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Effects of Extreme Tidal Events on Semipalmated Sandpiper (*Calidris pusilla*) Migratory Stopover in the Bay of Fundy, Canada

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Abstract.—The objective of this study was to determine the implications of extreme tidal events on duration of stay and behavior of Semipalmated Sandpipers (*Calidris pusilla*) during migratory stopover in Cobequid Bay, Nova Scotia. This area is part of the Bay of Fundy and experiences the largest tidal range in the world. Radiotelemetry was used to monitor duration of stay of 30 adult and seven juvenile Semipalmated Sandpipers. Adults arriving in Cobequid Bay early in the migration period experienced a greater number of extreme high tides (> 15 m) that submerged preferred roost sites, and stayed on average 8.1 days longer than those that arrived later. Juvenile duration of stay was not significantly different from adults. When tides exceeded 15 m, Semipalmated Sandpipers engaged in over ocean flocking at high tide; however, this behavior was not observed when high tides were 13.6 m or less. These extra flights led to higher energy expenditure by early migrants, requiring an estimated 3.8 to 4.3-day increase in length of stay to reach the same mass as later migrants. In the future, predicted sea level rise could increase the frequency of extreme tidal amplitudes and result in greater energetic costs during Semipalmated Sandpiper stopover.
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Key words.—Bay of Fundy, *Calidris pusilla*, Cobequid Bay, migration, over ocean flocking, roosting, Semipalmated Sandpiper, stopover, tides.

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In coastal areas, shorebird habitat choice is intrinsically linked to tidal levels. Distribution and abundance varies over a tidal cycle as shorebirds generally forage on beaches, marshes and mudflats during low tide and roost at high tide when these habitats are submerged (Burger *et al.* 1977, 1997; Rogers *et al.* 2006; Sprague *et al.* 2008). For long distance migrants, it is important that stopover sites offer predictable, abundant food sources and relative safety so sufficient mass can be gained for migration (Warnock 2010). However, predicted global sea level rise in the range of 0.18 m to 1.80 m (Meehl *et al.* 2007; Nicholls and Cazenave 2010) through the 21st century is likely to threaten the availability of these critically important shorebird habitats (Galbraith *et al.* 2002; Seavey *et al.* 2011). Tidal amplitude will increase, and though this may result in the formation of new shorebird habitat (Austin and Rehfisch 2003), in areas where humans protect shorelines with dykes or break walls, intertidal areas are expected to decrease (Galbraith *et al.* 2002; Dugan *et al.* 2008).

One way to examine potential future effects of sea level rise on shorebirds is to look at their response during extreme tidal events on perigee moons, when the moon is at its closest point to Earth. In 2014, particularly extreme tides occurred in July, August and September as a result of the perigee moon combined with the syzygy, or alignment, of the Earth-Moon-Sun interface. The Bay of Fundy, Canada, is an ideal place to study this phenomenon because it is home to the most extreme tides in the world (O'Reilly *et al.* 2005) and hosts 50% or more of the world population of Semipalmated Sandpipers (*Calidris pusilla*; Mawhinney *et al.* 1993) during their fall migration from Arctic breeding grounds to South America. Furthermore, it is expected to experience greater sea level rise than the global average (Greenberg *et al.* 2012). Semipalmated Sandpipers are a bird of particular interest because from the 1970s through the late 1990s, significant declines in this species were noted across much of its range (Morrison *et al.* 1994, 2012; Gratto-Trevor *et al.* 2012; Smith *et al.* 2012), and based on survey data, this trend was clearly supported within the Bay of Fundy (Morrison *et al.* 2001).

Semipalmated Sandpipers in the Bay of Fundy routinely forage on invertebrate-rich mudflats during low tides and roost during high tides on sand and cobble beaches (Hicklin 1987; Sprague *et al.* 2008; Neima 2017). However, there have been instances where alternative behaviors were observed around high tide. Both the use of nontraditional roost sites (MacKinnon *et al.* 2008) and alternative behaviors such as extended periods of flight have been noted (Dekker *et al.* 2011). Such flight around high tide is termed "over ocean flocking" and is different from regular directional or predator avoidance flights in that it involves the use of air currents to remain airborne and thus requires less energy than regular flight (Dekker 1998; Ydenberg *et al.* 2010). Over ocean flocking is thought to reduce vulnerability to predators; it has been noted to be a direct response to predation events (Dekker and Ydenberg 2004; Dekker *et al.* 2011), as well as to limited availability of safe roosting options during high tide (Hötker 2000; Dekker *et al.* 2011).

The objectives of this study were to: 1) determine the effect of tidal extremes on Semipalmated Sandpiper activity around high tide; and 2) determine the implications of over ocean flocking for stopover duration for both juveniles and adults.

METHODS

Study Area

This study was conducted in Cobequid Bay, Nova Scotia, Canada (Fig. 1), one of the innermost terminals of the Bay of Fundy. In both 2013 and 2014, Cobequid Bay hosted approximately 20% of all Semipalmated Sandpipers counted in the Bay of Fundy - over 58,000 birds in 2014 (Bliss 2015). The Bay of Fundy, specifically Cobequid Bay, experiences the largest tidal amplitude in the world, in excess of 16 m (O'Reilly *et al.* 2005). Cobequid Bay is a very dynamic landscape, with constant changes to sedimentation patterns and the extent of salt marsh habitat as a result of human activities and natural forces (Baker and van Proosdij 2004). Around Cobequid Bay, there is an extensive series of provincially managed dykes and other shoreline protection features that protect over 2,000 ha of marshes and agricultural lands, as well as houses and other anthropogenic features (Robinson *et al.* 2004).

Capture and Tracking

Using mist nets, we captured Semipalmated Sandpipers at Fort Belcher, Nova Scotia, Canada (45° 21′ 39.60″ N, 63° 24′ 36.00″ W) (Fig. 1) during two periods in August 2014. The first group, which we referred to as early migrants because they were captured prior to the migratory peak, was captured on 9 August. The second group, termed late migrants, was obtained on 19-21 August. The migratory peak in 2014 occurred on approximately 11 August (based on aerial surveys; J. Paquet, unpubl. data). Captured birds were immediately removed

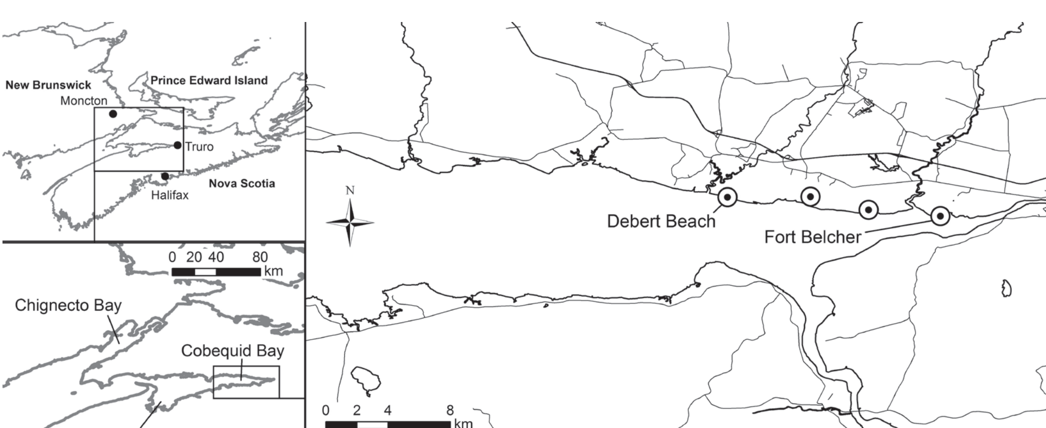

Figure 1. Radio telemetry receiver locations in Cobequid Bay, Nova Scotia. Each bullseye represents the site of a radio telemetry receiver. Inset maps show the location of the study area with Maritime Canada, and the location of Cobequid Bay relative to other segments of the Bay of Fundy.

from nets. We then measured flattened, straightened wing cord, and obtained mass to the nearest 0.1 g using an electronic balance. A total of 37 birds caught at Fort Belcher were affixed with uniquely coded radio transmitters (0.35 g; NTQB-2 Lotek Wireless Inc.), including 15 adults in the early capture period, and 15 adults and 7 juveniles in the late capture period. Juveniles migrate later in the season than adults (Morrison 1984), and thus were not present during the earlier capture period. We only attached transmitters to light birds (< 30.0 g) to ensure that tagged birds in both capture groups were recent arrivals and therefore would be able to be tracked during the majority of their stay in the region. Each transmitter had a burst rate of 6 sec and an expected battery life of 38 days. To attach the transmitter, we clipped the contour feathers just above the uropygial gland and used cyanoacrylate glue to secure the device (Sprague *et al.* 2008).

We tracked the Semipalmated Sandpipers using a stationary array of four towers located around Cobequid Bay: one at Fort Belcher, one at Debert Beach (45° 22′ 30.00″ N, 63° 32′ 2.40″ W), and two located between these sites (Cobequid 2: 45° 22′ 26.40″ N, 63° 31′ 40.80″ W, and Cobequid 3: 45° 22′ 26.40″ N, 63° 28′ 48.00″ W) (see Fig. 1 for tower locations). Each of these towers had two nine-element Yagi antennas positioned horizontally on a mast at least 6 m high and separated by 68° to 120° for maximum coverage of the bay. The antennas had a detection range of approximately 15 km (Taylor *et al.* 2011; Mitchell *et al.* 2015) and were attached to an automated receiver (Motus Wildlife Tracking System) at the base of each tower, which recorded tag identity, time, signal strength and tower location whenever a transmitter's radio pulse was detected. The towers were functional between 4 August 2014 and 9 October 2014; the end date was at least 3 weeks after the final detection of any radio-tagged bird in Cobequid Bay. We supplemented these towers with aerial tracking on 11 days between 16 August 2014 and 11 September 2014. A Lotek SRX 600 receiver (Lotek Wireless Inc.) was connected to two wing-mounted, H-style antennas on a Cesna 172 fixed wing airplane, then a survey was flown at 90-150 m elevation around the entire coast of Cobequid Bay.

High Tide Observations

We monitored the prevalence of roosting and over ocean flocking at Fort Belcher and Debert Beach (Fig. 1), which are both common roosting sites, in two periods: one following the first round of tagging (11-14 August 2014) and one following the second tagging period (22-27 August 2014). The first observation round was during a period of extremely high tidal fluctuation (high tides > 15 m), whereas the later period covered days with more moderate tides (high tide ≤ 13.6 m). All tide height data were obtained from Fisheries and Oceans Canada (2014) for Burntcoat Head, located 20-30 km from our receiver stations. We began each observation period at least 1 hr before high tide and continued for 3.75-5.00 hr, until the tide receded to the point that roosting birds spread out and started to forage or move away from the site. Due to the tidal cycle on those days, we completed all observations between 10:30 hr and 19:00 hr. During the observation periods, two observers noted the start and end of visible over ocean flocking events, as well as the number of Semipalmated Sandpipers present at the observation site. Flocks were visible with spotting scopes at a distance of up to 8 km. Although we were unable to distinguish between Semipalmated Sandpipers and other similar sized shorebirds, including White-rumped Sandpipers (*C. fuscicollis*) and Least Sandpipers (*C. minutilla*), at this distance, Semipalmated Sandpipers are the most abundant shorebird in the Bay of Fundy at this time, representing more than 95% of birds present (Hicklin 1987).

Potential Cost of Over Ocean Flocking

To estimate the energetic implications of over ocean flocking, we obtained a series of metabolic estimates from the literature. When possible, we used information from Semipalmated Sandpipers, but when it was unavailable we used data from related shorebird species. We calculated the cost of flying (Hötker 2000) relative to roosting (Piersma *et al.* 2003), for birds of both 30 g and 35 g, to represent a range of masses expected during the migratory stopover period. The costs were based on basal metabolic rates calculated using the formula from Kersten and Piersma (1987). Then, we estimated the cumulative added cost that Semipalmated Sandpipers using over ocean flocking would have incurred relative to those that roosted at high tide, and converted this to grams of fat lost based on Johnston's (1970) energetic conversion estimate.

Statistical Analyses

We determined length of stay to be the time elapsed between the time of capture and the last detection in Cobequid Bay. In our analysis of length of stay, we excluded all birds detected for less than 5 days (totaling seven birds) because we were not confident that these data reflected an accurate length of stay for birds using Cobequid Bay to fuel their migration to South America. These values were all > 3 SD away from the grand mean of the rest of the birds, indicating that the probability of them coming from the same distribution of data points is < 0.001. Of the excluded birds, three were detected only on the day of capture, suggesting transmitter loss or failure, or departure from the detectable area. A fourth bird left Cobequid Bay after capture and was later detected in the Southern Bight of the Minas Basin. Three others that stayed for less than 5 days were also excluded because a stay of that length would be insufficient to allow for adequate weight gain to complete a non-stop flight to South America (Dunn *et al.* 1988), meaning these birds would not have been relying exclusively on the resources in Cobequid Bay.

Although we restricted the mass range of birds that were given radio-tags, it was still possible that mass on tagging would influence duration of stay, given that birds arrive light and leave heavy. To assess this, we conducted a model II reduced major axis regression (R package lmodel2; Legendre 2013) of duration of stay on size-adjusted mass at capture. We controlled for differences due to structural bird size to better reflect an individual's fat load using the equation from Winker *et al.* (1992):

$$\text{Size adjusted mass } \left(\frac{g}{mm^3}\right) = \left[\frac{\text{mass}}{(\text{wing chord})^3}\right] \times 10{,}000$$

After finding no effect of mass on duration of stay, we assessed differences in duration of stay between rounds of capture and age using a one-way ANOVA, with a combination of capture period and age (early adult, late adult, late juvenile) as a fixed factor. We completed a power analysis on non-significant results for the analysis of age (R package pwr; Champely *et al.* 2015). We also assessed any differences in size-adjusted mass between groups using a one-way ANOVA, with size adjusted mass as the response factor and group as a fixed factor. For both analyses, we followed up significant ANOVA results with post hoc comparisons using Tukey's HSD test. We completed all statistical analyses using the statistical program R (R Development Core Team 2014). We assessed parametric assumptions of normality and homogeneity of variances using Shapiro-Wilk normality tests and visual analysis of Q-Q plots, and Levene's test of homogeneity of variance, respectively.

RESULTS

The 37 individually radio-tagged birds were detected in Cobequid Bay for 0 to 30.1 days after capture (Fig. 2); 30 were detected for ≥ 5 days and were retained for analysis. Size-adjusted mass at capture had no effect on duration of stay (Regression, $F_{1,28} = 0.079$, $P = 0.35$, $r^2 = 0.003$), which was not surprising given that we restricted the mass of birds receiving transmitters to < 30 g. Although there was a significant difference in size-adjusted mass between the various groups of Semipalmated Sandpipers (ANOVA, $F_{2,27} = 8.08$, $P = 0.002$; Table 1), this was the result of juveniles

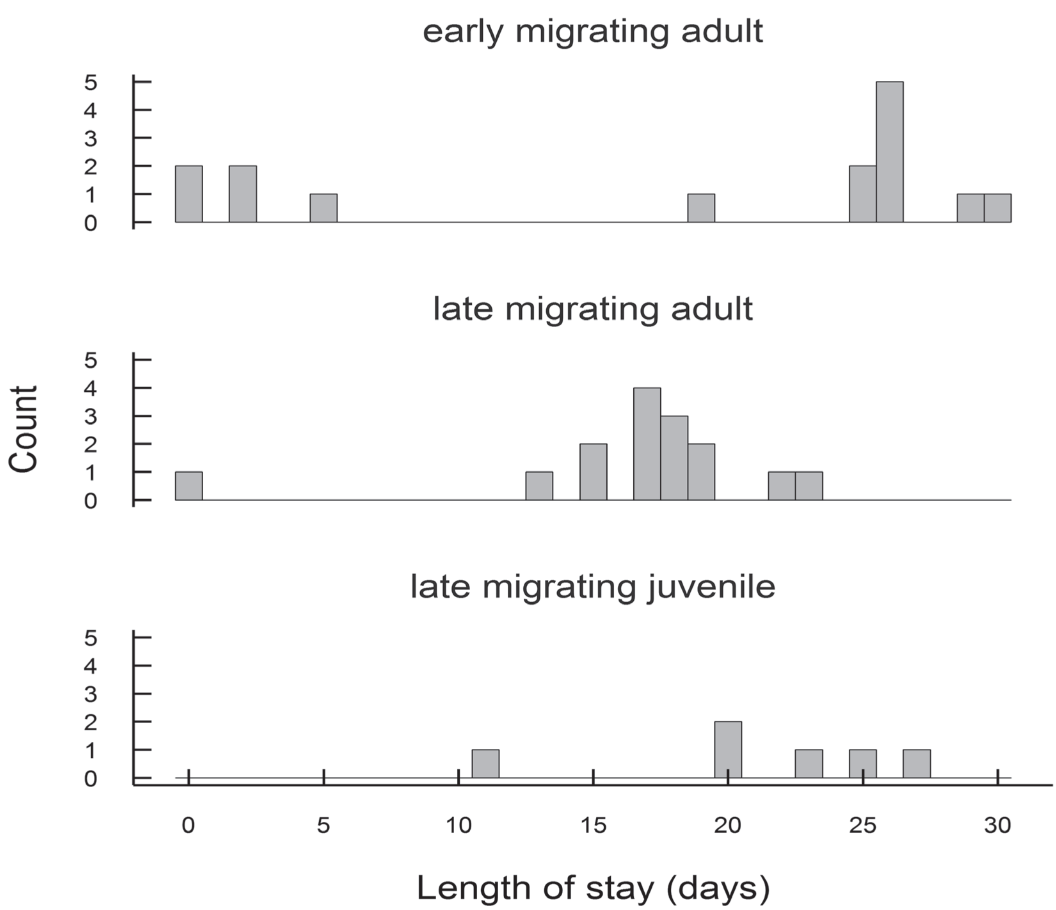

Figure 2. Histogram of duration of stay for Semipalmated Sandpipers caught in Cobequid Bay, Nova Scotia (*n* = 36), grouped by age (juvenile and adult) and capture period (early vs. late migrants). The early capture period was 9 August 2014, and the late capture period was 19-21 August 2014. One late-caught juvenile was excluded because it spent the majority of its time in other areas of the Bay of Fundy.

being lighter than both early (Tukey's test, $P = 0.03$) and late ($P = 0.001$) caught adults. Mass of early and late caught adults (Table 1) did not differ significantly ($P = 0.40$).

Duration of stay varied among the groups of Semipalmated Sandpipers (ANOVA, $F_{2,27} = 17.54$, $P < 0.001$; Table 1). Adult birds caught early in August stayed on average 8.2 days longer than adult birds caught later in August (Tukey's test, $P < 0.001$). Juveniles stayed on average 3.1 days longer than adults caught in the same period, though this difference was not statistically significant ($P = 0.16$; Table 1). However, the statistical power of this test was low; we had only 32% power to detect a difference in length of stay of 3 days.

Over ocean flocking was observed only during the early period of observations (11-14 August), a time of extreme tide levels in Cobequid Bay. This behavior was noted on every observation day in that period (n = 4 days, mean ± SD = 96 ± 12 min per tide, Range = 79-107 min), during which high tide heights ranged from 15.1 to 15.4 m and there was very little beach available for roosting. During the tides exceeding 15 m, water flooded the salt marsh at the upper edge of the mudflats and came to the base of the dyke below the observation point at Fort Belcher. At Debert Beach, only a small amount of cobble beach that bordered farmland, cottages and a treed area remained. On these dates, birds were present at roosting sites when beach was available, but then gradually departed as the tide rose. Conversely, on observation days when no over ocean flocking was observed (22-27 August), high tides ranged from 12.8 to 13.6 m, which left some mudflat and additional beach area available for roosting throughout the high tide period at Fort Belcher and Debert Beach. Tides ≥ 15 m were present from 11-14 August 2014, then not again until 9-12 September 2014, when most birds had departed. Therefore, all Semipalmated Sandpipers caught early in August experienced at least eight high tides ≥ 15 m from day of capture to day of departure. By contrast, birds caught in the second capture period experienced on average only one tide ≥ 15 m before they departed the region.

Early migrating Semipalmated Sandpipers would have expended at least 147.8-165.4 kJ (range for 30-35 g bird) more energy while in flight around high tide than later migrants that roosted during more moderate high tides, based on the duration of over ocean flocking that we observed. This equates to an additional 3.8 to 4.3 g of fat burned (Johnston 1970) during their time in the region.

Discussion

Semipalmated Sandpipers that used Cobequid Bay as a migratory stopover in 2014 faced a range of tidal conditions. In August 2014, we experienced the perigee, syzygy of the Earth-Moon-Sun interface, generating tides of an unusually high magnitude. These high tides exceeding 15 m are observed irregularly, and the number that occur during the height of Semipalmated Sandpiper migration through Cobequid Bay (fourth week of July through the first week of September) varies annually. For example, there were no such tides in 2012, 11 in 2013, and eight in 2014 (Fisheries and Oceans Canada 2014). When these tides occur, little traditional roosting habitat is available for Semipalmated Sandpipers around high tide. In other locations in the Bay of Fundy, Semi-

Table 1. Mean mass at capture of radio-tagged birds and duration of stay for Semipalmated Sandpipers caught in Cobequid Bay, Nova Scotia. Birds selected for radio-tagging were < 30 g during both the early (9 August 2014) and late (19-21 August 2014) capture periods.

			Mass (g)		Size Adjusted Mass (g/mm^3)		Duration of Stay (days)	
Capture Period	Age	N	Mean	SD	Mean	SD	Mean	SD
Early	Adult	10	25.4	1.5	0.27	0.031	26.1	2.88
Late	Adult	14	26.9	2.2	0.29	0.032	17.8	2.55
Late	Juvenile	6	20.7	0.8	0.23	0.019	20.9	5.41

palmated Sandpipers have responded to very high tides by roosting on roads or sheer cliff faces (MacKinnon *et al.* 2008), or by taking refuge in inland fields and meadows (Wilson 1990). However, in Cobequid Bay, the loss of traditional roosting habitat during tides greater than 15 m was associated with over ocean flocking.

Results of our radio tracking study support the hypothesis that the extra energy expenditure associated with over ocean flocking slowed the rate of fat gain in early migrating Semipalmated Sandpipers. Adult Semipalmated Sandpipers that migrated through Cobequid Bay early in the season, and therefore engaged in over ocean flocking during periods of extreme tides, remained in the area on average 8.1 days longer than those that migrated later and did not exhibit over ocean flocking. Because average mass of birds captured in the two periods did not differ significantly, this difference is not attributable to having tagged birds later in their stay in the second period.

Early birds that used over ocean flocking would have expended substantially more energy than the later migrants that roosted during more moderate tides. Based on an estimated rate of mass gain of 1 g/day, as supported by Davidson (1984), Zwarts *et al.* (1990) and Lindström (1995), earlier migrants would have needed to stay a minimum of 3.8 to 4.3 days longer than later migrants to reach the same mass at departure. This is based on observed over ocean flocking and may be a low estimate if birds also engaged in over ocean flocking in areas where they were not visible. This does not account for the entire difference in duration of stay between early and late migrants in Cobequid Bay, but mass is only one of several factors contributing to departure timing in Semipalmated Sandpipers (Lank 1983; Dunn *et al.* 1988). Shorebird departures are also linked to weather conditions, especially wind direction and speed (Lank 1983; Butler *et al.* 1997), so later migrants may be more likely to leave as soon as they are sufficiently prepared, thus avoiding storms that occur more frequently late in the season (Environment and Climate Change Canada 2014), increased precipitation, and colder temperatures (Government of Canada 2016). Thus, some difference in length of stay between early and late migrants should be expected and has been observed among Semipalmated Sandpipers using other areas of the Bay of Fundy (Neima 2017) and Maine (Dunn *et al.* 1988).

To separate effects of over ocean flocking on duration of stay from expected seasonal differences, it is necessary to compare results with those from other areas with similar weather conditions but differences in roosting habitat availability. In 2014, differences in duration of stay between early and late migrating Semipalmated Sandpipers varied among areas of the Bay of Fundy. The difference observed in Cobequid Bay exceeded the difference observed in the Southern Bight of the Minas Basin (~60 km away) by 1.5 days and Chignecto Bay (~75 km away) by 6.0 days (Neima 2017). These areas within the Bay would have experienced similar seasonal weather patterns. Tidal amplitude is only slightly lower in Minas Basin, but typically at least 1-2 m less in Chignecto Bay than in Cobequid Bay (Fisheries and Oceans Canada 2014). During periods of very high tides in these other locations around the Bay of Fundy, some alternate roost sites, such as rock outcrops, fields, and retaining walls, have been used (Wilson 1990; MacKinnon *et al.* 2008). Our rough estimate of an extension of 3.8 to 4.3 days in duration of stay based on energetic costs of over ocean flocking thus aligns quite well with differences observed between the sites, especially with Chignecto Bay where the smaller tidal amplitude coupled with alternate roosting areas suggests less need to fly during high tide. It seems highly likely that being forced into over ocean flocking does have energetic consequences that can manifest in increased durations of stay. An alternate explanation for differences both within and between sites is that variable food resources over time and space may affect rate of fattening. However, Semipalmated Sandpipers have a very broad and opportunistic diet (MacDonald *et al.* 2012; Quinn and Hamilton 2012; Gerwing *et al.* 2016), and high densities of quality prey items are available throughout the Bay of Fundy during their staging period (Gerwing *et al.* 2015; Mann 2015).

Effects of extreme tidal fluctuation on juvenile migrants are less clear. Juveniles migrate later in the season, so were not present during the August period of extreme tides. The juveniles that we tagged late in the migration period did not exhibit a significantly different duration of stay than adults tagged at the same time, though there was a non-significant tendency for them to stay somewhat longer. This may have been linked to their lower mass on tagging. However, juvenile birds also tend to be less competent at foraging (Hand *et al.* 2010; van den Hout *et al.* 2013) and are more prone to choosing lower quality habitats (Warnock and Takekawa 1995), likely owing to inexperience and low social standing (Groves 1978). Therefore, exposure to conditions that lead to over ocean flocking could be even more energetically challenging for them, and additional work in this area is required to understand how they respond to loss of roosting habitat.

Movements between Cobequid Bay and other staging sites in the Bay of Fundy were very limited, even though it would take less time to fly to both the Southern Bight of the Minas Basin and Chignecto Bay from Cobequid Bay than the average time spent over ocean flocking during the early observation period. This is consistent with recent research that has also shown high regional fidelity and limited movements by Semipalmated Sandpipers between the arms of the Bay of Fundy (Sprague *et al.* 2008; White 2013; Neima 2017). These limited movements suggest that birds using Cobequid Bay are relying almost exclusively on the resources in the area to fuel their migration, despite the fact that extreme tides resulted in the loss of roosting habitat. Such dependence leaves them vulnerable to habitat change in the area. Sea level is anticipated to rise 1 m by 2100 (Greenberg *et al.* 2012). An increase of this magnitude would result in the extreme tides that we observed during this study becoming typical tides, and would result in less exposed mudflat at low tide. It is difficult to predict the overall response of the coastline to rising sea level, but in Cobequid Bay and other areas where dykes and other shoreline features are put into place to reclaim land for agriculture and development, the potential for new habitat creation is low and habitat loss is high (Galbraith *et al.* 2002; Dugan *et al.* 2008). Given this, and the behavioral differences we observed in response to a short-term increase in tide level, it seems likely that Semipalmated Sandpiper staging behavior, energetic costs and duration of stay at this site will change as sea level rises.

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