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Authors: Craik, Shawn R., Hanson, Alan R., Titman, Rodger D., Mahoney, Matthew L., and Tremblay, Éric

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Potential Impacts of Storm Surges and Sea-level Rise on Nesting Habitat of Red-breasted Mergansers (*Mergus serrator*) on Barrier Islands in New Brunswick, Canada

Shawn R. Craik[1,*], Alan R. Hanson[2], Rodger D. Titman[3], Matthew L. Mahoney[2] and Éric Tremblay[4]

[1]Département des Sciences, Université Sainte-Anne, Church Point, Nova Scotia, B0W1M0, Canada

[2]Environment Canada, Sackville, New Brunswick, E4L1G6, Canada

[3]Department of Natural Resource Sciences, McGill University, Sainte-Anne-de-Bellevue, Quebec, H9X3V9, Canada

[4]Kouchibouguac National Park of Canada, Kouchibouguac, New Brunswick, E4X2P1, Canada

[*]Corresponding author; E-mail: shawn.craik@usainteanne.ca

Abstract.—Predicted sea-level rise and increases in the frequency and magnitude of storm surges are potential threats to waterbird nests and associated breeding habitat on low-lying landforms, such as barrier islands. Sea-level rise in Northumberland Strait of eastern Canada, predicted to rise by at least 0.50-0.60 m by 2100, could permanently flood large tracts of barrier island habitat. Potential impacts of higher sea levels on breeding habitat of Red-breasted Mergansers (*Mergus serrator*) were studied on three barrier islands at Kouchibouguac National Park, New Brunswick, Canada. Objectives of the study were to: 1) identify the range of dates for which nests (n = 189) were active and thus vulnerable to flooding; 2) determine elevation and distance to water for each nest; 3) examine whether birds selected nest sites that were relatively elevated and far from water; and 4) estimate the proportion of nests that could be flooded under four plausible sea-level rise and storm surge scenarios. Peak nesting occurred during mid-June to mid-July. Red-breasted Mergansers generally sought elevated regions with beach grasses for nest placement. Nearly 50% of nests were < 2 m above mean sea level. Nest elevations were greater than a conservative estimate of sea-level rise of 0.60 m. However, ≥ 50% of these nests are predicted to be flooded during a high spring tide if sea levels are 0.60 m greater, and these impacts would be exacerbated when phased with a storm surge. A predicted surge of 2.55 m above mean sea level would inundate 90% of nests on the islands. Results indicate that predicted sea-level rise for Northumberland Strait over the next century threatens the habitat and survival of waterbird nests on barrier islands, particularly if there is little accretion to the islands during this period. Accordingly, rates of sediment accretion or erosion on the Tern Islands should be monitored closely as sea levels continue to rise.
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Key words.—barrier islands, *Mergus serrator*, nests, Northumberland Strait, Red-breasted Merganser, sea-level rise, storm surge.

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Climate warming through thermal expansion of sea water and melting of glaciers and ice sheets has accelerated rates of global sea-level rise (Parmesan and Matthews 2006). Sea level increased by an average of 1.7 mm/year during 1910-2010, but increased 3.2 mm/year during 1993-2010 (Nerem *et al.* 2010; Church and White 2011). The International Panel on Climate Change (IPCC) predicts that average sea level may increase by as much as 10-11 mm/year during the 21st century, resulting in an average increase of 0.75 m by year 2100 (90% CI: 0.52-0.98 m; Intergovernmental Panel on Climate Change 2013). Sea-level changes at regional scales may deviate from the global average as a result of ocean dynamic processes and movements of the sea floor (Valiela 2006).

Sea-level rise is a serious threat to the persistence of coastal habitats and their associated species (Galbraith *et al.* 2002; Reed 2006; Bayard and Elphick 2011). Barrier islands represent nearly 10% of all continental shoreline worldwide (Stutz and Pilkey 2011). Because they are low-lying and consist of highly erodible substrates (e.g., sand), barrier islands are particularly vulnerable to higher water levels (Moore *et al.* 2010). As sea level rises, a barrier island is increasingly susceptible to flooding and erosion during regular water-level fluctuations (e.g., high tides) and during storm surges if there is insufficient sand volume and relief to prevent inundation (Moore *et al.* 2007). Sea-level rise will increase the severity of flooding during storm surges and reduce the return period for each surge level (Bernier *et al.* 2006; Parkes *et al.* 2006). Ultimately, a barrier island lacking a sufficient supply of sand may respond to sea-level rise by disintegrating or drowning in place to transform into a marine sand body (Moore *et al.* 2010).

Globally, barrier islands provide important staging, wintering and breeding habitat for a large number of avian species (Erwin *et al.* 2006; Williams *et al.* 2007). Barrier islands are particularly attractive to ground-nesting waterbirds because they offer a variety of habitats for nest placement, including beaches and dunes (Elias *et al.* 2000) and salt marshes (Lauro and Burger 1989). Nesting success is relatively high on islands that are free of mammalian predators (McGowan *et al.* 2005). There is growing concern that flooding associated with sea-level rise and the greater frequency and intensity of storm surges will impact ground-nesting waterbirds through more frequent nest losses, significant changes in vegetation zonation, and loss of breeding habitat on poorly elevated islands (Hughes 2004; Erwin *et al.* 2006). Despite this, few studies have examined the potential impacts of higher water levels on waterbird nesting habitat (Erwin *et al.* 2006; Van der Pol 2010; Seavey *et al.* 2011). The probability of flooding of nesting habitat related to predicted sea levels is generally unknown at most sites, yet this information is critical for establishing conservation priorities and management initiatives for barrier islands and their breeding waterbird populations (Seavey *et al.* 2011).

We focus on the Red-breasted Merganser (*Mergus serrator*), a sea duck that breeds colonially with Larids (gulls and terns) on barrier islands in the Canadian Maritime Provinces (Young and Titman 1986; Erskine 1992). Red-breasted Mergansers nest in stands of beach grasses, and their nests are generally more elevated than those of larids (Craik and Titman 2009; Chabot 2014). Accordingly, the Red-breasted Merganser serves as a flood-risk indicator in this system because any level of water that reaches merganser nests would flood at least the majority of Larid nesting habitat.

Red-breasted Merganser nests were studied on the Tern Islands at Kouchibouguac National Park in eastern New Brunswick. The Tern Islands constitute an internationally significant Important Bird Area (IBA; Dietz and Chiasson 2000); they support the largest known nesting colony of Red-breasted Mergansers in the Canadian Maritime Provinces (up to 30 nests/ha), the largest colony of Common Terns (*Sterna hirundo*) in Canada (up to 2,300 nests/ha; Young and Titman 1986, É. Tremblay, unpubl. data), and a small number (< 10) of Ring-billed Gull (*Larus delawarensis*) nests annually. The islands lie in Northumberland Strait, where relative sea level is predicted to be 1.05 m higher by 2100 (lower bound estimate: 0.50 m; upper bound estimate: 1.50 m; Daigle 2012). This increase in sea level will exacerbate the severity of storm surges in Northumberland Strait, which are among the most intense in eastern North America (Bernier *et al.* 2006). Surges in excess of 1 m above mean sea level (MASL) occur at least once a year in eastern New Brunswick (Danard *et al.* 2003). The greatest flooding event recorded for Northumberland Strait was in January 2000, when a storm surge at high tide yielded a water level 2.55 MASL (Parkes *et al.* 2006). Like most barrier islands in the region, the Tern Islands are oriented in a north-south direction, making them vulnerable to flooding from relatively large waves originating from northeast winds (Forbes *et al.* 2004).

Our goal was to obtain information on the nesting ecology of Red-breasted Mergansers on the Tern Islands and to subsequently use these data to help predict potential impacts of higher water levels on Red-breasted Merganser nesting habitat. Specific objectives were to: 1) identify the range of dates for which Red-breasted Merganser nests were active and thus vulnerable to flooding; 2) determine elevation and distance to water for each nest; 3) examine whether birds selected nest sites that were relatively elevated and far from water; and 4) estimate the proportion of these nests that could be flooded under four plausible sea-level rise and storm surge scenarios for Northumberland Strait.

Methods

Study Site

We studied nests of Red-breasted Mergansers on the Tern Islands during 2002-2005. Three barrier islands (Tern Island 1, Tern Island 2, Tern Island 3; 46° 46' N, 64° 52' W) form a 3-ha archipelago that is sheltered from Northumberland Strait by the 90-ha South Kouchibouguac Dune (SK Dune; Fig. 1). The Tern Islands, SK Dune, North Kouchibouguac Dune (NK Dune), and North Richibucto Dune (NR Dune) combine to make a 25-km crescent of barrier islands at Kouchibouguac National Park. On Tern Islands, Red-breasted Mergansers place their nests in dense stands of marram grass (*Ammophila breviligulata*), whereas gulls and terns nest in sparsely vegetated areas (Craik and Titman 2009; Chabot 2014).

Maximum elevation of the Tern Islands during the study was 3.5 MASL. In contrast, elevations on the NK Dune, SK Dune, and NR Dune often exceeded 4 MASL, although some sections were low-lying, such as a portion of the SK Dune adjacent to Tern Islands 2 and 3 (Fig. 1). Red-breasted Mergansers and larids typically avoid nesting on the three larger barrier islands (R. D. Titman, unpubl.data), possibly due to the presence of red fox (*Vulpes vulpes*).

Data Collection

Nesting chronology. We found Red-breasted Merganser nests by systematically searching the Tern Islands once a week from late May to late July. Nest coordinates were recorded with a global positioning system (GPS model eTrex, Garmin Ltd.). We revisited active nests one to two times a week as hatching approached. Nest initiation dates were estimated by backdating, assuming that one egg was laid every 1.5 days (Craik and Titman 2009). We predicted hatch dates by aging two to three incubated eggs and assuming a 30-day incubation period (Westerskov 1950). For abandoned and depredated nests, date of failure was estimated as the mid-point of the period between the last visit when the nest was active and the subsequent visit (Johnson 1979). We minimized disturbance to nesting Red-breasted Mergansers and Larids by limiting island visits to a maximum of 1 hr and by not visiting the islands during periods of precipitation.

Nest elevation and distance to water. We determined the elevation (± 0.01 m) of each Red-breasted Mergan-

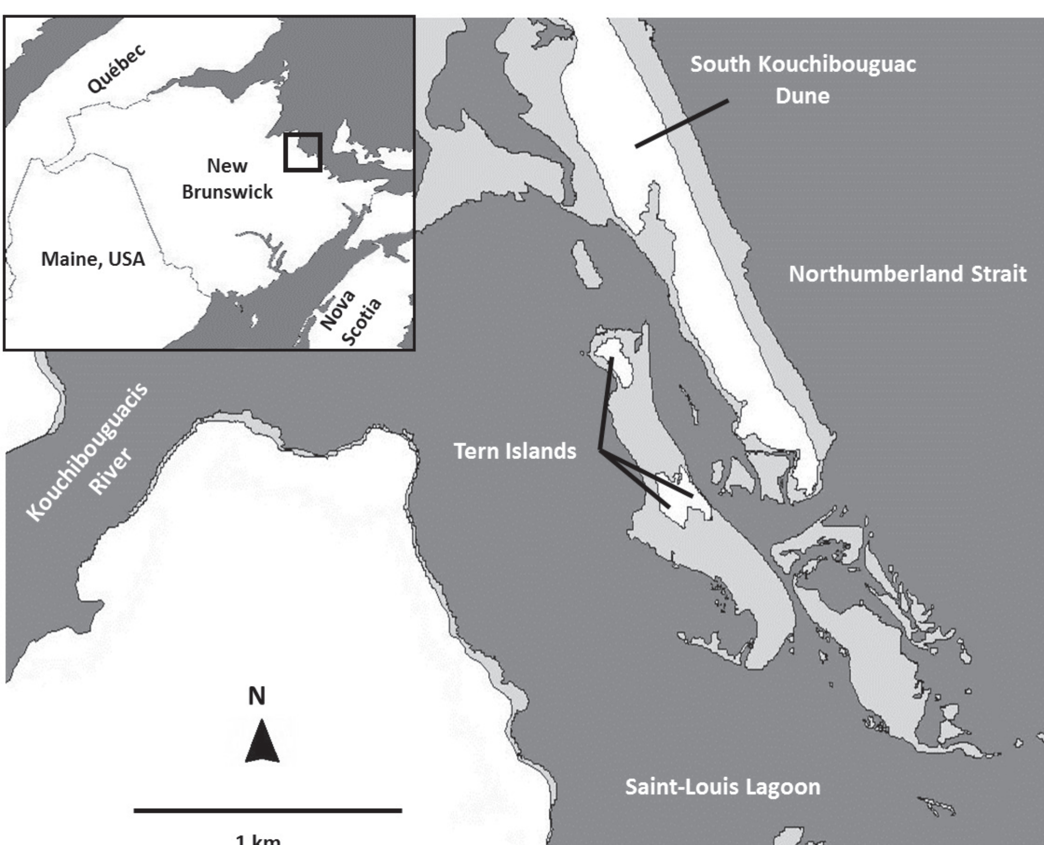

Figure 1. Tern Islands at Kouchibouguac National Park, New Brunswick, Canada, 2002-2005. Light shaded areas are intertidal zones.

ser nest by overlaying nest coordinates onto a digital elevation model (DEM) with ArcGIS (Environmental Systems Research Institute 2005). The DEM was derived from airborne light detection and ranging (LiDAR) data collected in 2004 (Webster *et al.* 2006). Nest elevations were measured relative to mean sea level (Canadian Geodetic Vertical Datum of 1928). The high resolution of the DEM (vertical error < 0.30 m) was validated with a GPS survey ($\bar{x}$ = 0.11 m, SD = 0.08 m, height difference; Webster *et al.* 2006). We measured distance to water (± 0.01 m) from each nest by determining the shortest distance between the center of the bowl and accumulation of dead eelgrass (*Zostera marina*) at the high tide line.

We examined whether Red-breasted Mergansers reduced nest flooding probabilities through selection of sites that are relatively elevated and far from shore. For each nest site in 2005, we measured elevation and distance to water at a single random site on the same island. The direction and distance from the nest to the random site were obtained with a random function in a spreadsheet; random numbers were assigned to the eight cardinal directions and a random number between 1 and 68 designated distances in meters (Craik and Titman 2009). We chose 68 m as the upper limit because it was the greatest distance recorded between a nest and the water on the Tern Islands during 2002-2004.

Flood-risk modeling. We considered four sea-level rise and storm surge scenarios that were derived from the LiDAR digital elevation data and based on Environment Canada's sea-level rise and climate change study in southeastern New Brunswick (Webster *et al.* 2006). Each scenario was overlaid onto nest locations to determine whether a given nest site would be inundated if exposed to the flooding event. The scenarios were: 1) 0.60 MASL, a lower-bound, and thus highly conservative, estimate of sea-level rise in the region over the next century (Daigle 2012); 2) 2.55 MASL, the water level associated with the January 2000 storm surge; 3) 3.05 MASL, the water level during the January 2000 storm occurring with 0.50 m sea-level rise; and 4) 3.25 MASL, the water level during the January 2000 storm occurring with 0.70 m sea-level rise. Flooding scenarios incorporated water levels that formed a horizontal plane extending landward from Northumberland Strait and known barriers and pathways of water movement (dune ridges, crests, depressions; Webster *et al.* 2006). The scenarios assumed a worst-case scenario that rapid sea-level rise outpaces the ability of the islands to increase elevation (no land accretion). We chose this type of static response because evidence indicates that recent erosion to the Kouchibouguac barrier island system has not been offset by sediment accretion to the islands (Arcand 2007). Accordingly, barrier island elevations may not keep pace with sea-level rise in the future (O'Carroll *et al.* 2006).

Statistical Analysis

Nesting chronology. We examined seasonal variation in Red-breasted Merganser nesting activity on the Tern Islands. For each year, the proportion of active nests was determined on every fourth day of the nesting season (16 May-12 August). Data from 2002, 2003, and 2005 were combined because nesting chronology in each year was similar. Nesting was later in 2004, likely due to the presence of a red fox on the Tern Islands during May and June.

Nest elevation and distance to water. Weighted average percentiles (5th, 10th, 25th, 50th, 75th, 90th, 95th) were used to determine the distribution of nest elevations. Elevation and distance to water from nest and random sites in 2005 were tested for normality with Shapiro-Wilks tests. Elevation was log transformed and distance to water was square-root transformed to improve normality (Shapiro-Wilks statistics ≥ 0.98). Elevation and distance to water were only weakly correlated (Pearson $r = 0.11$, $P = 0.18$), so discriminant function analysis was used to determine whether elevation and distance to water discriminated nest sites and random locations (Hair *et al.* 1995). Discriminant function loadings of ≥ ± 35 were important (Hair *et al.* 1995). We calculated probability values for discriminations using chance-corrections, which determined the proportion of correctly classified observations that exceeded chance (Titus *et al.* 1984). We performed analyses with SPSS (SPSS Inc. 2002), set significance levels at $P < 0.05$, and present values as means ± 95% confidence intervals (CI).

RESULTS

Nesting Chronology

A total of 189 nests was found on the Tern Islands during 2002-2005 (Table 1). Breeding was more synchronous in 2004 than during 2002-2003 and 2005. Average date of nest initiation during 2002-2003 and 2005 was 3 June (95% CI: 2-5 June, Range = 13 May-27 June), and in 2004 it was 18 June (95% CI: 15-20 June, Range = 6 June-1 July). Mean hatch date during 2002-2003 and 2005 was 19 July (95% CI: 17-21 July, Range = 1 July-7 August), and in 2004 it was 3 August (95% CI: 31 July-5 August, Range = 25 July-12 August). Overall, the majority of nests (≥ 75%) were active between 15 June and 20 July.

Nest Elevation and Distance to Water

Red-breasted Merganser nests were close to water vertically and horizontally (Table 1). Nearly 80% of nests were < 2.5 MASL, and all nests were < 3.35 MASL. Nest elevations on Tern Island 1 were generally greater than those on Tern Islands 2 and 3 (Table 1).

Table 1. Number of Red-breasted Merganser (*Mergus serrator*) nests, elevation and distance to water (± 95% CI), and the proportion (± 95% CI) of nests flooded under sea-level rise and storm surge scenarios on the Tern Islands at Kouchibouguac National Park, New Brunswick, Canada, 2002-2005. Elevation and sea-level rise scenarios are in meters above mean sea level (MASL; Canadian Geodetic Vertical Datum of 1928). The elevation of each nest on the Tern Islands was greater than a 0.60-m estimate of sea-level rise for Northumberland Strait over the next century.

Island	Total Number of Nests/Year[a]	Elevation	Distance to Water (m)	Proportion of Nests Flooded under the Sea-level Rise Scenario (m above mean sea level; MASL)		
				2.55	3.05	3.25
Tern Island 1	17, 22, 21, 42	2.30 ± 0.11	15.30 ± 1.53	0.73 ± 0.31	0.93 ± 0.08	0.98 ± 0.05
Tern Island 2	9, 12, 11, 16	2.02 ± 0.09	18.82 ± 3.94	0.95 ± 0.09	1.00 ± 0.00	1.00 ± 0.00
Tern Island 3	6, 12, 7, 14	1.95 ± 0.12	10.20 ± 1.76	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00
All islands	32, 46, 39, 72	2.16 ± 0.07	15.13 ± 1.38	0.89 ± 0.11	0.98 ± 0.03	0.99 ± 0.01

[a]For 2002, 2003, 2004, 2005, respectively.

Microhabitat at nests was different than at random sites ($\lambda = 0.9$, $\chi^2_2 = 11.6$, $P = 0.003$). Elevation of nests ($\bar{x}$ = 2.34 m, 95% CI: 2.22-2.46 m) was generally greater than that of random sites ($\bar{x}$ = 2.09 m, 95% CI: 2.00-2.18 m; DFA loading of 0.99). Nests were relatively dense on vegetated ridges 2.0-3.5 MASL, where there was little threat of flooding from regular tidal activity. Distance to water at nests ($\bar{x}$ = 12.58 m, 95% CI: 10.80-14.36 m) was similar to that at random locations ($\bar{x}$ = 12.97 m, 95% CI: 11.15- 14.79 m).

Flood-risk Modeling

The elevation of each nest on the Tern Islands was greater than a 0.60-m estimate of sea-level rise for Northumberland Strait over the next century. A storm surge of 2.55 MASL would inundate nearly 75% of nests on Tern Island 1 and 95% nests on Tern Islands 2 and 3 (Table 1). All nests on Tern Islands 2 and 3 would be flooded if water levels reached 3.05 MASL. Only eight and two nests on Tern Island 1 would escape flooding under the 3.05 and 3.25 m water-level scenarios, respectively (Table 1).

DISCUSSION

The magnitude of sea-level rise predicted over the next century indicates that many coastal habitats may become increasingly vulnerable to flooding and erosion during regular tidal activity (e.g., high tides) and storm surges. Barrier islands are among the most sensitive habitats to higher water levels because they are generally of low relief and consist of substrates that can be readily displaced by waves (e.g., sand; Moore *et al.* 2010). Despite this, few studies have considered the potential implications of higher water levels to organisms using low-lying coastal habitats such as barrier islands. Our study of Red-breasted Mergansers provides some of the first predictions of potential impacts of sea-level rise and storm surges for breeding bird habitat on barrier islands (Erwin *et al.* 2006; Van der Pol *et al.* 2010; Seavey *et al.* 2011).

One reason for the paucity of information on potential impacts of sea-level rise to bird habitat on barrier islands is a level of uncertainty with some assumptions to flood-risk modeling, which may make conclusions tenuous (Seavey *et al.* 2011; Sims *et al.* 2013). Our four flood-risk models consider two assumptions that contain uncertainty: 1) that future storm surge levels during the breeding season will be similar to those previously observed during winter; and 2) that rapid sea-level rise will outpace the ability of barrier islands at Kouchibouguac to increase their elevation (static habitat response).

The storm surge scenarios (2.55, 3.05, 3.25 MASL) were derived from the maximum high-water level known for Northumberland Strait (2.55 MASL; January 2000). The intensity and frequency of storm surges in winter (one to two storms/year) are generally greater than those during the breeding season (< 1/year; Parkes *et al.* 2006).

However, storm surge events in eastern Canada are predicted to increase in frequency and intensity over the next century (Parkes *et al.* 2006), and sea-level rise will yield higher water levels for each magnitude of storm surge (Danard *et al.* 2003). The flooding levels reached during the 2000 January event (then close to a 1 in 100 year event) are predicted to occur annually by 2100 (Daigle 2012). Accordingly, the occurrence of water levels capable of flooding nesting habitat on the Tern Islands (> 1.5 MASL) is expected to become more common throughout the year.

Modeling change in barrier island size and elevation is complex as it is a function of sediment supply, mean water level, and storm and wave forcing (Ollerhead and Davidson-Arnott 1995; Forbes *et al.* 2004). There is evidence that sand eroded from Kouchibouguac's large barrier islands (NK Dune, SK Dune, and NR Dune) is not being offset by sediment accretion elsewhere on the islands (static response). Arcand (2007) estimated that shoreline sections on the three dunes eroded by an average of 11.3 m (± 6.3 m) during the period 1974-2002. Shoreline erosion rates are not available for the Tern Islands. However, the size of the Tern Islands declined by nearly 50% between 1995 (8 ha) and 2002 (3.8 ha; Arcand 2007), and that area declined slightly (< 1 ha) during 2002-2013 (E. Tremblay, unpubl. data). Habitat lost was primarily from storm-wave overtopping of low-lying, unvegetated beach on the archipelago's southern end, which was adjacent to a gully between the SK Dune and the NR Dune. Accordingly, this portion of the island was directly exposed to large storm waves originating from northeast winds in Northumberland Strait, which contain more energy than waves in Saint-Louis Lagoon (Beach 1988). That erosion on the Kouchibouguac barrier islands is not being offset by sediment accretion indicates that the supply of sand in the immediate foreshore of the islands is possibly limited and that eroded sediments are being transported away from the islands (Forbes 1987). Accordingly, our assumption of no future accretion of the Tern Islands should be interpreted as a plausible scenario.

Despite the reduction in size of the Tern Islands during 1995-2002, numbers of Red-breasted Merganser and Common Tern nest attempts did not decline during this period (R. D. Titman, unpubl. data). Red-breasted Merganser and Common Tern breeding habitat is primarily on the northern portion of the islands, an area protected from waves coming from Northumberland Strait by the SK Dune. However, predicted climate change through sea-level rise, increases in the frequency and severity of storm surges, and a reduced ice season for Northumberland Strait (Parkes *et al.* 2006; Daigle 2012) may lead to more frequent storm-wave run-up that can breach the barrier islands. Breaching of the low-lying portion of the SK Dune adjacent to Tern Islands 2 and 3 would expose large tracts of low-lying waterbird habitat on the Tern Islands to storm waves originating from the northeast. Erosion due to storm-wave run-up coupled with a potentially limited local supply of sand may result in net losses of waterbird habitat on the Tern Islands.

The elevation of each Red-breasted Merganser nest was greater than a lower-bound 0.60-m estimate of sea-level rise for Northumberland Strait over the next century. This indicates that, alone, a modest increase in sea level may not pose a major threat to merganser breeding habitat on the Tern Islands. However, our 0.60-m scenario did not consider high tide level, which may reach 1.3-1.5 m during large spring tides at Kouchibouguac (Fisheries and Oceans Canada 2005). Spring tides occur on at least three occasions during the breeding season on the Tern Islands. Accordingly, over half of the merganser nests in our study would be flooded during a large spring tide if mean sea level was to increase by 0.60 m. Nearly 90% of nests would be flooded during a spring tide if sea level was to increase by 1.05 m, an intermediate level of sea-level rise predicted for the Kouchibouguac area by 2100 (Daigle 2012). Impacts associated with flooding during a high tide are exacerbated if a storm surge is phased with high tide. Thus, sea-level rise over the next century coupled with little to no sediment accretion on the Tern Islands may result in nest failures and loss of current breeding habitat for Red-breasted Mergansers through flooding and erosion. More severe loss of current breeding habitat is expected for Ring-billed Gulls and Common Terns considering that they nest in less elevated areas than Red-breasted Mergansers (Hanson *et al.* 2006; Chabot 2014).

The persistence of local breeding populations of waterbirds on barrier islands will depend on the degree to which a species' preferred nesting habitat keeps pace with sea-level rise (Seavey *et al.* 2011). Red-breasted Mergansers on the Tern Islands selected elevated nest sites, which may be a strategy for reducing flooding probabilities (Sargeant and Raveling 1992). However, selection of elevated nest sites are more likely a function of the species' preference for nesting in dense stands of beach grasses, which typically occur in relatively elevated regions (Craik and Titman 2009). Red-breasted Mergansers avoid elevated sites that lack dense vegetation (Craik and Titman 2009). Similarly, Common Terns nest in areas with small amounts of vegetation, regardless of elevation (Chabot 2014). Potential changes in vegetation abundance and distribution on the Tern Islands as a result of rapid sea-level rise and increased storms are not well understood; however, they may significantly influence the frequency of waterbird use of the islands for nesting in the future.

Our study raises concern over the potential impacts of predicted sea-level rise and increased frequency and severity of storm surges on breeding habitat of waterbirds on barrier islands. However, specific predictions as to how barrier islands will respond to climate change are generally lacking and require detailed landscape-level information (Van der Pol *et al.* 2010). Accordingly, there is a need to better understand local sediment loads, historical and current rates of land attrition and erosion, and vegetation dynamics for barrier islands supporting important waterbird breeding habitat, including that on the Tern Islands at Kouchibouguac National Park.

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