ROOST SITE SELECTION BY RED KNOTS (*Calidris canutus rufa*) IN DELAWARE BAY

by

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ABSTRACT

I monitored the roosting preferences of 53 Red Knots (*Calidris canutus rufa*) during their northbound migratory stopover in Delaware Bay in 2008 and 2009. The goal was to locate the high tide daytime and nighttime roosts as well as to determine the habitat characteristics that create suitable roost sites. Radio-tracking data were used in collaboration with aerial photos to map and locate high tide roost sites. Habitat surveys were used to determine environmental characteristics that correlated with roost site use. Birds preferred shoreline habitat during the day, but preferred inland habitat at night. Birds' preference for inland roost sites increased significantly at spring tides. The results of this study can inform local resource managers about the restoration and conservation of roost sites in Delaware Bay for shorebirds.

INTRODUCTION

The Red Knot (*Calidris canutus rufa*) is a long-distance migratory shorebird, known as a "long hop" migrant: single species flocks of birds fly non-stop for thousands of kilometers between a number of key migratory stopover sites, where they rest and feed (Niles et al. 2007). Every year Red Knots make one of the longest animal migrations known (Niles et al. 2007).

Red Knot populations have declined considerably over the past decade, perhaps because stopover sites are few and changes at these sites (especially rapid changes due to human activity) may create substantial risks for successful migration. In particular, changes in food availability comprise a potential major risk factor caused by human activity (Niles et al. 2007).

Delaware Bay is the most important stopover site for Red Knots in the Atlantic flyway during their northbound migration. It serves as the final stopover on the journey to the Canadian Arctic breeding grounds (Niles et al. 2007). In Delaware Bay, the birds feed predominantly on horseshoe crab (*Limulus polyphemus*) eggs (Harrington 1996; Botton et al 1994; Castro and Myers 1993; Tsipoura and Burger 1999). In the past, they could increase their body mass by 50-100% before their final nonstop flight to the breeding grounds (Baker et al 2004). Years of over-harvesting horseshoe crabs by humans at this stopover site has drastically decreased the Red Knot's food base (Niles et al 2007).

The effectiveness of a stopover site depends not only on the availability of high quality food, but also on presence of suitable low-predation roosting sites for birds between feeding periods (Rogers 2003); these are decreasing due to shoreline erosion. The availability of safe roosting sites is particularly important at night, when predation risk increases, and during high tides, when birds cannot feed (Rogers 2003, Rogers et al 2006).

Little is known about Red Knot roosting preferences in Delaware Bay, but it is recognized that energy and habitat limitations are important (Gill et al. 2001, Rogers et al. 2006, van Gils et al. 2006). When there is an unlimited amount of high quality food (such as horseshoe crab eggs) the birds can build up fat reserves at a very high rate to reach "a certain mass by a certain date" (Atkinson et al 2007). These birds are driven by a strong biological or physiological urge to depart the bay together. However, late-arriving birds depart before putting on as much mass as early-arriving birds, and in low food density years show lower adult survival (Baker et al 2004). Thus, birds are time-limited in their need to build up and conserve energy. It is in this context that roost sites are important as individuals may expend extra energy finding suitable roost sites. Having quality roost sites for birds is especially important during low food density years.

Daytime and nighttime high-tide roost sites are a research need in both the Red Knot Status Assessment (Niles et al. 2007) and the Delaware Shorebird Conservation Plan (in prep) to improve local management and protection. Local resource managers need to know whether particular roost sites are used on a daily basis, or whether the use of roost sites depends on ecological conditions.

Creating and improving existing roost sites may help decrease the birds' time and travel costs. Therefore, I investigated the roosting preferences of Red Knots in Delaware Bay. This research will aid local resource managers to determine whether and where to create or restore specific habitats, and to guide conservation efforts to purchase and protect land.

My goal was to identify the characteristics and locations of daytime and nighttime high tide roost sites used by Red Knots in Delaware Bay. Thus, I ask: (1) Where are Red Knots roosting in Delaware Bay? (2) What environmental habitat characteristics make suitable roost sites during high tide? (3) Do daytime and nighttime high tide roost locations differ?

METHODS

Study Site

I observed Red Knots along four areas of the coastline of Kent and Sussex Counties, Delaware. This coastal area has been designated a site of Hemispheric Importance by the

Western Hemisphere Shorebird Reserve Network (WHSRN). My study area consisted of several protected areas (e.g. the St. Jones Reserve, part of the Delaware National Estuarine Research Reserve (DNERR); Bombay Hook National Wildlife Refuge; Prime Hook State Wildlife Management Area), as well as private land and public boat harbors (Figure 1).

The southernmost area of the study was Prime Hook Beach; the northernmost area was Bombay Hook National Wildlife Refuge. The study area included several natural and human-made habitat types: 1) long narrow coastal sandy beaches; 2) mudflats; 3) tidal brackish/freshwater impoundments bordering the rivers; 4) estuarine wetlands; and 5) a boat harbor.

Field Techniques

***Bird Collection*.** In May-June of 2008-2009 I used cannon nets to capture Red Knots, in collaboration with wildlife biologists from Delaware Department of Natural Resources & Environmental Control (DNREC) and the Delaware Shorebird Project.

For radio-tagging purposes, I chose at random twenty-four birds in 2008 and twenty-nine birds in 2009. Each of these birds was fitted with an individually-coded leg flag and a metal USGS band. Differences in leg flags let us identify individual birds visually after their release. A radio-transmitter was attached to each of the 53 birds (Warnock and Warnock 1993). A small number of lower back feathers, well above the uropygial gland, were trimmed in order to superglue a radio-transmitter to the skin. Radio transmitters weighed 2.5 grams, less than 3% of the bird's body weight. The radio transmitters fall off the bird within three months, or when birds molted into non-breeding (i.e. basic) plumage.

Radio Telemetry. Each radio transmitter had a unique pulse-code and emitted on one of seven frequencies, with three to five birds being assigned to a given frequency. Having several birds per frequency means birds can be scanned more often.

I detected transmitted signals with a three-element Yagi antenna connected to a receiver. In 2008, four stationary receiver (detection) units were used (Figure 2). An additional stationary receiver unit was used in 2009, for a total of five receiver units. However, in 2009, one stationary receiver malfunctioned (all observations for Mispillion Harbor, Milford Neck Wildlife Management Area, and Milford Neck shoreline in 2009 were from physical observations, manual telemetry, and the Big Stone Beach stationary telemetry receiver unit) .

Stationary receivers scanned continuously for transmission signals, sampling each of the seven transmitter frequencies three times every thirty minutes. When a bird was detected, the following data were recorded on an R4500C unit using DSP (Digital Signal Processing) technology (Advanced Telemetry Systems, 470 First Ave N, Box 398, Isanti, MN 55040): frequency, the individual's unique code number, time, date, and signal strength.

First, some birds were detected by two separate stationary receiver stations. A *line of position* (LOP) was determined for each based on a calibration of signal strength vs. distance (see below). The location of the bird was fixed at the intersection of LOPs. Second, when a single receiver unit detected a bird, the bird location was determined from one LOP, signal strength in various arcs, and known habitat preferences (Figure 3), as described below. Third, a single stationary receiver was used in conjunction with a portable receiver. The compass bearing and location, using a Garmin ETREX GPS with an accuracy of ±3 m, from the portable receiver was recorded, and the birds' position was determined to be where this LOP (from the portable receiver) crossed the LOP from the stationary receiver.

There were 2,440 total detections in 2008, of which 849 occurred at high and low tide. In 2009, there were 375 total detections, of which 261 occurred at high and low tide. The large decrease in the number of observations in 2009, compared to 2008, was due to a stationary receiver failure.

Bird Locations. As noted above, bird locations were determined from stationary receivers in combination with (1) other stationary receivers and (2) a portable receiver. To obtain LOPs when using the stationary receivers, I converted signal strength to distance (Figure 3). A transmitter not attached to a bird was used to construct a calibration curve for signal strength *versus* distance. The transmitter was set low to the ground to simulate a Red Knot either foraging or roosting, at various distances from stationary receivers for 30 minute periods. As with the portable receiver unit, the location of the transmitter was recorded using a Garmin ETREX GPS with an accuracy of ±3 m.

Radio telemetry data were used in combination with ArcGIS geographical information systems (ESRI, 380 New York Street, Redlands, CA 9237308100) to map the location of each recorded bird observation. I overlaid the stationary receiver's location and yagi antenna direction on orthorectified 2007 aerial photos (1:28,000) (DE State Plane, NAD83 datum) of Sussex and Kent County, Delaware, using ArcGIS (Fig 3). Using the calculated distance from the signal strength calibration curve, I measured outward from the stationary receiver along the yagi antenna line of sight and used a temporary symbol to mark the location. I used the same procedure for the second yagi antenna. A LOP was created using a curved line connecting the two temporary markers. The location of the bird should be somewhere along the LOP. Using the recorded signal strength for each antenna in combination, I could determine which of the sub-sectors in which the bird was located.

The biology of Red Knots is sufficiently well known (Niles et al 2007) that most habitats along the LOP could be excluded, and Red Knots could be reliably located in appropriate habitat. For stationary receivers used with the portable receiver, bird positions were triangulated from the intersection of the LOPs from each.

Bird Morphormetrics. I recorded standard body measurements for the Delaware Shorebird Project. Each bird was weighed using a portable digital scale. Flattened wing length was measured using a wing ruler (Prater and Merchant), a procedure used to provide an accurate wing measurement for shorebirds' curved wings. Wing length was defined as the distance from the shoulder to the tip of the longest primary feather. I measured culmen length to the nearest 0.1 mm using a digital caliper (Prater and Merchant). I also measured total head-bill length in mm, using digital calipers, from the tip of the bill to the back of the head (Kalasz, pers comm.). Two other measurements were made by trained experts using a pictorial reference guide (Kalasz, pers comm): (1) The degree of development of breeding (ie. alternate) plumage was assessed using a photographic reference key (Kalasz, pers comm.);

(2) Body molt was determined by the amount and extent of new feathers emerging (Kalasz, pers comm).

Habitat. I recorded habitat characteristics for both known and potential roosting sites (identified in previous years) (Figure 4; Figure 5). Known and potential sites included: 1) "eat-outs": inland shallow, water filled, bare sites in the estuarine wetlands that line the Delaware coast, formed by snow geese foraging during the winters; 2) impoundments which are man-made reservoirs filled with water; and 3) narrow sandy shoreline beaches and washover areas along the Delaware coast line. At each known and potential site, water depth was measured to the nearest cm and substrate was recorded (sand, silt, mud, shell, or rock). I identified vegetation surrounding the inland eat-outs, impoundments, and along the shoreline (Figure 4; Figure 5).

Using tide tables and tidal reference stations located adjacent to each main study area, I determined times of high and low tide (Tides & Currents Pro for Windows version 3.0e Copyright 1993-2000 by Nobeltec Corporation). I determined the moon phase, sunrise, and sunset from NOAA tables. Moon phase was used as a variable to predict bird behavior during spring and non-spring tide events. Sunrise and sunset times were used to categorize each bird observation as either daytime or nighttime. Finally, weather conditions were recorded at a weather station in Milford. Precipitation amount, daily mean wind speed, and direction were recorded.

Statistics. Data were classified within-year and not between years, due to a change in methodology. All analyses were carried out using SPSS 17.0 (SPSS, Inc., Chicago, IL).

Chi-square Goodness of Fit: Chi-square goodness of fit tests for high tide *vs*. low tide, daytime *vs*. nighttime, and inland *vs*. exposed shoreline *vs*. shoreline were used to test the observed proportions against predicted proportions. In addition, chi-square goodness of fit tests were also used for inland *vs* shoreline during spring and non-spring high tide events. A Rao-Scott correction to the chi-square statistic was used to correct for non-independence (due to multiple observations per bird) by using "bird id" as a cluster.

Contingency Table: First, tide (high/low) was compared to habitat type (inland, exposed shoreline, and shoreline) to test whether the preference for shoreline habitat differed significantly during high *vs* low tide using a contingency table. Secondly, the preference for shoreline habitat was compared during daytime *vs* nighttime. I used a Contingency table analysis with a Rao-Scott correction to the chi-square statistic to correct for multiple observations per bird to test whether the preference for shoreline differed in different scenarios.

Habitat Type Rank: Habitat type (inland, exposed shoreline, and shoreline) was ranked by frequency of use to determine which habitat type and corresponding environmental characteristics were favored in 2008 and in 2009.

Logistic Regression: I used logistic regression to compare habitat preference (inland or shoreline) for spring tide *vs*. non-spring tide during high tide only (when the birds are roosting). The independent variable was Spring tide and the dependent variable was habitat type (inland/shoreline). GEE (General Estimating Equations) analysis was used to control for multiple observations per bird.

Negative Binomial Regression: I used negative binomial regression to compare the number of observations at each roost site based on the habitat characteristics (area, flight distance to feeding, and water depth) of the roost site. Each roost site served as the unit of observation, with the offset being the total number of observations for that roost site. GEE (General Estimating Equations) analysis was again used to control for multiple observations per bird.

RESULTS

Red Knots usually arrive in Delaware Bay in the beginning of May; the majority of birds arrive during the second half of May. Individual birds stay an average of 12 days to feed and replenish body fat stores. Nevertheless, by the end of May, most birds are on their way to their arctic breeding grounds.

In 2008, a flood year, data were collected on 10 out of a total of 24 radio-tagged Red Knots from 21 May through 4 June ("late season"). Widespread coastal flooding resulted from extremely high onshore winds and record rainfall from 9-13 May. Coastal marshes, including the study area, were flooded by about a meter of water. This record flooding reached as far as 2.41 km inland and delayed the start of the 2008 season. In 2009, data were collected on 18 out of a total of 29 radio-tagged Red Knots from 16 May through 3 June ("normal season").

In 2008 and 2009, several of the radio-tagged birds, for which no data were collected, were observed on the New Jersey shoreline of Delaware Bay. This confirmed the radio-tags were still attached but the birds were not in the immediate study area.

Red Knots typically forage for horseshoe crab eggs during the low, rising, and falling tides. The horseshoe crab eggs become unavailable at high tide and the foraging area decreases, causing the majority of birds to be displaced (Figure 4). Most birds find a roosting area during high tide because they are unable to feed, and in most cases, one high tide is during the daytime and the other during the nighttime.

Roosting Site Locations and Habitat Characteristics

The study area is composed of three habitat types: inland, exposed shoreline, and shoreline (Figure 4; Figure 5). Inland habitats consist of pockets of water surrounded by marsh vegetation. Exposed shoreline habitats ("wash-over" areas) consist mostly of flat areas of sand at the highest point of the shoreline which are never covered by high tide. Shoreline habitats consist of sand, mud, or rocks where the water meets the shore.

In both 2008 and 2009, I observed more birds in shoreline habitat than exposed shoreline and inland habitat (2008: 2, 18 N=125; adjusted F=7.180; x^2=25.552; p=0.005) (2009: 2, 18 N=132; adjusted F=15.427; x^2=21.273; p< 0.001) (Table 1), consistent with the importance of foraging to build up fat reserves.

I ranked known and potential roost locations for each habitat type (inland, exposed shoreline, and shoreline) by frequency of use for 2008 and 2009 (Table 2). Each year was ranked separately; however, the environmental characteristics for each habitat type were the same for both years.

The environmental characteristics of the most frequently used **inland** habitat were: an area of ≤ 50,215 m^2, silt substrate, ≤ 7.62 cm water depth, *S. alterniflora* vegetation surrounding the boundary, and an 850 meter flight distance to feeding areas. The environmental characteristics of the most frequently used **exposed shoreline** habitat were: an area of ≤ 15,000 m^2, sand substrate, 0.0 cm water depth, *S. alterniflora* vegetation surrounding the boundary. The environmental characteristics of the most frequently used **shoreline** habitat were: an area of ≥ 57,000 m^2, sand substrate, 0.0 cm water depth, *S. alterniflora Phragmites spp.* vegetation surrounding the boundary as well as no surrounding vegetation, and 0.0 meter flight distance to feeding areas.

The most frequented inland habitats were small, shallow pockets of water located in Milford Neck Wildlife Management Area, in both 2008 and 2009 (Figure 6). In contrast, the St. Jones Reserve (north of Mispillion Harbor) consists of large, mostly shallow (≤ 7.62 cm) water impoundments. While this area seems ideal for roosting purposes and is consistently used by several other shorebird species during the northbound migration, but is rarely used by Red Knots (pers. obsv.). Some birds reused roosting sites each year. In 2008, 20% of radio-tagged birds for which data were collected returned to the same high tide roost site on two or more occasions. In 2009, 33% of radio-tagged birds for which data were collected returned to the same high tide roost site on two or more occasions. See Figures 7 through 13 for Red Knot high and low tide locations during 2008 and 2009.

In 2009, the use of shoreline habitat peaked during neap tides (average tide heights), which corresponds to the first quarter, half, and three-quarter moon phase (Figure 14). The frequency of inland habitat use increased and shoreline use decreased during a spring tide (higher than average high tide height and lower than average low tide height), which corresponds with a new and full moon. The overall decrease in use of all habitat types in the study area after day 148 was due to the departure of Red Knots during days 148 and 149 (Figure 14).

The pattern was shown to be statistically significant for 2009 but not for 2008. For this analysis, only high tide data were used (Figure 15). During high tides in 2008, there was a significant preference for shoreline over inland habitat during spring tide events (1,4 N = 31, adjusted F= 170.551, x^2=11.645, p<0.001)(Figure 15), however, there was no difference in habitat preference during non-spring tide events (1,4 N = 24, adjusted F= 4.215, x^2=6.00, p=0.109)(Figure 15). During high tides in 2009, there was a significant overall preference for shoreline over inland habitat during both spring and neap tide events (spring tides: 1,7 N = 47, adjusted F= 6.948, x^2=3.596, p=0.034; non-spring tides: 1,11 N = 55, adjusted F= 19.488, x^2=30.564, p=0.001)(Figure 15). Logistic regression was used to determine if habitat type at roost sites (inland and shoreline) could be predicted based on a spring tide event. In 2008, preference for habitat type did not differ during a spring tide event compared to a neap tide event (β=0.329, *SE* β=0.5149, p=0.523)(Figure 15). However, in 2009 preference for shoreline habitat was significantly less during a spring tide event compared to a neap tide event (β=-1.357, *SE* β=0.6187, p=0.028)(Figure 15).

Thus, birds spend most of their time in shoreline habitat, but during a spring high tide a larger proportion spent more time at inland sites. The pattern of inland roost site use was the same for both years: small (~ 3,000 m^2 – 50,000 m^2) areas were used more than large (~ 100,000 m^2 – 285,000 m^2) areas; shallow (≤ 7.62 cm of water) areas were used more than deep (≥ 15.24 cm of water); flight distance to feeding ranged from 850 m – 2,050 m. Negative binomial regression was used to determine if site use could be predicted by habitat characteristics (area, water depth, and flight distance to feeding). However, none of these were significantly correlated with site use. There is the potential for differences but the sample size was too small to predict site use based on aforementioned habitat characteristics.

Habitat Preference based on Day and Night

In 2008 and 2009, there were significantly more daytime observations than nighttime observations (2008: 1,9 N=125; adjusted F=9.819; x^2=22.472; p=0.016) (2009: 1,11 N=132; adjusted F=82.578; x^2=46.091; p<0.001) (Table 1)(Figure 16). Sampling intensity was the same for day and night in both seasons. In practice, the majority of birds were foraging and/or roosting in Delaware during the day, then leaving the study area at night. The few birds that were in the study area at night left and/or arrived in the study area as well as moved their location within the study area; only one bird stayed in one location throughout the entire nighttime hours.

The use of inland, exposed shoreline, and shoreline habitat by Red Knots differed during daytime and nighttime high tide in 2009, but not in 2008. Birds preferred shoreline habitat during the daytime high tide, but during the nighttime high tide birds preferred inland habitat (2009: 2, 20 N=102; adjusted F=10.433; x^2=21.864; p=0.001) (2008: 2, 7 N=55; adjusted F=3.908; x^2=7.343; p=0.087) (Table 3).

Tidal Habitat Preference

In 2008, there was no difference in the proportion of observations of birds at high tide and low tide (1, 9 N=125; adjusted F=2.01; x^2=1.80; p=0.190) (Table 1). In 2009, there were significantly more birds observed at high tide than low tide (1, 11 N=132; adjusted F=189.278; x^2=39.273; p<0.001) (Table 1).

The fewer observations during low tide in 2009 could possibly be explained by the receiver failure in a critical foraging area with high food density. Also, 2008 was a flood year and extreme weather events (including increased wave action) in early May washed away the majority of horseshoe crab eggs on the beaches. The Mispillion Harbor beaches (where stationary receiver MH was located) are sheltered from the increased wave action; they were the only location along the Delaware shoreline with eggs until horseshoe crab spawning resumed and egg density built up again. Therefore, in 2009, the birds might not have been as concentrated during low tide in Mispillion Harbor, another possibility accounting for the decrease in observations.

In 2008, there was no difference in habitat type preference at high versus low tide (1, 13 N=125; adjusted F=1.334; x^2=2.161; p=0.285) (Table 3). However, in 2009, habitat type preference did differ significantly with tide. In 2009, birds preferred inland habitat during high tide, but during low tide they preferred some type of shoreline habitat (2, 18 N=132; adjusted F=5.444; x^2=6.323; p=0.018) (Table 3).

DISCUSSION

The Red Knots on which I am reporting on are unique because Delaware Bay is the only area in which this subspecies has been observed roosting inland. Where they spend their time differs with season, tide, and time of day. During daytime neap high tides (average tide heights), birds were observed in shoreline habitat. During nighttime neap high tides, birds were observed in both shoreline and inland habitat, but a majority remained in shoreline habitat. During daytime spring high tides (i.e. higher than average tide heights that flood most of the shoreline), birds were observed in both shoreline and inland habitats, but on nighttime spring high tides, birds were observed only in inland habitat.

Roosting Site Locations and Habitat Characteristics

For the majority of time, Red Knots roosted on some type of shoreline habitat (exposed shoreline and shoreline characterized by sandy areas surrounded by short vegetation), but during some conditions, such as a spring high tide, they moved inland to roost, at small shallow pockets of water located from 850 to 2,050 meters (direct flight distance) from foraging areas.

It is known that roost site selection differs among species of shorebirds as well as, among individuals within species (Peters and Otis 2007). Most birds used different roost sites each day but two individuals or 20% in 2008 and six individuals or 33% in 2009 reused roost sites twice or more. Previous studies have also indicated site fidelity (Gils and Piersma 1999; Leyrer et al 2006) by Red Knots, varying by season and region (Peters and Otis 2007).

In this study, roost site selection by Red Knots varied from year to year. Some inland roost sites were used in both years but in each year additional sites were used. The year to year differences reflect the dynamic nature of the ecological system within which Red Knots roost. As a result, roosting habitat is constantly changing. For example, there is shoreline loss due to erosion caused by extreme weather events as well as the creation of "wash-over" areas. The change of the inland roosting habitat is caused in part by over-wintering snow geese population density and behavior. Because the system is constantly changing, continuous management for roosting habitat, on the shoreline as well as inland, is extremely important to help decrease the birds' energy costs.

Habitat Preference based on Day and Night

There are few data on the nighttime behavior of Red Knots. Where are the birds going at night? Are the birds foraging at night as well as during the day? In the past, large flocks of Red Knots have been observed by researchers crossing the bay around sunset ("commuter flights")(Harrington 1996) to the Atlantic coast of New Jersey, to roost during the night in the numerous salt marshes (Harrington 1996) and on sand jetties in Stone Harbor (pers. comm. K. Kalasz).

In Delaware Bay, radio telemetry data indicate birds entering and leaving as well as changing their location within the study area during the night. Changing roosting sites is not energetically efficient for birds trying to maximize fat reserves in a short amount of time, which has selective advantages. The mobile nighttime behavior could be due to predation (e.g. red fox, *Vulpes vulpes*) or the need to forage when possible. Predator abundance was not measured in this study; however red fox were seen and feces and footprints were observed in the study area on a daily basis.

Although many Red Knots moved inland at night to roost, foraging for eggs would not be precluded during the night. The majority of the horseshoe crab eggs that Red Knots consume are located at the sand surface and Red Knots find their prey using tactile stimuli (Piersma et al 1995, 1998) and hence do not require light for finding their food (Gils and

Piersma 1999). Given the importance of adding sufficient mass in a short time to subsequent survival, some individuals could be expected to forage at night during low, rising, or falling tides depending on food density, time of arrival, or condition of the bird. This is an area in which future studies of the stopover ecology of Red Knots in Delaware Bay could lead to improved management of the species.

The use of different day-night roost sites varies among sub-species and locations. My study shows that a proportion of Red Knots in Delaware Bay roost inland and roost choice differs between day and night. As also found for this sub-species on its' wintering grounds in Tierra del Fuego (Sitters et al 2001). Similarly, *C. calidris piersmai* in Australia (Rogers et al 2006) show different roost site choice during the day and night. In contrast, *C. calidris canutus* in Mauritania (Leyrer et al 2006; Piersma et al 1993a) and *C. calidris islandica* in The Netherlands (van Gils and Piersma 1999) show no differences in day-night roost sites.

Recommendations

Red Knots spend most of their time in the shoreline habitat during the day. However, the availability of shoreline roost sites becomes limiting during spring high tides making much of the shoreline inaccessible for roosting. Therefore, suitable inland roosting habitat is essential at these times, especially during low food density years when there is additional stress of finding enough food to build up fat reserves.

The creation of a universal roost site management plan that spans all jurisdictional boundaries along the shoreline of Kent and Sussex counties is needed. I recommend that local resource managers restore and monitor the existing impoundments to benefit shorebirds, during their northbound migration, by adjusting the water levels to control pool size and also manage the surrounding vegetation of the impoundments. The impoundments could be drained: 1) a few days prior to a spring tide event, the effects of which last for three nights, to create suitable inland roosting habitat; 2) after a significant rain event to decrease water levels of the inland wetland habitat. In some areas it might also be possible to build exposed sites to provide shoreline habitat above the spring high tide water line. Such habitat would be closer to foraging sites, facilitating birds returning to night-feeding as the spring high tide receded, and in areas where there is little cover for red fox. In addition, conservation efforts should be focused on purchasing or protecting shoreline and inland estuarine impoundment habitat adjacent to the Delaware Bay shoreline, for the creation of shorebird roosting sites.

REFERENCES

Atkinson, P., Baker, A., Bennett, K., Clark, N., Clark, J., Cole, K., Dekinga, A., Dey, A., Gillings, S., Gonzalez, P., Kalasz, K., Minton, C., Newton, J., Niles, L., Piersma, T., Robinson, R., and Sitters, H. 2007. Rates of mass gain and energy deposition in red knot on their final spring staging site is both time- and condition-dependent. Jo of Applied Ecology 44:885-895.

Baker, A. J., González, P., Piersma, T., Niles, L., do Nascimento, I., Atkinson, P., Clark, N., Minton, C., Peck, M., and Aarts, G. 2004. Rapid population decline in red knot: fitness consequences of decreased refueling rates and late arrival in Delaware Bay. Proceedings of the Royal Society B 25:125-129.

Botton, M., Loveland, R., and Jacobson, T. 1994. Site Selection by Migratory Shorebirds in Delaware Bay, and its Relationship to Beach Characteristics and Abundance of Horseshoe Crab (*Limulus polyphemus*) eggs. The Auk 111(3):605-616.

Castro, G. and Myers, J.P. 1993. Shorebird Predation on Eggs of Horseshoe Crab during Spring Stopover on Delaware Bay. The Auk 110(4):927-930

Gill, J.A., Norris, K. and Sutherland, W.J. 2001. Why behavioural responses may not reflect the population consequences of human disturbance. Biological Conservation 20: 265-268.

Harrington, Brian. The Flight of the Red Knot. New York: W.W. Norton and Company, 1996. Print.

Hooker, B., Mangold, M., Michels, S., Spear, B. 2008. Review of the 2007 ASMFC Fishery Management Plan for Horseshoe Crab (*Limulus polyphemus*). Atlantic States Marine Fishery Commission, Washington D.C. 15pp.

Leyrer, J., Spaans, B., Camara, M., Piersma, T. 2006. Small home ranges and high site fidelity in red knots (*Calidris c. canutus*) wintering on the Banc d'Arguin, Mauritania. J Ornithol 147: 376–384.

Niles, L.J., Sitters, H.P., Dey, A.D., Atkinson, P.W., Baker, A.J., Bennett, K.A., Clark, K.E., Clark, N.A., Expoz, C., Gonzalez, P.M., Harrington, B.A., Hernandez, D.E., Kalasz, K.S., Matus, R., Minton, C.D., Morrison, R.I.G., Peck, M.K., Serrano, I.L. 2007. Status of the Red Knot (*Calidris canutus rufa*) in the Western Hemisphere. U.S. Fish and Wildlife Service Ecological Services, Region 5, Pleasantville, NJ.

Peters, K.A. and Otis, D.L. 2007. Shorebird roost-site selection at two temporal scales: is human disturbance a factor? Journal of Applied Ecology 44: 196-209.

Piersma, T., R. Hoekstra, A. Dekinga, A. Koolhaas, P. Wolf, P.Battley, and P. Wiersma. 1993a. Scale and intensity of intertidal habitat use by Knots *Calidris canutus* in the Western Wadden Sea in relation to food, friends and foes. Netherlands Jo of Sea Research 31(4):331-357.

Piersma, T., J. van Gils, P. de Goeij, and J. van der Meer. 1995. Holling's functional response model as a tool to link the food-finding mechanism of a probing shorebird with its spatial distribution. Journal of Animal Ecology 64:493–504.

Piersma T., van Aelst, R., Kurk, K., Berkhoudt, H., and Maas, L. 1998. A new pressure sensory mechanism for prey detection in birds: the use of principles of seabed dynamics? Proc. R. Soc. Lond. B 265: 1377-1383.

Roger, D.I. 2003. High-tide Roost Choice by Coastal Waders. Wader Study Group Bulletin 100:73-79.

Rogers, D.I., Battley, P.F., Piersma, T., Van Gils, J.A., and Rogers, K.G. 2006. High-tide habitat choice: insights from modeling roost selection by shorebirds around a tropical bay. Animal Behaviour 72: 563-575.

Tsipoura, N. and Burger, J. 1999. Shorebird diet during spring migration stopover on Delaware Bay. The Condor 101:635-644.

Sitters, H., Gonzalez, P., Piersma, T., Baker, A., and Price, D. 2001. Day and Night Feeding Habitat of Red Knots in Patagonia: Profitability versus Safety? J. Field Ornithol., 72(1):86–95.

Van Gils, J.A. 2006. Foraging in a tidally structured environment by Red Knots (*Calidris canutus*): ideal, but not free. Ecology 87(5): 1189-1202.

Van Gils, J. & Piersma, T . 1999. Day- and night-time movements of radio-marked Red Knots staging in the western Wadden Sea in July-August 1995. Wader Study Group Bull. 89:36-44.

Warnock, N. and Warnock, S. 1993. Attachment of radio-transmitters to sandpipers: review and methods. Wader Study Group Bull. 70:28-30.

Zar, Jarrold H. Biostatistical Analysis. 4th ed. New Jersey: Prentice Hall, 1999. Print.

Table 1. The use of inland, exposed shoreline, and shoreline habitat differed for 2008 and 2009 seasons, as well as for daytime and nighttime, and high tide and low tide. There were significantly more daytime registrations compared to nighttime registrations in both 2008 and 2009 ($p<0.05$; $p<0.001$); because birds spent more time in the area during the daytime. In both 2008 and 2009, there were significantly more registrations in shoreline habitat than exposed shoreline and inland ($p<0.05$; $p< 0.001$); because birds spent more time in shoreline habitat opposed to inland and exposed shoreline habitat.

	2008		2009	
	n (%)	p-value[a]	n (%)	p-value[a]
High Tide	55 (44.0)	0.190	102 (77.3)	<0.001
Low Tide	70 (56.0)		30 (22.7)	
Day	89 (71.2)	0.016	105 (79.5)	<0.001
Night	36 (28.8)		27 (20.5)	
Inland	25 (20.0)	0.005	26 (19.7)	<0.001
Exposed Shoreline	32 (25.6)		38 (28.8)	
Shoreline	68 (54.4)		68 (51.5)	

[a] p-value based on Rao-Scott adjusted F statistic, because, due to multiple observations per individual bird, I could not assume independence.

Table 2. All known and potential roost locations for each habitat type (inland, exposed shoreline, and shoreline) are ranked by frequency of use for 2008 and 2009. Although, each year was ranked separately, the outcome was the same for both years. These are the environmental characteristics of the most frequented habitat types. See text for further information.

Habitat Type	Area (m^2)	Substrate	Water Depth (cm)	Flight Distance to Feeding (m)	Surrounding Vegetation
Inland	≤ 50,215	Silt	≤ 7.62	850.0	*S. alterniflora*
Exposed Shoreline	≤ 15,500	Sand	0.00	0.0	*S. alterniflora*
Shoreline	≥ 57,000	Sand	0.00	0.0	*S. alterniflora; Phragmites spp.; none*

Table 3. The difference in birds' habitat preference based on tide was significant in 2009 (but not in 2008); birds preferred inland habitat during high tide, but during low tide they preferred some type of shoreline habitat (p=0.018). In 2009, birds preferred shoreline habitat during the daytime high tide, but at night high tide preferred inland habitat (p=0.001).

	2008				2009			
	Inland n (%)	Exposed Shoreline n (%)	Shoreline n (%)	p-value[a]	Inland n (%)	Exposed Shoreline n (%)	Shoreline n (%)	p-value[a]
High Tide	12(21.8)	17(30.9)	26 (47.3)	0.285	24(23.5)	31(30.4)	47(46.1)	0.018
Low Tide	13(18.6)	15(21.4)	42 (60.0)		2(6.7)	7(23.3)	21(70.0)	
Daytime High Tide	5 (12.8)	12 (30.8)	22 (56.4)	0.087	11(13.6)	27(33.3)	43(53.1)	0.001
Nighttime High Tide	7 (43.8)	5 (31.3)	4 (25.0)		13(61.9)	4(19.0)	4(19.0)	

[a] p-value based on Rao-Scott adjusted F statistic, because, due to multiple observations per individual bird, I could not assume independence.

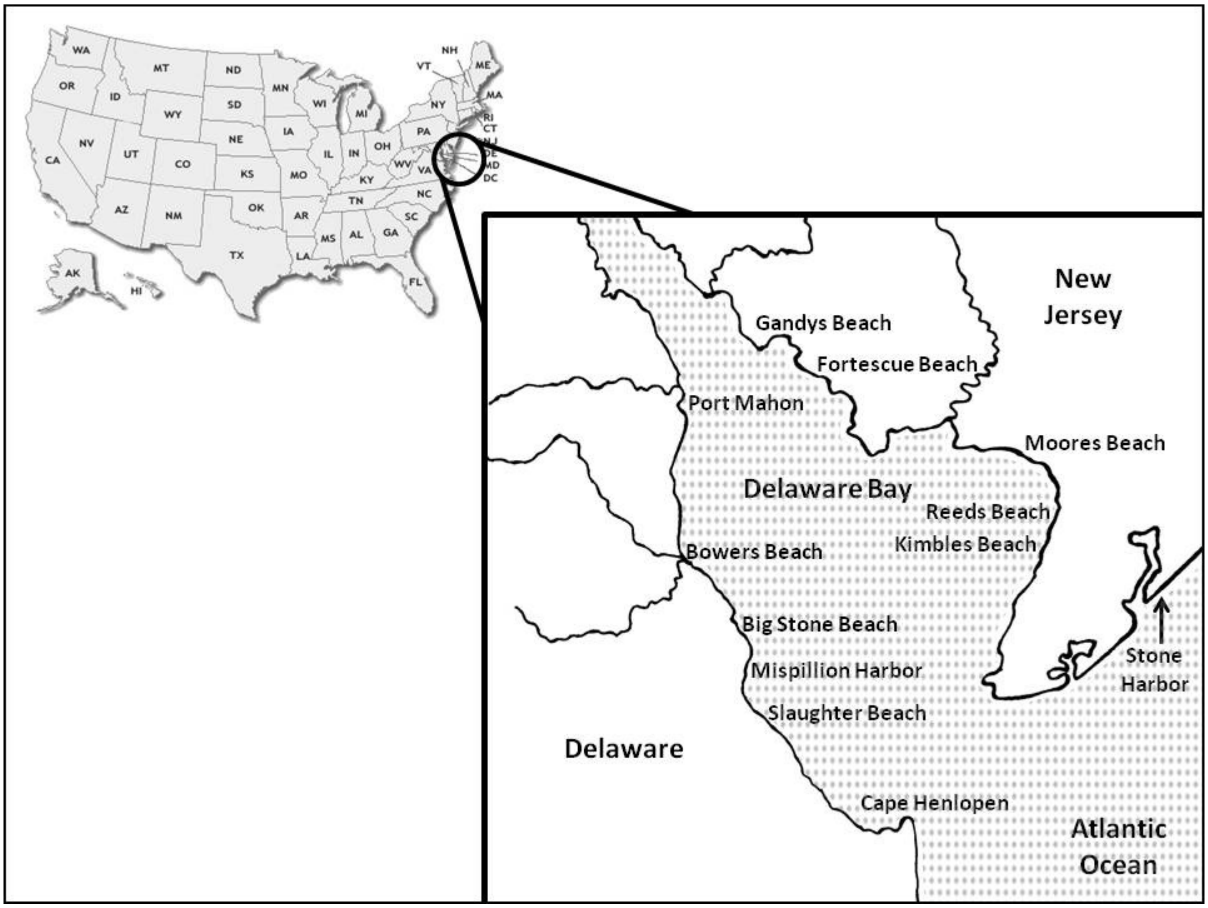

Figure 1. Delaware Bay serves as the Red Knots' final northbound migratory stopover site and the study location for my research during May and June 2008 and 2009.

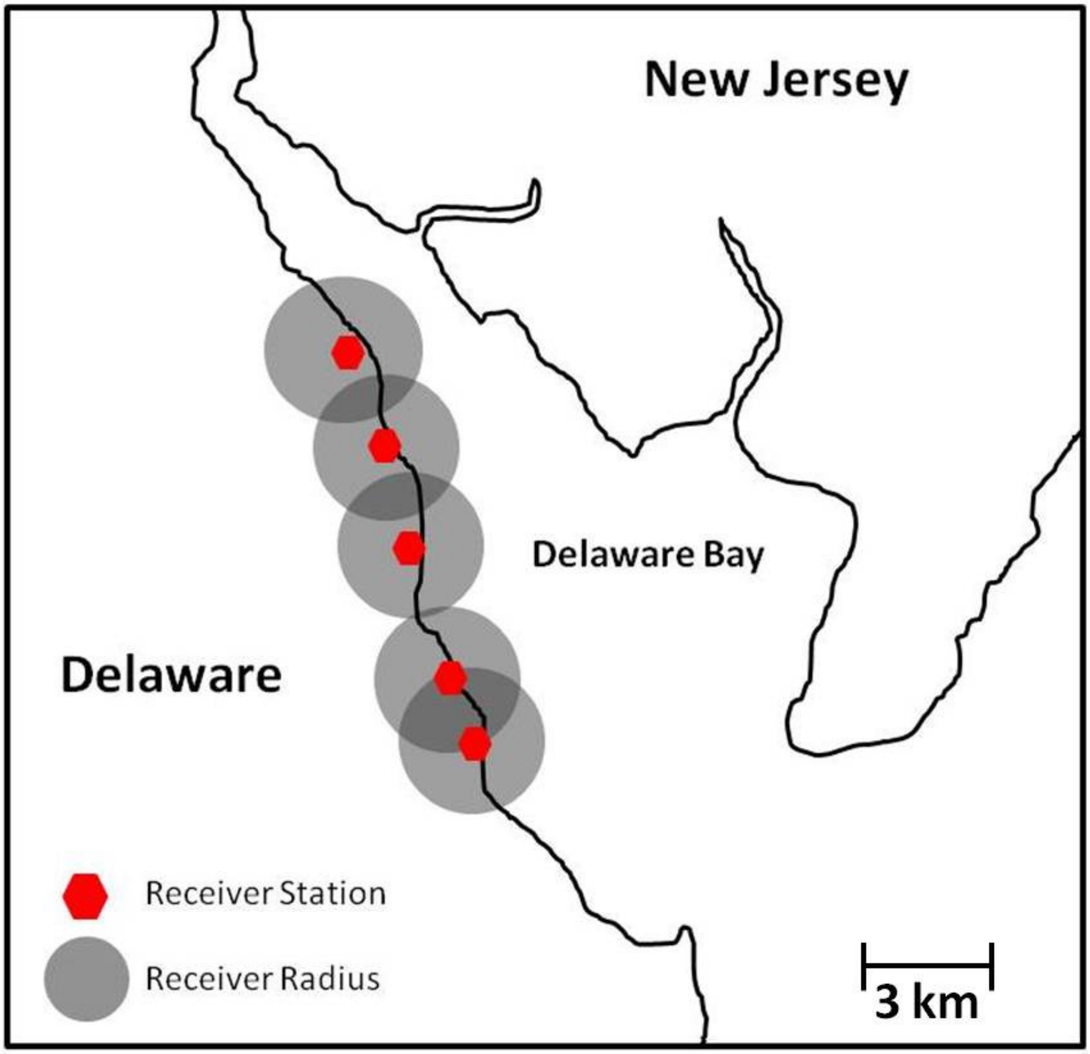

Figure 2. Map illustrating the location of the stationary receivers for 2008 and 2009. My study site was located in Kent and Sussex Counties, Delaware. Data were collected during May and June of 2008 and 2009.

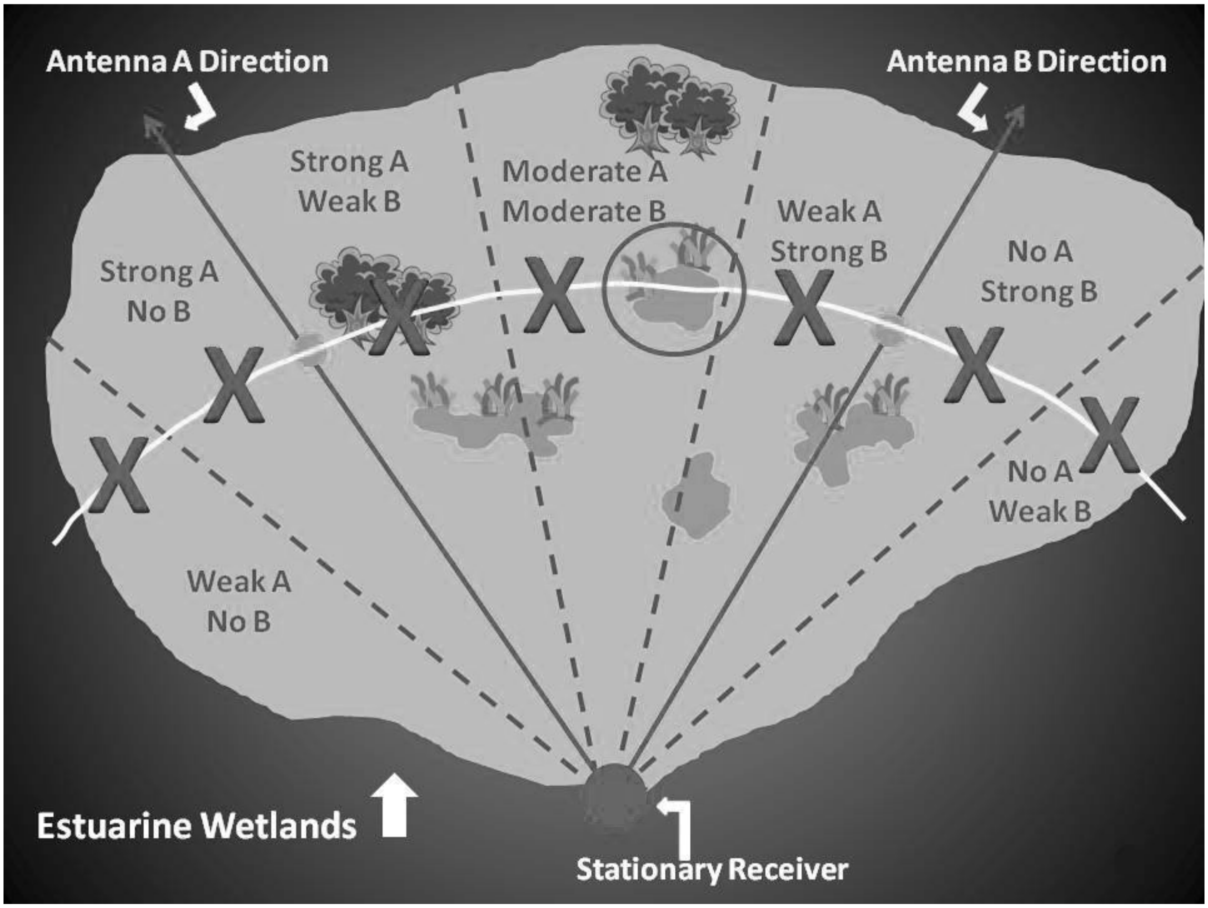

Figure 3. Diagram illustrating the use of stationary receivers to locate birds. Each of a pair of receivers has a maximum signal strength along the antenna direction (solid black line). Depending on the strength of the signal from each of the two antennas, birds can be located in one of seven sub-sectors delineated by arcs of position (dotted lines). In addition, calibration of signal strengths provided a calculated *line of position* (LOP) along which the bird was located. Further refinement of the birds' position used habitat avoidance (X) and preference (O). Note: diagram not to scale.

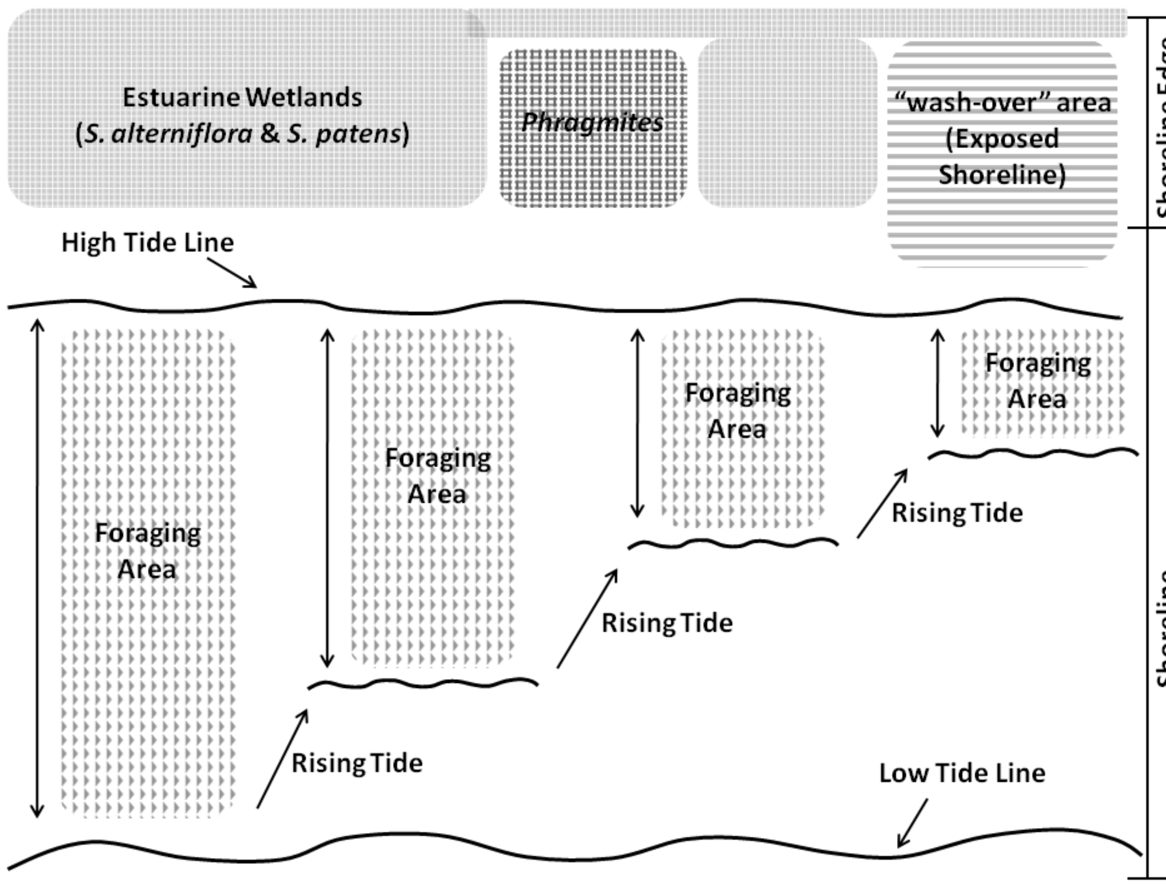

Figure 4. Aerial view of the shoreline and habitat types. Red Knots typically forage for horseshoe crab eggs during the low, rising, and falling tides. The horseshoe crab eggs become unavailable at high tide, and the foraging area decreases, causing the majority of birds to be displaced elsewhere.

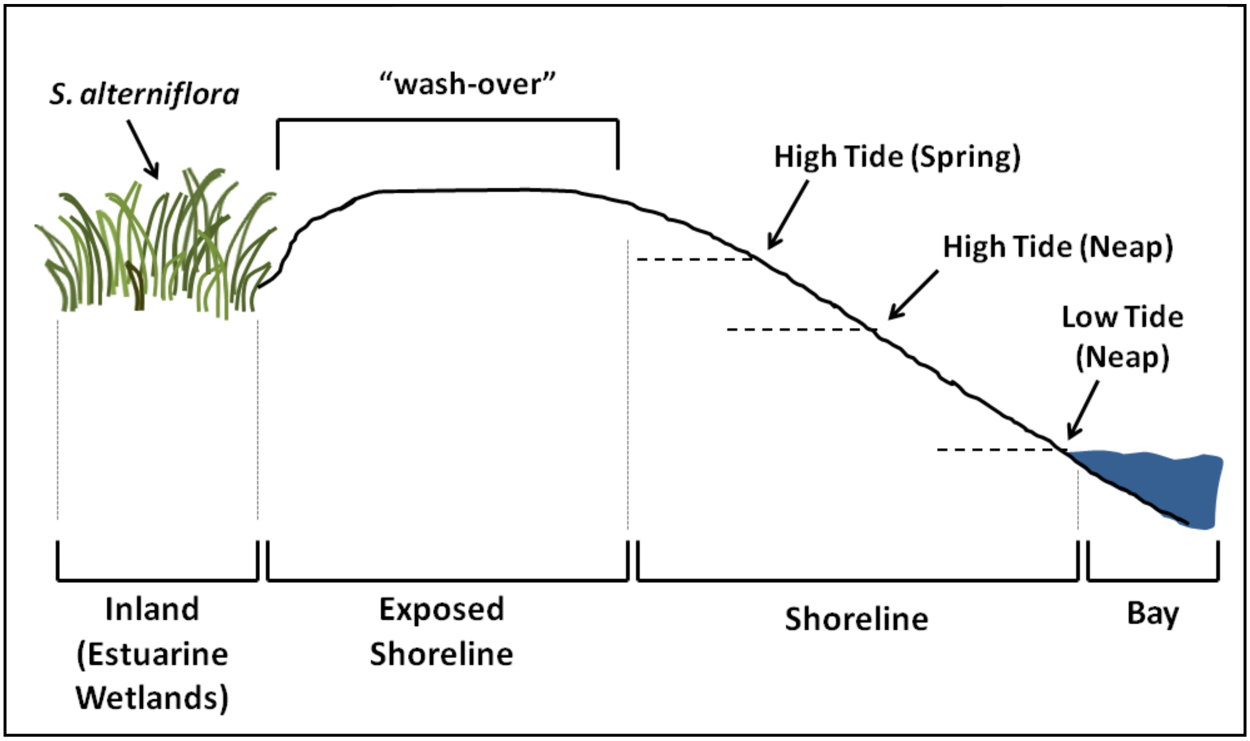

Figure 5. A cross-section view of the shoreline illustrating the differences in the exposed shoreline and shoreline habitat. Exposed shoreline habitats ("wash-over" areas) consist of mostly flat areas of sand at the highest point of the shoreline which are never covered by high tide. Shoreline habitats consist of sand, mud, or rocks where the water meets the shore.

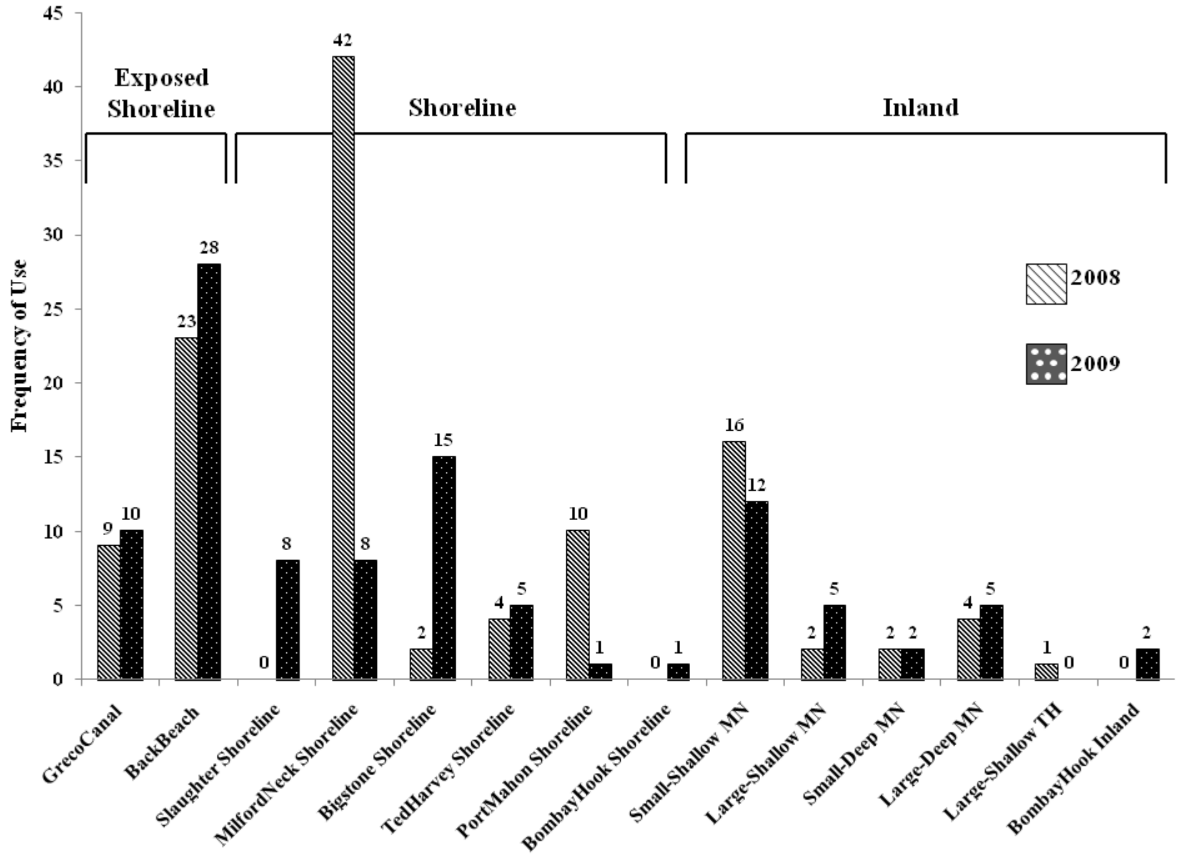

Figure 6. The pattern of use for exposed shoreline habitat was the same in both seasons. The Milford Neck (south end) and Bigstone (north end) shoreline are one long continuous shoreline. However, there is a political boundary in the middle, which is why there are two names that split one continuous shoreline into two separate sections. The decrease of Milford Neck shoreline use is attributed to the stationary receiver failure in 2009. The highest inland use was in small shallow Milford Neck areas. MN=Milford Neck; TH= Ted Harvey

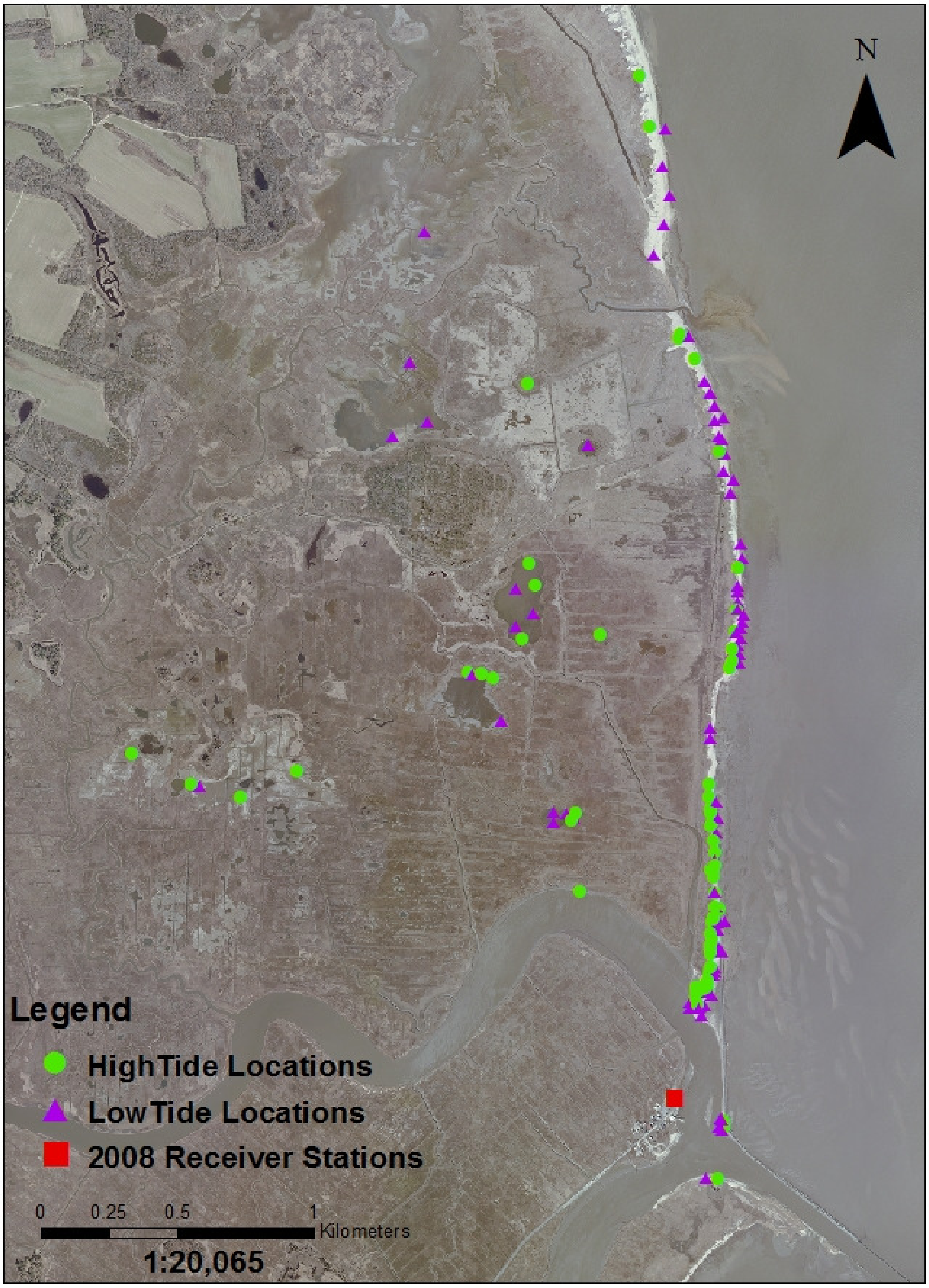

Figure 7. Map of high and low tide locations of Red Knots during 2008 in Mispillion Harbor, Milford Neck Wildlife Management Area, and Big Stone Beach.

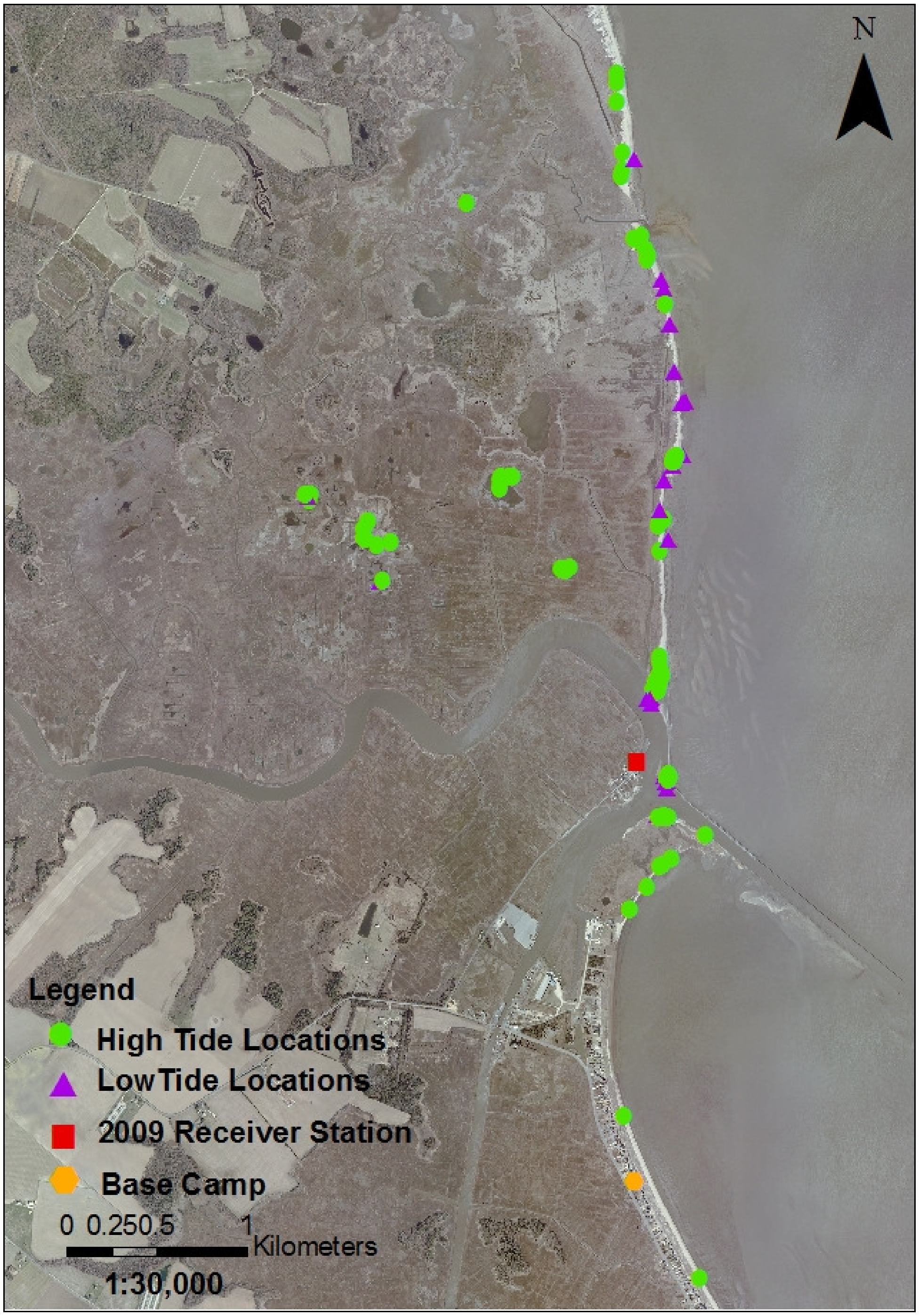

Figure 8. Map of high and low tide locations of Red Knots during 2009 in Slaughter Beach, Mispillion Harbor, Milford Neck Wildlife Management Area, and Big Stone Beach.

Figure 9. Map of high and low tide locations of Red Knots during 2008 in St. Jones Reserve and on Ted Harvey Beach.

Figure 10. Map of high and low tide locations of Red Knots during 2009 in St. Jones Reserve and on Ted Harvey Beach.

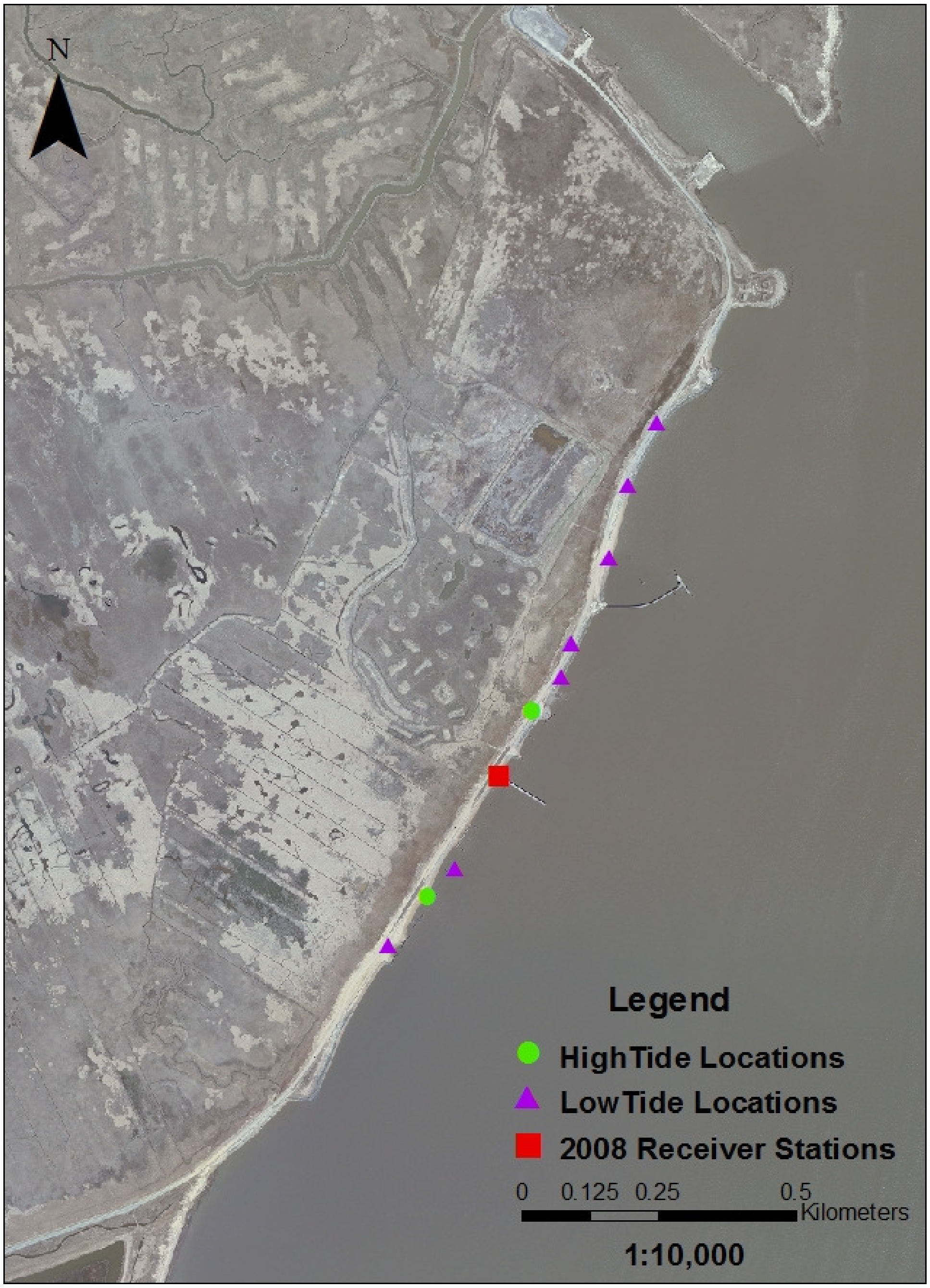

Figure 11. Map of high and low tide locations of Red Knots during 2008 in the Port Mahon area.

Figure 12. Map of high and low tide locations of Red Knots during 2009 in the Port Mahon area.

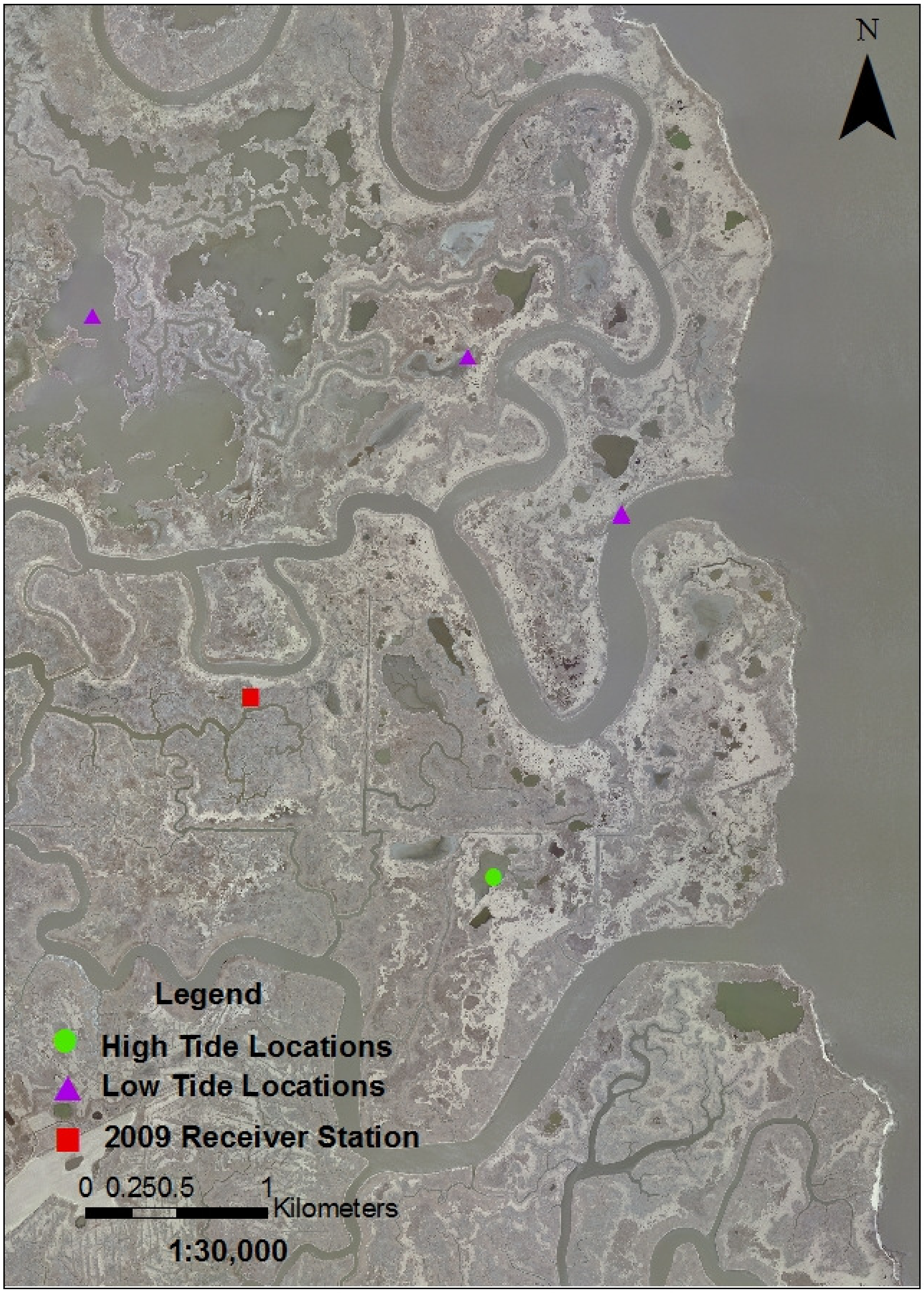

Figure 13. Map of high and low tide locations of Red Knots during 2009 in Bombay Hook National Wildlife Refuge.

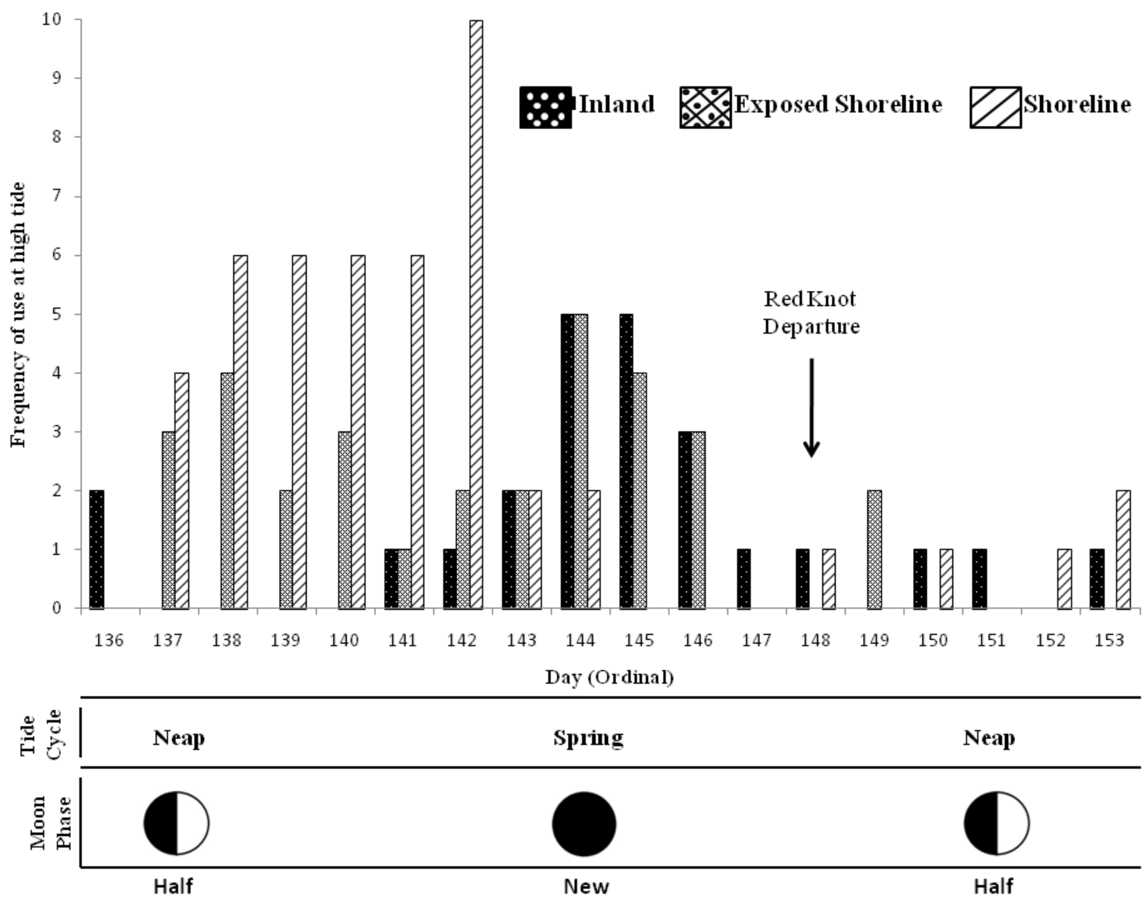

Figure 14. In 2009, the use of shoreline habitat peaked during the half moon phase, which corresponds with neap tide (average tide height) condition. The frequency of inland habitat use increased, and shoreline use decreased, as the new moon approached; this corresponds with a spring tide (higher than normal high tide height and lower than normal low tide height) event. The overall decrease in use of all habitat types in the study area after day 148 is due to the departure of Red Knots during days 148 and 149. The stopover duration of radio-tagged birds was not long enough to go through a full lunar cycle.

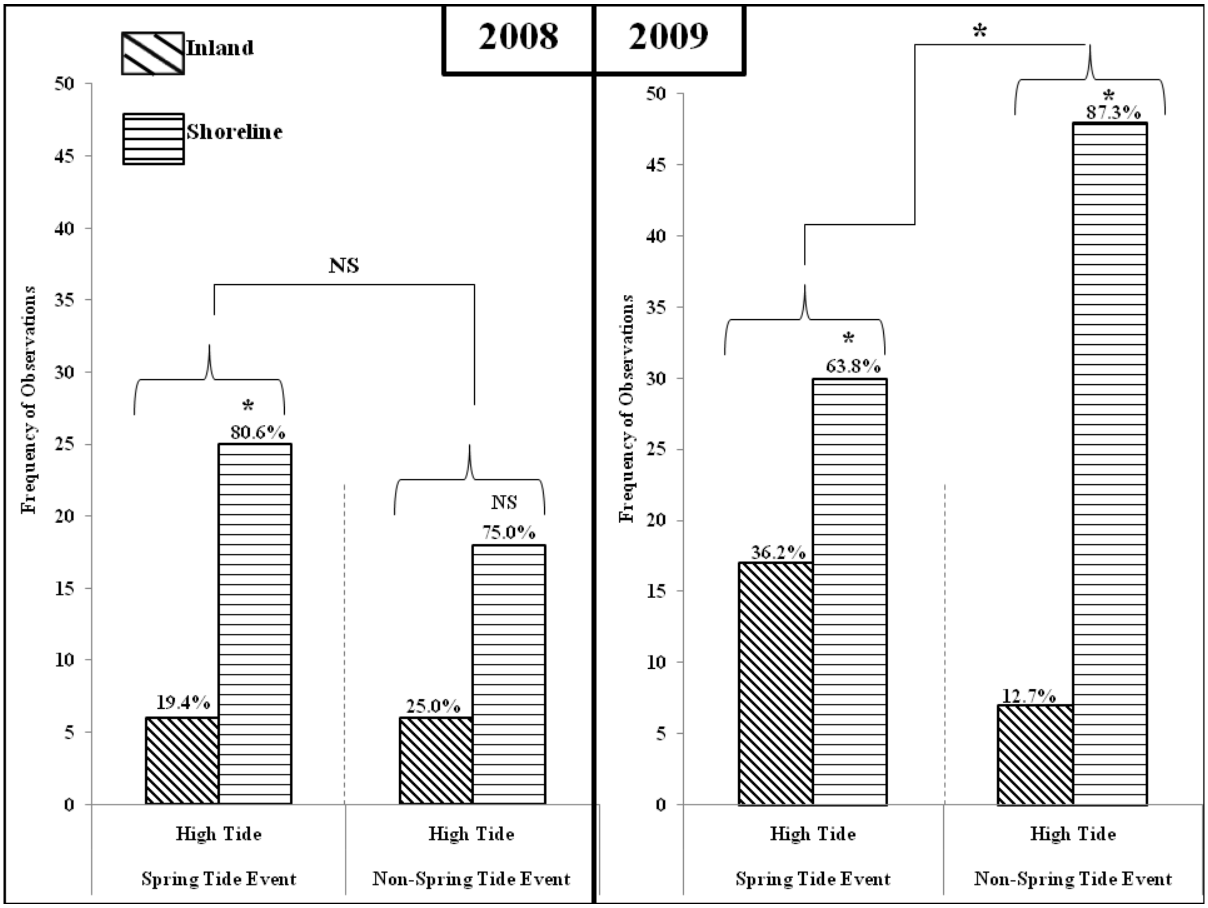

Figure 15. Overall, there were more observations in shoreline habitat compared to inland habitat in both 2008 and 2009, regardless of a spring tide event. During high tides in 2008, there was a significant preference for shoreline over inland habitat during spring tide events (1,4 N = 31, adjusted F= 170.551, x^2=11.645, p<0.001), however, there was no difference in habitat preference during non-spring tide events (1,4 N = 24, adjusted F= 4.215, x^2=6.00, p=0.109). During high tides in 2009, there was a significant overall preference for shoreline over inland habitat during both spring and non-spring tide events (spring tides:1,7 N = 47, adjusted F= 6.948, x^2=3.596, p=0.034; non-spring tides: 1,11 N = 55, adjusted F= 19.488, x^2=30.564, p=0.001). Logistic regression was used to determine if habitat type (inland and shoreline) could be predicted based on a spring tide event. In 2008, preference for habitat type did not differ during a spring tide event compared to a non-spring tide event (β=0.329, *SE* β=0.5149, p=0.523). However, in 2009 preference for shoreline habitat was significantly less during a spring tide event compared to a non-spring tide event (β=-1.357, *SE* β=0.6187, p=0.028).

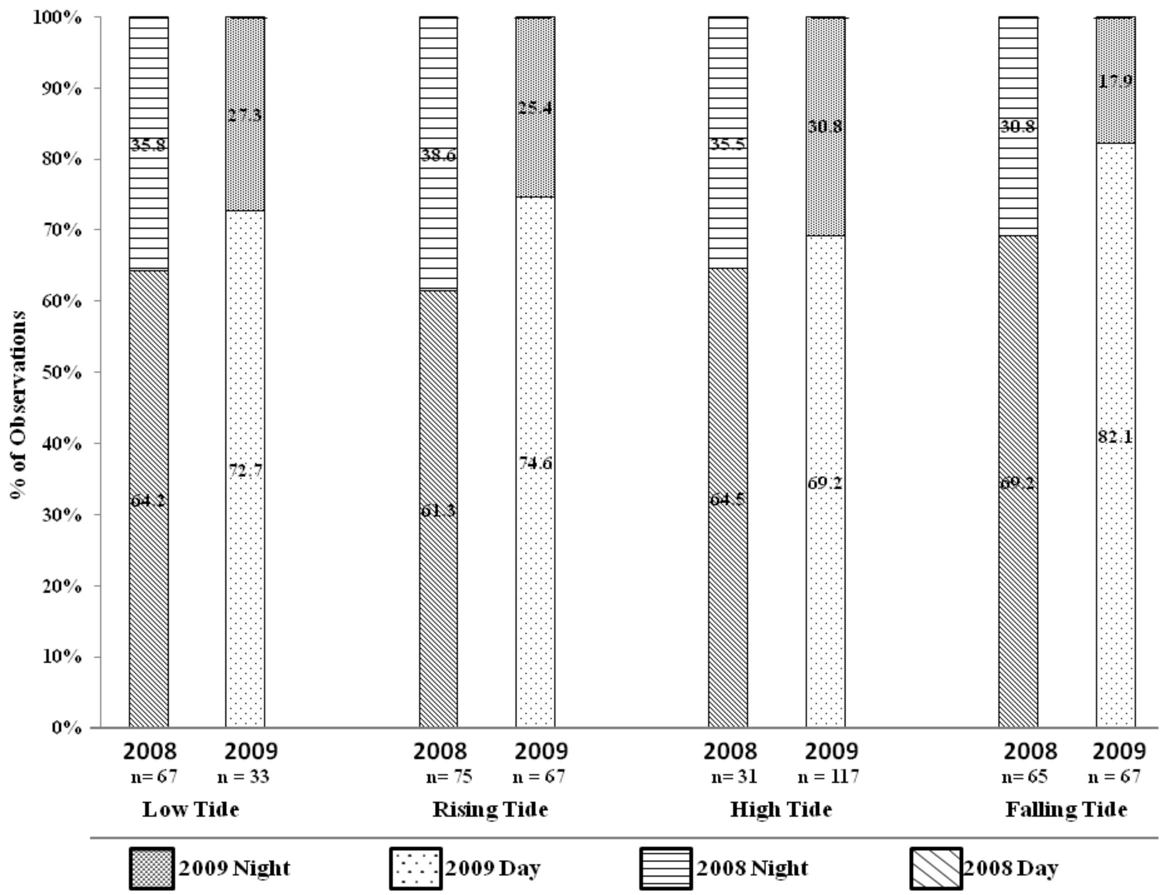

Figure 16. The same pattern of use for daytime and nighttime was seen for each tide cycle, in both 2008 and 2009. There was a slightly higher percentage of daytime use in 2009 compared to 2008. In 2008 and 2009, there were significantly more daytime observations than nighttime observations (2008: $p=0.016$; 1,9 $N=125$; $x^2=22.472$; adjusted $F=9.819$) (2009: $p<0.001$; 1,11 $N=132$; $x^2=46.091$; adjusted $F=82.578$).