FINAL PROJECT REPORT
SOUTHEAST CLIMATE ADAPTATION SCIENCE CENTER PROJECT

1. ADMINISTRATIVE

Principal Investigator:
Michael J. Osland
U.S. Geological Survey, Wetland and Aquatic Research Center
700 Cajundome Blvd.
Lafayette, LA 70506
Phone: 337-266-8664; email: mosland@usgs.gov

Project Title:
Identifying the Ecological and Management Implications of Mangrove Migration in the Northern Gulf of Mexico

SECASC Project Number:
039

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$51,604

2. PUBLIC SUMMARY

Climate change is transforming ecosystems and affecting ecosystem goods and services. Along the Gulf of Mexico and Atlantic coasts of the southeastern United States, the frequency and intensity of extreme freeze events greatly influences whether coastal wetlands are dominated by freeze-sensitive woody plants (mangrove forests) or freeze-tolerant grass-like plants (salt marshes). In response to warming winters, mangroves have been expanding and displacing salt marshes at varying degrees of severity in parts of north Florida, Louisiana, and Texas. As winter warming accelerates, mangrove range expansion is expected to increasingly modify wetland ecosystem structure and function. Because there are differences in the ecological and societal benefits that salt marshes and mangroves provide, coastal environmental managers are challenged to anticipate effects of mangrove expansion on critical wetland ecosystem services, including those related to carbon sequestration, wildlife habitat, storm protection, erosion reduction, water purification, fisheries support, and recreation. This project produced information that is relevant to scientists and coastal resource managers working within the transition zone between mangrove forests and salt marshes. The two primary products are: (1) an investigation that leverages data and information from a community-curated data network called the Mangrove Migration Network to refine temperature thresholds for mangrove range expansion in a warming

climate; and (2) a review article that examines current understanding of the effects of mangrove range expansion and displacement of salt marshes on wetland ecosystem services, including those related to carbon sequestration, wildlife habitat, storm protection, erosion reduction, water purification, fisheries support, and recreation.

3. TECHNICAL SUMMARY

Climate change is transforming ecosystems and affecting ecosystem goods and services. Along the Gulf of Mexico and Atlantic coasts of the southeastern United States, the frequency and intensity of extreme freeze events greatly influences whether coastal wetlands are dominated by freeze-sensitive woody plants (mangrove forests) or freeze-tolerant grass-like plants (salt marshes). In response to warming winters, mangroves have been expanding and displacing salt marshes at varying degrees of severity in parts of north Florida, Louisiana, and Texas. As winter warming accelerates, mangrove range expansion is expected to increasingly modify wetland ecosystem structure and function. Because there are differences in the ecological and societal benefits that salt marshes and mangroves provide, coastal environmental managers are challenged to anticipate effects of mangrove expansion on critical wetland ecosystem services, including those related to carbon sequestration, wildlife habitat, storm protection, erosion reduction, water purification, fisheries support, and recreation. The two primary products are: (1) an investigation that leverages data and information from a community-curated data network called the Mangrove Migration Network to refine temperature thresholds for mangrove range expansion in a warming climate; and (2) a review article that examines current understanding of the effects of mangrove range expansion and displacement of salt marshes on wetland ecosystem services, including those related to carbon sequestration, wildlife habitat, storm protection, erosion reduction, water purification, fisheries support, and recreation.

4. PURPOSE AND OBJECTIVES

The two primary products are: (1) an investigation that leverages data and information from a community-curated data network called the Mangrove Migration Network to refine temperature thresholds for mangrove range expansion in a warming climate; and (2) a review article that examines current understanding of the effects of mangrove range expansion and displacement of salt marshes on wetland ecosystem services, including those related to carbon sequestration, wildlife habitat, storm protection, erosion reduction, water purification, fisheries support, and recreation. The following two subsections describe the purpose and objectives associated with these two products. Throughout this document, sentences that are italicized come directly from the corresponding journal article.

Purpose and objectives for Primary Product 1: Temperature thresholds for black mangrove (*Avicennia germinans*) freeze damage, mortality, and recovery in North America: refining tipping points for range expansion in a warming climate.

This information comes from the following journal article published in the Journal of Ecology: Osland, M. J., R. H. Day, C. T. Hall, L. C. Feher, A. R. Armitage, J. Cebrian, K. H. Dunton, A. R. Hughes, D. A. Kaplan, A. K. Langston, A. Macy, C. A. Weaver, G. H. Anderson, K. Cummins, I. C. Feller, and C. M. Snyder. 2020. Temperature thresholds for black mangrove (*Avicennia germinans*) freeze damage, mortality, and recovery in North America: refining tipping points for range expansion in a warming climate. Journal of Ecology 108:654-665.

Background, purpose, and objectives (from Osland et al. 2020, Journal of Ecology):
Climate change is altering the frequency and intensity of climate extremes (USGCRP 2017), which is modifying the distribution of organisms and the structure and functioning of ecosystems (Parmesan et al. 2000, Jentsch et al. 2007, Smith 2011, Pecl et al. 2017, USGCRP 2018). In addition to rising mean temperatures, climate warming is leading to an increase in the frequency and intensity of record maximum temperatures (e.g., extreme heat waves) as well as a decrease in the frequency and intensity of record minimum temperatures (e.g., extreme freezing and chilling temperatures). For some ecosystems, comparatively small changes in the frequency or intensity of climate extremes can produce abrupt and comparatively large ecological changes (i.e., ecological regime shifts; Scheffer and Carpenter 2003, Folke et al. 2004). These rapid ecological transformations are often governed by climatic thresholds, and ecologists are increasingly challenged to identify where and when climatic-controlled tipping points may be crossed (Bahn et al. 2014, Frank et al. 2015, Kayler et al. 2015, Ratajczak et al. 2018). Here, we examined freezing temperature thresholds that control the range expansion of tropical woody plants (i.e., mangroves) in coastal wetland ecosystems of North America. Advancing understanding of plant sensitivity thresholds to freezing and chilling temperatures can help scientists and natural resource managers better anticipate and prepare for ecological transformations in a warming climate.

Most tropical organisms are sensitive to freezing and chilling temperatures (Sakai and Larcher 1987, Woodward 1987, Box et al. 1993, Larcher 2003, Boucek et al. 2016). Therefore, winter temperature regimes control the poleward distribution of most tropical biomes (Holdridge 1967, Whittaker 1970, Greller 1980). For example, in south Florida (USA), the northern range limits of tropical plant species are typically controlled by the frequency and intensity of freezing and/or chilling events, which are extreme climatic events that can kill plants and transform ecosystems. By the end of the century, warming winter temperature regimes due to anthropogenic climate change are expected to allow some freeze-sensitive tropical species to expand poleward into temperate biomes (Box et al. 1999, Vergés et al. 2014, Pecl et al. 2017, Carter et al. 2018). In coastal wetlands, warming winter extremes are expected to allow freeze-sensitive mangrove forests to expand into freeze-tolerant salt marsh ecosystems (Cavanaugh et al. 2014, Saintilan et al. 2014, Osland et al. 2017b). Mangrove forest range expansion and the potential replacement of salt marsh ecosystems is a landscape-level, ecological transformation that will have large ecological and societal ramifications (Guo et al. 2017, Kelleway et al. 2017). Hence, there is a need to advance understanding of the temperature thresholds that govern mangrove range expansion.

Winter temperatures greatly influence the ecological structure, function, and distribution of mangrove forests in North America, Asia, Australia, New Zealand, South Africa, and eastern South America; however, the ecological influence of winter temperature extremes (i.e., discrete freezing and/or chilling events) is strongest in eastern and central North America (Stuart et al. 2007, Lovelock et al. 2016, Osland et al. 2017b, Cavanaugh et al. 2018). In North America, the black mangrove (Avicennia germinans; hereafter, black mangrove or A. germinans) is the most freeze-tolerant mangrove species. Of the three common mangrove species in the region, A. germinans is the species that extends furthest north where it expands and contracts in response to the absence or presence of winter air temperature extremes, respectively (Sherrod and McMillan 1985, Giri and Long 2014, Rodriguez et al. 2016, Osland et al. 2018). Within the past decade, several studies have demonstrated that winter temperature thresholds determine the northern range limit of A. germinans in eastern and central North America (Osland et al. 2013, *Cavanaugh et al. 2014, Cavanaugh et al. 2015, Osland et al. 2017a, Osland et al. 2017b). Despite the use of divergent data sources, methods, and mangrove response variables, the temperature thresholds identified in those studies span a range between -3 to -9°C. Most prior studies have relied on remotely-sensed data of spatial or temporal changes in mangrove coverage; hence, there is a need for field-based freeze response studies that refine these temperature thresholds for mangrove biological responses to freezing.*

In particular, there is a need to identify and contrast temperature thresholds for A. germinans freeze damage, mortality, and biomass recovery. Regenerative buds allow A. germinans individuals to resprout and recover quickly from aboveground freeze damage (Tomlinson 1986). Thus, distinguishing temperatures that result in short-term vs. long-term damage would provide critical information for advancing understanding of freeze effects and for predicting future range dynamics. Leaf damage, for example, is potentially just a short-term freeze effect if leaf and biomass recovery occur rapidly within the first post-freeze growing season. In contrast, tree mortality is a longer-term freeze effect that can affect ecosystem stability if mangroves are removed from the system for multiple years or decades.

In this study, we integrated data from 38 sites spread across the mangrove range edge in the Gulf of Mexico and Atlantic coasts of the southeastern United States, including data from a regional collaborative network — the Mangrove Migration Network. A recent freeze event provided a unique opportunity to refine temperature thresholds that ultimately regulate the speed of mangrove expansion into coastal salt marshes. The 2018 freeze event affected 60% of the 38 sites, with minimum temperatures ranging from 0 to -7°C. Here we used temperature and vegetation data from before and after the freeze to quantify specific temperature thresholds for A. germinans leaf damage, mortality, and biomass recovery.

Purpose and objectives for Primary Product 2: The impacts of mangrove range expansion on wetland ecosystem services in the southeastern United States: current understanding, knowledge gaps, and emerging research needs

This information comes from the following journal article, which has been published in Global Change Biology:

Osland, M. J., A. R. Hughes, A. R. Armitage, S. H. Scyphers, J. Cebrian, S. H. Swinea, C. H. Shepard, M. S. Allen, L. C. Feher, J. A. Nelson, C. L. O'Brien, C. R. Sanspree, D. L. Smee, C. M. Snyder, A. P. Stetter, P. W. Stevens, K. M. Swanson, L. H. Williams, J. M. Brush, J. Marchionno, and R. Bardou. 2022. The impacts of mangrove range expansion on wetland ecosystem services in the southeastern United States: current understanding, knowledge gaps, and emerging research needs. https://doi.org/10.1111/gcb.16111

Background, purpose, and objectives (Osland et al. 2022, Global Change Biology):

In response to warming air and ocean temperatures, temperate ecosystems are being transformed by tropical organisms whose range limits are expanding poleward (Vergés et al. 2014, Osland et al. 2021). In North America, the transition between tropical and temperate ecosystems is greatly influenced by the frequency and intensity of winter temperature extremes, as the northern range limits of most tropical organisms are governed by extreme freezing temperatures (Boucek et al. 2016, Osland et al. 2021). Climate change is producing warmer winters with fewer extreme freeze events (USGCRP 2017, Carter et al. 2018), which allows tropical organisms to move north of their current range limits. Coastal environmental managers *near tropical-temperate transitions are increasingly faced with making natural resource management decisions related to the range expansion of these tropical organisms. Thus, there is a need to advance understanding of the ecological implications of range expansion. In this communication, we review the literature on the ecological and societal impacts of warming winters and tropical range expansion within coastal wetland ecosystems in the southeastern United States, where tropical mangrove forests are expected to invade and ultimately displace salt marshes as they continue to move north (Osland et al. 2013, Cavanaugh et al. 2014, Gabler et al. 2017).*

Mangrove forests and salt marshes are both highly productive coastal wetland ecosystems that occupy very similar geomorphic positions within tidal saline environments (Cahoon et al. 2020). Thus, there are many similarities in the ecosystem goods and services provided by these tree- and grass-dominated coastal wetlands. Both ecosystems are frequently ranked among the most valuable ecosystems on the planet (Costanza et al. 2014). In addition to providing habitat for fish and wildlife species, mangrove forests and salt marshes sequester large quantities of CO_2*, protect coastlines from storms, reduce erosion, improve water quality, support productive fisheries, and provide recreational opportunities (Barbier et al. 2011).*

Despite the similarities in the ecosystem goods and services provided by mangrove forests and salt marshes, there are trade-offs and differences in the magnitude, spatiotemporal scale, and characteristics of the good or service provided (Ewel et al. 1998, Barbier et al. 2011, Kelleway et al. 2017). Research on the ecological effects of mangrove expansion in the southeastern United States has accelerated rapidly in recent years. Here, we synthesize this recent knowledge to review current understanding of the effects of mangrove range expansion and displacement of salt marsh on the ecosystem services provided by coastal wetlands in the southeastern United States. We begin with a background section that describes the history and expected future of mangrove expansion within this region. Next, based on the current state of knowledge, we review changes in wetland ecosystem services that occur as salt marshes are replaced by mangroves. We also identify critical knowledge gaps and emerging research needs for improving our understanding and management of mangrove expansion and salt marsh displacement in the southeastern United States.

5. ORGANIZATION AND APPROACH

The following subsections describe the organization and approach for the project's two primary products.

Organization and approach for Primary Product 1: Temperature thresholds for black mangrove (*Avicennia germinans*) freeze damage, mortality, and recovery in North America: refining tipping points for range expansion in a warming climate.

This information comes from the following journal article published in the Journal of Ecology: Osland, M. J., R. H. Day, C. T. Hall, L. C. Feher, A. R. Armitage, J. Cebrian, K. H. Dunton, A. R. Hughes, D. A. Kaplan, A. K. Langston, A. Macy, C. A. Weaver, G. H. Anderson, K. Cummins, I. C. Feller, and C. M. Snyder. 2020. Temperature thresholds for black mangrove (*Avicennia germinans*) freeze damage, mortality, and recovery in North America: refining tipping points for range expansion in a warming climate. Journal of Ecology 108:654-665.

Description of approach (from Osland et al. 2020, Journal of Ecology):

Study Area and Overview

Our study was conducted near the northern range limit of mangrove species along the Gulf of Mexico and Atlantic Ocean coasts of North America. There are three common mangrove species in this region: A. germinans (black mangrove — the focal species for this study), Rhizophora mangle (red mangrove), and Laguncularia racemosa (white mangrove). Near these northern range limits, winter air temperature extremes greatly influence mangrove physiology (Stuart et al. 2007, Madrid et al. 2014, Cook-Patton et al. 2015, Hayes et al. 2020), reproduction (Dangremond and Feller 2016), and architecture (Doughty et al. 2016, Yando et al. 2016, Feher et al. 2017, Simpson et al. 2017). Freeze-tolerant salt marshes dominate areas that are too cold for mangrove forests, while mangroves dominate coastal reaches with mild winters. Hence, coastal wetlands in this region contain a dynamic mosaic of mangrove forest and salt marsh plants (Perry and Mendelssohn 2009, Langston et al. 2017, Weaver and Armitage 2018, Coldren et al. 2019, Macy et al. 2019).

This study was made possible by the collaborative contributions of scientists spread across the study area. Our analyses incorporate data from a total of 38 sites collected by nine organizations in three states and along two coasts (Fig. 1). While some sites are part of a coordinated network that was in place before the freeze event (i.e., the Mangrove Migration Network), other sites were strategically added after the freeze event to capture additional freeze effects in targeted locations. Due to differences in the timing and form of data inputs, there is some variation in plot size, number of trees measured per plot, number of plots per site, and the amount and type of temperature and vegetation data recorded at each site. For sites with tree- or plot-level data, the vegetation data were converted from tree-level data and/or plot-level data to site-level data using means of trees within plots and means of plots within sites. All subsequent analyses used site-level means.

Study Sites-Mangrove Migration Network

Ecologically-relevant freeze events do not occur every year in the study region (Stuart et al. 2007, Osland et al. 2017b). Therefore, knowledge of mangrove freeze damage and recovery dynamics has developed primarily from opportunistic observations conducted following freeze events (Lonard and Judd 1991, Olmsted et al. 1993, Ross et al. 2009). To prepare for future freeze events and better quantify the effects of winter temperature extremes upon mangroves near their northern range limit, a group of scientists working across the northern Gulf of Mexico launched the Mangrove Migration Network (MMN). This collaborative effort established a network of sites in 2014 along the northern range of mangrove distribution where plant community measurements could be collected consistently in concert with temperature measurements. Here, we incorporate data from seven MMN sites — three in Texas (Port Aransas, Galveston, and Bolivar), two in Louisiana (Port Fourchon and Chandeleur Island), and two in Florida (St. Joseph Bay and Cedar Key). At each MMN site, we established four to eight 100-m^2 plots during the winter of 2014-2015. Within each MMN plot, we tagged a total of six trees for monitoring. We collected additional vegetation data at each site, but the MMN vegetation data presented here come exclusively from pre- and post-freeze measurements of the tagged trees.

Study Sites Outside of the Mangrove Migration Network

In addition to the seven MMN sites, our analyses incorporated data from 31 non-MMN sites. Following the 2018 freeze event, the non-MMN sites were included to incorporate mangrove leaf damage, mortality, and recovery data from additional locations along: (1) the Atlantic coast of Florida (nine sites between Cape Canaveral and St. Augustine); (2) the Gulf of Mexico coast of

Florida (five sites between Cedar Key and Clearwater); and (3) Louisiana (two sites near Bay Junop and 15 sites between Golden Meadow and Port Fourchon). The 15 non-MMN sites in Louisiana between Golden Meadow and Port Fourchon span a land-ocean temperature gradient. Hereafter, we refer to these as the Louisiana gradient sites. During freeze events, mangrove damage and mortality are typically higher closer to Golden Meadow because temperatures are colder on the land side of this land-ocean temperature gradient (Osland et al. 2017a, Osland et al. 2019, Pickens et al. 2019). Conversely, mangrove damage and mortality are typically lower near and beyond Port Fourchon, where temperatures are warmer due to the proximity to the Gulf of Mexico.

The January 2018 freeze event

January 2018 was a comparatively cold month in the southeastern United States, with several events producing freezing temperatures along the north-central Gulf of Mexico coast. The coldest event — the one with temperatures cold enough to lead to mangrove freeze damage and mortality — occurred between 17-19 January 2018. The Northern Texas, Louisiana, Mississippi, Alabama, and northwest Florida coasts experienced the coldest temperatures during this event. On 19 January 2018 (i.e., the day after the focal freeze event for this study), RHD, MJO, and LCF traveled to the Port Fourchon area to evaluate the impacts of the freeze. The patterns of leaf damage enabled us to confidently attribute the damage and mortality to the event that occurred between 17-19 January 2018. The damage at the Port Fourchon site prompted the request for data collection at the other 37 sites.

Freeze Leaf Damage Data

Freeze-induced leaf damage was measured at 23 sites. For each of these sites, we determined the mean A. germinans leaf damage (%). This value represents the percent of leaves that were damaged by freezing temperatures. Freeze-damaged A. germinans leaves quickly turn brown and eventually fall from the tree (Osland et al. 2015). We used the contrast between green (live) and brown (freeze-damaged) leaves to visually estimate percent leaf damage (i.e., brown leaf area divided by the sum of the brown leaf area and the green leaf area). The Port Fourchon MMN site was visited the day following the freeze event, which prompted the request for data collection at the other 37 sites.

Freeze Mortality Data

We determined freeze mortality at 35 sites. At 15 Louisiana gradient sites and three MMN sites (Galveston, Bolivar, and Port Fourchon), we used mortality data collected near the end of the first post-freeze growing season (i.e., October-December 2018) to calculate percent mortality (i.e., number of dead individuals divided by the total number of individuals). For the Anastasia site, percent mortality was calculated using data collected in April 2019. We assigned a mortality value of 0% to the remaining 16 sites where leaf damage was less than 5% (i.e., where less than 5% of the leaves measured at the site were damaged); these sites did not have any freeze-induced mortality.

Freeze Biomass Recovery Data

Live but freeze-damaged A. germinans individuals will typically resprout vigorously from the base or stem of the plant. We quantified aboveground biomass recovery at 35 sites. At freeze-damaged sites, we determined pre- and post-freeze aboveground biomass of individual trees using an allometric equation that incorporates measurements of height and two perpendicular crown diameters (Osland et al. 2014). We determined the pre-freeze biomass using measurements of pre-freeze height and crown diameters. Post-freeze biomass was determined using the same measurements conducted near the end of the first post-freeze growing season.

For measurements of post-freeze biomass, we excluded any dead branches — only live portions of the plant were measured. We also measured the maximum height at which resprouting occurred (i.e., either from the base or the height of the tallest resprouting stem). At most freeze-damaged sites, percent biomass recovery was calculated as the 2018 end-of-growing season aboveground biomass divided by the pre-freeze aboveground biomass. For the Anastasia site, this calculation was determined using post-freeze data collected in April 2019. Our use of the term biomass recovery thus represents the fraction of the post-freeze biomass relative to the pre-freeze biomass and has a maximum value of 100%. At 16 sites where leaf damage was less than 5%, we assigned a recovery value of 100% because the mangroves at these sites had retained and grown beyond their pre-freeze biomass. Including these sites in the analyses enabled us to characterize the position of the asymptote for the temperature-biomass recovery relationship. At the Louisiana gradient sites, we did not have measurements conducted before the freeze. However, repeated measurements at the Port Fourchon MMN site indicate that, in the absence of a major storm, the freeze-damaged, dead branches remain on the tree during much or all of the first year following a freeze (MJO and RHD, personal observations and measurements). Thus, at Louisiana gradient sites, dead branches were used to quantify pre-freeze biomass, and live branches were used to quantify post-freeze biomass.

Temperature Data

Logger-based in situ temperature data were not available for all sites. Hence, for temperature data, we relied on a combination of logger-based data and gridded daily minimum temperate data produced by the PRISM Climate Group at Oregon State University (prism.oregonstate.edu) using the PRISM (Parameter-elevation Relationship on Independent Slopes Model) interpolation method (Daly et al. 2008). We chose the PRISM data because the PRISM model accounts for land-ocean temperature gradients (Daly et al. 2003, Daly et al. 2008, Daly et al. 2012). The resolution of the PRISM data was 2.5 arcmin (~4 km). We used site coordinates to extract the corresponding daily minimum temperature for each site from the gridded PRISM data for nineteen days (1-19 January 2018). For the freeze event (i.e., 17-19 January 2018), we used the site coordinates to extract the corresponding minimum temperature (i.e., the coldest temperature during the event) from the gridded PRISM data.

At six sites, we were able to obtain temperature data recorded using in situ temperature loggers. In 2014, we installed duplicate temperature loggers (HOBO U23-004; Onset Computer Corporation, Bourne, MA USA) at a height of 1-m aboveground within each MMN plot. Unfortunately, due to battery depletion and rodent damage, many of the temperature loggers installed at MMN sites were not operational during the 2018 freeze event. However, we were able to obtain logger-based temperature data from four MMN sites [Bolivar (two loggers), Port Fourchon (11 loggers), Chandeleur (four loggers), and St. Joseph Bay (three loggers)] and two non-MMN sites (one logger at each of the two Bay Junop sites). For these sites, we compiled daily logger-based and PRISM-based daily minimum temperature data for nineteen days (1-19 January 2018). For the freeze event that caused mangrove damage (i.e., 17-19 January 2018), we also determined the logger-based, event-specific minimum temperature (i.e., the coldest temperature recorded during the event). Then, we combined these event-specific logger-based data with the event-specific PRISM data to create a single dataset of the event-specific minimum temperature for all 38 sites. For the Galveston MMN site, which lacked logger data for this event, we used logger data from the nearby Bolivar MMN site, which is less than 5 km away and in a direction that is parallel to the coast (i.e., not across a land-ocean temperature gradient).

Data Analyses: Logger-based vs. PRISM-based temperatures

We developed a dataset that could be used to evaluate the relationship between the logger-based and PRISM-based temperature data. First, we used means to convert the logger-based temperature data to plot-level, site-level, and grid cell-level data. The two Bay Junop sites were located in the same grid cell. Hence, logger-based data from these two sites were averaged to produce a single grid cell-level mean. For each of five grid cells with logger data, we produced a dataset that contained logger-based and PRISM-based daily minimum temperature data for 1-19 January 2018. For each of these five grid cells, we used linear regression to evaluate the relationships between the logger-based and the PRISM-based temperature data. We also evaluated this relationship using combined data from all five grid cells.

Data Analyses: Temperature-Vegetation Thresholds

We used sigmoidal regression analyses to evaluate the relationships between the event-specific minimum temperature (i.e., the combined PRISM and logger dataset) and the following site-level response variables: (1) percent leaf damage; (2) percent mortality; and (3) percent biomass recovery. Regression analyses were conducted in Sigma Plot (Systat Software, San Jose, CA, USA). Spatial analyses were conducted in Esri ArcGIS (Environmental Systems Research Institute, Redlands, CA, USA).

Organization and approach for Primary Product 2: The impacts of mangrove range expansion on wetland ecosystem services in the southeastern United States: current understanding, knowledge gaps, and emerging research needs

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Osland, M. J., A. R. Hughes, A. R. Armitage, S. H. Scyphers, J. Cebrian, S. H. Swinea, C. H. Shepard, M. S. Allen, L. C. Feher, J. A. Nelson, C. L. O'Brien, C. R. Sanspree, D. L. Smee, C. M. Snyder, A. P. Stetter, P. W. Stevens, K. M. Swanson, L. H. Williams, J. M. Brush, J. Marchionno, and R. Bardou. 2022. The impacts of mangrove range expansion on wetland ecosystem services in the southeastern United States: current understanding, knowledge gaps, and emerging research needs. https://doi.org/10.1111/gcb.16111

This is a review article that contains input from coastal scientists and resource managers from across the region (i.e., Texas, Louisiana, Mississippi, Alabama, and Florida). The review examines current understanding of the effects of mangrove range expansion and displacement of salt marshes on wetland ecosystem services, including those related to carbon sequestration, wildlife habitat, storm protection, erosion reduction, water purification, fisheries support, and recreation. For the writing of the journal article, we invited 20 scientists from across the region to coauthor sections on the following topics: carbon sequestration, soil elevation change and vertical adjustments to sea-level rise, water quality: nutrient and sediment retention, coastal protection, coastal food webs and fisheries, insects and arthropod communities, avian communities, and recreation. We also organized meetings with resource managers, residents, and scientists regarding the ecological and management implications of mangrove range expansion. These conversations included 21 individuals (seven from Texas, six from Louisiana, and eight from Florida). The 20 coauthors of the review include individuals from the following 15 organizations, which represent a combination of federal, state, academic, and non-profit institutions in Texas, Louisiana, Mississippi, Alabama, and Florida: U.S. Geological Survey, Wetland and Aquatic Research Center, Lafayette, LA; Northeastern University Marine Science

Center, Nahant, MA; Department of Marine Biology, Texas A&M University at Galveston, Galveston, TX; Northern Gulf Institute, Mississippi State University, Stennis Space Center, MS; The Nature Conservancy, Gulf of Mexico Program, Key West, FL; University of Florida, Cedar Key, FL; University of Louisiana at Lafayette, Lafayette, LA; Texas Parks and Wildlife Department, Dickinson, TX; U.S. Fish and Wildlife Service, Austwell, TX; Dauphin Island Sea Lab, Dauphin Island, AL; Apalachicola National Estuarine Research Reserve, Eastpoint, FL; Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Research Institute, St. Petersburg, FL; Mission-Aransas National Estuarine Research Reserve, Port Aransas, TX; The Nature Conservancy, Corpus Christi, TX; Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Research Institute, Gainesville, FL.

Here is a relevant section from the review article that summarizes the organization and approach: *Despite the similarities in the ecosystem goods and services provided by mangrove forests and salt marshes, there are trade-offs and differences in the magnitude, spatiotemporal scale, and characteristics of the good or service provided (Ewel et al. 1998, Barbier et al. 2011, Kelleway et al. 2017). Research on the ecological effects of mangrove expansion in the southeastern United States has accelerated rapidly in recent years. Here, we synthesize this recent knowledge to review current understanding of the effects of mangrove range expansion and displacement of salt marsh on the ecosystem services provided by coastal wetlands in the southeastern United States. We begin with a background section that describes the history and expected future of mangrove expansion within this region. Next, based on the current state of knowledge, we review changes in wetland ecosystem services that occur as salt marshes are replaced by mangroves. We also identify critical knowledge gaps and emerging research needs for improving our understanding and management of mangrove expansion and salt marsh displacement in the southeastern United States.*

6. PROJECT RESULTS

The primary project results are summarized below via the abstracts from the project's two primary papers. The publication portion of this memorandum provides links to additional project results and products.

Primary Product 1 abstract from: Osland, M. J., R. H. Day, C. T. Hall, L. C. Feher, A. R. Armitage, J. Cebrian, K. H. Dunton, A. R. Hughes, D. A. Kaplan, A. K. Langston, A. Macy, C. A. Weaver, G. H. Anderson, K. Cummins, I. C. Feller, and C. M. Snyder. 2020. Temperature thresholds for black mangrove (*Avicennia germinans)* freeze damage, mortality, and recovery in North America: refining tipping points for range expansion in a warming climate. Journal of Ecology 108:654-665.

Near the tropical-temperate transition zone, warming winter temperatures are expected to facilitate the poleward range expansion of freeze-sensitive tropical organisms. In coastal wetlands of eastern and central North America, freeze-sensitive woody plants (mangroves) are expected to expand northward into regions currently dominated by freeze-tolerant herbaceous salt marsh plants. To advance understanding of mangrove range expansion, there is a need to refine temperature thresholds for mangrove freeze damage, mortality, and recovery. We integrated data from 38 sites spread across the mangrove range edge in the Gulf of Mexico and

Atlantic coasts of North America, including data from a regional collaborative network — the Mangrove Migration Network. In 2018, an extreme freeze event affected 60% of these sites, with minimum temperatures ranging from 0 to -7°C. We used temperature and vegetation data from before and after the freeze to quantify temperature thresholds for leaf damage, mortality, and biomass recovery of the black mangrove (Avicennia germinans) — the most freeze-tolerant mangrove species in North America. For A. germinans individuals near their northern range limit, our results indicate that temperature thresholds for leaf damage are close to -4°C, but temperature thresholds for mortality are closer to -7°C. Thresholds are expected to be warmer for more southern A. germinans individuals and for the other two common mangrove species in the region (Laguncularia racemosa and Rhizophora mangle). Regenerative buds allowed A. germinans to resprout and recover quickly from aboveground freeze damage. Hence, biomass recovery levels during the first post-freeze growing season were 90, 78, 62, and 45% for temperatures of -4, -5, -6, and -7°C, respectively. Due to a combination of vigorous resprouting and new recruitment from propagules, we expect full recovery at most sites within 1-3 years, assuming no further freeze events.

Primary Product 2 abstract from: Osland, M. J., A. R. Hughes, A. R. Armitage, S. H. Scyphers, J. Cebrian, S. H. Swinea, C. H. Shepard, M. S. Allen, L. C. Feher, J. A. Nelson, C. L. O'Brien, C. R. Sanspree, D. L. Smee, C. M. Snyder, A. P. Stetter, P. W. Stevens, K. M. Swanson, L. H. Williams, J. M. Brush, J. Marchionno, and R. Bardou. 2022. The impacts of mangrove range expansion on wetland ecosystem services in the southeastern United States: current understanding, knowledge gaps, and emerging research needs. https://doi.org/10.1111/gcb.16111

Climate change is transforming ecosystems and affecting ecosystem goods and services. Along the Gulf of Mexico and Atlantic coasts of the southeastern United States, the frequency and intensity of extreme freeze events greatly influences whether coastal wetlands are dominated by freeze-sensitive woody plants (mangrove forests) or freeze-tolerant grass-like plants (salt marshes). In response to warming winters, mangroves have been expanding and displacing salt marshes at varying degrees of severity in parts of north Florida, Louisiana, and Texas. As winter warming accelerates, mangrove range expansion is expected to increasingly modify wetland ecosystem structure and function. Because there are differences in the ecological and societal benefits that salt marshes and mangroves provide, coastal environmental managers are challenged to anticipate effects of mangrove expansion on critical wetland ecosystem services, including those related to carbon sequestration, wildlife habitat, storm protection, erosion reduction, water purification, fisheries support, and recreation. Mangrove range expansion may also affect wetland stability in the face of extreme climatic events and rising sea levels. Here, we review current understanding of the effects of mangrove range expansion and displacement of salt marshes on wetland ecosystem services in the southeastern United States. We also identify critical knowledge gaps and emerging research needs regarding the ecological and societal implications of salt marsh displacement by expanding mangrove forests. One consistent theme throughout our review is that there are ecological trade-offs for consideration by coastal managers. Mangrove expansion and marsh displacement can produce beneficial changes in some ecosystem services, while simultaneously producing detrimental changes in other services. Thus, there can be local-scale differences in perceptions of the impacts of mangrove expansion into salt marshes. For very specific local reasons, some individuals may see mangrove expansion

as a positive change to be embraced, while others may see mangrove expansion as a negative change to be constrained.

7. ANALYSES AND FINDINGS

The project's primary analyses and findings are summarized below via the abstracts from the project's primary two papers. The publication portion of this memorandum provides links to additional project results and products.

Primary Product 1 abstract from: Osland, M. J., R. H. Day, C. T. Hall, L. C. Feher, A. R. Armitage, J. Cebrian, K. H. Dunton, A. R. Hughes, D. A. Kaplan, A. K. Langston, A. Macy, C. A. Weaver, G. H. Anderson, K. Cummins, I. C. Feller, and C. M. Snyder. 2020. Temperature thresholds for black mangrove (*Avicennia germinans)* freeze damage, mortality, and recovery in North America: refining tipping points for range expansion in a warming climate. Journal of Ecology 108:654-665.

Near the tropical-temperate transition zone, warming winter temperatures are expected to facilitate the poleward range expansion of freeze-sensitive tropical organisms. In coastal wetlands of eastern and central North America, freeze-sensitive woody plants (mangroves) are expected to expand northward into regions currently dominated by freeze-tolerant herbaceous salt marsh plants. To advance understanding of mangrove range expansion, there is a need to refine temperature thresholds for mangrove freeze damage, mortality, and recovery. We integrated data from 38 sites spread across the mangrove range edge in the Gulf of Mexico and Atlantic coasts of North America, including data from a regional collaborative network — the Mangrove Migration Network. In 2018, an extreme freeze event affected 60% of these sites, with minimum temperatures ranging from 0 to -7°C. We used temperature and vegetation data from before and after the freeze to quantify temperature thresholds for leaf damage, mortality, and biomass recovery of the black mangrove (Avicennia germinans) — the most freeze-tolerant mangrove species in North America. For A. germinans individuals near their northern range limit, our results indicate that temperature thresholds for leaf damage are close to -4°C, but temperature thresholds for mortality are closer to -7°C. Thresholds are expected to be warmer for more southern A. germinans individuals and for the other two common mangrove species in the region (Laguncularia racemosa and Rhizophora mangle). Regenerative buds allowed A. germinans to resprout and recover quickly from aboveground freeze damage. Hence, biomass recovery levels during the first post-freeze growing season were 90, 78, 62, and 45% for temperatures of -4, -5, -6, and -7°C, respectively. Due to a combination of vigorous resprouting and new recruitment from propagules, we expect full recovery at most sites within 1-3 years, assuming no further freeze events.

Primary Product 2 abstract from: Osland, M. J., A. R. Hughes, A. R. Armitage, S. H. Scyphers, J. Cebrian, S. H. Swinea, C. H. Shepard, M. S. Allen, L. C. Feher, J. A. Nelson, C. L. O'Brien, C. R. Sanspree, D. L. Smee, C. M. Snyder, A. P. Stetter, P. W. Stevens, K. M. Swanson, L. H. Williams, J. M. Brush, J. Marchionno, and R. Bardou. 2022. The impacts of mangrove range expansion on wetland ecosystem services in the southeastern United States: current understanding, knowledge gaps, and emerging research needs. https://doi.org/10.1111/gcb.16111

Climate change is transforming ecosystems and affecting ecosystem goods and services. Along the Gulf of Mexico and Atlantic coasts of the southeastern United States, the frequency and intensity of extreme freeze events greatly influences whether coastal wetlands are dominated by freeze-sensitive woody plants (mangrove forests) or freeze-tolerant grass-like plants (salt marshes). In response to warming winters, mangroves have been expanding and displacing salt marshes at varying degrees of severity in parts of north Florida, Louisiana, and Texas. As winter warming accelerates, mangrove range expansion is expected to increasingly modify wetland ecosystem structure and function. Because there are differences in the ecological and societal benefits that salt marshes and mangroves provide, coastal environmental managers are challenged to anticipate effects of mangrove expansion on critical wetland ecosystem services, including those related to carbon sequestration, wildlife habitat, storm protection, erosion reduction, water purification, fisheries support, and recreation. Mangrove range expansion may also affect wetland stability in the face of extreme climatic events and rising sea levels. Here, we review current understanding of the effects of mangrove range expansion and displacement of salt marshes on wetland ecosystem services in the southeastern United States. We also identify critical knowledge gaps and emerging research needs regarding the ecological and societal implications of salt marsh displacement by expanding mangrove forests. One consistent theme throughout our review is that there are ecological trade-offs for consideration by coastal managers. Mangrove expansion and marsh displacement can produce beneficial changes in some ecosystem services, while simultaneously producing detrimental changes in other services. Thus, there can be local-scale differences in perceptions of the impacts of mangrove expansion into salt marshes. For very specific local reasons, some individuals may see mangrove expansion as a positive change to be embraced, while others may see mangrove expansion as a negative change to be constrained.

From the main text:
One consistent theme throughout this work is that there are ecological trade-offs for consideration by coastal scientists and natural resource managers. Mangrove expansion and marsh displacement can produce beneficial changes in some ecosystem services, while producing detrimental changes in other services. As a result, there is much variation in opinions regarding the social and ecological consequences of mangrove expansion. For the same location, some individuals may view mangrove expansion as a positive transformation to be fostered, while others may see it as a negative change to be prevented. Such variation in perceptions and impacts highlights the benefits of careful planning and discussion preceding management efforts (e.g., mangrove planting or removal) that could accelerate or constrain the pace of mangrove expansion.

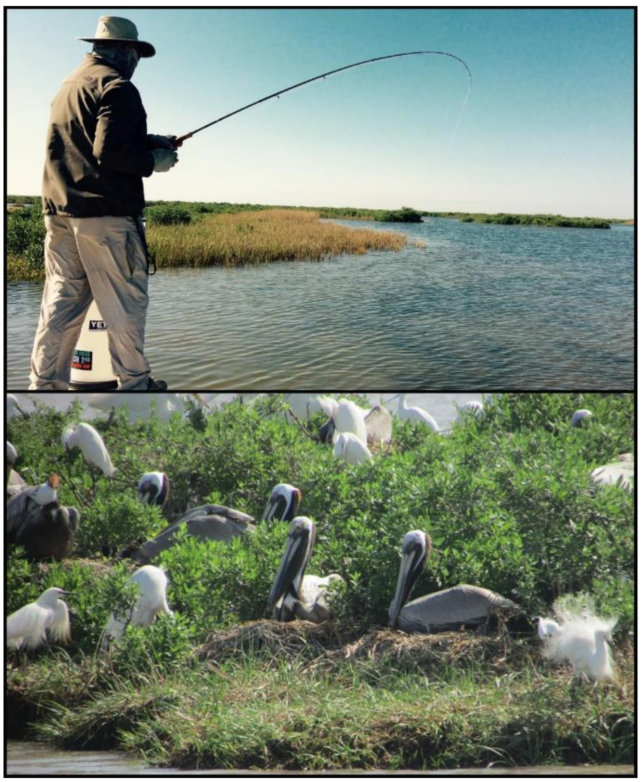
Example table and figures from the review:

Table 1. Mangrove expansion can produce beneficial changes in some ecosystem services while producing detrimental changes in other ecosystem services. Cedar Key (Florida) and Aransas (Texas) are two prominent areas where such trade-offs are observed. The table below shows some of the positive and negative changes associated with mangrove expansion in these two locations.

Location	Positive change associated with mangrove expansion	Negative change associated with mangrove expansion
Cedar Key (Florida)	*Improved coastal protection *Storm debris reduction *Enhanced pelican habitat *Increased aboveground carbon storage *Altered food webs and fisheries	*Loss of coastal views *Increased nuisance insects *Increased freeze vulnerability *Altered food webs and fisheries
Aransas (Texas)	*Improved coastal protection *Improved wind protection for fishing *Improved erosion control *Enhanced pelican habitat *Increased aboveground carbon storage *Increased soil carbon storage *Altered food webs and fisheries	*Reduced access to fishing grounds *Reduced whooping crane habitat and food resources *Increased freeze vulnerability *Altered food webs and fisheries

Figure 1. The effects of mangrove expansion on ecosystem goods and services are highly dependent upon the structure and composition of: (1) the expanding mangrove forests; and (2) the salt marsh that is being replaced. These photos illustrate some of the variation in marsh and mangrove plant communities near mangrove range limits in the southeastern United States. Upper photo: A mangrove-marsh ecotone in north Florida (near Cedar Key), which contains highly productive grass- and succulent plant-dominated marshes and comparatively tall (>6 m height) mangrove plants. Middle and Lower photos: Mangrove-marsh ecotones along the central and southern Texas coast (within Mustang Island State Park and Lower Rio Grande Valley National Wildlife Refuge, respectively), which contain less productive succulent plant-dominated marshes, comparatively short (< 2 m height) mangrove plants, and hypersaline salt flats that lack vascular plants (see right side of lower photo). Photo credits: Michael Osland

Figure 2. Across the southeastern United States, there is considerable variation in perceptions of the ecological and societal impacts of mangrove expansion into salt marsh. For very specific local reasons, some individuals may see mangrove expansion as a positive change to be embraced, while others may see mangrove expansion as a negative change to be constrained. These two photos provide an example of a negative and positive impact of mangrove expansion and salt marsh displacement. Upper photo (negative impact): Along Texas' central coast, mangrove expansion reduces viable fishing areas. While fly fishing is possible within the region's grass and succulent plant-dominated salt marshes, fly fishing for redfish (Sciaenops ocellatus) is not possible within dense meter-tall mangrove stands. Lower photo (positive impact): On Louisiana's barrier islands, expanding mangroves provide valuable habitat for brown pelicans (Pelecanus occidentalis). Photo credits: Travis Glidden (upper photo) and Louisiana Department of Wildlife and Fisheries (lower photo).



8. CONCLUSIONS AND RECOMMENDATIONS

- **From Osland et al. 2020, Journal of Ecology:** *To advance understanding of mangrove range expansion, there is a need to refine temperature thresholds for mangrove freeze damage, mortality, and recovery. We integrated data from 38 sites spread across the mangrove range edge in the Gulf of Mexico and Atlantic coasts of North America, including data from a regional collaborative network — the Mangrove Migration Network. For A. germinans individuals near their northern range limit, our results indicate that temperature thresholds for leaf damage are close to -4°C, but temperature thresholds for mortality are closer to -7°C. Thresholds are expected to be warmer for more southern A. germinans individuals and for the other two common mangrove species in the region (Laguncularia racemosa and Rhizophora mangle). Regenerative buds allowed A. germinans to resprout and recover quickly from aboveground freeze damage. Hence, biomass recovery levels during the first post-freeze growing season were 90, 78, 62, and 45% for temperatures of -4, -5, -6, and -7°C, respectively. Due to a combination of vigorous resprouting and new recruitment from propagules, we expect full recovery at most sites within 1-3 years, assuming no further freeze events.*

  What are the implications of our findings for mangrove range dynamics due to climate change? In response to warming winter temperature extremes (USGCRP, 2017), mangroves and other tropical organisms are expected to move northward into more temperate biomes in eastern and central North America (Osland et al., 2013, Cavanaugh et al., 2014, Carter et al., 2018). In combination with temperature projections and models of mangrove propagule dispersal (Van der Stocken, Carroll, Menemenlis, Simard, & Koedam, 2019a, Van der Stocken et al., 2019b), establishment (Krauss et al., 2008), and growth (Berger et al., 2008), the temperature thresholds identified for A. germinans leaf damage, mortality, and biomass recovery can be used to help scientists and natural resource managers better anticipate mangrove range dynamics in a warming world. Within the past several decades, ecologists have increasingly demonstrated the importance of experimental climate change studies that investigate the influence of climate extremes (Jentsch et al., 2007, Smith, 2011, Knapp et al., 2015). Our efforts highlight the large benefits that can come from mobilizing and coordinating existing regional partnerships to advance understanding of extreme events near species' range limits. With coordinated and comparatively modest inputs from multiple scientists spread across a regional range limit, we were able to build a dataset that significantly advances understanding of the impacts of winter climate extremes on A. germinans range dynamics. In a rapidly changing world where climate change is redistributing species and leading to range limit expansions and contractions, our work demonstrates the value of coordinated, regional collaborations for quantifying the effects of climate extremes on species range limits.
- **From Osland et al. 2022, Global Change Biology:** *In the past two decades, there has been a rapid increase in the number of studies investigating the effects of mangrove range expansion on ecosystem goods and services in the southeastern United States. This review synthesizes that information with an emphasis on impacts to carbon sequestration, wildlife habitat, storm protection, erosion prevention, water purification, fisheries support, and recreation. One consistent theme throughout this work is that there are ecological trade-offs for consideration by coastal scientists and natural resource managers. Mangrove expansion and marsh displacement can produce beneficial changes in some ecosystem services, while producing detrimental changes in other services. As a result, there is much variation in*

opinions regarding the social and ecological consequences of mangrove expansion. For the same location, some individuals may view mangrove expansion as a positive transformation to be fostered, while others may see it as a negative change to be prevented. Such variation in perceptions and impacts highlights the benefits of careful planning and discussion preceding management efforts (e.g., mangrove planting or removal) that could accelerate or constrain the pace of mangrove expansion.

9. MANAGEMENT APPLICATIONS AND PRODUCTS

This is a review article that contains input from coastal scientists and resource managers from across the region (i.e., Texas, Louisiana, Mississippi, Alabama, and Florida). The review examines current understanding of the effects of mangrove range expansion and displacement of salt marshes on wetland ecosystem services, including those related to carbon sequestration, wildlife habitat, storm protection, erosion reduction, water purification, fisheries support, and recreation. For the writing of the journal article, we invited 20 scientists from across the region to coauthor sections on the following topics: carbon sequestration, soil elevation change and vertical adjustments to sea-level rise, water quality: nutrient and sediment retention, coastal protection, coastal food webs and fisheries, insects and arthropod communities, avian communities, and recreation. We also organized meetings with resource managers, residents, and scientists regarding the ecological and management implications of mangrove range expansion. These conversations included 21 individuals (seven from Texas, six from Louisiana, and eight from Florida). The 20 coauthors of the review include individuals from the following 15 organizations, which represent a combination of federal, state, academic, and non-profit institutions in Texas, Louisiana, Mississippi, Alabama, and Florida: U.S. Geological Survey, Wetland and Aquatic Research Center, Lafayette, LA; Northeastern University Marine Science Center, Nahant, MA; Department of Marine Biology, Texas A&M University at Galveston, Galveston, TX; Northern Gulf Institute, Mississippi State University, Stennis Space Center, MS; The Nature Conservancy, Gulf of Mexico Program, Key West, FL; University of Florida, Cedar Key, FL; University of Louisiana at Lafayette, Lafayette, LA; Texas Parks and Wildlife Department, Dickinson, TX; U.S. Fish and Wildlife Service, Austwell, TX; Dauphin Island Sea Lab, Dauphin Island, AL; Apalachicola National Estuarine Research Reserve, Eastpoint, FL; Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Research Institute, St. Petersburg, FL; Mission-Aransas National Estuarine Research Reserve, Port Aransas, TX; The Nature Conservancy, Corpus Christi, TX; Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Research Institute, Gainesville, FL.

Here are some quotes from stakeholders/partners that describe the ways in which results of this project have or will be used:

Regarding the Osland et al. 2022 review (Global Change Biology): “The review of the impacts of mangrove range expansion on wetland ecosystem services was critical to moving mangrove migration and expansion research forward by clearly identifying topics and questions not investigated to date, yet so essential to understanding potential changes in coastal wetlands throughout the southeastern U.S.”
Caitlin Snyder, Apalachicola National Estuarine Research Reserve

“Mangrove expansion has been a highly visible signal for a suite of ecological changes occurring via climate change in the Gulf of Mexico. These synthesis papers by Dr. Osland and colleagues will help both scientists and the public understand the implications of changing habitats on coastal resources. These changes include impacts to fisheries, wildlife, and the social and economic benefits that people derive from coastal habitats.”
Michael Allen, University of Florida Nature Coast Biological Station

Regarding the Osland et al. 2022 review (Global Change Biology): “The review of the impacts of mangrove range expansion on wetland ecosystem services was critical to moving mangrove migration and expansion research forward by clearly identifying topics and questions not investigated to date, yet so essential to understanding potential changes in coastal wetlands throughout the southeastern U.S.”
Caitlin Snyder, Apalachicola National Estuarine Research Reserve

Regarding the Osland et al. 2020 study (2020, Journal of Ecology): “The analysis led by Osland (J Ecology 2020) has helped our research team develop specific and testable predictions about the rate and trajectory of black mangrove recovery on the Texas coast after a record-setting cold event in February 2021. This has enabled us to inform local management agencies about the need for and feasibility of mangrove planting as a restoration response to mitigate damage from the freeze event.”
Anna Armitage, Texas A&M Galveston

Regarding the Osland et al. 2022 review (Global Change Biology): “Identifying what controls the conversion of low marshes to tall forests in coastal areas of Florida should bring attention to those factors that should be included in climate models. Doing so will ultimately help us understand where and when these changes will occur in the coming years. An extensive review of over 50 papers outlines how coastal fauna will be affected by these changes. These include important recreational fisheries that will need to be managed differently as more or less species cross state boundaries or arrive in novel areas.”
Phil Stevens, Florida Fish and Wildlife Conservation Commission

"The USGS Wetland and Aquatic Research Center is at the forefront of researching how climate change is affecting the northern Gulf of Mexico. Tall Timbers Research Station has been able to gain valuable insight and data on how coastal wetlands are transitioning from salt marsh to mangrove forest in north Florida because of their work. Both the USGS and the Apalachicola National Estuarine Research Reserve (ANERR) have collaborated with Tall Timbers to monitor these changes over time to record the possible beginnings of a landscape-scale transformation."
Karen Cummins, Tall Timbers Research Station

Regarding the Osland et al. 2020 study (Journal of Ecology): “The Osland et al. 2020 paper on temperature thresholds for black mangrove freeze damage, mortality, and recovery is critical for anticipating and predicting the level of damage we will expect from future freezes. We are also able to pair these thresholds with long-term temperature records to look back in time (100+ years) and predict historical patterns of mangrove expansion and contraction as a comparison to today. These historical analyses are currently informing our understanding of black mangrove range expansion in the northern Gulf of Mexico.”

Randall Hughes, Northeastern University

Regarding the Osland et al. 2020 study (Journal of Ecology): "The referenced paper by Osland et al. (2020) is a crucial piece of the global climate change puzzle that is and has been very useful to managers and researchers in trying to explain and predict the effects of global warming and sea level rise on the distribution and abundance of coastal plants, particularly, in our case, black mangrove (*Avicenna germinans*). The coastal wetlands of Louisiana are positioned at the interface of tropical and temperate climates and thus are particularly vulnerable to dramatic effects of climate change. The conversion of herbaceous wetlands to forested wetlands on a landscape scale is one of the distinct possibilities that are predicted, and indeed, has already begun. Such a change can have a profound effect on the regional wetlands and, consequently, on their management."
Tommy Michot, USGS and University of Louisiana at Lafayette (retired)

Regarding the Osland et al. 2020 study (Journal of Ecology): "Temperature thresholds for *A. germinans* were used to advance understanding of the distribution and structure of mangroves in the Apalachicola region, located at along a rapidly changing range limit in the Northeastern Gulf of Mexico."
Caitlin Snyder, Apalachicola National Estuarine Research Reserve

Regarding the Osland et al. 2020 study (Journal of Ecology): "This is a very important paper because it presents an accurate analysis of temperature values at which colonizing mangroves in the Gulf of Mexico succumb. Thus, this paper adds crucial information to climate change models for the generation of robust predictions of the rate and extent of mangrove expansion in the Gulf of Mexico."
Just Cebrian, Northern Gulf Institute, Mississippi State University

Regarding the Osland et al. 2022 review (Global Change Biology): "This paper summarizes what is known about changes in coastal ecosystem services and benefits as mangroves expand and replace marshes. The information presented is useful for scientists, managers and other users as a first baseline of possible/expected changes resulting from the replacement of marshes with mangroves. Most importantly, though, the paper identifies glaring gaps that need further work for a better understanding of how mangrove expansion will affect human well-being."
Just Cebrian, Northern Gulf Institute, Mississippi State University

10. OUTREACH

Informal outreach regarding these topics occurred via the communications and conversations with the 30 coauthors on the project's two primary products. The coauthors include individuals from 22 organizations, which represent a combination of federal, state, academic, and non-profit institutions in Texas, Louisiana, Mississippi, Alabama, and Florida. The formal outreach products included below are separated into the following two categories: (1) Publications and Data Releases; and (2) Presentations.

<u>Publications and Data Releases</u>

1. Osland, M. J., R. H. Day, C. T. Hall, L. C. Feher, A. R. Armitage, J. Cebrian, K. H. Dunton, A. R. Hughes, D. A. Kaplan, A. K. Langston, A. Macy, C. A. Weaver, G. H. Anderson, K.

Cummins, I. C. Feller, and C. M. Snyder. 2020. Temperature thresholds for black mangrove (*Avicennia germinans*) freeze damage, mortality, and recovery in North America: refining tipping points for range expansion in a warming climate. Journal of Ecology 108:654-665. https://doi.org/10.1111/1365-2745.13285

2. Osland, M. J., R. H. Day, C. T. Hall, L. C. Feher, A. R. Armitage, J. Cebrian, and C. M. Snyder. 2019. Temperature thresholds for black mangrove freeze damage, mortality, and recovery: Refining tipping points for range expansion in a warming climate. U.S. Geological Survey data release. https://doi.org/10.5066/P9WUX46Y
3. Osland, M. J., A. R. Hughes, A. R. Armitage, S. H. Scyphers, J. Cebrian, S. H. Swinea, C. H. Shepard, M. S. Allen, L. C. Feher, J. A. Nelson, C. L. O'Brien, C. R. Sanspree, D. L. Smee, C. M. Snyder, A. P. Stetter, P. W. Stevens, K. M. Swanson, L. H. Williams, J. M. Brush, J. Marchionno, and R. Bardou. 2022. The impacts of mangrove range expansion on wetland ecosystem services in the southeastern United States: current understanding, knowledge gaps, and emerging research needs. https://doi.org/10.1111/gcb.16111
4. Osland, M. J., R. H. Day, and T. C. Michot. 2020. Frequency of extreme freeze events controls the distribution and structure of black mangroves (*Avicennia germinans*) near their northern range limit in coastal Louisiana. Diversity and Distributions 26:1366-1382. https://doi.org/10.1111/ddi.13119
5. Osland, M. J., J. B. Grace, G. R. Guntenspergen, K. M. Thorne, J. A. Carr, and L. C. Feher. 2019. Climatic controls on the distribution of foundation plant species in coastal wetlands of the conterminous United States: knowledge gaps and emerging research needs. Estuaries and Coasts 42:1991-2003. https://doi.org/10.1007/s12237-019-00640-z
6. Osland, M. J., P. W. Stevens, M. M. Lamont, R. C. Brusca, K. M. Hart, J. H. Waddle, C. A. Langtimm, C. M. Williams, B. D. Keim, and A. J. Terando. 2021. Tropicalization of temperate ecosystems in North America: The northward range expansion of tropical organisms in response to warming winter temperatures. Global Change Biology 27:3009-3034. https://doi.org/10.1111/gcb.15563
7. Snyder, C. M., L. C. Feher, M. J. Osland, C. M. Miller, A. R. Hughes, and K. L. Cummins. 2021. The distribution and structure of mangroves (*Avicennia germinans* and *Rhizophora mangle*) near a rapidly changing range limit in the northeastern Gulf of Mexico. Estuaries and Coasts https://doi.org/10.1007/s12237-021-00951-0
8. Snyder, C. M., L. C. Feher, M. J. Osland, C. M. Miller, A. R. Hughes, and K. L. Cummins. 2021. The distribution and structure of mangroves (*Avicennia germinans* and *Rhizophora mangle*) near a rapidly changing range limit in the northeastern Gulf of Mexico: U.S. Geological Survey data release, https://doi.org/10.5066/P90NGKNR

Presentations

1. Osland, M.J., 2019, Climate change impacts to coastal wetlands along the Gulf of Mexico, Society of Wetland Scientists.
2. Osland, M.J., Enwright, N.M., Griffith, K., and Borchert, S.M., 2019, Incorporating future change into current conservation planning: Barriers to and opportunities for landward migration of coastal wetlands with sea-level rise, Gulf Coast Land Conservation Conference.
3. Osland, M.J., Day, R.H., Hall, C.T., Feher, L.C., Armitage, A.R., Cebrian, J., Hughes, A.R., Kaplan, D.A., Langston, A.K., Macy, A., Weaver, C. and Feller, I.C., 2019, Temperature thresholds for mangrove freeze damage, mortality, and recovery: refining tipping points for tropicalization, Coastal and Estuarine Research Federation.

4. Osland, M.J., 2020, Mangroves vs. salt marshes: tropicalization of coastal wetlands in the northern Gulf of Mexico, National Academy of Science Gulf Research Program's Committee on Long Term Environmental Trends in the Gulf of Mexico. https://www.nationalacademies.org/event/11-09-2020/committee-on-long-term-environmental-trends-in-the-gulf-of-mexico-meeting-3-part-1

LITERATURE CITED

Bahn, M., M. Reichstein, J. S. Dukes, M. D. Smith, and N. G. McDowell. 2014. Climate–biosphere interactions in a more extreme world. New Phytologist **202**:356-359.

Barbier, E. B., S. D. Hacker, C. Kennedy, E. W. Koch, A. C. Stier, and B. R. Silliman. 2011. The value of estuarine and coastal ecosystem services. Ecological Monographs **81**:169-193.

Boucek, R. E., E. E. Gaiser, H. Liu, and J. S. Rehage. 2016. A review of subtropical community resistance and resilience to extreme cold spells. Ecosphere **7**:Article e01455.

Box, E. O., D. W. Crumpacker, and E. D. Hardin. 1993. A climatic model for location of plant species in Florida, USA. Journal of Biogeography **20**:629-644.

Box, E. O., D. W. Crumpacker, and E. D. Hardin. 1999. Predicted effects of climatic change on distribution of ecologically important native tree and shrub species in Florida. Climatic Change **41**:213-248.

Cahoon, D. R., K. L. McKee, and J. T. Morris. 2020. How plants influence resilience of salt marsh and mangrove wetlands to sea-level rise. Estuaries and Coasts **44**:883-898.

Carter, L., A. Terando, K. Dow, K. Hiers, K. E. Kunkel, A. Lascurain, D. Marcy, M. Osland, and P. Schramm. 2018. Southeast. Pages 743-808 *in* D. R. Reidmiller, C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, and B. C. Stewart, editors. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. U.S. Global Change Research Program, Washington, DC, USA.

Cavanaugh, K. C., J. R. Kellner, A. J. Forde, D. S. Gruner, J. D. Parker, W. Rodriguez, and I. C. Feller. 2014. Poleward expansion of mangroves is a threshold response to decreased frequency of extreme cold events. Proceedings of the National Academy of Sciences **111**:723-727.

Cavanaugh, K. C., M. J. Osland, R. Bardou, G. Hinijosa-Arango, J. M. López-Vivas, J. D. Parker, and A. S. Rovai. 2018. Sensitivity of mangrove range limits to climate variability. Global Ecology and Biogeography **27**:925-935.

Cavanaugh, K. C., J. D. Parker, S. C. Cook-Patton, I. C. Feller, A. P. Williams, and J. R. Kellner. 2015. Integrating physiological threshold experiments with climate modeling to project mangrove species' range expansion. Global Change Biology **21**:1928-1938.

Coldren, G. A., J. A. Langley, I. C. Feller, and S. K. Chapman. 2019. Warming accelerates mangrove expansion and surface elevation gain in a subtropical wetland. Journal of Ecology **107**:79-90.

Cook-Patton, S. C., M. Lehmann, and J. D. Parker. 2015. Convergence of three mangrove species towards freeze-tolerant phenotypes at an expanding range edge. Functional Ecology **29**:1332-1340.

Costanza, R., R. de Groot, P. Sutton, S. van der Ploeg, S. J. Anderson, I. Kubiszewski, S. Farber, and R. K. Turner. 2014. Changes in the global value of ecosystem services. Global Environmental Change **26**:152-158.

Daly, C., M. Halbleib, J. I. Smith, W. P. Gibson, M. K. Doggett, G. H. Taylor, J. Curtis, and P. P. Pasteris. 2008. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. International Journal of Climatology **28**:2031-2064.

Daly, C., E. H. Helmer, and M. Quiñones. 2003. Mapping the climate of Puerto Rico, Vieques and Culebra. International Journal of Climatology **23**:1359-1381.

Daly, C., M. P. Widrlechner, M. D. Halbleib, J. I. Smith, and W. P. Gibson. 2012. Development of a new USDA plant hardiness zone map for the United States. Journal of Applied Meteorology and Climatology **51**:242-264.

Dangremond, E. M., and I. C. Feller. 2016. Precocious reproduction increases at the leading edge of a mangrove range expansion. Ecology and Evolution **6**:5087-5092.

Doughty, C. L., J. A. Langley, W. S. Walker, I. C. Feller, R. Schaub, and S. K. Chapman. 2016. Mangrove range expansion rapidly increases coastal wetland carbon storage. Estuaries and Coasts **39**:385-396.

Ewel, K. C., R. R. Twilley, and J. E. Ong. 1998. Different kinds of mangrove forests provide different goods and services. Global Ecology and Biogeography Letters **7**:83-94.

Feher, L. C., M. J. Osland, K. T. Griffith, J. B. Grace, R. J. Howard, C. L. Stagg, N. M. Enwright, K. W. Krauss, C. A. Gabler, R. H. Day, and K. Rogers. 2017. Linear and nonlinear effects of temperature and precipitation on ecosystem properties in tidal saline wetlands. Ecosphere **8**:e01956.

Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson, and C. S. Holling. 2004. Regime shifts, resilience, and biodiversity in ecosystem management. Annual Review of Ecology, Evolution, and Systematics **35**:557-581.

Frank, D., M. Reichstein, M. Bahn, K. Thonicke, D. Frank, M. D. Mahecha, P. Smith, M. Van der Velde, S. Vicca, and F. Babst. 2015. Effects of climate extremes on the terrestrial carbon cycle: concepts, processes and potential future impacts. Global Change Biology **21**:2861-2880.

Gabler, C. A., M. J. Osland, J. B. Grace, C. L. Stagg, R. H. Day, S. B. Hartley, N. M. Enwright, A. S. From, M. L. McCoy, and J. L. McLeod. 2017. Macroclimatic change expected to transform coastal wetland ecosystems this century. Nature Climate Change **7**:142-147.

Giri, C. P., and J. Long. 2014. Mangrove reemergence in the northernmost range limit of eastern Florida. Proceedings of the National Academy of Sciences **111**:E1447-E1448.

Greller, A. M. 1980. Correlation of some climate statistics with distribution of broadleaved forest zones in Florida, USA. Bulletin of the Torrey Botanical Club **107**:189-219.

Guo, H., C. Weaver, S. P. Charles, A. Whitt, S. Dastidar, P. D'Odorico, J. D. Fuentes, J. S. Kominoski, A. R. Armitage, and S. C. Pennings. 2017. Coastal regime shifts: Rapid responses of coastal wetlands to changes in mangrove cover. Ecology **98**:762-772.

Hayes, M. A., A. C. Shor, A. Jesse, C. Miller, J. P. Kennedy, and I. Feller. 2020. The role of glycine betaine in range expansions; protecting mangroves against extreme freeze events. Journal of Ecology **108**:61-69.

Holdridge, L. R. 1967. Life Zone Ecology. Tropical Science Center, San Jose, Costa Rica.

Jentsch, A., J. Kreyling, and C. Beierkuhnlein. 2007. A new generation of climate-change experiments: events, not trends. Frontiers in Ecology and the Environment **5**:365-374.

Kayler, Z. E., H. J. De Boeck, S. Fatichi, J. M. Grünzweig, L. Merbold, C. Beier, N. McDowell, and J. S. Dukes. 2015. Experiments to confront the environmental extremes of climate change. Frontiers in Ecology and the Environment **13**:219-225.

Kelleway, J. J., K. Cavanaugh, K. Rogers, I. C. Feller, E. Ens, C. Doughty, and N. Saintilan. 2017. Review of the ecosystem service implications of mangrove encroachment into salt marshes. Global Change Biology **23**:3967-3983.

Langston, A. K., D. A. Kaplan, and C. Angelini. 2017. Predation restricts black mangrove (*Avicennia germinans*) colonization at its northern range limit along Florida's Gulf Coast. Hydrobiologia **803**:317-331.

Larcher, W. 2003. Physiological plant ecology: ecophysiology and stress physiology of functional groups. Springer-Verlag, Berlin, Germany.

Lonard, R. I., and F. W. Judd. 1991. Comparison of the effects of the severe freezes of 1983 and 1989 on native woody plants in the Lower Rio Grande Valley, Texas. The Southwestern Naturalist **36**:213-217.

Lovelock, C. E., K. W. Krauss, M. J. Osland, R. Reef, and M. C. Ball. 2016. The physiology of mangrove trees with changing climate. Pages 149-179 *in* G. Goldstein and L. S. Santiago, editors. Tropical tree physiology: adaptations and responses in a changing environment. Springer, New York, New York, USA.

Macy, A., S. Sharma, E. Sparks, J. Goff, K. L. Heck, M. W. Johnson, P. Harper, and J. Cebrian. 2019. Tropicalization of the barrier islands of the northern Gulf of Mexico: A comparison of herbivory and decomposition rates between smooth cordgrass (*Spartina alterniflora*) and black mangrove (*Avicennia germinans*). PLOS ONE **14**:e0210144.

Madrid, E. N., A. R. Armitage, and J. López-Portillo. 2014. *Avicennia germinans* (black mangrove) vessel architecture is linked to chilling and salinity tolerance in the Gulf of Mexico. Frontiers in Plant Science **5**:503.

Olmsted, I., H. Dunevitz, and W. J. Platt. 1993. Effects of freezes on tropical trees in Everglades National Park Florida, USA. Tropical Ecology **34**:17-34.

Osland, M. J., R. H. Day, A. S. From, M. L. McCoy, J. L. McLeod, and J. J. Kelleway. 2015. Life stage influences the resistance and resilience of black mangrove forests to winter climate extremes. Ecosphere **6**:Article 160.

Osland, M. J., R. H. Day, C. T. Hall, M. D. Brumfield, J. L. Dugas, and W. R. Jones. 2017a. Mangrove expansion and contraction at a poleward range limit: climate extremes and land-ocean temperature gradients. Ecology **98**:125-137.

Osland, M. J., R. H. Day, J. C. Larriviere, and A. S. From. 2014. Aboveground allometric models for freeze-affected black mangroves (*Avicennia germinans*): equations for a climate sensitive mangrove-marsh ecotone. PLOS ONE **9**:e99604.

Osland, M. J., N. Enwright, R. H. Day, and T. W. Doyle. 2013. Winter climate change and coastal wetland foundation species: salt marshes vs. mangrove forests in the southeastern United States. Global Change Biology **19**:1482-1494.

Osland, M. J., L. C. Feher, K. T. Griffith, K. C. Cavanaugh, N. M. Enwright, R. H. Day, C. L. Stagg, K. W. Krauss, R. J. Howard, J. B. Grace, and K. Rogers. 2017b. Climatic controls on the global distribution, abundance, and species richness of mangrove forests. Ecological Monographs **87**:341-359.

Osland, M. J., L. C. Feher, J. López-Portillo, R. H. Day, D. O. Suman, J. M. Guzmán Menéndez, and V. H. Rivera-Monroy. 2018. Mangrove forests in a rapidly changing world: global change impacts and conservation opportunities along the Gulf of Mexico coast. Estuarine, Coastal and Shelf Science **214**:120-140.

Osland, M. J., A. M. Hartmann, R. H. Day, M. H. Ross, C. T. Hall, L. C. Feher, and W. C. Vervaeke. 2019. Microclimate influences mangrove freeze damage: implications for range expansion in response to changing macroclimate Estuaries and Coasts **42**:1084-1096.

Osland, M. J., P. W. Stevens, M. M. Lamont, R. C. Brusca, K. M. Hart, J. H. Waddle, C. A. Langtimm, C. M. Williams, B. D. Keim, and A. J. Terando. 2021. Tropicalization of temperate ecosystems in North America: The northward range expansion of tropical organisms in response to warming winter temperatures. Global Change Biology **27**:3009-3034.

Parmesan, C., T. L. Root, and M. R. Willig. 2000. Impacts of extreme weather and climate on terrestrial biota. Bulletin of the American Meteorological Society **81**:443-450.

Pecl, G. T., M. B. Araújo, J. D. Bell, J. Blanchard, T. C. Bonebrake, I.-C. Chen, T. D. Clark, R. K. Colwell, F. Danielsen, B. Evengård, L. Falconi, S. Ferrier, S. Frusher, R. A. Garcia, R. B. Griffis, A. J. Hobday, C. Janion-Scheepers, M. A. Jarzyna, S. Jennings, J. Lenoir, H. I. Linnetved, V. Y. Martin, P. C. McCormack, J. McDonald, N. J. Mitchell, T. Mustonene, J. M. Pandolfi, N. Pettorelli, E. Popova, S. A. Robinson, B. R. Scheffers, J. D. Shaw, C. J. B. Sorte, J. M. Strugnell, J. M. Sunday, N. Tuanmu, A. Verges, C. Villanueva, T. Wernberg, E. Wapstra, and S. E. Williams. 2017. Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. Science **355**:eaai9214.

Perry, C. L., and I. A. Mendelssohn. 2009. Ecosystem effects of expanding populations of *Avicennia germinans* in a Louisiana salt marsh. Wetlands **29**:396-406.

Pickens, C. N., T. M. Sloey, and M. W. Hester. 2019. Influence of salt marsh canopy on black mangrove (*Avicennia germinans*) survival and establishment at its northern latitudinal limit. Hydrobiologia **826**:195-208.

Ratajczak, Z., S. R. Carpenter, A. R. Ives, C. J. Kucharik, T. Ramiadantsoa, M. A. Stegner, J. W. Williams, J. Zhang, and M. G. Turner. 2018. Abrupt change in ecological systems: inference and diagnosis. Trends in Ecology and Evolution **33**:513-526.

Rodriguez, W., I. C. Feller, and K. C. Cavanaugh. 2016. Spatio-temporal changes of a mangrove–saltmarsh ecotone in the northeastern coast of Florida, USA. Global Ecology and Conservation **7**:245-261.

Ross, M. S., P. L. Ruiz, J. P. Sah, and E. J. Hanan. 2009. Chilling damage in a changing climate in coastal landscapes of the subtropical zone: a case study from south Florida. Global Change Biology **15**:1817-1832.

Saintilan, N., N. C. Wilson, K. Rogers, A. Rajkaran, and K. W. Krauss. 2014. Mangrove expansion and salt marsh decline at mangrove poleward limits. Global Change Biology **20**:147-157.

Sakai, A., and W. Larcher. 1987. Frost Survival of Plants: Responses and Adaptation to Freezing Stress. Springer-Verlag, Berlin, Germany.

Scheffer, M., and S. R. Carpenter. 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. Trends in Ecology & Evolution **18**:648-656.

Sherrod, C. L., and C. McMillan. 1985. The distributional history and ecology of mangrove vegetation along the northern Gulf of Mexico coastal region. Contributions in Marine Science **28**:129-140.

Simpson, L., T. Osborne, L. Duckett, and I. Feller. 2017. Carbon storages along a climate induced coastal wetland gradient. Wetlands **37**:1023-1035.

Smith, M. D. 2011. The ecological role of climate extremes: current understanding and future prospects. Journal of Ecology **99**:651-655.

Stuart, S. A., B. Choat, K. C. Martin, N. M. Holbrook, and M. C. Ball. 2007. The role of freezing in setting the latitudinal limits of mangrove forests. New Phytologist **173**:576-583.

Tomlinson, P. B. 1986. The botany of mangroves. Cambridge University Press, New York, New York, USA.

USGCRP. 2017. Climate Science Special Report: Fourth National Climate Assessment, Volume I. U.S. Global Change Research Program, Washington, DC, USA.

USGCRP. 2018. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. U.S. Global Change Research Program, Washington, DC, USA.

Vergés, A., P. D. Steinberg, M. E. Hay, A. G. B. Poore, A. H. Campbell, E. Ballesteros, K. L. Heck, D. J. Booth, M. A. Coleman, D. A. Feary, W. Figueira, T. Langlois, E. M. Marzinelli, T. Mizerek, P. J. Mumby, Y. Nakamura, M. Roughan, E. van Sebille, A. Sen Gupta, D. A. Smale, F. Tomas, T. Wernberg, and S. K. Wilson. 2014. The tropicalization of temperate marine ecosystems: climate-mediated changes in herbivory and community phase shifts. Proceedings of the Royal Society B: Biological Sciences **281**:20140846.

Weaver, C. A., and A. R. Armitage. 2018. Nutrient enrichment shifts mangrove height distribution: Implications for coastal woody encroachment. PLOS ONE **13**:article e0193617.

Whittaker, R. H. 1970. Communities and ecosystems. The McMillan Company, New York, New York, USA.

Woodward, F. I. 1987. Climate and plant distribution. Cambridge University Press, Cambridge.

Yando, E. S., M. J. Osland, J. M. Willis, R. H. Day, K. W. Krauss, and M. W. Hester. 2016. Salt marsh-mangrove ecotones: using structural gradients to investigate the effects of woody plant encroachment on plant-soil interactions and ecosystem carbon pools. Journal of Ecology **104**:1020-1031.