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Coastal wetland adaptation to sea level rise: Quantifying potential for landward migration and coastal squeeze

Sinéad M. Borchert[1] | Michael J. Osland[2] | Nicholas M. Enwright[2] | Kereen T. Griffith[3]

[1]Borchert Consulting at U.S. Geological Survey, Wetland and Aquatic Research Center, Lafayette, Louisiana

[2]U.S. Geological Survey, Wetland and Aquatic Research Center, Lafayette, Louisiana

[3]Griffith Consulting at U.S. Geological Survey, Wetland and Aquatic Research Center, Lafayette, Louisiana

Correspondence
Sinéad M. Borchert, Borchert Consulting at U.S. Geological Survey, Wetland and Aquatic Research Center, Lafayette, LA 70506
Email: sborchert@usgs.gov

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Abstract

1. Coastal wetland ecosystems are expected to migrate landwards in response to rising seas. However, due to differences in topography and coastal urbanization, estuaries vary in their ability to accommodate migration. Low-lying urban areas can constrain migration and lead to wetland loss (i.e. coastal squeeze), especially where existing wetlands cannot keep pace with rising seas via vertical adjustments. In many estuaries, there is a pressing need to identify landward migration corridors and better quantify the potential for landward migration and coastal squeeze.
2. We quantified and compared the area available for landward migration of tidal saline wetlands and the area where urban development is expected to prevent migration for 39 estuaries along the wetland-rich USA Gulf of Mexico coast. We did so under three sea level rise scenarios (0.5, 1.0, and 1.5 m by 2100).
3. Within the region, the potential for wetland migration is highest within certain estuaries in Louisiana and southern Florida (e.g. Atchafalaya/Vermilion Bays, Mermentau River, Barataria Bay, and the North and South Ten Thousand Islands estuaries).
4. The potential for coastal squeeze is highest in estuaries containing major metropolitan areas that extend into low-lying lands. The Charlotte Harbor, Tampa Bay, and Crystal-Pithlachascotee estuaries (Florida) have the highest amounts of urban land expected to constrain wetland migration. Urban barriers to migration are also high in the Galveston Bay (Texas) and Atchafalaya/Vermilion Bays (Louisiana) estuaries.
5. *Synthesis and applications*. Coastal wetlands provide many ecosystem services that benefit human health and well-being, including shoreline protection and fish and wildlife habitat. As the rate of sea level rise accelerates in response to climate change, coastal wetland resources could be lost in areas that lack space for landward migration. Migration corridors are particularly important in highly urbanized estuaries where, due to low-lying coastal development, there is not space for wetlands to move and adapt to sea level rise. Future-focused landscape conservation plans that incorporate the protection of wetland migration corridors can increase the adaptive capacity of these valuable ecosystems and simultaneously decrease the vulnerability of coastal human communities to the harmful effects of rising seas.

KEYWORDS
climate change adaptation, coastal squeeze, coastal wetlands, mangroves, marsh, sea level rise, urbanization, wetland migration

1 | INTRODUCTION

Natural resource management has been undergoing a paradigm shift in recent decades as decision makers are increasingly challenged to prepare for and respond to the ecological effects of climate change (Heller & Zavaleta, 2009; Hulme, 2005; Lawler, 2009; Mawdsley, O'Malley, & Ojima, 2009; Stein, Glick, Edelson, & Staudt, 2014). Climate change adaptation efforts are particularly important in low-lying coastal regions that are threatened by rising seas (Hinkel et al., 2014; Nicholls, Hoozemans, & Marchand, 1999; Titus et al., 2009). As global temperatures continue to increase, warming oceans coupled with melting ice sheets and glaciers are expected to accelerate the rate of sea level rise (Church et al., 2013; Sweet et al., 2017). Coastal and estuarine ecosystems are particularly vulnerable to accelerated sea level rise (Ellison, 2015; Kirwan & Megonigal, 2013; Nicholls & Cazenave, 2010; Scavia et al., 2002; Thorne et al., 2018). Climate-smart conservation efforts along the coast can increase the adaptive capacity of valuable coastal ecosystems and also protect coastal communities from the harmful impacts of sea level rise (Arkema et al., 2013; Duarte, Losada, Hendriks, Mazarrasa, & Marbà, 2013; Spalding et al., 2014; Stein et al., 2014).

Sea level rise is expected to transform many coastal wetlands and negatively affect some of the goods and services that these ecosystems support (Craft et al., 2009; Kirwan et al., 2010; Runting, Lovelock, Beyer, & Rhodes, 2017; Yoskowitz, Carollo, Pollack, Santos, & Welder, 2017). Coastal wetlands are highly productive ecosystems that provide many benefits to society, including erosion control, coastal protection during storms, water filtration, flood reduction, carbon sequestration, recreational opportunities and maintenance of productive coastal fisheries (Barbier et al., 2011; Costanza et al., 2014; Morgan, Burdick, & Short, 2009; Sutton-Grier, Wowk, & Bamford, 2015). Given the threat of wetland loss in response to sea level rise, coastal managers are increasingly challenged to maximize the adaptive capacity of coastal wetlands. Despite their high sensitivity to sea level rise, many coastal wetlands are resilient ecosystems that have the capacity to adjust to sea level rise through two primary adaptation mechanisms (Kirwan & Megonigal, 2013; Rogers et al., 2016; Woodroffe et al., 2016). The first adaptation mechanism involves vertical adjustments due to feedbacks between plant growth, inundation and sediment deposition (Krauss et al., 2014; McKee, 2011; Morris, Sundareshwar, Nietch, Kjerfve, & Cahoon, 2002; Nyman, Walters, Delaune, & Patrick, 2006). The second adaptation mechanism involves the landward migration of wetlands into, and at the expense of, adjacent upslope or upriver ecosystems (Doyle, Krauss, Conner, & From, 2010; Enwright, Griffith, & Osland, 2016; Langston, Kaplan, & Putz, 2017; Williams, Ewel, Stumpf, Putz, & Workman, 1999). If the rate of sea level rise surpasses the ability of coastal wetlands to keep pace via vertical adjustments, certain wetland ecosystems may be submerged and converted to subtidal ecosystems (Couvillion, Beck, Schoolmaster, & Fischer, 2017; Jankowski, Törnqvist, & Fernandes, 2017). Hence, under higher rates of sea level rise, local wetland loss rates are expected to be high and landward migration is expected to become the primary mechanism for coastal wetland adaptation to sea level rise.

To maximize the adaptive capacity of coastal wetlands, there is a pressing need in many estuaries to better identify, manage and protect low-lying, undeveloped lands that could facilitate the landward migration of these ecosystems (Ellison, 2015; Lester & Matella, 2016; Rogers, Saintilan, & Copeland, 2014; Wigand et al., 2017). Estuaries differ in their ability to accommodate wetland migration due to variability in physiographic setting and the historical extent of wetland and anthropogenic development. High gradients in slope and other topographic barriers along an estuary's coastline can limit the surface area available for wetland migration (Doyle et al., 2010; Enwright et al., 2016; Stralberg et al., 2011; Thorne et al., 2018). Low-lying infrastructure and anthropogenic shoreline protection features can also function as barriers to landward migration, as coastal wetlands are squeezed between the encroaching ocean and the human-built environment (i.e. coastal squeeze; Doody, 2013; Pontee, 2013; Torio & Chmura, 2013; Woodroffe et al., 2016). For climate-smart conservation planning purposes that target the most vulnerable estuaries, there is a need for regional analyses that quantify and compare the potential for estuaries to accommodate landward migration and/or prevent migration via coastal squeeze.

More than half of the contiguous United States's coastal wetlands are located along the northern Gulf of Mexico coast (Field, Reyer, Genovese, & Shearer, 1991) and these wetlands benefit the region's growing coastal communities (Engle, 2011; Yoskowitz et al., 2017). Despite valuable county-level assessments of the potential for landward migration (Doyle et al., 2010; Enwright et al., 2016) and widespread recognition that wetlands in this region are highly vulnerable to sea level rise (Day et al., 2013; Jankowski et al., 2017; Kirwan & Guntenspergen, 2010; Williams, Pinzon, Stumpf, & Raabe, 1999), the relative ability of the region's estuaries to accommodate landward migration has not been assessed. In this study, we investigated the following questions for estuaries along the northern Gulf of Mexico coast (United States): (a) which estuaries have the largest amount of land available for the landward migration of tidal saline wetlands (i.e. mangrove forests, saltmarshes and salt flats); and (b) which estuaries have the largest amount of low-lying, urban lands that are expected to prevent landward migration of tidal saline wetlands (i.e. which estuaries have a high potential for coastal squeeze)? For 39 estuaries, we quantified and compared the potential for landward migration and coastal squeeze, under three alternative future sea level rise scenarios (0.5, 1.0 and 1.5 m by 2100).

2 | MATERIALS AND METHODS

2.1 | Study area

Our study area includes 39 estuaries along the United States's northern Gulf of Mexico coast (Table 1). These estuaries are located in the following five states: Texas, Louisiana, Mississippi, Alabama and Florida (Figure 1). To identify estuary boundaries, we used the estuarine drainage area (EDA), coastal drainage area (CDA) and fluvial drainage area data contained within the National Oceanic and Atmospheric Administration's (NOAA) Coastal Assessment Framework (CAF). All drainage areas of the same name and CDAs entirely adjacent to an EDA were merged. Two CDAs (G025 and G033) were merged with the EDA with which they shared the most coastline (i.e. North Ten Thousand Islands). The Everglades CDA spanned two EDAs (North Ten Thousand Islands and South Ten Thousand Islands); hence, it was split perpendicularly where the EDAs met and the two resulting polygons were merged with their respective EDAs. We excluded two estuaries, Withlacoochee (Florida) and Rio Grande (Texas), because they include very small sections of the coastline that represent the mouths of the Withlacoochee and Rio Grande Rivers respectively.

2.2 | Elevation and tidal datum data

For more details regarding the data and methodology used in this study, see Enwright, Griffith, and Osland (2015) and Enwright et al. (2016). For elevation data, we utilized digital elevation models (DEMs) that were created using airborne topographic light detection and ranging (lidar) elevation data. The vertical datum for these lidar-based DEMs was the North American Vertical Datum of 1988 (NAVD88). We used NOAA's VDatum software tool version 3.1 (Parker, 2003) to transform the vertical datum of the DEMs from NAVD88 to a tidal datum, mean higher high water (MHHW; Schmid, Hadley, & Waters, 2014). The EDA boundaries identify estuarine drainage areas, whereas the VDatum data are provided within VDatum regions, which are NOAA tidal datum modeling regions. Our study area includes 39 estuaries and nine VDatum regions; hence, each VDatum region includes multiple estuaries.

2.3 | Wetland and urban development data

Tidal saline wetlands in the northern Gulf of Mexico include graminoid saltmarshes, succulent saltmarshes, salt flats and mangrove forests (Odum, McIvor, & Smith, 1982; West, 1977; Withers, 2002). Climatic drivers greatly influence the distribution, abundance and diversity of tidal saline wetlands in this region (Feher et al., 2017; Gabler et al., 2017; Osland et al., 2016). In recognition of this diversity and due to a lack of consistency in thematic resolution of wetland ecosystems in land cover datasets, we combined these different wetland plant communities into a single tidal saline wetland class. We created a current tidal saline wetland surface using the best available data from the U.S. Fish and Wildlife Service's (USFWS's) National Wetlands Inventory (NWI). Information from the NWI was used to determine the presence or absence of tidal saline wetlands in each cell. Cells with tidal saline wetlands were defined as those that contained estuarine intertidal wetland NWI classes. We used two data sources to identify current urban areas, including data contained within SLEUTH (Slope, Land use, Excluded, Urban, Transportation and Hillshade) output produced by Terando et al. (2014) and the developed land cover classes (i.e. developed high intensity, developed medium intensity, developed low intensity and developed open space) contained within the 2011 U.S. Geological Survey (USGS) National Land Cover Database. See Enwright et al. (2015, 2016) for more details regarding the wetland and developed land cover.

2.4 | Identifying the tidal saline wetland boundary

Prior to considering how sea level rise scenarios would influence the future location of tidal saline wetlands, we determined the current tidal saline wetland boundary. Within each VDatum region, we used the elevation data relative to MHHW data for the most recent tidal epoch, the tidal saline wetland presence/absence data and a recursive partitioning approach to determine the elevation threshold for the tidal saline wetland boundary (Enwright et al., 2015, 2016). Elevation uncertainty in densely vegetated coastal wetlands is a common problem that affects coastal habitat modelling efforts. Prior studies have shown that the aerial topographic lidar data used to create DEMs can overpredict elevation by as much as 60 cm in coastal wetlands (Buffington, Dugger, Thorne, & Takekawa, 2016; Enwright et al., 2018; Medeiros, Hagen, Weishampel, & Angelo, 2015). Several techniques have been developed to deal with elevation uncertainty; for example simple lidar processing techniques like the minimum bin approach (Schmid, Hadley, & Wijekoon, 2011) or the incorporation of error estimates into probabilistic models (Enwright et al., 2018) to more advanced techniques that determine lidar corrections that are based upon relationships between lidar error and biomass (Buffington et al., 2016; Medeiros et al., 2015). These approaches offer exciting advancements and are leading to better elevation products that can be incorporated into wetland habitat change studies. In this study, we expect that our use of a data-driven approach (i.e. the use of habitat data in combination with elevation data to develop an elevation threshold per VDatum region) may have helped to reduce some of the issues related to elevation uncertainty, particularly in comparison with efforts that use an elevation threshold based solely on a tidal datum (i.e. without the use of habitat data).

TABLE 1 For a 1-m sea level rise scenario by the year 2100, the estuary-specific area available for landward migration of tidal saline wetlands and the area where low-lying urban lands are expected to prevent tidal saline wetland migration. Numbers in parentheses are descending order ranks

Estuary code	Estuary name	State	Area available for wetland migration (km²; rank)	Area with urban barriers to wetland migration (km²; rank)
AEB	Apalachee Bay	FL	337 (14)	13 (25)
AAB	Apalachicola Bay	FL	427 (11)	11 (30)
AB	Aransas Bay	TX	159 (20)	22 (16)
AVB	Atchafalaya/Vermilion Bays	LA	3,676 (1)	70 (5)
AO	Austin-Oyster	TX	19 (36)	7 (32)
BB	Barataria Bay	LA	1,664 (3)	38 (13)
BCS	Big Cypress Swamp	FL	17 (38)	54 (7)
BR	Brazos River	TX	127 (23)	4 (35)
BRC	Breton/Chandeleur Sound	LA	76 (30)	2 (39)
CL	Calcasieu Lake	LA	547 (9)	38 (12)
CH	Charlotte Harbor	FL	111 (26)	160 (1)
CB	Choctawhatchee Bay	FL	101 (28)	14 (22)
CCB	Corpus Christi Bay	TX	69 (31)	17 (20)
CP	Crystal-Pithlachascotee	FL	201 (18)	93 (3)
EMS	East Mississippi Sound	MS/AL	129 (22)	13 (26)
ES	Econfina-Steinhatchee	FL	57 (32)	6 (34)
FB	Florida Bay	FL	420 (12)	9 (31)
FK	Florida Keys	FL	7 (39)	50 (10)
GB	Galveston Bay	TX	625 (7)	80 (4)
LLM	Lower Laguna Madre	TX	270 (15)	14 (23)
MB	Matagorda Bay	TX	189 (19)	13 (24)
MER	Mermentau River	LA	2,184 (2)	53 (8)
MR	Mississippi River	LA	108 (27)	3 (37)
MO	Mobile Bay	AL	465 (10)	22 (17)
NTTI	North Ten Thousand Islands	FL	1,102 (6)	21 (18)
PAB	Pensacola Bay	FL	115 (25)	20 (19)
POB	Perdido Bay	AL/FL	53 (33)	11 (29)
RB	Rookery Bay	FL	38 (35)	33 (15)
SL	Sabine Lake	TX/LA	565 (8)	39 (11)
SAB	San Antonio Bay	TX	120 (24)	7 (33)
SB	Sarasota Bay	FL	18 (37)	51 (9)
STTI	South Ten Thousand Islands	FL	1,190 (5)	3 (38)
STB	St. Andrew Bay	FL	92 (29)	16 (21)
SR	Suwannee River	FL	249 (16)	12 (27)
TB	Tampa Bay	FL	50 (34)	106 (2)
TTB	Terrebonne/Timbalier Bays	LA	406 (13)	36 (14)
ULM	Upper Laguna Madre	TX	245 (17)	12 (28)
W	Waccasassa	FL	152 (21)	3 (36)
WMS	West Mississippi Sound	LA/MS	1,417 (4)	68 (6)

2.5 | Identifying future tidal saline wetlands

To identify future tidal saline wetlands, we used the identified tidal saline wetland threshold elevation and the sea level rise increment for each of three sea level rise scenarios (0.5, 1.0 and 1.5 m by 2100; Enwright et al., 2015, 2016). The 0.5-m "Intermediate-Low", 1.0-m "Intermediate" and 1.5-m "Intermediate-High" sea level rise scenarios were selected from a recent report on sea level rise scenarios for

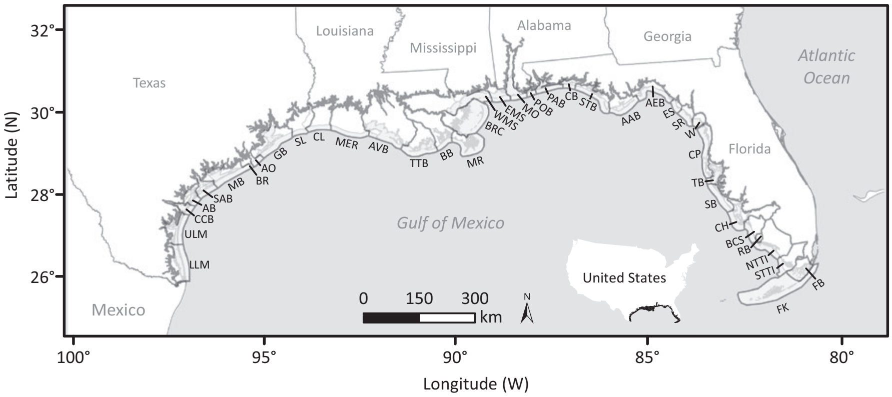

FIGURE 1 Study extent showing the 39 focal estuaries along the northern Gulf of Mexico coast (United States). See Table 1 for estuary codes. Darker grey lines indicate estuary boundaries whereas the lighter grey lines within estuaries represent the coastline and state boundaries

the United States (Sweet et al., 2017). We assumed that the regional elevation thresholds identified using contemporary data would remain constant into the future.

2.6 | Estuary-level analyses of migration and coastal squeeze

To identify spatial variation in the potential for wetland migration across northern Gulf of Mexico estuaries, we quantified the following information for each of the 39 estuaries: (a) the area available for the landward migration of tidal saline wetlands; and (b) the area of current urban development that may act as barrier to future migration (i.e. coastal squeeze). For comparative purposes, we scaled these two variables from 0 to 1 by dividing the estuary-level results by the maximum value for all estuaries. We assumed that current urban lands would be protected from inundation in the future and become barriers to wetland landward migration; hence, the urban barrier to future migration designation consisted of cells that were classified as currently urban and low enough in the landscape that they would have been available for wetland migration if they were not urban. For these cells, we assume that future anthropogenic activities (e.g. levee construction) will prevent future wetland migration. In contrast, lands that were classified as being available for future wetland landward migration consisted of cells that were not urban and also not constrained by adjacent levees or natural topographic barriers as described in Enwright et al. (2015, 2016).

For the 1-m sea level rise scenario, we created a bivariate plot that illustrates the relative potential for wetland migration as well as the relative potential for urban barriers to prevent wetland migration for each estuary. To elucidate and compare the amount of area affected, we produced similar bivariate plots with area-based axes. For these latter analyses, we grouped estuaries by state (Texas, Florida, and one category for Louisiana, Mississippi and Alabama) and compared three sea level rise scenarios (0.5-, 1.0-, and 1.5-m sea level rise by 2100) for each group. We also used the area-based results to create maps that depict the potential for landward migration and coastal squeeze. Esri ArcGIS 10.4.1 (Environmental Systems Research Institute, Redlands, CA, USA) was used to create maps and conduct all spatial analyses. Bivariate plots were created in R (R Core Team, 2017).

3 | RESULTS

Our analyses illustrate differences in the potential for landward wetland migration and coastal squeeze across northern Gulf of Mexico estuaries (Figures 2 and 3). Under the 1.0-m sea level rise scenario, the potential for landward wetland migration is highest in estuaries in low-sloping, coastal Louisiana and southern Florida (Figures 2a and 3; Table 1). For landward migration potential, the Atchafalaya/Vermilion Bays (AVB; 3,676 km^2; 20%), Mermentau River (MER; 2,184 km^2; 12%) and Barataria Bay (BB; 1,664 km^2; 9%) estuaries are the highest ranking and account for 42% of the total landward migration expected in the study area (Figure 3; Table 1). The West Mississippi Sound (WMS), South Ten Thousand Islands (STTI) and North Ten Thousand Islands (NTTI) estuaries ranked fourth, fifth and sixth respectively (Figure 3; Table 1). The relative rankings of estuaries by wetland migration potential under the 0.5- and 1.5-m sea level rise scenarios are similar to the 1.0-m sea level rise scenario; however, the amount of area affected is lower and higher respectively (Figures 4–6).

Across the Gulf of Mexico, there is high variation in the amount of low-lying urban lands that are expected to impede future wetland migration (Figures 2b and 3; Table 1). The estuaries along Florida's south-central coast, from Homosassa Springs to Naples, are highly developed and contain a large amount of low-lying urban land that is expected to limit landward migration of wetlands (Figure 2b). In terms of area, the Charlotte Harbor (CH), Tampa Bay (TB) and Crystal-Pithlachascotee (CP) estuaries contain the highest potential barriers to wetland migration (160 km^2 [13%], 106 km^2 [9%] and 93 km^2 [8%] respectively, under the 1.0-m sea level rise scenario; Figure 3; Table 1). Outside of Florida, urban barriers to migration are high in the Galveston Bay (GB) estuary due to urban sprawl of the greater Houston area into low-lying areas (80 km^2; 6%; Figure 3; Table 1). The Atchafalaya/Vermilion Bays (AVB) and West Mississippi Sound (WMS) estuaries ranked fifth and sixth, respectively, in terms of urban barriers to migration (70 and 68 km^2, and 6% and 5% respectively; Figure 3; Table 1). Altogether, these six estuaries account for 46% of the total amount of land in the study area where urban barriers are expected to constrain wetland migration (Table 1). For coastal squeeze, the relative rankings of estuaries under the 0.5- and 1.5-m sea level rise scenarios are

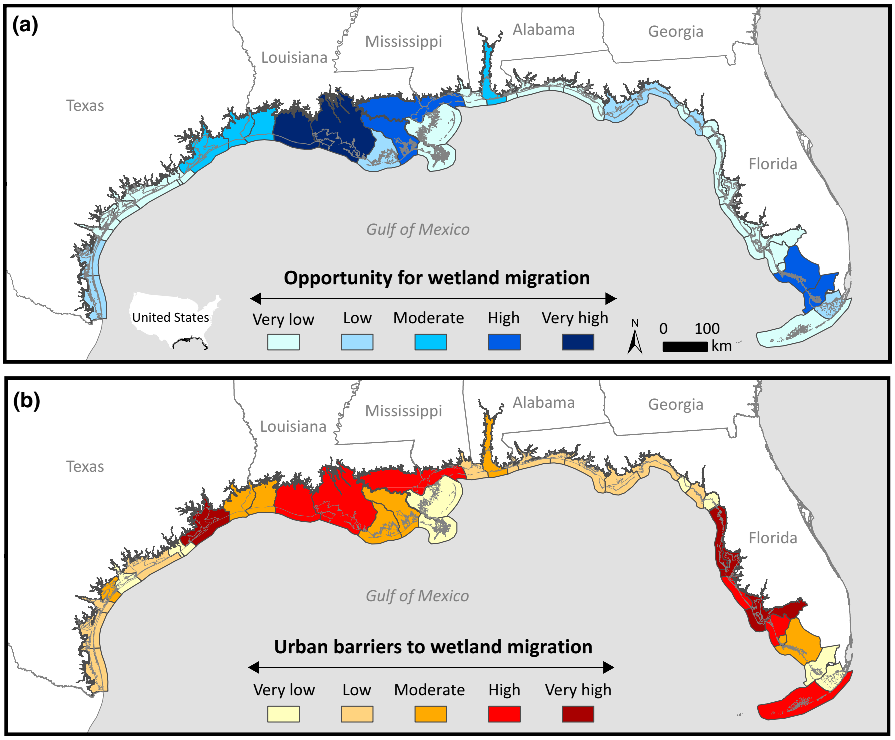

FIGURE 2 For a 1-m sea level rise "by 2100" scenario, the estuary-specific: (a) area available for landward migration of tidal saline wetlands; and (b) area of low-lying urban lands that are expected to prevent landward migration of tidal saline wetlands. Note that some estuaries have both a large amount of land available for wetland migration and a large amount of land where urban barriers are expected to prevent migration. For (a), the categories include: Very Low (0–229 km²), Low (230–459 km²), Moderate (460–918 km²), High (919–1,837 km²) and Very High (1,838–3,676 km²). For (b), the categories include: Very Low (0–9 km²), Low (10–19 km²), Moderate (20–39 km²), High (40–79 km²) and Very High (80–160 km²) [Colour figure can be viewed at wileyonlinelibrary.com]

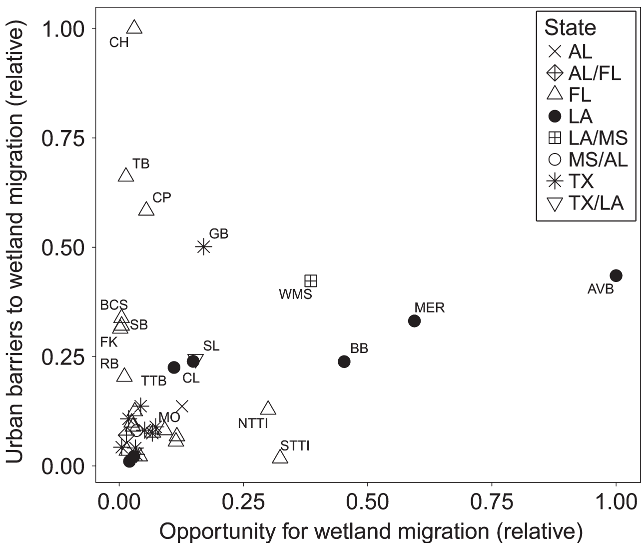

FIGURE 3 For a 1-m sea level rise by 2100 scenario, the estuary-specific relative area available for landward migration of tidal saline wetlands versus the relative area of low-lying urban lands that are expected to prevent landward migration of tidal saline wetlands. Estuary codes are in Table 1

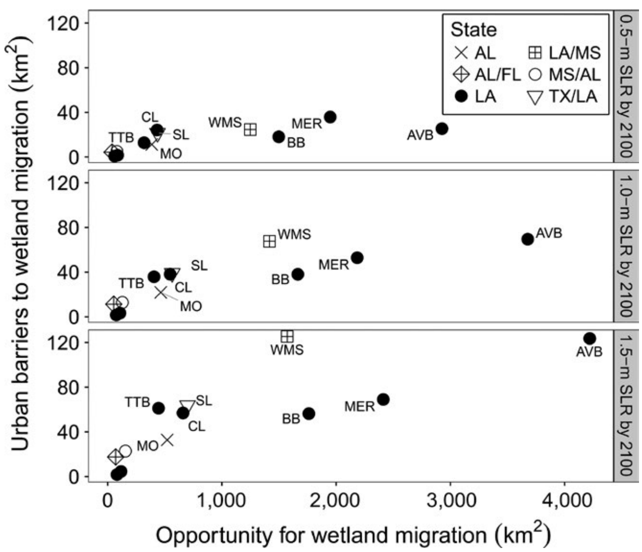

FIGURE 4 For estuaries within and bordering the states of Louisiana, Mississippi and Alabama (United States), the estuary-specific area available for landward migration of tidal saline wetlands versus the area of low-lying urban lands that are expected to prevent landward migration of tidal saline wetlands, for 0.5-, 1.0- and 1.5-m sea level rise (SLR) by 2100 scenarios. Estuary codes are in Table 1

generally similar to the 1.0-m sea level rise scenario; the amount of landward migration that is expected to be prevented by urban barriers is lower and higher respectively (Figures 4–6). However, under the higher sea level rise scenario, these results reveal certain estuaries where the urban barriers to migration will greatly increase (e.g. see Atchafalaya/Vermilion Bays [AVB] and West Mississippi Sound [WMS] in Figure 4, Galveston Bay [GB] in Figure 5 and Charlotte Harbor [CH] in Figure 6).

4 | DISCUSSION

Although coastal scientists have long recognized that landward migration corridors are an important strategy for maximizing the adaptive capacity of coastal wetlands in response to sea level rise (Scavia et al., 2002; Titus, 1986, 1998; Williams, Pinzon, et al., 1999; Woodroffe et al., 2016), data limitations in many estuaries have

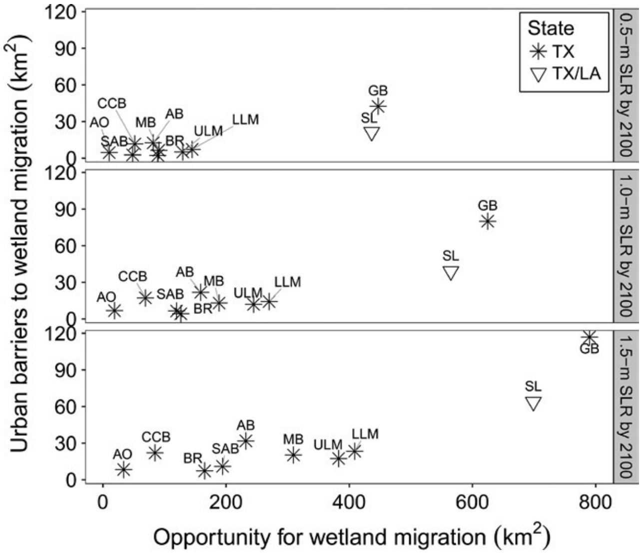

FIGURE 5 For estuaries within and bordering the state of Texas (United States), the estuary-specific area available for landward migration of tidal saline wetlands versus the area of low-lying urban lands that are expected to prevent landward migration of tidal saline wetlands, for 0.5-, 1.0- and 1.5-m sea level rise (SLR) by 2100 scenarios. Estuary codes are in Table 1

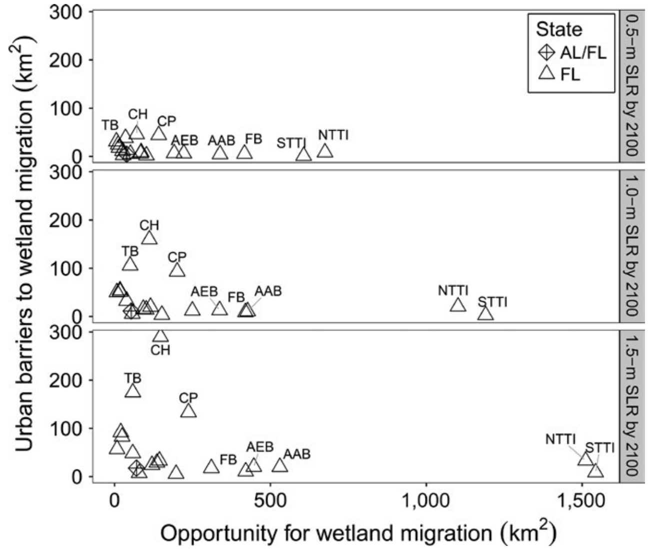

FIGURE 6 For estuaries within and bordering the state of Florida (United States), the estuary-specific area available for landward migration of tidal saline wetlands versus the area of low-lying urban lands that are expected to prevent landward migration of tidal saline wetlands, for 0.5-, 1.0- and 1.5-m sea level rise (SLR) by 2100 scenarios. Estuary codes are in Table 1

hindered efforts to quantify the potential for landward migration and coastal squeeze. In the past decade, the quality and availability of relevant elevation, tidal datum, coastal wetland and land use data have been rapidly improving (Buffington et al., 2016; Enwright et al., 2018; Medeiros et al., 2015; Passeri et al., 2015). As a result, there has been a large increase in the number of studies that have quantified landward migration and/or coastal squeeze. Most of these studies have been conducted in Australia and the United States, but the potential for landward migration has also been examined along the coasts of Martinique, the United Kingdom, Germany, Kenya and Canada (Table 2). Some of these studies have focused upon the effects of sea level rise on habitat for fish and wildlife species (e.g. Torio & Chmura, 2015; Traill et al., 2011), while others have examined the implications for certain ecosystem services (e.g. Craft et al., 2009; Feagin, Martinez, Mendoza-Gonzalez, & Costanza, 2010; Runting et al., 2017; Yoskowitz et al., 2017).

Most studies have focused on landward migration within a particular estuary, but several studies have included assessments conducted at regional scales (Doyle et al., 2010; Enwright et al., 2016; Geselbracht, Freeman, Birch, Brenner, & Gordon, 2015). For example, in a comparison of 14 estuaries along the Pacific coast of the continental United States, Thorne et al. (2018) identified estuaries where future wetland losses are expected to be large. These regional assessments play an important role because they enable resource managers to identify priority areas following comparison of the potential for wetland landward migration and coastal squeeze across cities, counties, estuaries and/or states. Ideally, regional analyses should be followed by customized models developed to address a specific local decision. Due to local hydrologic, geomorphic and biotic variation, the utility of wetland landward migration models is often improved when the spatial extent is limited to smaller areas where high-resolution and locally relevant data are available (Doyle, Chivoiu, & Enwright, 2015; Passeri et al., 2015).

One of our primary objectives in this study was to compare the capacity of the estuaries along the northern Gulf of Mexico coast to accommodate landward migration. Our regional-scale comparison identifies certain estuaries where the potential for landward migration and coastal squeeze are high (see colour intensity of estuaries in Figure 2, see isolated estuaries in Figures 3–6 and see low estuary ranks in Table 1). Those analyses indicate that the potential for landward migration of wetlands is very high in the following six estuaries: (1) Atchafalaya/Vermilion Bays (AVB; Louisiana); (2) Mermentau River (MER; Louisiana); (3) Barataria Bay (BB; Louisiana); (4) West Mississippi Sound (WMS; Louisiana/Mississippi); (5) South Ten Thousand Islands (STTI; south Florida); and (6) North Ten Thousand Islands (NTTI; south Florida). These are estuaries where ecological impacts and transformations due to sea level rise are expected to be very large. Within each of these six estuaries, large areas of land will be affected by sea level rise as tidal saline wetlands migrate landward and replace upslope and upriver ecosystems (Doyle et al., 2010; Flower, Rains, & Fitz, 2017; Howard et al., 2017; Krauss, From, Doyle, Doyle, & Barry, 2011; Langston et al., 2017; Williams, Pinzon, et al., 1999). Hence, these are estuaries where there is much value in future-focused and climate-smart conservation planning efforts that promote landward migration and also manage habitats at risk of conversion to tidal saline wetlands.

In addition to identifying estuaries with high potential to accommodate landward migration, we also sought to identify estuaries where the potential for coastal squeeze is high. In these estuaries, low-lying urban lands are expected to prevent the

TABLE 2 Studies that have investigated the potential for wetland landward migration and/or coastal squeeze. For each study, we show the country, spatial scale and a subtopic that was emphasized

Study	Country	Spatial scale	Emphasized subtopic
Alizad, Hagen, Morris, Bacopoulos, et al. (2016)	United States	Portion of estuary	Dynamic modelling
Alizad, Hagen, Morris, Medeiros, et al. (2016)	United States	Single estuary	Dynamic modelling
Craft et al. (2009)	United States	Multiple estuaries	Ecosystem services
Di Nitto et al. (2014)	Kenya	Portion of estuary	Adaptation strategies
Doyle et al. (2010)	United States	Regional	Ecosystem responses
Enwright et al. (2016)	United States	Regional	Barriers & opportunities
Feagin et al. (2010)	United States	Portion of estuary	Economic tradeoffs
Flower et al. (2017)	United States	Multiple estuaries	Everglades National Park
Geselbracht, Freeman, Kelly, Gordon, and Putz (2011)	United States	Single estuary	Conservation planning
Geselbracht et al. (2015)	United States	Multiple estuaries	Adaptation planning
Krolik-Root, Stansbury, and Burnside (2015)	United Kingdom	Single estuary	Coastal zone management
Linhoss, Kiker, Shirley, and Frank (2014)	United States	Portion of estuary	Conservation planning
Mills et al. (2016)	Australia	Portion of estuary	Conservation planning
Rogers et al. (2014)	Australia	Single estuary	Ecosystem responses
Runting et al. (2017)	Australia	Portion of estuary	Conservation planning
Schile et al. (2014)	United States	Portion of estuary	Conservation planning
Schleupner (2008)	Martinique	National	Coastal zone management
Sterr (2008)	Germany	National	Coastal zone management
Stralberg et al. (2011)	United States	Single estuary	Conservation planning
Thorne et al. (2018)	United States	Regional	Ecosystem responses
Titus et al. (2009)	United States	Regional	Shoreline protection
Torio and Chmura (2013)	United States/Canada	Multiple marshes	Conservation planning
Torio and Chmura (2015)	United States	Multiple marshes	Fish habitat conservation
Traill et al. (2011)	Australia	Portion of estuary	Threatened native rodent
Yoskowitz et al. (2017)	United States	Single estuary	Ecosystem services

landward migration of coastal wetlands, which could result in wetland loss if the existing wetlands are not able to adjust to sea level rise via vertical elevation change. We assumed that shoreline protection infrastructure would be used to protect these low-lying urban communities (Gittman et al., 2015; Hill, 2015; Sutton-Grier et al., 2015). Our analyses identified the following six estuaries as having a large amount of urban land that is expected to impede wetland migration: (1) Charlotte Harbor (CH; Florida); (2) Tampa Bay (TB; Florida); (3) Crystal-Pithlachascotee (CP; Florida); (4) Galveston Bay (GB; Texas); (5) Atchafalaya/Vermilion Bays (AVB; Louisiana); and (6) West Mississippi Sound (WMS; Louisiana/Mississippi). Note that the latter three estuaries are estuaries that have both a large amount of land available for wetland migration and a large amount of land where urban barriers are expected to prevent migration. The first three estuaries in Florida are highly urbanized (Terando et al., 2014), and have very little land available for landward migration. Hence, under higher rates of sea level rise where existing wetlands are not able to keep pace with sea level rise via vertical adjustments, the potential for coastal wetland loss (i.e. coastal squeeze) in these estuaries is very high. Urban lands that are expected to serve as barriers to migration are highly vulnerable to sea level rise. Within the identified highly urbanized estuaries, we expect that efforts to protect these low-lying, urban lands and/or respond to sea level rise-related flooding events will be expensive. Climate-smart conservation efforts in these urban estuaries, including the facilitation of landward migration through land protection or the removal of existing infrastructure, will require a greater upfront cost because property values are often high (Feagin et al., 2010; Runting et al., 2017). However, the indirect cost of failing to preserve landward migration corridors may be much higher. Conservation efforts that protect landward migration corridors today and maximize the future ability of coastal wetlands to adapt to sea level rise will enable future generations to benefit from the many ecosystem goods and services they provide.

5 | CONCLUSIONS

In the face of accelerated sea level rise and rapid coastal urbanization, coastal managers and conservation planners are increasingly challenged to develop strategies that will increase the adaptive capacity of coastal ecosystems and maintain important ecosystem goods and services for future generations. Regional-scale comparisons of the potential for wetland landward migration and coastal squeeze can help coastal decision makers identify estuaries where climate change adaptation efforts are likely to be most important. Coastal wetland ecosystems can protect shorelines, sequester carbon, reduce flooding, provide seafood, create recreational opportunities, and support valuable fish and wildlife habitat. Climate-smart conservation practices, including the identification, protection and management of landward migration corridors can minimize future wetland loss, protect ecosystem services for future generations, and reduce harmful sea level rise related impacts to coastal communities.

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AUTHORS' CONTRIBUTIONS

S.M.B., N.M.E., K.T.G. and M.J.O. conceived the ideas and designed methodology; N.M.E., K.T.G. and S.M.B. collected the data; S.M.B., K.T.G. and N.M.E. analysed the data; S.M.B. and M.J.O. led the writing of the first manuscript draft. All authors contributed critically to subsequent drafts and gave final approval for publication.

DATA ACCESSIBILITY

Data available from the U.S. Geological Survey's ScienceBase Catalog. https:/doi.org/10.5066/F7S75F7K (Borchert, Osland, Enwright, & Griffith, 2018).

ORCID

Sinéad M. Borchert http://orcid.org/0000-0002-6665-7115

Michael J. Osland http://orcid.org/0000-0001-9902-8692

Nicholas M. Enwright http://orcid.org/0000-0002-7887-3261

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