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Projected changes in mangrove distribution and vegetation structure under climate change in the southeastern United States

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Abstract

Aim: The climate change-induced transition from grass-dominated marshes to woody-plant-dominated mangrove forests has the potential to impact the ecosystem goods and services provided by coastal wetlands. To better anticipate and prepare for these impacts, there is a need to advance understanding of future changes in mangrove distribution and coastal wetland vegetation structural properties due to warming winters.

Location: Southeastern United States.

Time Period: Recent (1981–2010) and future (2071–2100).

Major Taxa Studied: Coastal wetland vegetation.

Methods: We estimated changes in mangrove distribution and coastal wetland vegetation structure using known climate-ecological relationships, recent climate data for the period 1981–2010, and future projected climate data for the period 2071–2100. We quantified potential changes in mangrove presence, mangrove relative abundance, coastal wetland vegetation height, and coastal wetland vegetation aboveground biomass under two Shared Socio-Economic Pathway scenarios (SSPs; SSP2-4.5 and SSP5-8.5), which correspond to intermediate and high greenhouse gas emissions scenarios, respectively.

Results: Our analyses indicate that mangrove presence and relative abundance will dramatically increase in the northern Gulf of Mexico and the southeast Atlantic coast of the United States, particularly under the high emissions scenario. Because of the higher stature of mangroves relative to salt marsh vegetation, this expansion will cause a transformative change in coastal wetland vegetation height and aboveground biomass in many areas. However, along the arid southern Texas coast, low precipitation and high salinities are expected to constrain mangrove expansion and growth.

Rémi Bardou, Michael J. Osland, and A. Randall Hughes shared co-first authorship and contributed equally to this publication.

Main Conclusions: Our results show where and to what extent climate change, in the form of winter temperature warming, is projected to enable the transition from shorter, grass-dominated salt marshes to taller, woody plant-dominated mangrove forests in the southeastern United States, with consequent impacts on ecosystem goods and services.

KEYWORDS
climate change, coastal wetlands, mangrove range expansion, range expansion, southeastern United States, tropicalization, winter warming

1 | INTRODUCTION

In recent decades, the impacts of global climate change have become increasingly defined and of concern, causing shifts in the geographical distribution and abundance of species and associated ecosystem properties (Chen et al., 2011; Pecl et al., 2017; Rosenzweig et al., 2008). The direction of climate-driven range shifts across latitude and elevation is often predictable. For instance, a global meta-analysis revealed that terrestrial taxa had moved poleward at a median rate of 17 km per decade and to higher elevations at a median rate of 11 m per decade (Chen et al., 2011). However, species vary in the rate and degree of climate-induced range shifts, blurring the boundaries between formerly distinct ecological communities, and resulting in novel transition zones where new combinations of species overlap (Alexander et al., 2015; Gilman et al., 2010; Pecl et al., 2017). The effects of such rapid changes in species composition on ecological processes are often unknown, but impacts on ecosystem function are likely, particularly if range expansions involve habitat-forming, foundation species (Christiaen et al., 2016; HilleRisLambers et al., 2013; Osland et al., 2015).

Vegetated coastal wetland ecosystems in subtropical and temperate regions are particularly susceptible to the climate-induced range shifts of tropical mangroves into temperate salt marshes. Changes in the distribution and abundance of salt marsh plants and mangroves can have important cascading effects on ecological functions (Altieri et al., 2007; Bishop et al., 2013; Ellison et al., 2005; Osland et al., 2015) and the human communities that depend on their ecosystem services, including primary production, buffering of wave stress, nutrient sequestration, and filtering of land-derived wastewater (Barbier et al., 2011; Ewel et al., 1998; Friess et al., 2020). Encroachment of mangroves into marsh habitat is likely to increase the provision of some services, while reducing others (Johnston & Caretti, 2017; Kelleway et al., 2017; Osland et al., 2022; Scheffel, Heck, & Rozas , 2017), and the degree of these changes will depend on mangrove relative abundance, morphology, and biomass. Therefore, understanding not just future changes in mangrove presence but also changes in mangrove ecosystem properties is critical to predicting their changing functions and the cascading effects on ecosystems and society.

The southeastern United States is a key region where tropical mangroves are expanding into temperate salt marshes due to climate change. As winter warming alleviates past geographic limits set by cold intolerance, mangroves are expected to continue to expand northward at the expense of salt marshes in parts of the northern Gulf of Mexico (Gabler et al., 2017; Kang et al., 2024; Osland et al., 2013) and Atlantic coasts (Cavanaugh et al., 2019). To better anticipate and prepare for future change, there is a need to advance understanding of potential future mangrove distribution and associated changes in coastal wetland ecosystem properties due to warming winters. Here, we evaluated projected changes in mangrove distribution and coastal wetland vegetation structure in the southeastern United States under climate change, using known climate-ecological relationships, recent climate data for the period 1981–2010, and future projected climate data for the period 2071–2100 under two Shared Socio-Economic Pathways (SSPs): the SSP2-4.5 and SSP5-8.5 scenarios, which correspond to intermediate and high greenhouse gas emissions scenarios, respectively. More specifically, we quantified potential changes in mangrove presence, mangrove relative abundance, coastal wetland vegetation height, and coastal wetland vegetation aboveground biomass under recent climatic conditions and under the two alternative future climate scenarios.

2 | MATERIALS AND METHODS

2.1 | Study area

Our study area included the Gulf of Mexico and Atlantic coasts of the southeastern United States (Figure 1), which is a region that encompasses the northern limit of mangroves in eastern North America. Mangroves are most abundant in southern and central regions of Florida, but stunted mangrove stands also occur along both coasts of north Florida, as well as in Louisiana and Texas (Bardou et al., 2023; Osland et al., 2013). The northern extent of mangrove distributions is controlled primarily by cold intolerance (Cavanaugh et al., 2013; Duke et al., 1998; McMillan & Sherrod, 1986) with mangrove populations limited by freeze intensity and duration (Cavanaugh et al., 2019; Cook-Patton et al., 2015; Osland, Feher, et al., 2017). Thus, winter warming due to climate change is understood to be driving the observed encroachment of mangroves into marsh systems in the northern Gulf of Mexico as well as along the Atlantic coast (Cavanaugh et al., 2013; Osland, Day, et al., 2017).

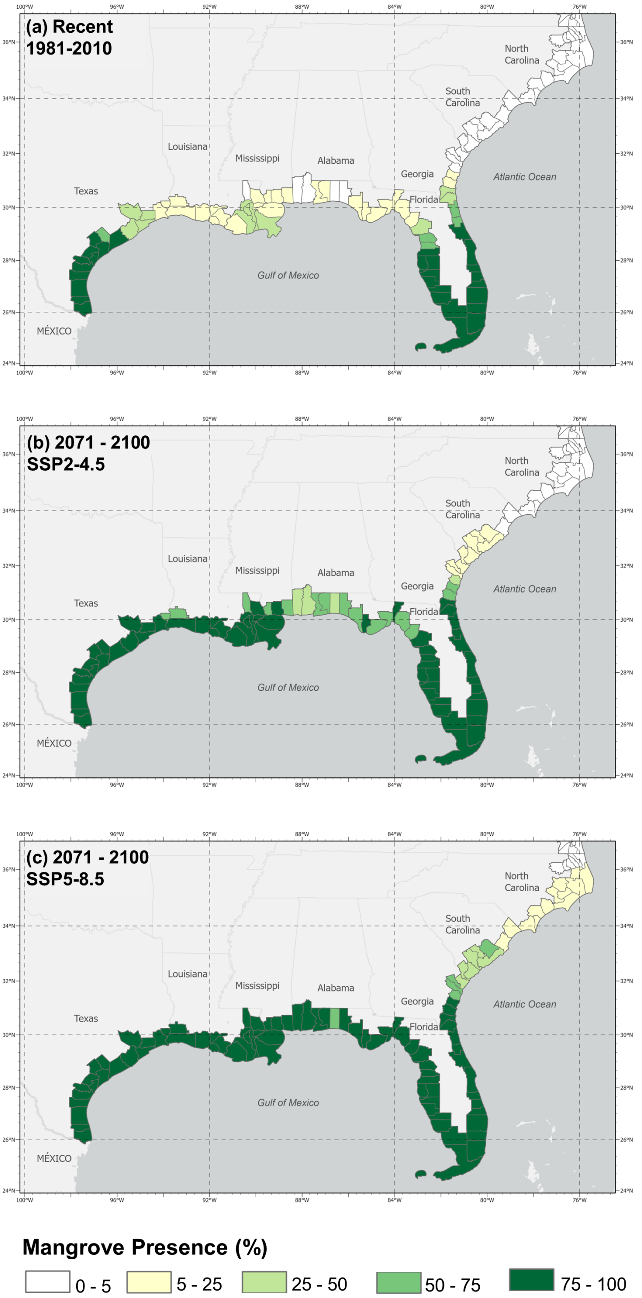

FIGURE 1 Maps of county-level probability of mangrove presence under (a) recent climatic conditions (1981–2010) and two alternative future climate scenarios based upon two emissions scenarios: (b) SSP2-4.5 (2071–2100), and (c) SSP5-8.5 (2071–2100). Each of the coloured polygons represents a coastal county that contains coastal wetlands. Our data are provided at a coarse spatial scale to indicate broad areas (i.e., counties) where mangroves are projected to be present within tidal saline wetlands. However, within these broad areas, we are cautious not to specify the exact location where mangroves will be present. Sea-level rise is one of the primary reasons for our selection of this coarse spatial scale. Beyond just winter warming, coastal wetlands are highly vulnerable to accelerated sea-level rise and many other aspects of climate change. Please see section 4.1 for more information regarding these interactions. SSP, Shared Socio-Economic Pathway.

We used a two-step process to develop a coastal grid of 1-km cells that could be used for subsequent analyses. We began with a national grid of 1-km cells that matched the spatial registration of the 1-km climate data used in our analyses, which we obtained from the AdaptWest Project (2022). Next, to isolate our analyses to areas in the southeastern United States that have coastal wetlands, we removed all cells within our study area that were not located within 100 meters of estuarine wetlands as defined by the National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program (C-CAP) land cover data (NOAA, 2016). These two steps produced a grid that contained 36,271 1-km cells along the Gulf of Mexico and Atlantic coasts of the southeastern United States. For each of these cells, we acquired mangrove distribution data, recent climate data, and future climate data.

2.2 | Recent and future climate data

We obtained recent climate data (1981–2010) and future climate data (2071–2100) from the AdaptWest database (Wang et al., 2016), for the following two climatic variables: Extreme Minimum Temperature (EMT) and the Mean Annual Precipitation (MAP). EMT represents the absolute coldest temperature recorded during the 30-year period, which is relevant because extreme minimum temperatures govern the distribution and structure of mangroves in this region (Feher et al., 2017; Gabler et al., 2017; Osland et al., 2019). MAP was incorporated because the western side of our study area spans a precipitation gradient that interacts with temperature to affect coastal wetlands. Decreased precipitation and freshwater inputs in that region can lead to hypersaline conditions that influence plant community structure and function (Gabler et al., 2017; Osland et al., 2014, 2019).

The recent climate data (i.e., EMT and MAP) were based on data produced by the PRISM Climate Group (Oregon State University; prism.oregonstate.edu) using the PRISM (Parameter-elevation Relationship on Independent Slopes Model) interpolation method (Daly et al., 2008). The future climate data were based on downscaled data from the Coupled Model Intercomparison Project Phase 6 (CMIP6) database, which corresponds to the 6th IPCC (Intergovernmental Panel on Climate Change (IPCC), 2023). The ensemble mean projections are average projections from eight CMIP6 models, which tend to be the most representative for projecting climate warming (Hausfather et al., 2022; Tokarska et al., 2020). We obtained future projected climate data for EMT and MAP for the period 2071–2100 under two Shared Socio-Economic Pathways (SSPs): the SSP2-4.5 and SSP5-8.5 scenarios, which correspond to intermediate and high greenhouse gas emissions scenarios, respectively.

2.3 | Known climate–ecological relationships

Known relationships were used to describe the interaction between EMT and mangrove presence (Osland et al., 2013); mangrove relative abundance (Osland et al., 2013, 2014); coastal wetland vegetation height (Feher et al., 2017); and coastal wetland vegetation aboveground biomass (Feher et al., 2017; Gabler et al., 2017) (Table 1). Mangrove presence represents the probability (%) that an individual mangrove plant is present within a grid cell, calculated using an equation (AIC: 210) that was developed via logistic regression with temperature and GIS-based mangrove presence data (Osland et al., 2013). Mangrove relative abundance represents the percent of tidal saline wetlands in a grid cell that are dominated by mangrove forests, calculated using an equation that was developed via sigmoidal regression (R^2: 0.82) with temperature and GIS-based mangrove and tidal saline wetland area data (Osland et al., 2013). For example, mangrove relative abundance would be 50% when the tidal saline wetlands in a grid cell contain an even mixture of salt marsh and mangrove forest. In contrast, a grid cell would have a mangrove relative abundance of 100% when all tidal saline wetlands in that cell are dominated by mangrove forests. Coastal wetland vegetation height represents the mean height of tidal saline wetlands in a grid cell area (i.e., the mean height of mangrove forests, salt marshes, and salt flats, if present), calculated using equations that were developed via sigmoidal regressions (R^2: 0.59 for temperature; R^2: 0.89 for precipitation) using temperature data, precipitation data, and literature-derived tidal saline wetland vegetation height data (Feher et al., 2017). Similarly, coastal wetland vegetation aboveground biomass represents the mean aboveground biomass of tidal saline wetlands in a grid cell area, calculated using equations that were developed via sigmoidal regressions (R^2: 0.79 for temperature; R^2: 0.73 for precipitation) using temperature data and literature-derived aboveground biomass data (Feher et al., 2017) or using precipitation data and field-based aboveground biomass data (Gabler et al., 2017).

To incorporate the role of precipitation in our projections, we identified MAP-based equations that could be used to account for the influence of precipitation on mangrove relative abundance (Osland et al., 2014), coastal wetland vegetation height (Feher et al., 2017), and coastal wetland vegetation aboveground biomass (Feher et al., 2017; Gabler et al., 2017). These equations were applied to cells with a MAP of less than 995 mm, which has been identified as a threshold MAP value for coastal wetlands in this region (Osland et al., 2014). For each of the cells with an MAP of less than 995 mm, the two calculated values were compared (i.e., the temperature-based value and the precipitation-based value) and the lower calculated value was assigned to the cell.

2.4 | Future mangrove projections

We used the future climate projections and the climate-ecological equations to project the future distribution and relative abundance of mangroves in the southeastern United States at the end of the century (2070–2100) under the intermediate (SSP2-4.5) and high (SSP5-8.5) greenhouse gas emissions scenarios. We also projected potential changes in coastal wetland vegetation height and aboveground biomass. For visualization, we projected these changes at the county level. Because mangrove presence is directly correlated to the absolute minimum temperature (Osland et al., 2013), our county-level mangrove presence projections are based on the value of the warmest cell within county boundaries. For the other response variables (county-level mangrove relative abundance, coastal wetland vegetation height, and coastal wetland aboveground biomass), we used the mean of all coastal climate cells within county boundaries. Finally, we used the county-level data to produce state- and region-level means and standard errors for the four response variables under recent climatic conditions, and the two future climate scenarios. These data are available in the associated data release (Bardou et al., 2024). For Florida, we restricted these metrics to counties in north Florida where mangroves are not yet fully dominant relative to marshes. Along the Gulf of Mexico coast of north Florida, these metrics were calculated from data for the following 12 counties, ordered from east to west: Levy, Dixie, Taylor, Jefferson, Wakulla, Franklin, Gulf, Bay, Walton, Okaloosa, Santa Rosa, and Escambia. Along the Atlantic coast of north Florida, these metrics were calculated from data for the following five counties,

TABLE 1 Literature-derived equations used to project mangrove presence, mangrove relative abundance, coastal wetland vegetation height, and coastal wetland vegetation aboveground biomass.

Response variable	Equation for wet climates (i.e., MAP > 995 mm)	Equation for dry climates (i.e., MAP < 995 mm)	Equation source(s)
Mangrove presence	$y=(\exp(8.76+0.87\times EMT))/(1+(\exp(8.76+0.87\times EMT)))$	$y=(\exp(8.76+0.87\times EMT))/(1+(\exp(8.76+0.87\times EMT)))$	Osland et al. (2013)
Mangrove relative abundance (%)	$y=74/(1+\exp(-((EMT+6.97)/0.5)))$	$y=100/(1+\exp(-((MAP\text{-}765)/173)))$	Osland et al. (2013, 2014)
Coastal wetland vegetation height (m)	$y=13.6/(1+\exp(-((EMT+0.7)/4.3)))$	$y=27.1/(1+(\exp(-((MAP\text{-}1544.5)/180))))$	Feher et al. (2017)
Coastal wetland aboveground biomass ($t\,ha^{-1}$)	$y=181.4/(1+\exp(-((EMT+2.6)/4.2)))$	$y=181.4/(1+\exp(-(EMT+2.6)/4.2))\times 1.1556/(1+\exp(-(MAP\text{-}1329.3807)/254.0658))$	Feher et al. (2017); Gabler et al. (2017)

Note: Within equations: EMT, extreme minimum temperature; MAP, mean annual precipitation; Y, response variable. For each of the cells with an MAP of less than 995 mm, the two calculated values were compared (i.e., the temperature-based value and the precipitation-based value) and the lower calculated value was assigned.

ordered from south to north: Volusia, Flagler, St, Johns, Duval, and Nassau (Table 2).

3 | RESULTS

3.1 | Mangrove presence

Our analyses indicate that the potential for mangrove presence will dramatically increase in the northern Gulf of Mexico and the southeast Atlantic coast of the United States in the future. The potential expansion of mangroves into new areas varies across the two emissions scenarios. Under the intermediate emissions scenario, Mississippi is projected to experience the greatest increase in mangrove presence in the Gulf of Mexico, going from an average probability of 9% to 72% (Table 2; Figure 1b). The range-expansion zone of the Gulf of Mexico coast of north Florida will also see increases, and even Alabama, which currently has no mangroves, is projected to have a 39% probability of mangrove presence within the state's coastal wetlands (Table 2; Figure 1b). At the county level, there is at least a 30% probability of mangrove presence in all Gulf of Mexico counties, with most counties having a 75%–100% chance (Figure 1b). On the Atlantic coast, the probability of mangrove presence in the range expansion region of Florida increases to 92% under the intermediate emissions scenario, and it increases from near-zero to 34% state-wide in Georgia (Table 2; Figure 1b). The probability of mangrove presence is consistently predicted to be greater than 25% in most Georgia counties, with a non-zero probability as far north as South Carolina (Figure 1b). These county- and state-level probabilities increase under the high emissions scenario, with greater than 77% average probability of mangrove presence in all Gulf of Mexico states (Table 2; Figure 1c), and averages of 65% and 33% in Georgia and South Carolina, respectively. From the county perspective, all Gulf of Mexico counties are predicted to have greater than 73% probability of mangrove presence under the high emissions scenario, and non-zero probabilities extend as far north in the Atlantic as the southern coast of North Carolina (Figure 1c; Table 2).

3.2 | Mangrove relative abundance

Mangrove relative abundance is also predicted to increase throughout our study region under both emissions scenarios. Under the intermediate emissions scenario, mangrove relative abundance increases to an average of 1.6% in Mississippi, 9% in Louisiana, and 42% in Texas (Table 2; Figure 2b). These state-wide averages hide substantial variation by county, where mangrove relative abundance increases up to 25% in parts of southeastern Louisiana, up to 25% in parts of the Big Bend of north Florida, and up to 40%–70% for parts of the Texas coast where precipitation is not limiting (i.e., between Corpus Christi and the Texas–Louisiana border). Mangrove relative abundance also increases considerably along the Atlantic coast of Florida and south Georgia. In particular, the range expansion region of north Florida increases to 51% mangrove relative abundance (Table 2; Figure 2b). Some individual counties in these areas are projected to have mangrove relative abundances up to 74% in north Florida. With high emissions, we project relative abundances of greater than 20% mangroves throughout most counties in the northern Gulf of Mexico and along the Atlantic coast of Florida and southern Georgia (Figure 2c). These relative abundance projections will also be modulated by interactions with accelerated sea-level rise, precipitation, and other climate change factors. Please see the discussion section for more information regarding these interactions and our use of a coarse spatial scale to present these results.

3.3 | Coastal wetland vegetation height

Because of the higher stature of mangroves relative to salt marsh vegetation, coastal wetland vegetation height is projected to increase with intermediate emissions from less than 1.0 m on average state-wide in the northern Gulf of Mexico to 1.2 to 2.0 m (Table 1; Figure 3b). In some counties in this region, particularly those near the current range edge in Florida, coastal vegetation height is projected to increase to as high as 5.5 m (Figure 3b). Similarly, along the Atlantic coast, coastal vegetation height in north Florida is projected to double to approximately 3.1 m (from 1.4 m) and be up to 2.3 m in the southernmost county in Georgia (Table 2; Figure 3b). Under high emissions, coastal vegetation height in most northern Gulf of Mexico counties not limited by precipitation is projected to increase to greater than 2 m, with state-wide averages of 1.7–2.9 m (Table 2; Figure 3c). Vegetation height along the Atlantic coast changes much more under the high emissions scenario, with an average increase of 2.9 m in north Florida, 1.1 m in Georgia, and 0.8 m in South Carolina (Table 2). These vegetation height projections will also be modulated by interactions with accelerated sea-level rise, precipitation, and other climate change factors (see Section 4).

3.4 | Coastal wetland aboveground biomass

Projections for increases in the aboveground biomass of coastal vegetation largely mirror those of height, shifting from $<19\,\mathrm{t\,ha^{-1}}$ on average in states of the northern Gulf of Mexico to between 23 and $37\,\mathrm{t\,ha^{-1}}$ on average under intermediate emissions and $33–53\,\mathrm{t\,ha^{-1}}$ on average under high emissions (Table 2; Figure 4). Nearly all counties along the upper Texas coast, where precipitation is not limiting, and one county in Louisiana are projected to have greater than $45\,\mathrm{t\,ha^{-1}}$ of coastal vegetation aboveground biomass under the high emissions scenario (Figure 4c).

Along the Atlantic coast, coastal wetland aboveground biomass increases from averages of 11 and $7\,\mathrm{t\,ha^{-1}}$ in recent years in Georgia and South Carolina, respectively, to 22 and $15\,\mathrm{t\,ha^{-1}}$ under an intermediate emissions scenario and 32 and $22\,\mathrm{t\,ha^{-1}}$ under a high emissions scenario (Table 2; Figure 4b). Under high emissions, all the north Florida counties along the Atlantic coast have coastal wetland aboveground biomass

TABLE 2 State-level means and standard errors (SE; in parentheses) of projected mangrove presence, mangrove relative abundance, coastal wetland vegetation height, and coastal wetland vegetation aboveground biomass under recent climatic conditions (1981–2010; Recent) and two alternative future climate scenarios, SSP2-4.5 (2071–2100; Future-Int) and SSP5-8.5 (2071–2100; Future-High), which correspond to intermediate and high greenhouse gas emissions scenarios, respectively.

	Presence (% probability)			Abundance (%)			Height (m)			Aboveground biomass (t ha^{-1})		
State	Recent	Future-Int	Future-High	Recent	Future-Int	Future-High	Recent	Future-Int	Future-High	Recent	Future-Int	Future-High
TX	68.2 (7.6)	94.4 (2.4)	98.9 (0.5)	14.9 (4.1)	42.2 (5.7)	56.1 (4.4)	0.9 (0.1)	1.4 (0.3)	1.7 (0.4)	15.7 (2.6)	26.5 (4.6)	33.3 (6.2)
LA	20.0 (2.7)	79.8 (3.1)	95.3 (0.9)	0.0 (0.0)	9.0 (2.3)	51.6 (5.2)	1.0 (0.0)	2.0 (0.1)	2.9 (0.1)	18.4 (0.9)	37.2 (1.5)	52.8 (1.8)
MS	9.0 (1.6)	72.0 (3.5)	93.3 (1.2)	0.0 (0.0)	1.6 (0.6)	36.0 (8.1)	0.8 (0.0)	1.7 (0.1)	2.6 (0.1)	14.8 (0.7)	32.7 (1.3)	47.2 (1.9)
AL	2.3 (0.2)	38.7 (2.1)	77.4 (2.3)	0.0 (0.0)	0.1 (0.0)	2.6 (0.7)	0.5 (0.0)	1.2 (0.0)	1.9 (0.1)	10.3 (0.2)	23.5 (0.5)	34.7 (1.0)
FL-Gulf[a]	10.3 (2.5)	68.5 (3.9)	91.5 (1.8)	0.0 (0.0)	3.1 (2.0)	32.5 (5.4)	0.8 (0.0)	1.7 (0.1)	2.5 (0.1)	14.9 (0.9)	32.2 (1.5)	46.5 (2.0)
FL-Atlantic[b]	51.2 (10.5)	95.4 (1.7)	99.1 (0.4)	1.3 (1.1)	51.0 (11.3)	72.6 (0.9)	1.4 (0.2)	3.7 (0.3)	4.3 (0.4)	27.3 (3.1)	55.3 (5.4)	74.6 (6.4)
GA	3.4 (1.3)	33.9 (9.8)	65.1 (8.7)	0.0 (0.0)	0.2 (0.1)	6.6 (4.1)	0.6 (0.1)	1.2 (0.1)	1.7 (0.2)	10.7 (1.1)	22.2 (2.5)	32.3 (3.5)
SC	0.8 (0.2)	9.4 (2.1)	32.6 (4.9)	0.0 (0.0)	0.0 (0.0)	0.1 (0.0)	0.4 (0.0)	0.8 (0.0)	1.2 (0.1)	7.4 (0.5)	14.7 (0.9)	21.9 (1.3)
NC	0.1 (0.0)	1.5 (0.2)	6.4 (0.8)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.2 (0.0)	0.5 (0.0)	0.7 (0.0)	4.1 (0.2)	8.9 (0.4)	13.2 (0.5)

Note: For Florida, we restricted these metrics to counties in north Florida where mangroves are not yet fully dominant relative to marshes.

Abbreviations: AL, Alabama; FL, Florida; GA, Georgia; LA, Louisiana; MS, Mississippi; NC, North Carolina; SC, South Carolina; SSP, shared socio-economic pathway; TX, Texas.

[a] Along the Gulf of Mexico coast of north Florida (denoted as FL-Gulf), metrics were calculated from data for the following twelve counties, ordered from east to west: Levy, Dixie, Taylor, Jefferson, Wakulla, Franklin, Gulf, Bay, Walton, Okaloosa, Santa Rosa, and Escambia.

[b] Along the Atlantic coast of north Florida (denoted as FL-Atlantic), metrics were calculated from data for the following five counties, ordered from south to north: Volusia, Flagler, St, Johns, Duval, and Nassau.

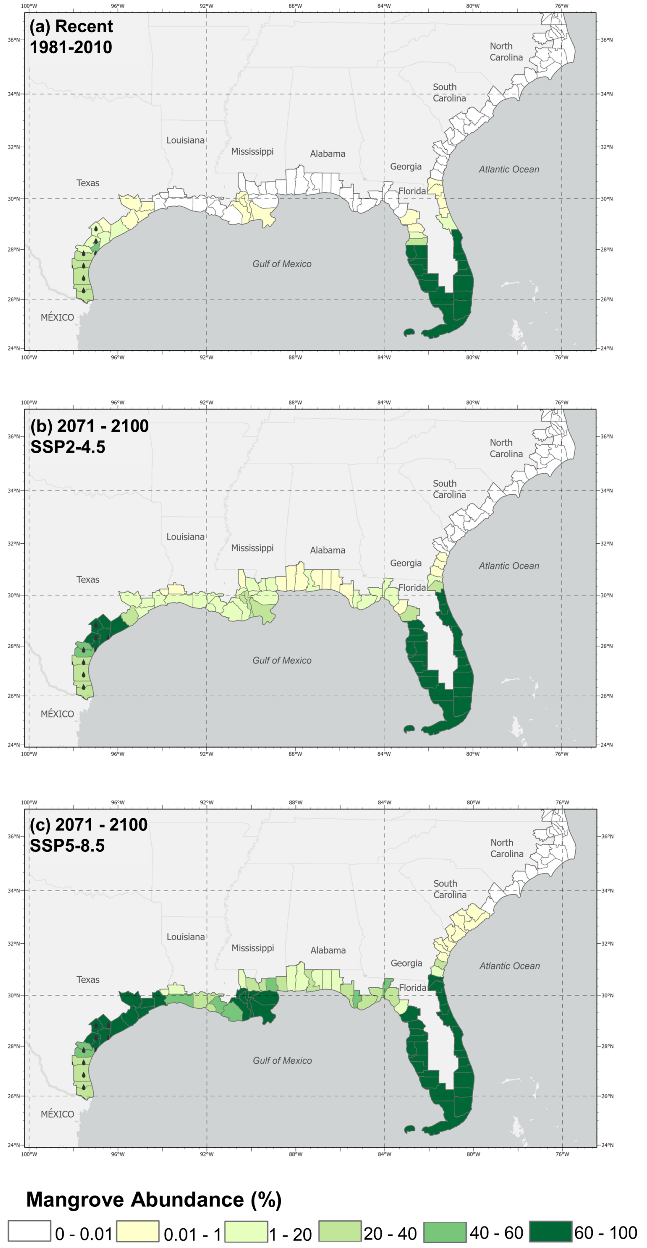

FIGURE 2 Maps of county-level mangrove abundance under (a) recent climatic conditions (1981–2010) and two alternative future climate scenarios based upon two emissions scenarios: (b) SSP2-4.5 (2071–2100), and (c) SSP5-8.5 (2071–2100). Mangrove abundance reflects the per cent of coastal wetlands dominated by mangrove forests. Each of the coloured polygons represents a coastal county that contains coastal wetlands. Along the western Gulf of Mexico, within counties denoted with the black water droplets where precipitation is below 995 mm, we expect that low freshwater availability will modulate the potential for mangrove expansion and growth. Our data are provided at a coarse spatial scale to indicate broad areas (i.e., counties) where mangroves are projected to dominate tidal saline wetlands. However, within these broad areas, we are cautious not to specify the exact location where mangroves will become dominant. Sea-level rise is one of the primary reasons for our selection of this coarse spatial scale. Beyond just winter warming, coastal wetlands are highly vulnerable to accelerated sea-level rise and many other aspects of climate change. Please see section 4.1 for more information regarding these interactions. SSP, Shared Socio-Economic Pathway.

values greater than 45 t ha^{-1}, with greater than 25 t ha^{-1} extending into most counties of Georgia (Figure 4c). These aboveground biomass projections will also be modulated by interactions with accelerated sea-level rise, precipitation, and other climate change factors (see Section 4).

4 | DISCUSSION

In this study, we used known climate-ecological relationships and future climate projections to project potential changes in mangrove presence, relative abundance, vegetation canopy height, and vegetation aboveground biomass across the southeastern United States for the end of the century (2071–2100) under two alternative greenhouse gas emissions scenarios (Bardou et al., 2023). Our research builds from past efforts to quantify climate-mangrove relationships (Bardou et al., 2021; Cavanaugh et al., 2013; Feher et al., 2017; Gabler et al., 2017; Osland et al., 2013, 2014, 2019) and projects future changes in mangrove distribution and structure due to climate change (e.g., Cavanaugh et al., 2015; Gabler et al., 2017; Gouvêa et al., 2022; Osland et al., 2013). We anticipate that our findings will be of use for scientists and managers working in salt marshes in north Florida, Alabama, Mississippi, Louisiana, Texas, Georgia, and South Carolina. Within these states, our results provide information that can be used to better anticipate and prepare for future mangrove range expansion.

Coastal scientists working near current mangrove range limits in Texas, Louisiana, and Florida are well versed in the ecological and societal impacts of mangrove expansion and encroachment into salt marshes in response to warming winter temperatures (Osland et al., 2021). For example, in parts of Louisiana (e.g., Port Fourchon) and north Florida (e.g., Cedar Key, Apalachicola, and St. Augustine), this awareness stems from three decades of observing mangrove expansion and encroachment into salt marshes (Cavanaugh et al., 2019; Osland, Day, et al., 2017; Snyder et al., 2021; Stevens et al., 2006) and oyster beds (Hesterberg et al., 2022; McClenachan et al., 2021). In central Texas (e.g., Corpus Christi and Port Aransas), observations of mangrove expansion (Armitage et al., 2015; Montagna et al., 2011) and contraction (Everitt et al., 1996; Kaalstad et al., 2023; Martinez et al., 2023) have underscored the critical role of extreme freeze events in governing mangrove-marsh dynamics. However, for salt marshes to the north of current range limits (i.e., in Georgia, Alabama, Mississippi, and parts of Louisiana, north Texas, and north Florida), there is a need for better information regarding the potential changes in wetland structure and function due mangrove range expansion for wetland scientists and managers.

Our analyses indicate that the potential for mangrove presence will dramatically increase in the northern Gulf of Mexico and the southeast Atlantic coasts of the United States due to

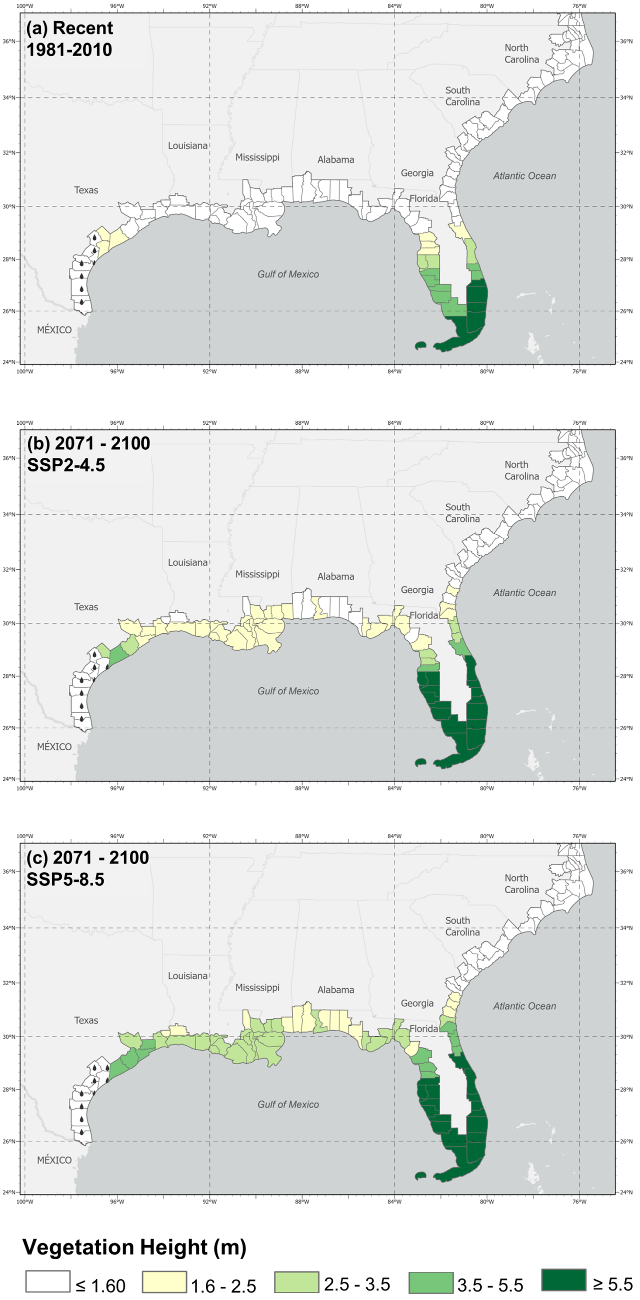

FIGURE 3 Maps of county-level coastal wetland vegetation height under (a) recent climatic conditions (1981–2010) and two alternative future climate scenarios based upon two emissions scenarios: (b) SSP2-4.5 (2071–2100), and (c) SSP5-8.5 (2071–2100). Vegetation height reflects the average height of all coastal wetland vegetation within the county (i.e., mangrove and marsh). Each of the coloured polygons represents a coastal county that contains coastal wetlands. Along the western Gulf of Mexico, within counties denoted with the black water droplets where precipitation is below 995 mm, we expect that low freshwater availability will modulate the potential for mangrove expansion and growth. Our data are provided at a coarse spatial scale to indicate broad areas (i.e., counties) where mangroves are projected to be a major contributor to vegetation height in tidal saline wetlands. However, within these broad areas, we are cautious not to specify the exact location where vegetation height will change. Sea-level rise is one of the primary reasons for our selection of this coarse spatial scale. Beyond just winter warming, coastal wetlands are highly vulnerable to accelerated sea-level rise and many other aspects of climate change. Please see section 4.1 for more information regarding these interactions. SSP, Shared Socio-Economic Pathway.

warming winter temperatures. Under the high emissions scenario, our projections of mangrove presence extend all the way to South Carolina. Although mangroves are expected to be present in these states, our analyses indicate that tidal saline wetlands in the Carolinas and Georgia would continue to be dominated by salt marshes. Our future projections of mangrove abundance, wetland vegetation aboveground biomass, and wetland vegetation height can be used to identify areas where winter warming has the potential to transform coastal wetlands. For example, under the high emissions scenarios, tidal saline wetlands in parts of north Florida, Louisiana, and Texas are expected to have mangrove abundances greater than 50%, compared to current values of nearly 0%. The height and aboveground biomass of the vegetation in these coastal wetlands is expected to increase from values typical of salt marshes (i.e., heights of <1.5 m and aboveground biomass values of less than 30 t ha^{-1}) to values typical of mangrove forests (i.e., heights greater than 2.5 m and aboveground biomass values greater than 45 t ha^{-1}). This transition from a short, grass-dominated marsh ecosystem to a taller, woody-plant dominated mangrove forest ecosystem is a major ecological regime shift that will affect many ecosystem goods and services.

4.1 | Climate change and sea-level rise interactions

Our data are provided at a coarse spatial scale to indicate broad areas (i.e., counties) where mangroves are projected to dominate tidal saline wetlands. However, within these broad areas, we are cautious not to specify the exact location where mangroves will become dominant. Sea-level rise is one of the primary reasons for our selection of this coarse spatial scale. Beyond just winter warming, coastal wetlands are highly vulnerable to accelerated sea-level rise and many other aspects of climate change. As a result, tidal saline wetlands are expected to be found in different positions in the landscape. For example, due to rapidly rising seas and saltwater intrusion, many current tidal saline wetlands are expected to drown and convert to open water (Saintilan et al., 2023), while other tidal saline wetlands are expected to migrate landward into adjacent freshwater and upland ecosystems (Osland et al., 2022). Some coastal wetlands may be unable to adapt to sea-level rise due to anthropogenic barriers that prevent landward movement and lead to coastal squeeze (Borchert et al., 2018). In colder climates, salt marsh graminoid plants are expected to migrate landward (Herbert et al., 2015; Ury et al., 2021; White et al., 2022). However, in more tropical climates, mangrove trees are expected to migrate landward (Krauss et al., 2011; Ross et al., 2000). Sea-level rise and warming winter temperatures are expected to interact to enable mangroves

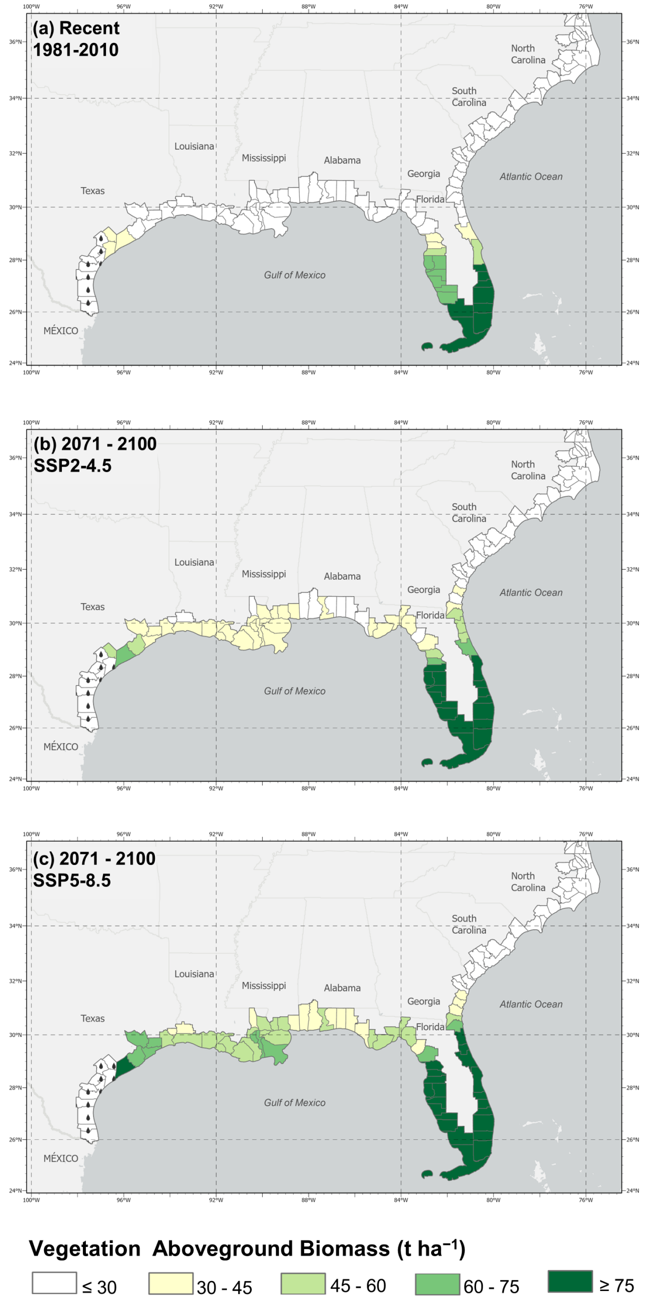

FIGURE 4 Maps of county-level coastal wetland vegetation aboveground biomass under (a) recent climatic conditions (1981–2010) and two alternative future climate scenarios based upon two emissions scenarios: (b) SSP2-4.5 (2071–2100), and (c) SSP5-8.5 (2071–2100). Aboveground biomass reflects the average aboveground biomass of all coastal wetland vegetation within the county (i.e., mangrove and marsh). Each of the coloured polygons represents a coastal county that contains coastal wetlands. Along the western Gulf of Mexico, within counties denoted with the black water droplets where precipitation is below 995 mm, we expect that low freshwater availability will modulate the potential for mangrove expansion and growth. Our data are provided at a coarse spatial scale to indicate broad areas (i.e., counties) where mangroves are projected to dominate tidal saline wetlands and contribute to vegetation aboveground biomass. However, within these broad areas, we are cautious not to specify the exact location where aboveground biomass will change. Sea-level rise is one of the primary reasons for our selection of this coarse spatial scale. Beyond just winter warming, coastal wetlands are highly vulnerable to accelerated sea-level rise and many other aspects of climate change. Please see section 4.1 for more information regarding these interactions. SSP, Shared Socio-Economic Pathway.

to migrate landward into freshwater marshes and freshwater forested wetlands to the north of current mangrove range limits. The coarse spatial scale of our projections means that our results are relevant to those future tidal saline wetland areas, even if they are in different positions in the landscape due to accelerated sea-level rise.

Our results also take into consideration the interaction between warming winters and changing precipitation regimes. Along the northwestern Gulf of Mexico near the Texas-Mexico border, low precipitation and low freshwater inputs to estuaries can produce hypersaline conditions that limit the coverage of mangroves and other vascular plants (Gabler et al., 2017; Osland et al., 2014). From a temperature perspective alone, the southern Texas coast could be dominated by mangrove forests. However, low precipitation in the future is expected to continue to produce hypersaline conditions and coastal wetlands being dominated by unvegetated salt flats instead of mangroves (Gabler et al., 2017).

4.2 | The impacts of mangrove range expansion on ecosystem services and management strategies

Mangrove ecosystems, as they expand poleward, present both challenges and opportunities for coastal management strategies in the southeastern United States (Kelleway et al., 2017; Osland et al., 2021). Mangroves can be seen as potentially providing a cost-effective solution to some of the challenges brought about by climate change. With their expansion, mangroves can offer enhanced coastal protection, strengthening resilience against storm surges and acting as effective buffers, reducing wave energy, and preventing erosion (Sánchez-Núñez et al., 2019; Sandilyan & Kathiresan, 2015). They also serve as vital carbon sinks (Alongi, 2020) and provide habitats for various species of fish, birds, and other wildlife (Field et al., 1998). However, their expansion into areas traditionally dominated by salt marshes may alter existing ecological dynamics, potentially threatening local biodiversity and disrupting established ecosystems (Scheffel, Heck, & Johnson, 2017). The colonization of mangroves into existing coastal environments may necessitate updates to management practices to account for the altered physical and ecological characteristics of the coastline.

From a socio-economic perspective, the expansion of mangroves might impact fisheries, tourism, and local real estate values (Osland et al., 2021). The modification of coastal landscapes could render some areas less attractive for recreation and tourism, while potentially altering the availability of fish stocks and other resources crucial to commercial and recreational fisheries (Carrasquilla-Henao et al., 2019). While mangroves are crucial for natural shoreline stabilization, their unchecked expansion might necessitate alterations to existing infrastructure, such as drainage systems, to prevent flooding and facilitate water flow.

Adaptive and proactive coastal management strategies, including the deliberate promotion or restriction of mangrove expansion, have already been implemented in parts of the southeastern United States. Local human interventions, such as planting or removal, can play a significant role in shaping this expansion (Zimmer et al., 2022). Deliberate plantings can accelerate the spread of mangroves, especially if supported by policies and community initiatives. Conversely, mangrove removal to preserve the current coastal marshes or to prevent potential ecological disruptions, can impede this natural migration. Decisions to either promote mangrove planting or inhibit their expansion through removal or trimming could benefit from a thorough understanding of the ecological, social, and economic impacts in the context of climate change and sea-level rise. Both actions come with their set of ecological, economic, and social implications for consideration and strategic planning. Regulatory frameworks may also need to adapt to facilitate the optimal coexistence of salt marshes and mangrove ecosystems and human activities, while also safeguarding the health and resilience of these vital coastal ecosystems. Thus, the poleward expansion of mangroves underscores the value of an integrated, interdisciplinary approach to coastal management, bridging the gap between ecological science, social science, policy, and practical on-the-ground management strategies.

In the face of accelerating climate change and rising sea levels, coastal managers seek information that can help them better anticipate and prepare for future ecological transformations. Our projections can help coastal managers identify areas where mangrove range expansion is projected due to warming winter temperatures. Given the multifaceted implications of mangrove expansion, coastal managers within these areas may need to adopt a balanced approach, weighing the immediate benefits against potential long-term repercussions. Collaborative efforts between ecologists, policymakers, practitioners, and local communities can help devise strategies that promote ecological health and resilience, while also catering to the socio-economic needs of these regions.

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CONFLICT OF INTEREST STATEMENT

The authors declare they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

These data are publicly available from Bardou et al. 2024 and available at https://doi.org/10.5066/P9S60DG8.

Bardou, R., Hughes, A.R., and Osland, M.J., 2024, Projected mangrove distribution and ecosystem properties in the southeastern United States under climate change: U.S. Geological Survey data release, https://doi.org/10.5066/P9S60DG8.

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BIOSKETCH

Rémi Bardou is broadly interested in the processes that control the range limits of mangroves in North America. This work on mangrove projections in the southeastern United States represents a major component of his Postdoctoral project, for which he and the other co-authors collaborated on questions of mangrove distributions and dynamics in the southeastern United States.

Author contributions: RB, MJO, and ARH conceived and initiated this study; RB analysed current and future climate data; RB, MJO, and ARH developed the approach for projecting changes in distribution and structure with input from all authors; RB prepared the figures; ARH and MJO prepared the tables; RB, MJO, and ARH wrote the first manuscript draft. All authors contributed to subsequent manuscript drafts and gave final approval for publication.

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