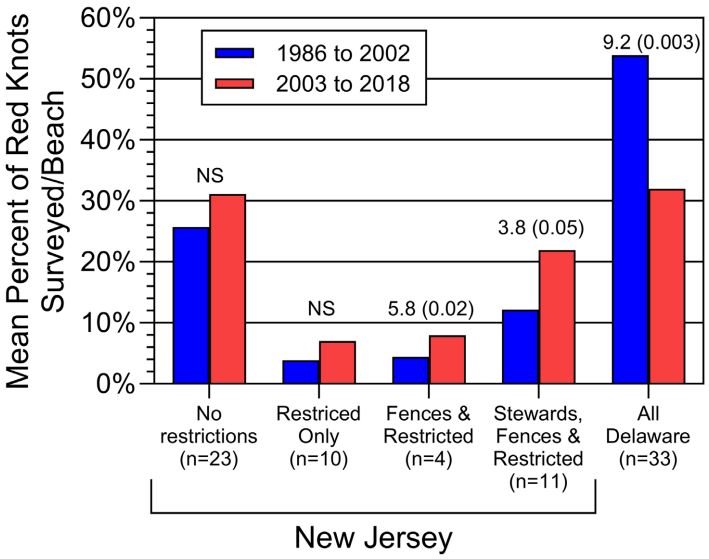

Figure 5. Summary of the effect of protection efforts on the mean percent of red knots/beach for different management categories on Delaware Bay. The number of beaches in each category is also shown.

Comparison of red knot use of New Jersey and Delaware Bay beaches:

New Jersey has used more intensive protection efforts on its beaches (including restricted access) than Delaware, and although many different environmental conditions have occurred over the period from 1986 to 2018, it is instructive to examine where red knots have concentrated during peak migration each May (Figure 6). Three-year running averages were used to illustrate the pattern more clearly. Over this period there was a significant increase in the number of knots using the New Jersey beaches (compared to Delaware beaches) during the peak migration period (tau = 0.46, $p > 0.0003$) (also see Figure 5, where X^2 was also significant for the period 1986-2002 compared to 2003-2018).

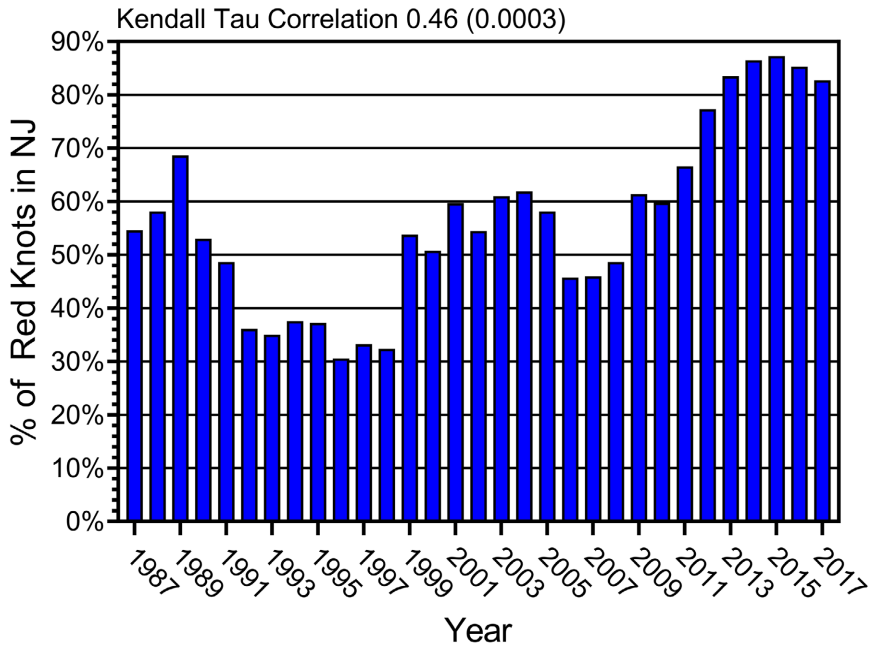

Figure 6. Percent of ed knots present on New Jersey beaches during the aerial counts from 1986 to 2018 (3-year running averages, after Dey *et al.* 2020 [45]).

6. DISCUSSION

In an economy with decreasing funds and personnel for conservation, it is essential to determine the human activities that disrupt the foraging (or roosting) behavior of migratory shorebirds at stopover sites. And it is important to examine the efficacy of different protective efforts. Determining the actual increase in fitness of each measure may not be possible, but connections can be made. Knots and other shorebirds need to gain sufficient weight at Delaware Bay to make the 4000+ km journey to the Arctic to breed. Knots are both time-pressed and food-stressed. If they do not reach this weight, then they may not make it to the Arctic at all, or they may not be able to breed successfully on arrival. Recently, Duijins *et al.* [42] showed that weight gain at northbound stopovers is related to both successful breeding and survival in red knots. It seems obvious that to gain sufficient weight shorebirds need to have ample opportunity to forage optimally in time and space. Red knots have only a three-week window to gain this weight, if a given knot arrives at the beginning of the stopover period and remains the whole time. In fact, most knots do not do this (based on data from knots fitted with geolocators, Burger, Unpubl. data). Thus, they have less than three weeks to almost double their weight (see references in introduction). Time that birds are disturbed is time wasted. The stunning photographs of a flock of thousands of shorebirds taking flight from a feeding beach carries a critical cost for the Knots.

This paper focused on the studies that have examined the effect of human activities on foraging shorebirds, experimental studies examining the efficacy of beach closure (voluntary or not), and the efficacy of conservation efforts (e.g., beach restrictions, fences/signs, stewards). The synthesis and analysis indicated that: 1) people engage in a range of activities on beaches, 2) their presence often results in birds flying away from such disturbances, 3) shorebirds (and knots) often return later than laughing gulls following a disturbance, and thus lose prime foraging space at the water line's swash zone during high tide, 4) the activities of people from the early 1980s to 2002 increased, and their detrimental effect on shorebirds increased (e.g. red knots and other shorebirds spent more time flying away and being disturbed over the years), 5) the foraging behavior and presence of red knots is often more disrupted by some human activities than is that of other species, 6) experimental studies suggested that shorebirds avoided oyster aquaculture racks, and that red knots may be more wary of racks, 7) experimental studies showed that more knots and other shorebirds concentrated in areas that were closed than when they were open to use by recreationists, 8) NJ implemented more management conservation efforts on more beaches than did Delaware (14 vs 1), 9) knots and other shorebirds often concentrated on the beaches that were managed (e.g. fences, stewards), 10) comparison of the beaches where conservation efforts (fencing and signs, stewards) were implemented averaged a significantly higher percentage of red knots in 2003-2018 than prior to implementation of these efforts, 11) there are often more red knots and other shorebirds on NJ beaches than on the Delaware side of the bay, and 12) from 1986 to 2018 there has been a significant increase in the percentage of knots using the New Jersey side of the Bay (which continued to the present, A. Dey, S. Feigin, Unpubl. data). Altogether, these studies and analyses show that knots are disturbed when people are on the beach or in the intertidal, that knots use beaches that are experimentally closed more than when the same beaches are open to the public, and that knots concentrated on beaches where access is restricted, there are fences, and stewards are present. Over the years, this resulted in more knots foraging on the New Jersey side of the Bay than in earlier years.

During each spring migration through Delaware Bay the foraging conditions on the Bay are paramount to their gaining sufficient weight to migrate to the Arctic and breed successfully [42]. Being able to forage undisturbed is only one of the necessary foraging conditions. Presumably without interference during foraging, knots can forage continuously for longer periods, consuming more food, and gaining more weight quickly. This is particularly advantageous for knots that have less time to spend on the Bay (e.g. they travel from Tierra del Fuego rather than Florida to the Bay). Moreover, knots that are less efficient foragers (perhaps less competitive with other knots) have longer to forage undisturbed. Foraging undisturbed may allow them to make the necessary weight threshold, allowing them to reach the Arctic earlier, in good condition. All of these could lead to higher survival and an ability to breed earlier (thus a greater chance to be successful) [42]. Since the primary conservation goal is to increase *rufa* red knot populations, improvements in the

foraging conditions at a major stopover (such as Delaware Bay) will improve the carrying capacity of the population during that stopover. Delaware Bay will no longer be a bottleneck that has the potential to decrease the survival and reproductive potential of knots migrating to breeding grounds. Protection efforts on Delaware Bay thus contribute significantly to the conservation strategy for *rufa* red knots. Of course, if the red knot population does recover, then there will be an even greater need for there to be foraging beaches where there is high horseshoe crab egg density, and no disruptions from human activities.

While any one protective or conservation measure can clearly be shown to aid the shorebirds, particularly red knots, it is important to note that it is the matrix of efforts that is essential. The birds cannot forage without a large enough prey base, which depends upon a healthy horseshoe crab spawning population. The crabs cannot spawn without suitable spawning beaches (which in some cases requires restoration and placing sand on beaches scoured clean by storms [59]). The birds cannot forage undisturbed on beaches that are covered with oyster aquaculture racks or oystermen cleaning the racks (thus the regulations of USFWS are essential) [58]. Shorebirds cannot forage on the beaches if there are too many people (constantly interrupting their foraging), thus the need for beach stewards, restricted beaches, and effective law enforcement. Red knots foraged on a number of different beaches, on both the New Jersey and the Delaware Bay side. However, in any given year the peak counts were not on the same beaches, but they shifted from beach to beach. This suggests that their use of specific beaches is not predictable in any given year, and a sufficient number of beaches need to be present to allow them to find sufficient foraging opportunities to gain sufficient weight to successfully reach the Arctic. It is essential to have a large number of beaches on the New Jersey side that are restricted, fenced, and have stewards. Restrictions alone (e.g. signs without stewards) do not result in a higher percentage of knots using them (compared to no restrictions). The fencing, signs and stewards are essential to providing undisturbed foraging.

One important question, however, is whether the protection efforts on New Jersey beaches merely drew red knots to these beaches, but in the larger sense did not contribute to the survival or addition of more red knots to populations overall. The survival and potential increases in the *rufa* red knot populations likely requires good foraging conditions (e.g. prey availability, lack of predators, lack of human disturbance, available habitat) at breeding sites, stopover sites, and wintering sites. That numbers of red knots using Delaware Bay have continued to decline [45] is cause for concern, and we suggest a revision of our thinking and models about the relationship between the prey base (including population trends of horseshoe crabs and their eggs), knot foraging behavior and selection of stopover sites, knot weight gain on Delaware Bay (and elsewhere), and population dynamics. Foraging conditions on Delaware Bay one year may influence their use of the Bay in subsequent years, as well as survival of knots that experienced "bad" foraging conditions (e.g. low prey levels, inclement weather). We believe that the relationships are complex, and that foraging conditions (including prey availability, predator presence, and human disturbance) need to be modelled together. The data in this paper addressed the question of whether stewards and conservation efforts are successful in providing opportunities for shorebirds to forage undisturbed, and we used a 32-year data set that compared pre- and post-conservation efforts (including stewards). Clearly, stewards and other protection measures provide disturbance-free conditions for foraging, but optimal foraging opportunities requires suitable foraging habitat and prey availability as well.

7. CONCLUSIONS

Reducing human disturbances and disruptions is only one aspect of improving foraging opportunities for shorebirds, but it is an important component of conservation. Any one study of the effect of human activities on shorebirds, and possible disruptive effects, may be limited by some methodological issues. Any one study of the efficacy of closing beaches, or of implementing protection efforts (beach restrictions, fencing, signs, stewards, law enforcement) may likewise be flawed in some way. However, when we consider that there have been several studies of the deleterious effects of some human activities (including frequency, intensity, or duration of disturbances) since the 1980s, and there have been both experimental and observational studies of the efficacy of conservation efforts, we feel that it is imperative to use a weight-of-evidence

approach. We therefore conclude that: 1) some human activities (especially those with high frequency and intensity) adversely affect the ability of shorebirds to forage in certain habitats and on some beaches, 2) shorebirds feed on beaches where food is available and abundant, and there are no disruptions that reduce the time and space where red knots and other shorebirds can forage optimally, and 3) conservations efforts (ropes, fencing, stewards) are essential to provide sufficient time and space for foraging shorebirds to move among beaches to gain sufficient weight for successful northward migration. Further, restricting public access to beaches increases the public's ability to observe shorebirds and horseshoe crabs since roped barriers prevent people from moving closer to the birds, the shorebirds acclimate to the barrier and to the presence of people, and often feed quite close to the barrier.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest regarding the publication of this paper.

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