Challenges and Opportunities for Sustaining Coastal Wetlands and Oyster Reefs in the Southeastern United States

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Abstract

Formed at the confluence of marine and fresh waters, estuaries experience both the seaside pressures of rising sea levels and increasing storm severity, and watershed and precipitation changes that are shifting the quality and quantity of freshwater and sediments delivered from upstream sources. Boating, shoreline hardening, harvesting pressure, and other signatures of human activity are also increasing as populations swell in coastal regions. Given this shifting landscape of pressures, the factors most threatening to estuary health and stability are often uncertain. To identify the greatest contemporary threats to coastal wetlands and oyster reefs across the southeastern United States (Mississippi to North Carolina), we summarized recent population growth and land-cover change and surveyed estuarine management and science experts. From 1996 to 2019, human population growth in the region varied from a 17% decrease to a 171% increase (mean= +43%) with only 5 of the 72 SE US counties losing population, and nearly half growing by more than 40%. Individual counties experienced between 999-19,253 km^2 of new development (mean: 5,725 km^2), with 1-5% (mean: 2.6%) of undeveloped lands undergoing development over this period across the region. Correspondingly, our survey of 169 coastal experts highlighted development, shoreline hardening, and upstream modifications to freshwater flow as the most important local threats facing coastal wetlands. Similarly, experts identified development, upstream modifications to freshwater flow, and overharvesting as the most important local threats to oyster reefs. With regards to global threats, experts categorized sea level rise as the most pressing to wetlands, and acidification and precipitation changes as the most pressing to oyster reefs. Survey respondents further identified that more research, driven by collaboration among scientists, engineers, industry professionals, and managers, is needed to assess how precipitation changes, shoreline hardening, and sea level rise are affecting coastal ecosystem stability and function. Due to the profound role of humans in shaping estuarine health, this work highlights that engaging property owners, recreators, and municipalities to implement strategies to improve estuarine health will be vital for sustaining coastal systems in the face of global change.

Key Words

Coastal ecosystems, oyster reef, development, mangrove, population growth, salt marsh

1. Introduction

Worldwide, humans are altering physical and biological processes through the engineering of landscapes and watersheds, and modification of biochemical cycles, sediment transport processes, and food webs (Rockström et al., 2009). Such anthropogenic impacts are particularly pronounced in the coastal zone, where more than 40% of the global human population resides (IPCC, 2014) and where coastal ecosystems have been manipulated, built over, and intensively harvested for centuries (Holland et al., 2004; Tonkin et al., 2018). Since the Industrial Revolution, human modification of the coastal zone has continued to increase (Lotze et al., 2006). For instance, the intensity of commercial fishing, shellfish harvesting, and timber extraction is ramping up in estuarine and near-shore environments around the world (Bertness et al., 2004; Essington et al., 2015). Likewise, both commercial and residential development continues to climb along many coastlines despite the encroaching pressure of sea level rise. Simultaneously, escalation in boating, snorkeling, fishing and other recreational activities are introducing pollution (e.g., oil products, debris), shifting species' distributions, and physically damaging the many coastal systems that are visited by people (Altieri et al., 2012; Bell et al., 2015; Wall et al., 2005). Layered over and interacting with these local stressors, global climate change-related shifts in sea level, changing ocean chemistry in the form of acidification, changes in precipitation patterns, and intensifying storms threaten the persistence of coastal ecosystems (Statham, 2012; Tonkin et al., 2018).

In many places, the constellation of contemporary threats to coastal ecosystems are changing in part due to the relatively rapid increase in the density of people living in close proximity to the coast (Wong et al., 2017). This continued influx of people is driving changes in the composition of upstream land-use, as natural and agricultural lands are converted to residential, urban, and industrial complexes. In turn, these activities are altering the quantity and quality of water and sediment reaching the coast (Kirwan & Megonigal, 2013). Higher population densities are also intensifying human use of and interactions with coastal ecosystems. In particular, shoreline armoring and recreational fishing in estuaries have risen dramatically across the United States as development of coastal counties increases and as estuaries host larger numbers of residents and recreators (Bell et al., 2015; Gittman et al., 2015). However, there is tremendous regional variation in the rate at which coastal areas are experiencing population growth and being urbanized, resulting in a patchwork of challenges for the conservation and management of coastal ecosystems and their services (Mallin et al., 2001).

To counteract compounding and evolving pressures on estuarine systems, natural resource managers have been regulating fisheries and shellfish harvesting pressure, removing impoundments to restore hydrological connectivity, restoring habitats, and improving water quality (Bayraktarov et al., 2016; Liu et al., 2016). While some of these interventions are showing signs of success, the effectiveness of others, such as restoring bivalves, remains unclear (e.g. Moberg & Rönnbäck, 2003). Both the changing nature of stressors on estuaries and the varied success of management actions are challenging scientists and stakeholders to identify which of all of the current and emerging threats are most important to address to sustain estuarine ecosystems. Such up-to-date analyses are urgently needed as managers attempt to prioritize where limited resources should be invested to achieve the greatest benefits in ecosystem health and the level of services they provide.

To advance understanding of this changing landscape of threats and management actions, we pursue two primary objectives in this study. First, we seek to provide easy-to-use information about contemporary rates of human population growth and land-use change to scientists, natural resource managers, and local to federal decision-makers. By integrating US Census Bureau data related to population change and NOAA C-CAP (National Oceanic and Atmospheric Administration Coastal Change Analysis Program) data related to land-use change across the southeastern United States, we aim to help this stakeholder community contextualize how the changes in human density and land use that they may observe at a given study site or estuary compare to rates observed at county, sub-region (i.e. Mississippi-Alabama, Northwest Florida, South Florida, Northeast Florida, Georgia, South Carolina and North Carolina; sub-regions defined by both geopolitical boundaries and the eco-geomorphic similarity of coastal wetlands and reefs) and region (all 72 counties) scales. Second, we aim to synthesize expert opinion regarding the greatest threats to coastal wetland and oyster reef ecosystems at the sub-regional scale to provide scientists guidance regarding which threats to focus future research on to resolve their actual (as opposed to perceived) importance in controlling estuarine ecosystem health. In identifying consensus of expert opinion from a workshop and survey, we also share results that are of immediate use to decision-makers tasked with prioritizing where resources could be invested to mitigate the threats generally thought to be most damaging to coastal ecosystems.

2 Methods

2.1 Study Region and Coastal Ecosystem Focus

We focus this study in the southeastern United States, a region that includes nearly 29,000 km of coastline—nearly 20% of the total US coastline— and that has experienced significant coastal population growth, including more intense human activity in estuaries (NOAA Office of Coastal Management, 2015; Trueblood et al., 2013). Similar to many other coastal areas around the world, this region, which encompasses the 72 coastal counties in Mississippi, Alabama, Florida, Georgia, South Carolina, and North Carolina (Fig. 1), is vulnerable to sea level rise (Crotty et al., 2020; Saha et al., 2011; Voss et al., 2013) and intensifying storm events (Knutson et al., 2015; Stansfield et al., 2020), factors that may be exacerbating the effects of anthropogenic stressors on coastal ecosystems. Due to significant heterogeneity in geology, climate and demographics, the physical forcing factors, biological diversity, and human use of the coastal zone vary greatly across this region.

We constrained our study to the six states that were within reasonable driving distance to northeast Florida where our team held an *Edges of Our Estuaries* workshop in October 2018, an event which supported the conceptual development and defined the objectives of this paper. Texas and Louisiana, although in the southeastern US, were considered too far to ask participants to travel from without compensation and are thus not considered in this study. In this workshop, leading estuary experts and natural resource managers from this region convened to share their knowledge of contemporary threats to estuaries and to brainstorm where additional research may be needed most to support successful estuary management.

This workshop was followed by an analysis of contemporary — i.e. since 1996 — changes in human population density and land use change and a survey that allowed our team to collect standardized information from workshop participants as well as a large number of estuary scientists and natural resource managers across the 72-county study area than could not attend the workshop. In this survey, we asked coastal experts to identify the threats perceived to be the most threatening to coastal wetlands (i.e., salt marshes and mangrove forests) and oyster reefs structured by the Eastern oyster, *Crassostrea virginica* within the sub-region that each survey participant was most knowledgeable about. We focus on these two habitats as they are the most spatially dominant intertidal/ shallow sub-tidal coastal ecosystems in the region and, due to their different ecology and elevational distributions, are likely to be threatened by unique combinations stressors and thus pose distinct challenges with regards to their management.

2.2. Changes in Human Population Density Across the Southeastern US

To evaluate the scales at which human population densities have shifted in recent decades, we gathered US Census data for the period spanning 1996 to 2016 US. To evaluate trends in population growth at a sub-region scale, we grouped the 72 counties into seven sub-regions: Alabama and Mississippi (AL/MS), West Florida (WF), South Florida (SF), East Florida (EF), Georgia (GA), South Carolina (SC), and North Carolina (NC) (see dark lines delineating each region in Figures 1a and 1b and a summary of counties in each region in Table S1). US Census Bureau data (https://www.census.gov/data.html) were used to calculate population growth and to evaluate changes in population density (people per km^2) over the study period (1996– 2016) for each sub-region. All analyses related to spatial and temporal trends in population change were conducting in SAS Enterprise Guide 8.3.

2.3 Land Cover Classification

To then evaluate the patterns and rates of land cover change that have occurred in recent decades across the southeastern US, we gathered land cover data from NOAA C-CAP, (https://coast.noaa.gov/digitalcoast/data/ccapregional.html) for the period spanning 1996 to 2016. Of note, the NOAA C-CAP database provides updated landcover data at a 4- to 6-year interval (while the census estimates are produced annually). Following the NOAA C-CAP Regional Land Cover Classification Scheme (https://coast.noaa.gov/digitalcoast/training/ccap-land-cover-classifications.html), land cover classes were grouped into one of the following categories: Estuarine Wetlands (>0.5% ocean-derived salinity), Palustrine Wetlands (<0.5% ocean-derived salinity), Undeveloped Lands (i.e. grasslands, forests, shrub/scrub, bare land), Agriculture (cultivated and pasture/hay), Water, and Developed (i.e. high, medium and low intensity developed and developed open space such as parking lots). See Supplemental Methods and Table S2 for details about data processing and the land cover classes in each category.

2.4 Land Conversion Rates

To assess potential differences in how efficiently people have converted lands from 'Natural Lands' (i.e., those dominated by natural or agricultural vegetation cover types: Estuarine Wetland, Palustrine Wetland, Undeveloped Lands and Agriculture land cover classes) to Developed lands as population density has generally increased across the region, we calculated 'Area of Newly Developed Land Per New Resident Per Year'. We define this metric as the area of Natural Land, in m^2, that was converted to Developed Land standardized by change in population in the sub-region and year for the 1996 to 2001, 2001 to 2006, 2006 to 2010, and 2010 to 2016 time periods. High values of this metric indicate sub-regions for which the increase in new residents observed during a given time period was associated with large areas of land converted to development. Land cover change analyses were conducted in ArcGIS Version 10.6 using the Spatial Analyst Toolbox. Rate of land cover change and land conversion rate analyses were conducted in SAS Enterprise Guide 8.3.

2.5 Workshop and Stakeholder Survey

In the months following our two-day workshop (described briefly above), we prepared an *Estuary Expert Survey* in Qualtrics and distributed this survey via email to estuarine experts, including those who attended the workshop and others identified by regional experts, across the seven sub-regions. The survey included questions related to each expert's region of expertise, occupation and age, as well as their perceptions of local and climate stressors to coastal wetlands and oyster reefs in specific regions (see Table S4 for a list of survey questions; the UF IRB board approved the exemption of this survey). Considering the potential subjectivity in responses from respondents, results from the survey are considered and presented herein as "perceptions" rather than "true" quantitative evidence. Below, we present the survey results related to threats to each ecosystem type in the results and summarize the future research directions identified in the survey and workshop in the discussion.

Among threats listed in the survey, local threats for both wetlands and oyster reefs included eutrophication, industrial pollutants (e.g., heavy metals, persistent organic pollutants), boat activity (e.g., wakes, fuel leakage), shoreline hardening, upstream/watershed modifications to freshwater flow, residential/commercial development, and modifications to sediment dynamics (e.g., dredging, spoil deposits). Consumer/herbivore (e.g., snails, crabs) outbreaks, which have been reported in the literature as having important impacts on wetlands across the region over the last 20+ years (Angelini et al., 2018; Crotty et al., 2020; Silliman et al., 2005; Vu et al., 2017) were listed as a potential local threat only for wetlands; overharvesting and disease were listed as potential local threats only for oyster reefs. Climate threats for both wetlands and oyster reefs included changes in precipitation, changes in temperature extremes, increased storms, and sea level rise. Acidification was listed as a climate-related threat only for oyster reefs. Survey respondents were asked to distribute a total of 20 ‘threat points’ across the various local and climate-change related factors for each ecosystem type. This particular set of threats was compiled by our team of authors based on its cumulative knowledge of the literature related to well-described stressors to coastal wetlands and oyster reefs in this region.

Forty-five participants attended the 2-day, 16-hour workshop and 169 responses to the survey were received. Sixty-four survey responses were from respondents with expertise in East Florida estuaries (38% of all responses), 27 from Alabama/Mississippi and 24 from North Carolina (14%), while West Florida, South Florida, Georgia and South Carolina were each represented by 12 to 15 survey responses (about 8%). Primarily, respondents were from academia, state government, and non-profit agencies, followed by federal government, National Estuarine Research Reserve System (NERRS), and local government sectors. The most common age range among the respondents was 35-44, followed by 25-34 and 45-54 (see Figure S3 for details).

3.0 Results

3.1 Population Change Across the Southeastern US

US Census Bureau data revealed that the total US population grew by over 58 million persons (21.8%), from 269,394,284 to 328,239,523, between 1996 and 2019. In the southeastern US, seven coastal counties, all in Florida, experienced increases in population of more than 200,000 people over this 23-year time period, and 60 of the 72 coastal counties experienced increases in human population of between 0 and 200,000 people (Figure 1a). Four coastal counties in North Carolina and one in Florida experienced population losses over the study period, with the greatest loss of 7,104 persons occurring in Monroe County, Florida located in the southwestern Everglades region.

In evaluating percent changes in population growth (Figure 1b), a somewhat different pattern in human demographic change emerged with several counties with moderate populations in 1996 experiencing particularly fast proportional growth over this time period. Specifically, six counties experienced growth of over 100%, meaning the population more than doubled over this 23-year period. Flagler and St Johns Counties in Florida grew by 171 and 149%, respectively; Brunswick County, NC and Horry County, SC grew by 127% and 116% respectively; Walton County in West Florida grew by 111%, and Lee County in South Florida grew by 103%.

In evaluating changes in population density, or the number of people per km^2, we found that population density increased steadily over time in all seven sub-regions, with the greatest increases occurring in South Florida where the density increased from 173 to 239 people per km^2, or by 38%, between 1996 and 2016, and in East Florida where the density increased from 103 to 146 people per km^2, or by 42% (Fig. 2B). Coastal counties in North Carolina sustained the lowest population density in the region, starting with 21 people per km^2 in 1996 and increasing to only 29 people per km^2 in 2016, a 38% increase. Alabama-Mississippi, Georgia, South Carolina and West Florida all had similar population density ranges, and rates of change in population density, as they increased from 53 to 63, 48 to 60, 41 to 63, and 38 to 53 people per km^2, respectively, from the start to end of this contemporary period.

3.2 Land Cover Change Across the Southeastern US

Utilizing NOAA's C-CAP data to evaluate land cover change since 1996, we found that all regions experienced the greatest increases in 'Developed' lands compared to the other land cover categories (Figure 3; county-level land use change data are available in Table S3 and see Figure S1 for re-scaled versions of Figure 3 panels). Florida experienced larger net increases in Developed land cover compared to the other states and sub-regions, with developed area in South Florida growing by 18% (1,103 km^2) from 1996 to 2016. After South Florida, increases in

Developed Lands were greatest in East Florida, followed by West Florida, South Carolina, North Carolina, Alabama-Mississippi and Georgia.

To accommodate development, land cover was primarily lost from Undeveloped Lands (i.e. grassland, mixed forest, scrub/shrub), and from both Palustrine and Estuarine Wetland habitats across the region (Figure 3). Losses in Undeveloped Land area ranged from 313 km^2 in East Florida to 113 km^2 in Alabama-Mississippi, while declines in Palustrine Wetland area between 1996 and 2016 were greatest in South Florida (421 km^2) followed by North Carolina (199), South Carolina (174 km2), West Florida (167 km2), East Florida (163 km2), Alabama-Mississippi (89 km2), and, finally, Georgia (26 km^2). Estuarine Wetland losses were generally an order of magnitude lower than Palustrine Wetland losses and were highest in South Florida (45 km^2), followed by South Carolina (12 km^2), North Carolina (10 km^2), East Florida (8 km^2), Georgia (4 km^2) and Alabama-Mississippi (4 km^2). Estuarine Wetland area increased slightly in West Florida (3 km^2), occurring as a result of these salt-tolerant wetlands expanding into open water and palustrine wetland areas. South Florida was the only sub-region where the greatest land cover loss occurred in Agricultural lands, with 643 km^2, or 12%, of lands of this cover type being lost in this sub-region since 1996. Finally, the area covered by water increased across all seven sub-regions, with the increase ranging from 9 km^2 for Georgia to 159 km^2 for South Florida. Visual inspection of land use change maps reveals that the gains in 'water' were mostly due to new manmade retention structures, including stormwater ponds.

3.3 Land Conversion Rates

We discovered that the Area of Newly Developed Land Per New Resident Per Year, a metric calculated to assess land conversion rates, followed a similar temporal pattern across all regions, dropping from the 1996-2001 to the 2001-2006 period, before increasing in the 2006-2010 period, and then dropping again in the 2010-2016 period. This varying trend suggests that there have not been steady reductions (or gains) in the rate at which lands are being developed to accommodate new residents across this region in recent decades. Georgia coastal counties exhibited the third highest land conversion rates at the beginning of our study period (12.7 m^2 of land developed per new resident per year for 1996–2001) but then became the sub-region exhibiting the highest land conversion rates (i.e. 9.3 m^2 for 2001–2006, 24.0 m^2 for 2006–2010, and 3.8 m^2 for 2010–2016) for the remaining time periods. South Florida counties exhibited the lowest land conversion rate per capita for all time periods with between 0.7-9.9 m^2 of land being developed for each new resident per year across the evaluated time periods (Figure 4). These results generally highlight that less densely populated sub-regions have exhibited higher land conversion rates than highly populated areas where limited area remains to accommodate additional development.

3.4 Synthesis of Local and Climate Threats

In evaluating the responses to the survey, we found that development (inclusive of both residential and commercial) and modifications to freshwater flow were perceived by survey participants as the most important local stressors for both estuarine wetlands (mangroves and salt marshes) and oyster reefs in most sub-regions (Figure 5a). The only exception to this result was that modifications to freshwater flow were perceived to have only a negligible effect on coastal wetlands and oyster reefs in South Carolina. For wetlands, development was ranked as the most important local threat in five of the seven regions (Alabama-Mississippi, East Florida, Georgia, South Carolina, North Carolina), while modifications to freshwater flow was ranked as the most important in the other two regions (West Florida, South Florida), and shoreline hardening of tertiary importance in many sub-regions. Consumer outbreaks were perceived as the least important local stressor to wetlands in all regions.

When asked to reflect on the most important local threats to oyster reefs, the top stressors for most regions were modifications to freshwater flow, development, and overharvesting (Figure 5b). Modifications to freshwater flow was identified as most important in the three western regions (Alabama-Mississippi, West Florida, South Florida), development as most important in three regions (East Florida, Georgia, South Carolina), while overharvesting was perceived as the most important stressor in North Carolina and also a stressor of moderately high importance in the other sub-regions.

In terms of climate stressors, sea level rise was perceived as most important for wetlands in all seven sub-regions (Figure 6a). In oyster reefs, perception of climate stressors was more variable in that precipitation change was ranked as the most important stressor in four of the seven sub-regions (Alabama-Mississippi, West Florida, South Carolina, North Carolina); while acidification was ranked as the most important stressor in two regions (South Florida, East Florida) and the second most important stressor in three regions (Alabama-Mississippi, West Florida, North Carolina, Figure 6b). In Georgia, the greatest perceived threat facing oysters was sea level rise, although temperature and precipitation change were also similarly highly ranked.

4.0 Discussion

4.1 Integration of Population Growth, Land Cover Change and Expert Survey Results

Together, our analyses of population growth, land cover change and the expert survey suggest that estuaries across the southeastern US are under widespread and increasing stress from escalating coastal populations and the associated development and other modifications to the landscape that this growth involves. Indeed, we found that the greatest conversion of land in coastal counties involved the expansion of Developed Land over the 20-year period examined. Associated with this transformation, estuary experts highlighted that threats associated with development are, in many places, posing the greatest pressures on wetlands and oyster reefs across the region. Indeed, many of the threats identified as key drivers of estuarine health in our survey, such as shoreline hardening, have been related to increases in population and/or developed land cover that accompany population change (Gittman et al., 2015; Scyphers et al., 2011; Valiela, 2006). Similarly, modifications to freshwater flow are common by-products of development as natural areas are re-graded or channel flows are modified to accommodate site development. Thus, this work summarizes the widespread consensus among estuary experts that human population growth in coastal areas is continuing to place additional stress on these valuable systems and the functions and services that they support. Given that climate change poses additional threats to coastal ecosystems – with salt marshes and mangroves being perceived in our survey to be most threatened by sea level rise and oyster reefs by precipitation changes, acidification, and overharvesting (in North Carolina only) by our survey of 169 experts – our work reinforces the notion that coastal managers face tremendously complex challenges derived from both humans and climate, and from changes to the land and the sea, in maintaining estuary health and functioning.

Below, we summarize the research that experts identified in our workshop as that which is most urgently needed to guide adaptive management in the face of this shifting landscape of pressures on estuaries in the years to come. We also present possibilities for addressing each research need, and, where relevant, potential impediments to succeeding in producing the necessary research. Our intent is to begin to prioritize the socio-ecological and economic research needed to support management and policy in this region, and the many other coastal areas experiencing similar interactions among local and global stressors.

4.2. Real-Time Monitoring of Threats

To better assess the relative importance of different threats facing estuaries, participants highlighted a particularly strong desire to expand near real-time monitoring of threats such as boat wave-energy, shoreline erosion, and salinity, nutrient and pollutant fluctuations. Participants highlighted that information about such stressors is often shared with them too slowly for proactive decision-making and management to occur. Filling this gap requires the integration of new technology able to transmit data from sensors in real-time and analytical systems able to efficiently intercept such data, process it into useful products, and share resulting products with decision-makers. Novel, real-time data streams, such as those produced by citizen scientists through app-based reporting systems related to beach or coastal conditions (e.g Mote Marine Laboratory's Beach Conditions Reporting System: https://visitbeaches.org/) have the potential to significantly expand real-time monitoring of harmful algae blooms and marine debris at relatively low cost (Hardison et al., 2019; van der Velde et al., 2017). Similar applications many also support the real-time evaluation of significant and sudden changes in habitat or species abundance (Scyphers et al., 2015). The challenges of implementing any of these activities include having the personnel to develop and manage data collection/citizen scientist programs, maintaining consistency in data collection procedures, providing thorough quality control of the data, and securing the resources needed to train and maintain this technologically advanced workforce.

4.3 Mapping with Higher Temporal and Spatial Resolution

Habitat maps are time consuming and costly to produce, especially at large scales relevant for comprehensive management. However, information about the spatial distribution and condition of estuarine habitats is vital for informing when and where management interventions may be needed to bolster degraded habitats. NOAA's C-CAP provides nation-wide land cover information in map format for public use. This information is standardized across the US, released approximately every 5 years, and displays at 30-m resolution, making it appropriate for regional analyses. In terms of tracking habitat change at scales relevant to individual property owners and many managers (and the impacts of acute events such as oil spills or extreme storms), this spatial and temporal resolution is insufficient, however. Annual, high-resolution data (i.e., 0.5-m resolution), such as imagery collected by small unmanned aerial systems (sUASs), has the potential to fill some of these data gaps and inform management actions. As sUASs and their accompanying hardware and software become more affordable and accessible to non-technical users, the availability of high-resolution habitat data will increase, but will necessarily be patchy. Programs such as NOAA's CoastWatch and AquaWatch programs, Duke University's Coastal Ecology, Geomorphology, and Drones program (https://sites.duke.edu/justinridge/research/) and Grand Bay NERR's high-resolution drone mapping projects (http://grandbaynerr.org/gis-projects/) are examples of habitat assessment with finer spatial and temporal resolution. Nevertheless, implementing these programs face challenges during preliminary stages relating to training and licensing, rapidly changing technology, privacy concerns, and inconsistent sUAS legislation across states and agencies. Our survey and workshop highlighted a critical need for the expansion of standardized, high-frequency and high-resolution mapping programs and the development of analytical software to rapidly process such data into reliable information about habitat expansion/retreat and changes in ecosystem health.

4.4 Improved Assessment and Synthesis of Management Activities

Evaluation of the effectiveness of different management activities can be difficult to achieve because many funding opportunities only cover abbreviated time periods or do not cover project management, maintenance, or monitoring expenses. In the absence long-term support, evaluating restoration or management project effectiveness – or lack of effectiveness – over time scales sufficient to gauge project success remains out of reach for many managers and scientists. In many cases, the benefits of management actions can take years to materialize and even longer for focal ecosystems to reach their full functionality. Citizen scientists have the potential to help provide extended monitoring in some circumstances, but the metrics used to evaluate project success often must be pared down and simplified to find a balance between sustained participation and reliable data. Such citizen science programs have included monitoring wildlife use of restored sites, documenting changes to shorelines following installation of living shorelines or wave attenuation projects, or counting oysters to assess recruitment success (Greber et al., 2011). Data gathered from citizen science volunteers can be shared among agencies to facilitate identification of successful/unsuccessful projects, helping stretch limited resources. Beyond engagement of citizen scientists (an approach that introduces other ancillary challenges as highlighted above), experts highlighted the need for more funding resources and opportunities to be made available for the assessment of implemented projects. They also emphasized that resulting information about what management interventions have been particularly successful/unsuccessful and over what time scales needs to be widely shared and easily accessible to support future project design and assessment.

4.5 Communication Between Agencies and Stakeholders

Agencies and industries often face resource and responsibility challenges that lead to overburdened staff. Academic researchers are similarly burdened by teaching, research, mentoring and service responsibilities and constrained funding. These very real constraints can result in a lack of time and capacity to share information and fully engage stakeholders, thereby reinforcing institutional silos and truncating knowledge sharing. While multi-sector collaboration and coordination to help create efficiencies in information transfer,ecosystem assessment and management are improving in many coastal areas, participants of our workshop and survey highlighted that there remains a great need for cultivating synergies among institutions with similar goals of improving understanding coastal environments and sustaining their functionality. Forming ‘working groups’ among agencies and stakeholders is one way to establish regular communication and share information. As an example, the “Oyster and Water Quality Task Force” (https://gtmnerr.wixsite.com/owqtf) hosted by the Guana Tolomato Matanzas National Estuarine Research Reserve engages agencies, academic institutions, private citizens, and businesses. The task force meets quarterly to share progress on objectives and action items developed by the group to address common goals related to the intersection between oyster population sustainability and water quality. They conduct activities such as table discussions on specific topics to engage attendees and seek new information the group can use, act on, or share. This task force also supports priority grant-funded research by writing letters of support and serving as a stakeholder group for research teams looking for an efficient way to engage the community. Similar efforts to engage stakeholders, researchers, and managers in focused, shared discussions to prioritize actions are vital for building trust in decision making about how to manage estuarine resources and for leveraging limited resources and diverse expertise to develop more holistic, and deeply vetted solutions. Efforts to quantify the short- and longer-term benefits of such working groups related to improving decision-making and/or identifying efficiencies in management, monitoring, proposal development, etc. are needed, however, to help inform the value of participant's investing time in such coordination.

4.5 Education of Users and the Public

Technology is rapidly improving, as are management strategies and data resources. As new tools emerge for assessing threats to wetlands and oyster reefs, there is a need to provide easily accessible resources for scientists, managers and stakeholders to enable them to more rapidly locate and learn how to use these tools. Resources could include self-paced training, summary documents, and local workshops. The NOAA Office for Coastal Management, Digital Coast Training Calendar (https://coast.noaa.gov/digitalcoast/training/calendar.html) is an example of such a training resource for accessing and learning how to use this agency's tools. Continuing to provide updates, training through, for instance, Sea Grant Extension programs, and points of contact for online resources and new technology is necessary to ensure these tools are being applied correctly by end-users. At our workshop, participants celebrated the value of such resource libraries that are being developed and urged continued improvements and expansions of more such resources.

4.7 Conclusions: Opportunities for Improving Estuary Health

The persistence of coastal ecosystems in the southeastern US is being challenged by a broad range of stressors derived from both the land and sea. Coastal populations are increasing in most coastal counties throughout the study area, and the magnitude of this increase that we herein document is worrisome. The average annual growth for the US from 1996 to 2019 was between 0 and 33% (21.8%, Figure 1b). Of the 72 coastal counties in this study, 45 had growth greater than this national average and more than half of those (27) were in Florida. Indeed, we discovered that the loss of undeveloped lands, agricultural lands and wetlands were also greatest in Florida with a loss of 3.3% compared to the overall study area loss of 2.6%. The coastal margins of the other states in our focal region seem to be on similar, albeit generally slower, trajectories of population growth. Increasing human population and the associated development, and the intensified use of ecosystems, amplifies the effects of pollution, runoff, impervious surfaces, boating traffic, recreation activities and a wide variety of other anthropogenic impacts in ecosystems that are already stressed (McKinney, 2002).

As estuarine experts confirm that they perceive development to be a significant local stressor for both wetlands and oyster reefs, this work highlights critical need for development policies and practices to prioritize low-impact development strategies and lessen downstream impacts. Interest in low-impact development (LID) strategies has been growing in recent years both as a response to rising sea levels and as a means to improve environmental conditions such as water quality (Dietz, 2007). Research and programs that help community and policy makers quickly identify the most effective and cost-efficient LID strategies are needed to offset the vigorous pace of population growth and development. In addition, we found that sea level rise was the climate stressor most commonly perceived as being most threatening to coastal wetlands, and precipitation change the most common climate stressor for oyster reefs. These results highlight that interventions designed to reduce the severity of these climate change impacts have an important role to play in estuarine management. Such actions may include regional efforts to improve sediment delivery to coastal areas to better support salt marsh and mangrove vertical accretion, or water and land use management strategies that improve riverine baseflows and stabilize the ground water table. In many cases, the limiting factors to addressing these challenges are the money, manpower and technology necessary to design, implement and monitor projects large enough to derive estuarine-wide benefits. Thus, efforts to collaborate and creatively pool resources are likely key to achieving the holistic estuarine management structure needed to sustain these systems. Our workshop and survey indicate that there is widespread awareness that such collaboration is vital, indicating that research and management may soon be conducted regularly at the scales and with the level of coordination needed to meaningfully improve the condition and functionality of estuaries in this region.

Author Contributions

Tricia Kyzar: Conceptualization, Methodology, Formal analysis, Data Curation, Writing – Original Draft, Visualization. Ilgar Safak: Methodology, Formal analysis, Data Curation, Writing – Original Draft, Visualization. Just Cebrian: Conceptualization, Writing – Review & Editing. Mark W. Clark: Conceptualization, Writing – Review & Editing. Nicole Dix: Investigation, Data Curation, Writing – Original Draft. Kaitlyn Dietz: Investigation, Resources, Data Curation. Rachel K. Gittman: Investigation, Resources, Data Curation. John Jaeger: Conceptualization, Writing – Review & Editing. Kara R. Radabaugh: Conceptualization, Writing – Review & Editing. Annie Roddenberry: Conceptualization, Writing – Review & Editing. Eric L. Sparks: Conceptualization, Resources, Writing – Review & Editing. Benjamin Stone: Conceptualization, Writing – Review & Editing. Gary Sundin: Conceptualization, Writing – Review & Editing. Carter S. Smith: Investigation, Resources, Data Curation. Michelle Taubler: Resources, Data Curation. Christine Angelini: Conceptualization, Methodology, Writing – Original Draft, Revision,.

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Figure 1

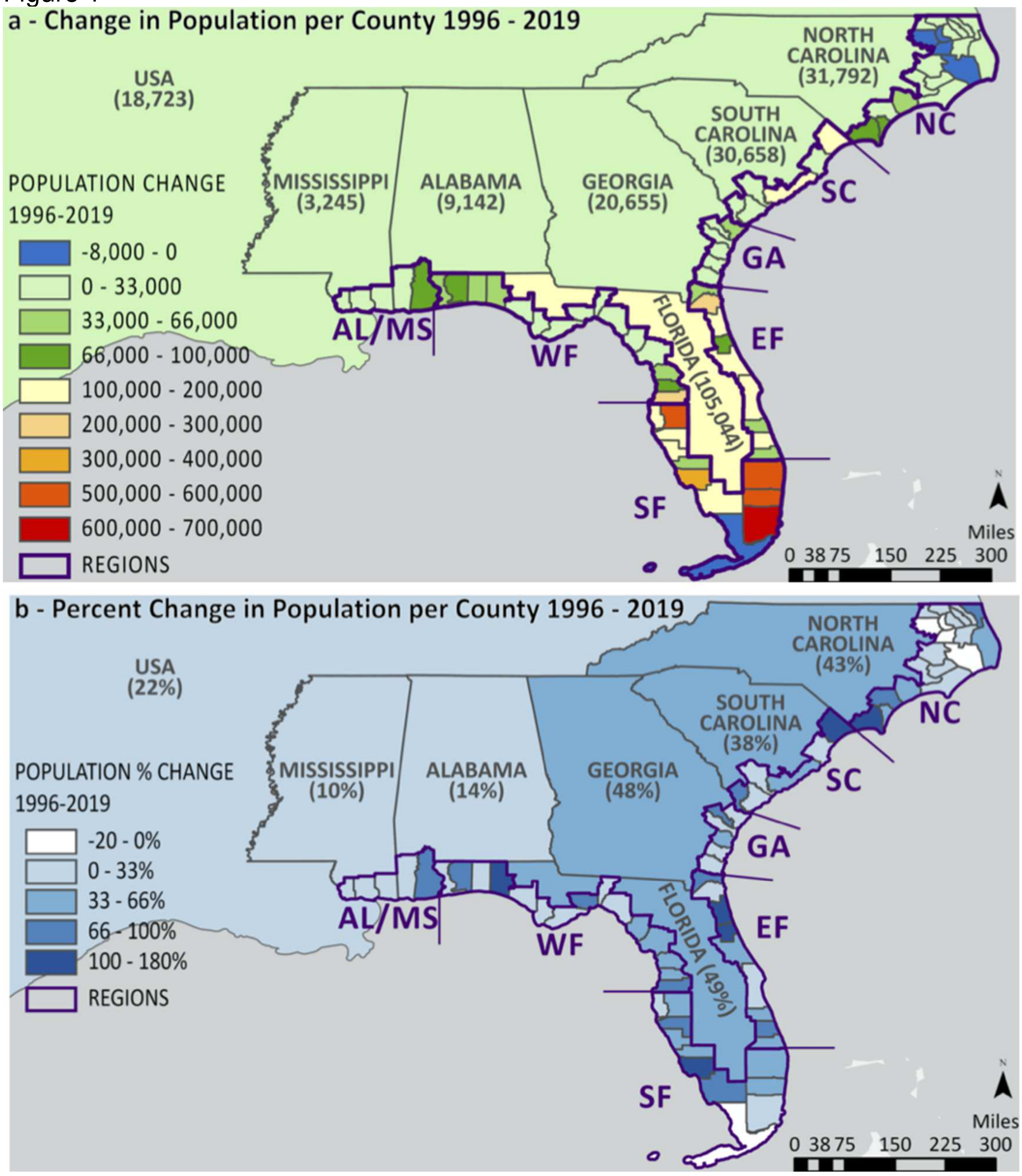


Figure 1. Population change (a) and the percent change in human population (b) between 1996 and 2019 across the southeastern US. In (a), the colors denote the change in the number of people per coastal county, the state (i.e. the color of the state shows the average change in the number of people per county inclusive of all counties in the state), and the entire US (i.e. the background color of the US shows the average population growth per county across the US); the numbers reported next to each state are the average number of new people per county across the state, and the number reported under USA is the average change in new people per county across the US. In (b), color denote the percent change in population per coastal county, the state (averaged across all counties) and the USA (averaged by the number of counties). In both panels, dark purple lines denote boundaries of each sub-region. All data were derived from the US Census Database.

Figure 2

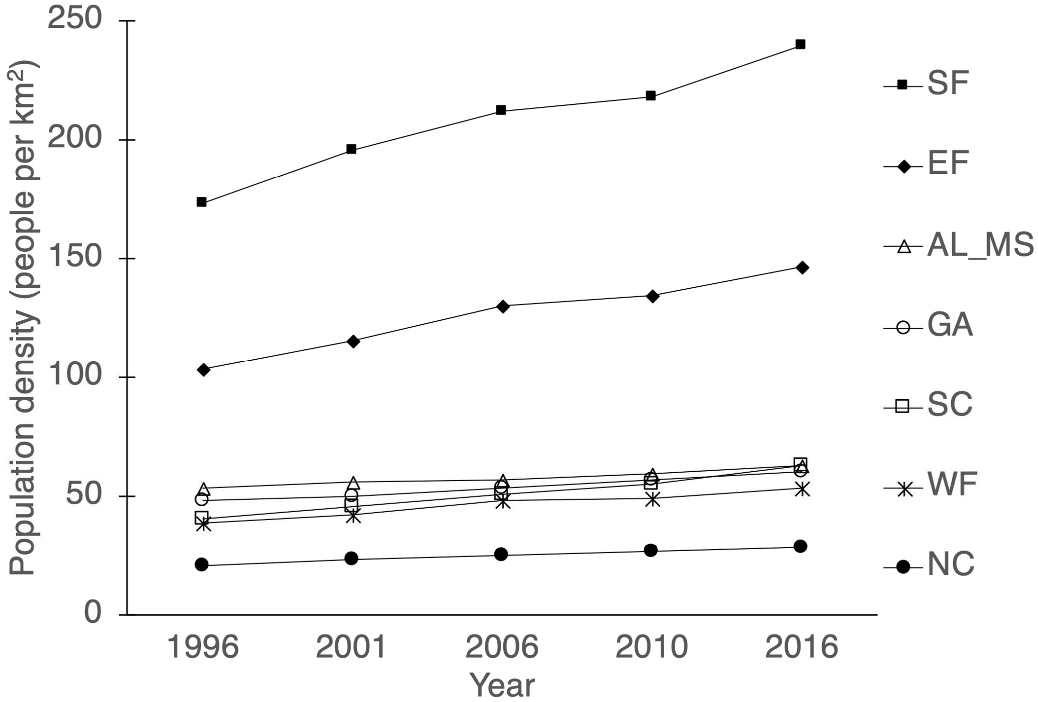


Figure 2. Population density, reported as the number of people per km^2, between 1996 and 2016 in each sub-region of the southeastern United States. All data were derived from the US Census Database.

Figure 3.

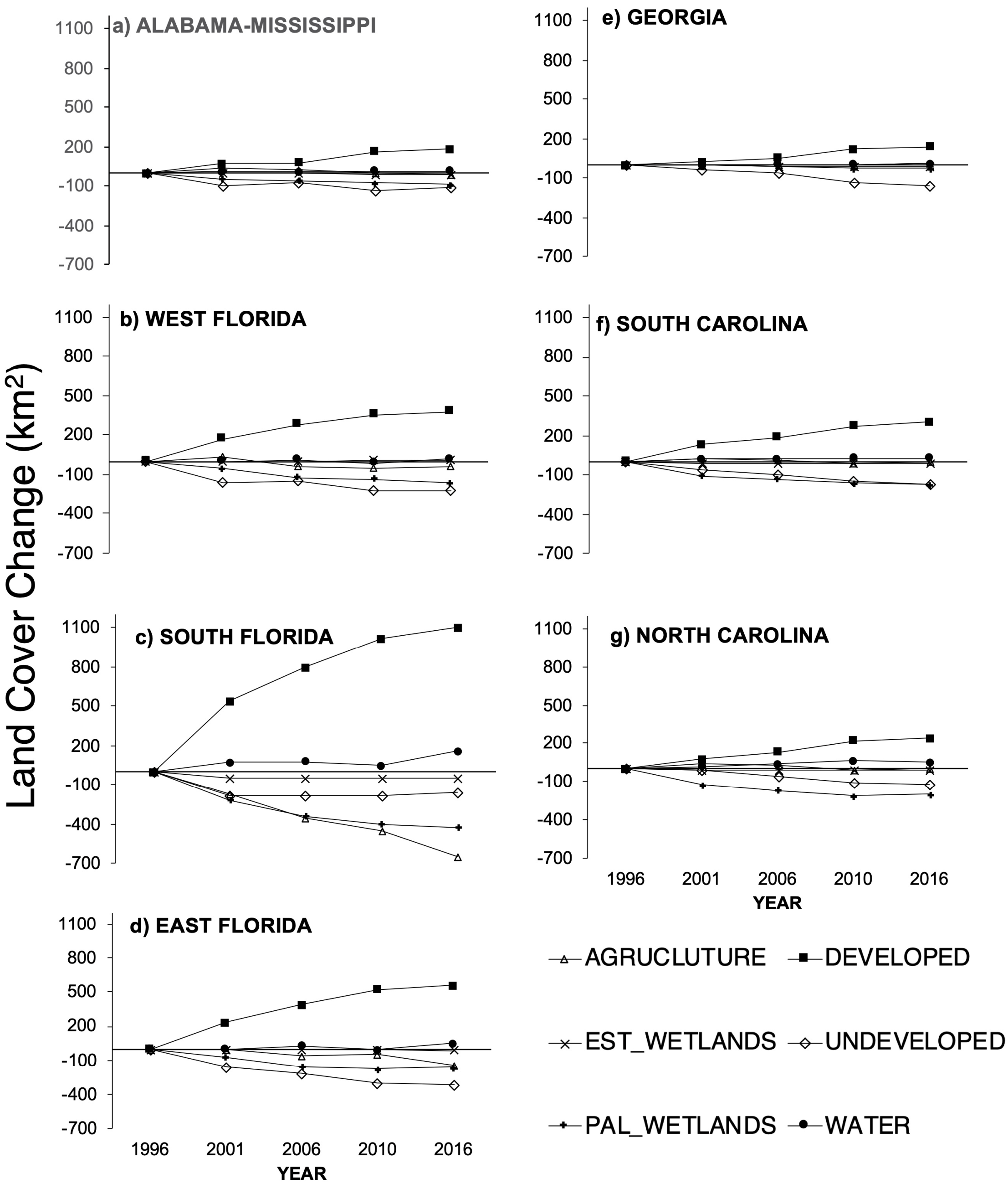


Figure 3. Change in the cover of developed (black square), water (black circle), undeveloped lands (open diamond), agriculture (open triangle) and wetland (open circle) land cover types since 1996 in Alabama-Mississippi (a), West Florida (b), South Florida (c), East Florida (d), Georgia (e), South Carolina (f), North Carolina (g) sub-regions. All data are derived from the NOAA C-CAP database.

Figure 4.

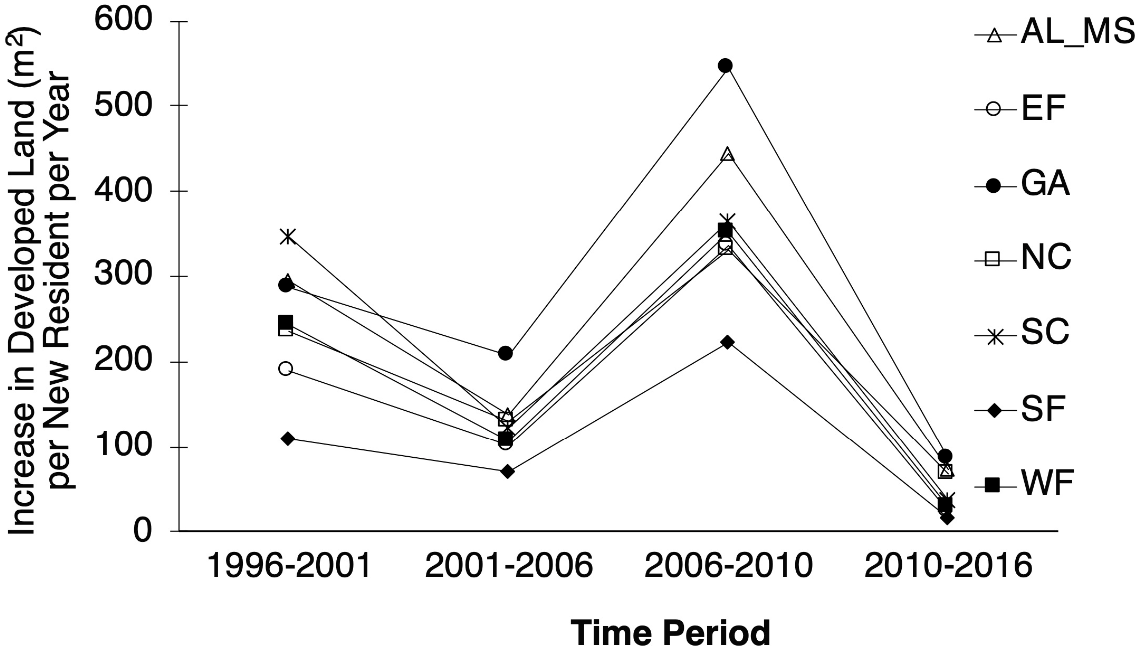


Figure 4 – Developed land conversion per capita (m^2 of newly developed land per person per year) in intervals of 1996-2001, 2001-2006, 2006-2010 and 2010-2016. Different colors and symbols represent different sub-regions as noted in the legend on the right.

Figure 5.

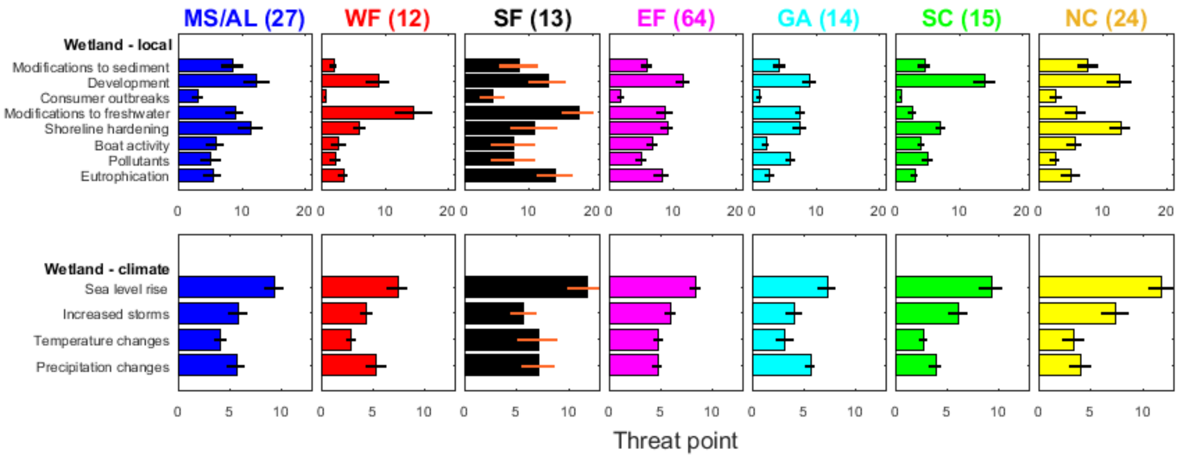


Figure 5 – Expert opinion regarding the relative importance of different local (top panels) and climate-change related (bottom panels) stressors to wetlands. Alabama/Mississippi (AL/MS) is shown with dark blue, West Florida (WF) with red, South Florida (SF) with black, East Florida (EF) with pink, Georgia (GA) with light blue, South Carolina (SC) with green, and North Carolina (NC) with yellow. Horizontal lines on each bar show ± one standard error of the mean points (out of 20 total points) assigned to each factor for all respondents reporting on each sub-region. The numbers in parentheses next to the region names indicate the number of survey responses from that region.

Figure 6.

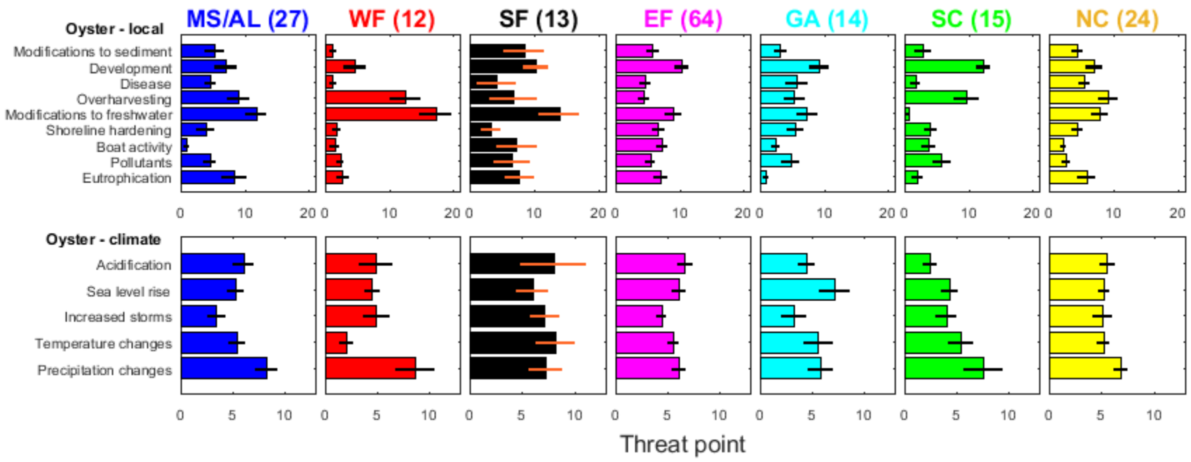


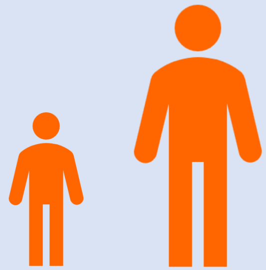
Figure 6 - Expert opinion regarding the relative importance of local (top panels) and climate-change related (bottom panels) stressors to oyster reefs. Panels show each of the sub-regions arranged from West to East along the coast with Alabama/Mississippi (AL/MS) shown in blue, West Florida (WF) in red, South Florida (SF) in black, East Florida (EF) in magenta, Georgia (GA) in cyan, South Carolina (SC) in green, and North Carolina (NC) in yellow. Horizontal lines (black, except for South Florida where the lines are orange for clarity) at each bar show the standard errors. The numbers in parentheses next to the region names indicate the number of survey responses from that region.

Challenges and Opportunities for Sustaining Coastal Wetlands and Oyster Reefs in the Southeastern United States

Estuaries and oysters face challenges from land and sea

- Sea level rise
- Increasing storms
- Development
- Human interactions

Mississippi through North Carolina coastal counties, 1996-2016



Population growth up to 171%

2,920 km^2 lands converted to development

Coastal experts identified challenges
- Development
- Shoreline hardening
- Upstream modifications to freshwater flow

Conclusion

Municipalities, property owners, recreators must implement strategies to improve estuarine health and persistence

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