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Review

Sea level rise impacts on rural coastal social-ecological systems and the implications for decision making

A. Bhattachan[a,*], M.D. Jurjonas[b], A.C. Moody[a], P.R. Morris[c], G.M. Sanchez[a,d], L.S. Smart[a,d], P.J. Taillie[a], R.E. Emanuel[a], E.L. Seekamp[b]

[a] Department of Forestry and Environmental Resources, North Carolina State University, United States
[b] Department of Parks, Recreation, and Tourism Management, North Carolina State University, United States
[c] Department of Forest Biomaterials, North Carolina State University, United States
[d] Center for Geospatial Analytics, North Carolina State University, United States

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ABSTRACT

Many rural coastal regions are distinctly vulnerable to sea level rise because of their remoteness, isolation from central planning agencies, and poverty. To better plan for future sea level changes in these regions, an interdisciplinary approach to assess the social and environmental impacts of sea level rise and their dynamic feedbacks is important. In this paper, we use a socio-ecological system framework to investigate sea level rise impacts to the Albemarle-Pamlico Peninsula, a rural, low-lying coastal region in eastern North Carolina. Specifically, we show that 42% of the region could be inundated and property losses of up to US $14 billion could be incurred with 100 cm of sea level rise. We also synthesize the impacts of sea level rise on the region's social-ecological system and present strategies to strengthen the adaptive capacity of the ecosystem, markets and communities. We conclude with a discussion on the differing climate change risk perceptions amongst the stakeholders as well as implications for decision-making. Sea level rise will continue to threaten the functioning of this social-ecological system of rural, low-lying coastal communities. A socio-ecological system framework provides a lens through which the impacts of sea level rise can be evaluated for rural, low-lying coastal communities. The framework presented here necessitates interdisciplinary research and highlights the importance of mutual learning amongst stakeholders in other rural coastal regions.

1. Introduction

Low-lying coastal regions around the world are vulnerable to sea level rise (Rowley et al., 2007). An estimated 10% of the world's population live within coastal zones below 10-m elevation despite these regions only covering 2% of the world's land area (McGranahan et al., 2007), and rising seas are already affecting low-lying areas, with the rate of sea level rise expected to accelerate in response to global climate change. According to the Intergovernmental Panel on Climate Change (2013), the average global sea level rise is likely going to be between 28–61 cm and 52–98 cm (Representative Concentration Pathway, RCP2.6 and RCP8.5, respectively) by the year 2100. In recent decades, sea level rise has out-paced the 20th century average, reaching rates as high as 3 mm per year since 1993 (Church and White, 2011; Hay et al., 2015; Kopp et al., 2016) and driven primarily by thermal expansion of oceans and loss of glaciers and ice-sheets (Church et al., 2013). The direct environmental consequences of sea level rise to the coast include increased flooding and erosion, intrusion of saltwater into surface waters and wetland loss (Fitzgerald et al., 2008; Vitousek et al., 2017). Furthermore, these environmental impacts have the potential to damage coastal real estate and infrastructure, drive the collapse of coastal economies, and spur migration of people and industries from coastal regions (Nicholls et al., 2007), including the Atlantic and Gulf shores of the coastal US (Hauer, 2017).

Research on adaptation to sea level rise generally focuses on urban areas, where the greatest losses in property value are possible (Tang, 2008; Weiss et al., 2011); yet, rural coastal communities face unique adaptation challenges to sea level rise (Barbier, 2015; Dahl et al., 2017; Jurjonas and Seekamp, 2018). Developed coastlines tend to have higher property values and stronger tax bases from tourism and also receive disproportionate attention for adaptation planning and disaster relief (IPCC, 2013), whereas rural communities tend to hold populations that are more disadvantaged and vulnerable to sea level rise impacts as a result of their remoteness, isolation from central planning agencies, and

* Corresponding author.
E-mail address: abhatta9@ncsu.edu (A. Bhattachan).

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poverty (Donner and Rodriguez, 2008; Davies et al., 2009; Hardy et al., 2017). Rural lands also make up a large fraction of coastal regions worldwide (Small and Nicholls, 2003), and in some countries the rural coastal population is growing at a faster rate than the urban population (McGranahan et al., 2007). The mid-Atlantic coastal plain of the United States contains more than twice as much agricultural land area as urban land area (22% and 9%, respectively) (Brown et al., 2005). With this in mind, this paper fills a gap in resilience research by synthesizing the challenges facing climate change adaptation in rural, low-lying coastal areas using a case study from coastal North Carolina. Our study highlights that the widely-dispersed nature of economic impacts within such natural resource dependent economies may deemphasize the large-scale aggregate losses anticipated in such regions and further constrain socio-ecological resilience in rural coastal zones.

Our paper is organized around the overarching theme of social and ecological impacts of sea level rise to a rural coastal system. Our discussion is primarily focused on the impacts of sea level rise; however, we also discuss other effects of climate change in this region such as drought, hurricane intensity and storm surge flooding. To contextualize our discussion of the sea level rise threats and adaptation challenges facing rural, low-lying coastal areas, we focus on the 7500 km^2 peninsula between the Albemarle and Pamlico Sounds of coastal North Carolina (Section 1.1) and present a conceptual model of the coupled social-ecological system dynamics (Section 1.2). We then review several categories of impacts of sea level rise on coastal regions, including impacts to hydrological cycles (Section 2.1), ecological systems (Section 2.2), and coastal economies and markets (Section 2.3). The paper concludes with discussions of the adaptive capacities of rural coastal communities, their societal resilience (Section 3) and risk perceptions, and implications for decision-making (Section 4).

1.1. Focal area: the Albemarle-Pamlico Peninsula

The Albemarle-Pamlico Peninsula (hereafter APP; Fig. 1) is a rural coastal landscape that ranges in elevation from 42 m above mean sea level to 5 m below mean sea level. Nearly half (44%) of the APP is less than 1 m above mean sea level. The peninsula is surrounded by the second largest estuarine complex in North America, the Albemarle-Pamlico estuary system, which is protected from the Atlantic Ocean by a chain of barrier islands. By 2100, projected sea level rise in North Carolina is very likely to be between 24 and 94 cm for conservative greenhouse gas emissions scenarios (RCP2.6) and between 42 and 132 cm for high-end emissions scenarios (RCP8.5) (Kopp et al., 2015). Regardless of future emissions, it is very likely that the rate of sea level rise during the 21st century will exceed rates observed during the 20th century, increasing the incidence of coastal flooding (Kopp et al., 2015). Moreover, Dahl et al. (2017) identified the APP as a socioeconomically vulnerable region within the United States that will require attention and additional resources to adapt to sea level rise.

Wetlands make up more than 50 percent of the land cover on the APP, and this proportion represents only a small remnant of the historical wetlands that existed prior to timber extraction in the 19th and 20th centuries and large-scale agricultural conversion that began in the 1970s (Carter, 1975; Richardson, 1983; Moorhead and Brinson, 1995). The APP has a temperate climate (Peel et al., 2007) with a historic mean annual temperature of 16.1 °C (5.9 °C in January to 26.1 °C in July), and receives 1265 mm yr^{-1} of rainfall. The region has had nine Category 3 and stronger hurricanes, as well as numerous other large-scale tropical and extra-tropical storms between 1984 and 2015 (State Climate Office of North Carolina, 2015). Extensive flooding and damage to natural ecosystems and human infrastructure is common within the region even during low intensity tropical storms, such as Hurricane Irene (2011 Category 1 hurricane), due to relatively flat and low-terrain elevation.

According to the United States Census Bureau (2010), an estimated 105,124 people live on the APP; unlike most other areas of the southeastern US, population growth on the APP is expected to be minimal in the coming decades (North Carolina Office of State Budget and Management, 2014). Forestry and agriculture are the principal economic engines of the region, although industries related to fishing, hunting, and tourism are also important (North Carolina State University Cooperative Extension, 2015). Given the strong connection between rural nature and economic dependence on natural resources (e.g., Leach et al., 1999; Pretty, 2003; Bodin and Crona, 2008), the APP is characterized by strong connections between local communities and environmental resources. Yet with 44% of its land area lying below 1-m elevation, both the people and natural resources of the APP face threats associated with sea level rise and coastal inundation.

1.2. The APP as a social-ecological system

The complexity of natural resource management warrants a holistic research approach that fully considers interactions and feedbacks between social and ecological systems. This approach, referred to as the social-ecological systems (SES) framework is based on integration of theories and principles from social and natural sciences (Berkes and Folke, 1998; Anderies et al., 2004; Ostrom, 2009; Collins et al., 2010). This coupled approach acknowledges the inextricable linkages between human communities (and institutions) and ecological processes (Hull et al., 2015), making it an ideal framework for considering climate change vulnerabilities within the APP.

To illustrate the linkages and feedbacks inherent in social-ecological systems, we developed a conceptual model (Fig. 2) that considers sea level rise stressors to the ecological and social systems in rural, low-lying coastal areas. According to our conceptual model, the primary pathway for sea level rise to influence low-lying coastal regions is through changes to the quality, quantity and distribution of freshwater resources (arrow 1). Variability in precipitation and temperature as a result of global climate change also directly affect freshwater resources. Therefore, freshwater resources represent a fundamental part of this conceptual model, linking sea level rise to changes in the hydrologic cycle, and ultimately producing significant impacts on both social and ecological systems (arrow 2). In this paper, we explore the linkages and feedbacks in rural, coastal, social-ecological systems, drawing specific examples from the APP. The following sections reference the linkages and feedbacks presented in the SES framework of Fig. 2. Using this SES framework, we seek to answer two major questions: 1) How does sea level rise impact both the people and natural resources in a rural, coastal socio-ecological system? 2) How can people adapt and respond to the impacts of sea level rise on such a system?

2. Sea level rise impacts on the APP

In this section, we review literature about sea level rise impacts on natural systems, as well as impacts to markets and ecosystems services, contextualizing our review with applications to the APP.

2.1. Hydrological processes and sea level rise

The flat and low-lying nature of the APP strongly influences hydrological processes of the region and makes the peninsula especially sensitive to sea level rise. In turn, the flow and distribution of both saline and fresh waters have had major impacts on human activities within the region, prompting both artificial drainage and flood control projects for more than 200 years. The indigenous peoples of the region cleared and managed land for crop cultivation prior to European colonization, but there is neither historical documentation nor physical evidence that these peoples practiced large-scale manipulation of drainage on the peninsula. The earliest evidence of large-scale, artificial drainage on the APP is estimated to be 1787, when a 10 km long canal was constructed between a large freshwater lake and the Albemarle Sound to regulate water level in the lake (Heath, 1975). The clearing

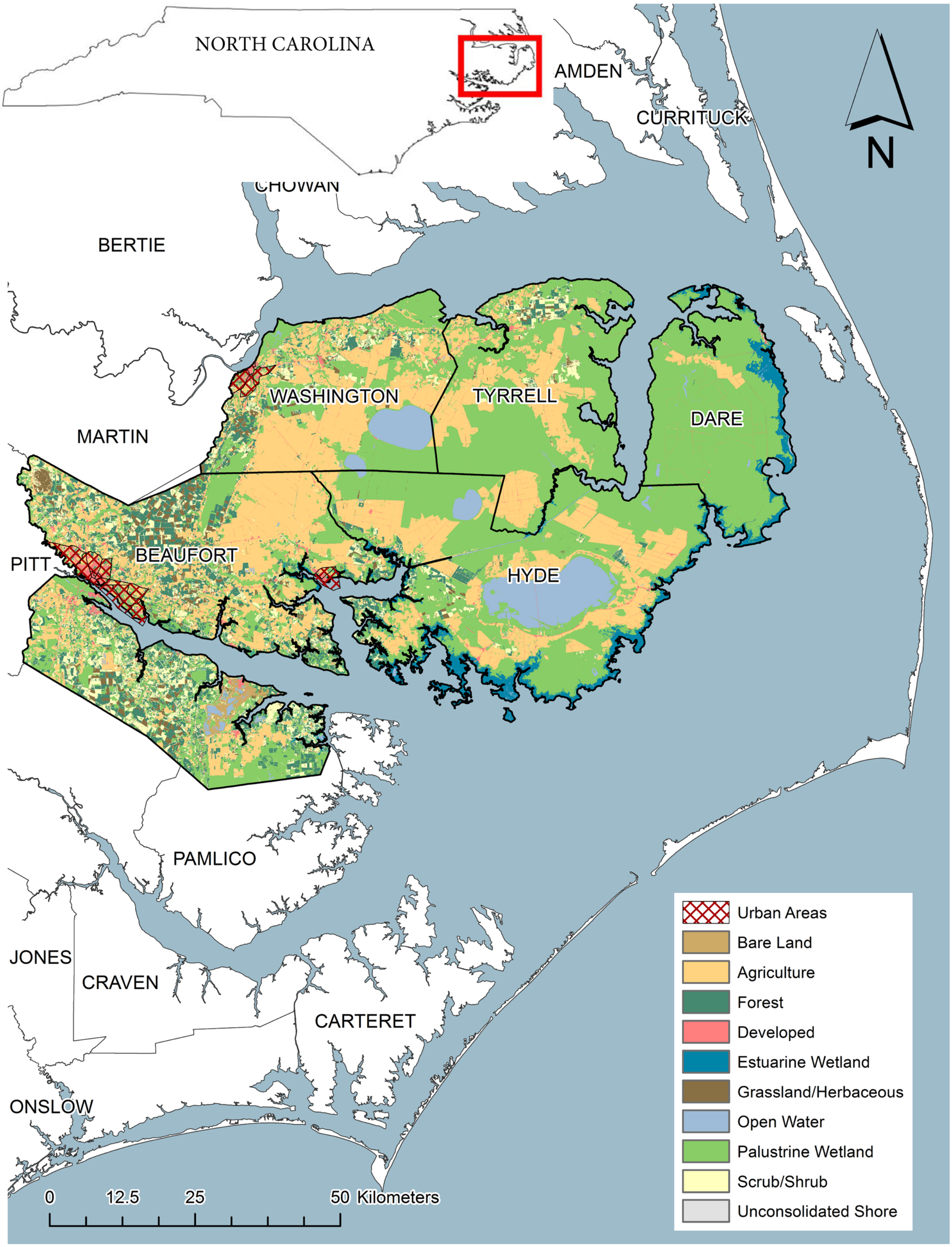

Fig. 1. The Albemarle-Pamlico Peninsula in eastern North Carolina. The land-cover data used are from 2010 and acquired from the NOAA's Coastal Change Analysis Program (C-CAP).

and draining of the peninsula accelerated after 1900 for farming and industry (McMullan et al., 2016), with over 30% of the APP used for farming by early 1980. Around that time the average length of the artificial drainages of farmland was 12.5 km per square kilometer (Heath, 1975). Currently, there are approximately 8,700 km of artificial drainage canals on the APP (United States Geological Survey, 2015).

Annual precipitation normally exceeds annual evapotranspiration on the APP (Daly et al., 2008; Sanford and Selnick, 2013). Non-evaporated soil moisture or surficial water storage in wetlands eventually discharges to the estuary, either as surface runoff or groundwater

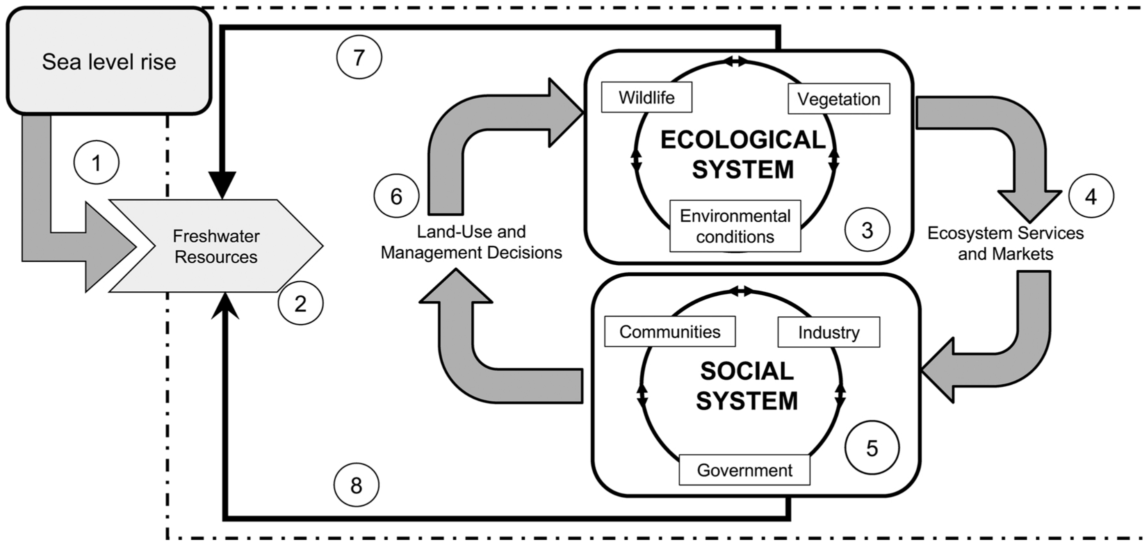

Fig. 2. Conceptual model of the SES in the Albemarle-Pamlico Peninsula. The numbers represent system components and the linkages between them. 1. Climate change as an external stressor; 2. Changes to freshwater resources has implications to the ecological and social systems; 3. Interactions between biotic and abiotic components of the ecological system; 4. The feedback between ecological and social systems via ecosystem services provisioning and natural capital value in local markets; 5. Social interactions and information sharing between stakeholders; 6. Land use management, adaptation, and mitigation decisions feedback into the ecological system; 7. Ecological responses to changes in freshwater resources; 8. Human-induced (e.g., policy, markets) changes that affect the freshwater resources.

discharge. However, relatively small topographic gradients result in low discharge rates, although the extensive artificial drainage network throughout most of the APP may greatly increase rates of discharge during wet periods (Heath, 1975; Richardson, 1983). The artificial drainage network also increases vulnerability to saltwater intrusion by connecting the estuary and freshwater-dependent inland environments (Ardón et al., 2013; Bhattachan et al., 2018). Bhattachan et al. (2018) showed that ditching of the landscape has increased the vulnerability of the freshwater dependent wetland ecosystems to saltwater intrusion on the APP. Even in places with no artificial drainages on the APP, the overall vulnerability to saltwater intrusion has increased because of changes to regional flow paths (Bhattachan et al., 2018). Vulnerability is defined as the extent to which the socio-ecological system is unable to deal with the negative effects of climate change and climate variability (IPCC, 2013) including sea level rise, saltwater intrusion and drought. Artificial drainages increase the vulnerability by potentially serving as pathways of saltwater exposure during droughts, and they may also do so during coastal storms, when storm surges or high tides send brackish water flowing inland along canals and ditches (Ardón et al., 2013). In the latter case, the flat terrain of the region may exacerbate inundation of landscapes by saltwater. Around the APP, dikes, flood gates, and pumping stations were installed to protect low-lying areas closer to the coast from both inundation and saltwater exposure during coastal storms (Heath, 1975).

Inundation modeling has been used to demonstrate the vulnerability of low-lying coastal regions to sea level rise using both simple approaches that do not consider connectivity of the artificial drainage network (Moorhead and Brinson, 1995; Titus and Richman, 2001) and more sophisticated approaches that take network connectivity into account (Poulter and Halpin, 2008). In the simplest case, inundation can by simulated by tabulating the area of a digital elevation model (DEM) that lies below the elevation of sea level or storm surge elevation. When network connectivity is taken into account, coastal inundation only occurs where a grid cell is below the elevation of sea level (or storm surge) and an adjacent grid cell is inundated as well.

We illustrate the different results produced by these two methods (with and without network connectivity) using a 6 m grid resolution DEM of the APP subjected to scenarios of 25, 50, 75 and 100 cm of sea level rise (Fig. 3a). The digital elevation model (6-m resolution) from the North Carolina Flood Plain Mapping Program was used for inundation modeling. The differences in the magnitude of area inundated for each scenario indicate the effects of network connectivity on patterns of inundation. Most notably, low-lying but topographically protected areas farther away from the coast are inundated in the simplest case (without network connectivity) and not inundated when connectivity is taken into account. The projected sea-level rise of 100 cm will inundate 3307 km^2, or 44% of the APP without considering connectivity and 3144 km^2, or 42% of the APP with connectivity considered (Fig. 3a, Table S1). In the case of the APP, an additional 163 km^2 or 2% of the total land area below 100 cm elevation would be protected from inundation due to lack of connectivity with the estuary. The difference in inundated area between the two methods is relatively small; however, the impacts are widely dispersed across the APP (Fig. 4).

The landward movement of brackish water (i.e. saltwater intrusion) is already occurring on parts of the APP and in similar coastal regions elsewhere in response to drought, tides, and human activities. Saltwater intrusion has the potential to impact large portions of the APP given the region's characteristic flat terrain and extensive artificial drainage network. Episodic intrusion events can elevate salinity in natural channels, drainage ditches, and adjacent soils to levels that may have ecological consequences for freshwater-dependent ecosystems. In situ observations from a major drainage canal on the APP (Fig. S1) show that even during a relatively wet year (2016), episodic saltwater intrusion events may elevate salinity to levels that are harmful to freshwater-dependent ecosystems (Fig. 2, arrow 2). We measured specific conductance using a conductivity logger (OnSet Instruments, Bourne, MA) and calculated salinity from water temperature (°C) and specific conductance (in µS/cm) data, measured in 15-minute intervals between February and August 2016. The average salinity of water in a canal in the APP is mostly stable around 0.1 ppt (Fig. S1). The threshold of 0.5 ppt (dashed line in Figure S1) is important because freshwater wetlands are found in places with salinity below 0.5 ppt and increased exposure to salinities above this threshold could lead to conversion of freshwater wetlands to brackish marsh (Krauss et al., 2009). In particular, baldcypress (*Taxodium* sp.), which is a significant wetland tree species in the US southeastern coastal plains, show signs of stress at salinities as low as 1 ppt (Powell et al., 2016). Although these trees can tolerate and survive high salinities if the surface water is quickly diluted by rainfall or other freshwater inputs (Conner and Inabinette, 2005), the

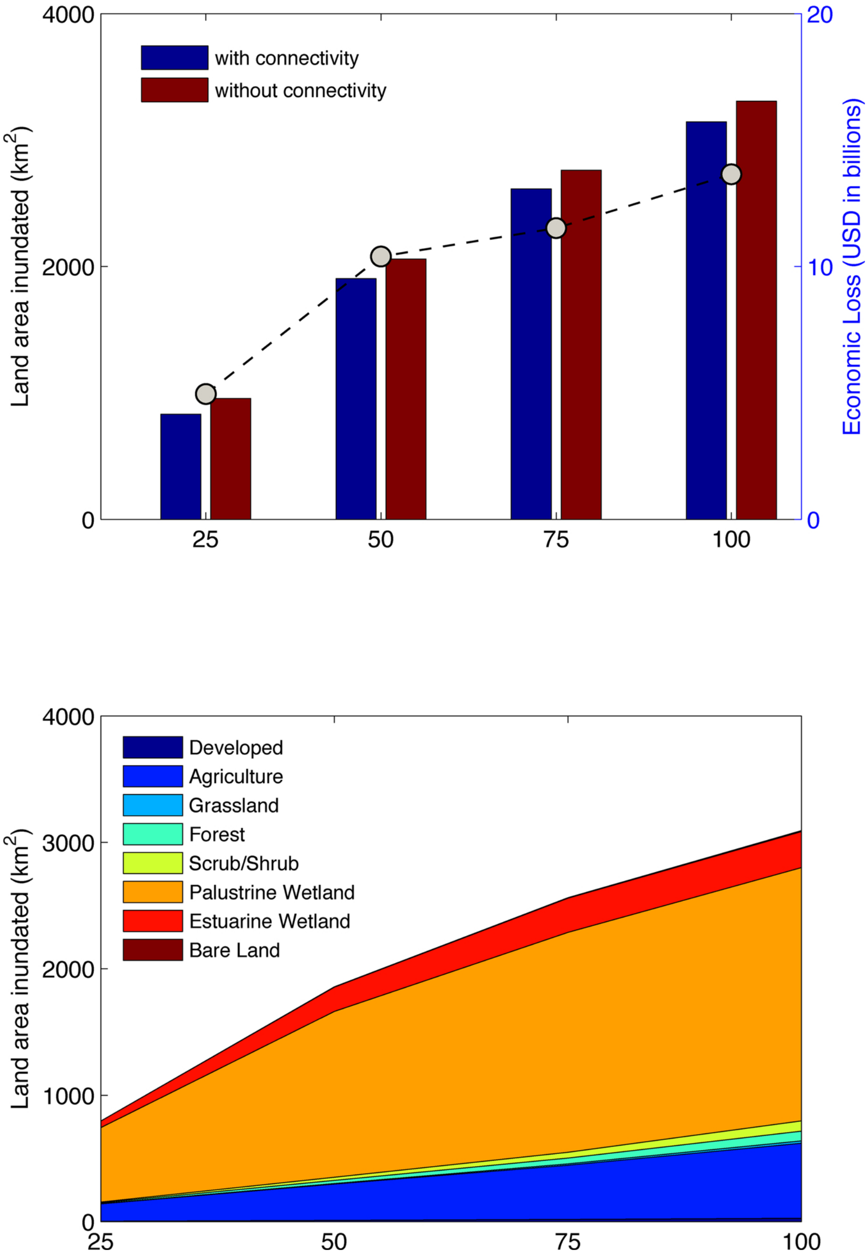

Fig. 3. a) The land area inundated (in km^2) in the Albemarle-Pamlico Peninsula in North Carolina under 25, 50, 75, and 100 cm sea level rise. Both ‘zero side rule’ (D0) and ‘eight-side rule’(D8) approaches were used. The economic loss (land and building values in US $) was calculated for each scenario. b) The land area inundated (in km^2) for habitat type in the Albemarle-Pamlico peninsula for each sea level rise scenario.

increasing likelihood of drought in the southeastern US (Carter et al., 2014) combined with sea level rise and the extensive artificial drainage network on the APP suggest that baldcypress and other freshwater dependent species will continue to be impacted.

While it is understood that rural coastal regions such as the APP are vulnerable to sea level rise in the long-term, the future spatial and temporal trajectory for saltwater intrusion events remain largely uncertain as it depends on both rates of sea level rise and decisions involving water management and associated infrastructure. Given the extensive network of artificial drainages functioning to support many land uses across the APP, the vulnerability of the landscape is highly dependent on complex interactions of multiple land managers responding to external forcings and events as these apply to their use of the land. What this means for the hydrologic system is that greater incidence of saltwater intrusion in the future would have major implications on ecosystem services associated with the ecological system in the APP.

2.2. Ecological impacts of sea level rise

The APP provides a number of ecosystem services that support human communities (Fig. 2, arrow 4), including local economies and livelihoods (Barbier et al., 2011), as well as harboring some of the highest biodiversity in all of North America (Noss et al., 2015). In this study, we use the definition of ecosystem services stated by the IPCC (2013) as the functions and processes of the ecosystem (e.g., ecological system in the APP) that benefit society at large. We show that the inundation of the APP under scenarios of sea-level rise (Fig. 3a) will impact the ecosystem services that the region provides (Fig. 3b, Table S1). Apart from permanently inundating the landscape, the landward movement of brackish water from the coast onto the coastal plain has a pronounced effect on the ecology and biogeochemistry of coastal

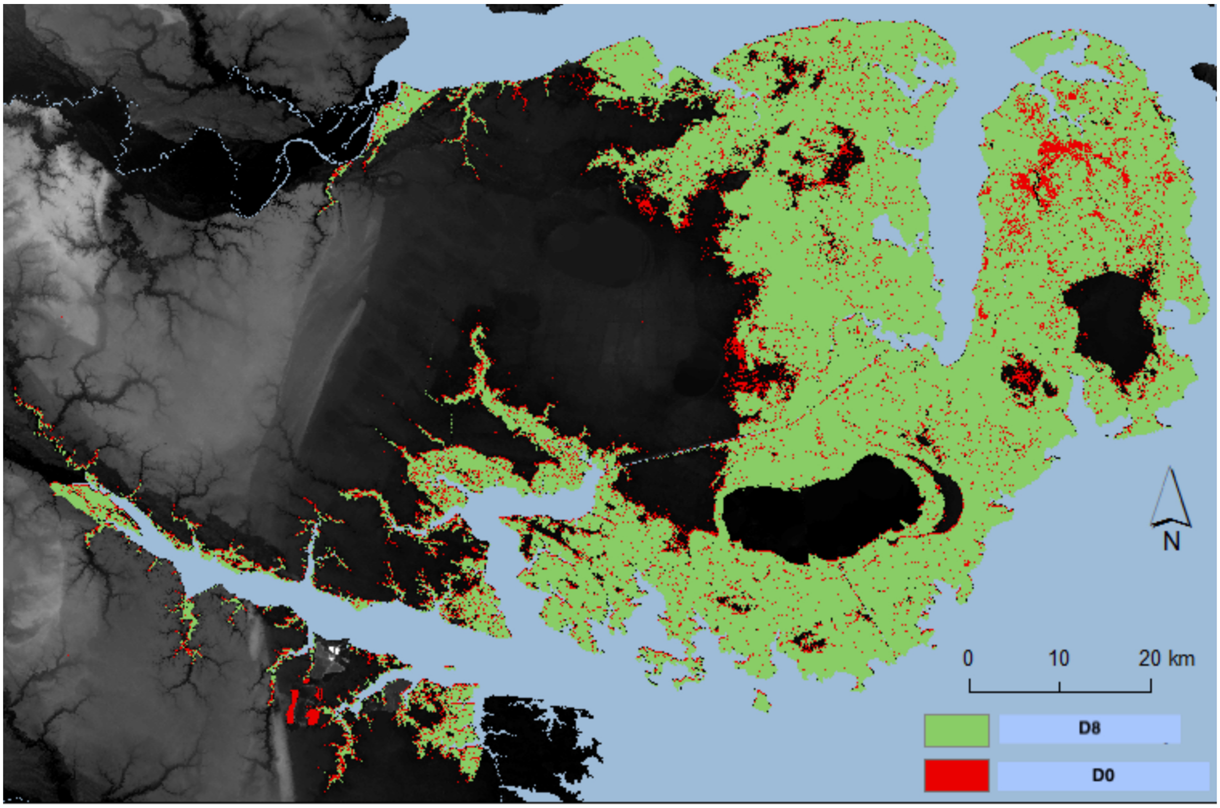

Fig. 4. The land area inundated in the Albemarle-Pamlico Peninsula in North Carolina under 100 cm of sea level rise. The cells that are inundated with zero-side (D0) and eight side (D8) rules are displayed in green and red respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

environments (Brinson et al., 1995; Moorhead and Brinson, 1995; Ardón et al., 2013).

Plant species vary widely in their tolerance to water and salt related soil conditions, specifically water table depth, flooding frequency, and soil salt content (Krauss et al., 2000; Friess et al., 2012). Changes in these conditions have been shown to influence the composition and distribution of coastal plant habitats, in turn altering the value of the ecosystem services they provide (Baldwin and Mendelssohn, 1998; Crain et al., 2004). In coastal herbaceous marshes of eastern North America, the vegetation composition and structure are already responding to climate change (Callaway et al., 2007). As such, the ability of these marshes to buffer against flooding, storms and shoreline erosion may also change (Koch et al., 2009).

Vulnerability of coastal marshes to sea level rise may be overestimated as marshes worldwide have the potential to accrete at rates similar to rate of sea level rise (Kirwan et al., 2016). For example, the marsh coverage in Swan Quarter National Wildlife Refuge in the APP has expanded slightly since 1938 (Poulter, 2005) despite projected submergence of 60% of regularly and irregularly flooded marshes by 2100 under 1 m sea level rise (2.66 mm per year of relative seal level rise) (United States Fish and Wildlife Service, 2012). The expansion of salt marshes inland due to saltwater intrusion has been observed elsewhere in the southeastern US as well (e.g., Williams et al., 1999; Raabe and Stumpf, 2016; Craft et al., 2009) and the ability of marshes to migrate upland is only restricted by topography or anthropogenic barriers such as dikes (Brinson et al., 1995; Raabe and Stumpf, 2016). One concern is the migration of these marshes into landscapes previously occupied by forests and the implications of this land use change for carbon sequestration, animal habitat, and other ecosystem services.

Sea level rise and saltwater intrusion may drastically reduce the ability of both freshwater and brackish coastal wetlands to sequester carbon (Craft et al., 2009; Mcleod et al., 2010), and enhances nitrogen loss from wetland soils (e.g., Ardón et al., 2013), while reducing rates of nitrification in sediments (Joye and Hollibaugh, 1995). Persistent flooding and salinization exacerbated by drought may limit the regeneration of trees, promoting osmotic stress and sulfide toxicity in sediments that ultimately cause tree mortality (Brinson et al., 1995; Williams et al., 1999; Craft, 2012). As forests decline and salt-tolerant shrubs and herbaceous plants overtake these landscapes, many parts of the APP and similar regions elsewhere will experience a gradual transition from forest to herbaceous marsh land-cover (Brinson et al., 1995; Linhoss et al., 2015). Forest to marsh conversion in coastal regions could affect the accounting of ecosystem services as carbon sequestration and sediment trapping are favored in marshes (Craft, 2012). Regardless of whether marsh accretion keeps pace with sea level rise, these ecological changes suggest that sea level rise and saltwater intrusion will evoke complex responses from coastal ecosystems.

Ecological responses to sea level rise and saltwater intrusion are also expected to have significant impacts on the distribution and abundance of many wildlife taxa (Hunter et al., 2015) and the linkages between vegetation and wildfire are represented in the SES framework (Fig. 2) by #3. For example, Greenberg et al. (2006) suggest that low-lying coastal regions provide important habitat for a disproportionate number of species of conservation concern, such as black rail (*Laterallus jamaicensis*), wood stork (*Mycteria americana*) and diamondback terrapin (*Malaclemys terrapin*). How these species may respond to future conditions is uncertain; yet, it is important to understand and predict responses, particularly for anticipating and mitigating novel stressors on sensitive or already-threatened species. Although it is likely that some species will respond negatively, others may benefit from these changing conditions.

Hurricane-induced inundation can also have ecological impacts, as the region has experienced nine Category 3 or stronger hurricanes between 1984 and 2015. In 1999, over the course of six weeks in

September and October, Hurricanes Dennis, Floyd and Irene delivered precipitation that generated runoff to the Pamlico Sound equal to 83% of the total volume of the estuary, more than six times as much runoff is typically delivered during this period (Paerl et al., 2001). This unprecedented rainfall and record flooding had detrimental effects to the benthic and fish populations as the estuaries in the Pamlico Sound experienced vertical stratification and bottom water hypoxia (Paerl et al., 2001). However, the recovery of the Pamlico Sound was relatively rapid after the hurricane and the ecological impacts were not as damaging or persistent over the long term as expected (Burkholder et al., 2004).

The expected storm surge of a Category 3 storm could be as high as 4 m in Pamlico and Albemarle Sounds and could inundate up to 500 km^2 of area upstream of the rivers draining in the Albemarle and Pamlico Sounds (Peng et al., 2004). The intensity of hurricanes may increase in the future with global climate change (Knutson et al., 2010); hence, the increased vulnerability of coastal areas to flooding (Sweet and Park, 2014) and coastal vegetation to salinization (Powell et al., 2016) also seems likely. The negative effects on ecosystem functioning and provisioning of ecosystem services on the APP because of sea level rise and saltwater intrusion, in turn, could have a pronounced impact on the local economy and livelihoods.

2.3. Sea level rise impacts on the APP's economy

Rural, low-lying coastal communities often have economies that are dependent on local natural resources (Fig. 2, arrow 4), and sea level rise has the potential to diminish these resources. On the APP, approximately 3300 km^2 of woody and herbaceous wetlands are used for the region's hunting and fishing industry, and together with approximately 1600 km^2 of cropland and approximately 530 km^2 of managed timber, these lands make up nearly 83% of the total land area of the peninsula (United States Department of Agriculture Data Gateway, 2014). These resources have contributed approximately US $367 million per year in agriculture cash receipts and US $343 million per year from forest output (North Carolina Department of Agriculture: Agriculture Statistics, 2014; North Carolina State University Cooperative Extension, 2015).

Residents on the APP are especially vulnerable to economic impacts associated with climate change, given the natural resource-based economy of the region. For example, saltwater intrusion into agricultural lands during both coastal storms and droughts may result in reduced crop yields, land degradation and abandonment of agricultural fields (e.g., Qi and Qui, 2011). Further, sea level rise will reduce the overall area used for agriculture on the APP as portions of the peninsula become inundated. A substantial area (approximately 600 km^2) of agricultural land on the APP will likely become inundated with 100 cm sea level rise (Table S1). The land cover data used in this analysis was obtained from the NOAA's Coastal Change Analysis Program (C-CAP). Not only will sea level rise impact the area of arable lands on the APP, but it also has the potential to reduce the areal extent of coastal wetlands (Nicholls and Cazenave, 2010), altering both habitat and the productivity of estuarine nurseries (Fig. 2, arrow 4) vital to the commercial fishing industry (Beck et al., 2001; Scavia et al., 2002).

We performed an analysis to quantify the potential economic impact of property loss associated with sea level rise, using parcel data from each county's (Beaufort, Dare, Hyde, Tyrrell and Washington) tax assessor office. Using results of landscape inundation (with connectivity), we overlaid parcel data for land and building values for the APP. Compounding permanent inundation associated with gradual sea level rise, coastal storms already cause substantial economic losses due to temporary flooding, wind damage, and other impacts. A recent study suggested that despite the hurricane risk, coastal development will continue to flourish in the Mid-Atlantic region of the US (e.g., Walls et al., 2018). Kopp et al. (2015) suggested that coastal flood damage from sea level rise in North Carolina would likely exceed $17 billion by 2100. Given the assumption that the potential inundation is permanent, hence under scenarios of future sea level rise, the economic loss of land and infrastructure on the APP will be substantial ranging from approximately US $5 to 14 billion under scenarios of future sea level rise (Table S1).

Of the US $14 billion in infrastructure losses that we estimated in the 100 cm of sea level rise scenario (Table S1), residential and commercial buildings constitute about 28 percent (US $4 billion). The real estate sector for the APP is not as large as the Outer Banks barrier islands of North Carolina, a major center of tourism for the southeastern US. A study by Bin et al. (2011) found that although the area of the Outer Banks is much smaller (approximately 260 km^2) than the APP, the loss of residential property from 80 cm of sea level rise is projected to be approximately US $1 billion with about 8 percent of the total residential properties affected. Even under the 75 cm sea level rise projections on the APP, the total loss of residential and commercial buildings in substantial (US $ 3 billion). Yet, the economic losses are widely distributed over the APP, whereas losses on the highly developed and tourism-centered Outer Banks are expected to be about an order of magnitude greater per unit land area (Bin et al., 2011).

Although tourism on the APP is not a primary economic driver, permanent inundation of land in the region will likely have negative impacts on cultural heritage tourism. Archaeological sites associated with indigenous people of the region are already threatened by erosion along the estuarine shoreline (Lautzenheiser et al., 2011). In addition to these archaeological sites, historic houses, churches and museums are threatened by sea level rise (North Carolina Interagency Leadership Team, 2012). Nevertheless, enhancing the nature-based tourism industry, which currently focuses on hunting and non-consumptive wildlife recreation, with cultural tourism may be a viable adaptation strategy for the region, particularly as the major beach tourism areas on the Outer Banks continue to experience climate change-related property losses. However, limited local leadership and a lack of long-term monitoring of economic impacts has challenged previous attempts at ecotourism development in the region (Peroff et al., 2017).

If the tourism economy shifts inland, it is possible that APP communities could capture significant tourism revenue. For example, in 2013 tourism revenue reduced local taxes per capita by nearly US $2800 annually for the most developed county on the Outer Banks (Dare County) but only by an average of US $110 annually for two counties (Tyrrell and Washington Counties) on the APP (North Carolina Department of Commerce, 2014). Additionally, tourism and travel related revenues created about 12,000 jobs in Dare County in 2013, whereas approximately 100 jobs were created in Tyrrell and Washington Counties during the same period (North Carolina Department of Commerce, 2014). Any substantial shift of tourism revenue to the APP could provide subsequent increases in the tax base available for municipal and county-level climate adaptation planning and response. Yet, the high density of potential economic loss due to sea level rise on the Outer Banks currently overshadows the substantial but geographically dispersed potential economic losses on the APP, drawing away the attention of policy-makers and regional climate adaptation planning efforts.

Such diversion of attention and resources elsewhere exacerbates the vulnerability of the APP to sea level rise, reemphasizing the geographic remoteness and relative poverty of the APP region compared to the Outer Banks. In this way, the APP illustrates a key aspect of climate change vulnerability for rural coastal regions worldwide: the widely-dispersed nature of economic impacts compared to urban coastal areas may deemphasize the aggregate losses that these regions will likely experience in the coming decades. With this in mind, the remaining sections of this paper examine adaptation strategies, risk perceptions, and decision-making related to sea level rise in the APP specifically, as well as low-lying rural coastal SES more generally.

3. Adapting to sea level rise

Coastal communities have adapted to past sea level rise (Day et al., 2007; VanKoningsveld et al., 2008); however, the combination of accelerated sea level rise and concentrated anthropogenic activities along the coast (Small and Nicholls, 2003) have limited the adaptive capacity of these communities in recent decades (Nicholls et al., 2007). Although there are many linkages between vulnerability, resilience and adaptive capacity (Fig. 1 in Cutter et al., 2008), we define adaptive capacity as the capacity of the socio-ecological system to respond to sea level rise through mitigation and adaptation (IPCC, 2013). Moreover, we assert that the future of these communities—including their economies, land use patterns, and vulnerability—will be defined by their adaptive capacity. Similarly, we define resilience as the ability of the socio-ecological system to absorb and cope with the hazards of climate change (IPCC, 2013), such as sea level rise and saltwater intrusion, while maintaining essential functions. In this study, we consider resilience as an integral part of adaptive capacity (e.g., Adger, 2006) and, thus, similar to Jurjonas and Seekamp (2018), embed adaptive capacity as an indicator of resilience which then that functions as a counterforce to the vulnerability within the communities of the SES.

As represented in our SES framework by arrow 6, the adaptive capacity of the social system could also have feedbacks affecting the resilience of the ecological system. For example, on the APP, collaboration between the US Fish and Wildlife Service, The Nature Conservancy and a large utility company to mitigate the impacts of saltwater intrusion at the Alligator River National Wildlife Refuge has resulted in the restoration of estuarine and terrestrial ecosystems, including oyster reefs and salt tolerant wetlands (Dow et al., 2013). Additionally, the construction of new roads at a higher elevation with bridges at higher clearance (e.g., Tang et al., 2013) could save future renovation costs and prove useful for disaster mitigation.

Landowners on the APP have also received government funding for projects to adapt to sea level rise and saltwater intrusion (Fig. 2, #5). Specifically, the US Department of Agriculture subsidizes tide gate (i.e. infrastructure that maintains unidirectional flow) construction for drainage and irrigation canals to prevent saltwater intrusion into agricultural lands (North Carolina Natural Resources Conversation Service, 2016). Dikes have been built around communities like Swan Quarter as well as critical infrastructure such as wastewater treatment facilities, roads and electrical stations across the APP. Many agricultural fields are also diked and equipped with pumps for protection against storm surges and high tides. The local municipal and county governments are responsible for the stormwater management and disaster preparedness of the communities using the local tax base (Lane et al., 2013a). These adaptation efforts on the APP illustrate the value of government agencies (at local, state and federal levels), non-governmental organizations and private companies working together to build resilience to climate change impacts.

Projects aimed at increasing adaptive capacity require a strong local economy; however, an aging population and rural to urban migration are weakening the local economies and tax base by reducing the workforce and increasing the dependence on migrant labor (Donner and Rodriguez, 2008). For example, the average resident of Hyde County is more than 65 years old, demonstrating declining adaptive capacity as the population is aging out of the workforce; however, the median age of the population on the APP is projected to increase slightly in the next 20 years (North Carolina Office of State Budget and Management, 2014). Yet, minimal population growth or even population decline in the region in coming decades (North Carolina Office of State Budget and Management, 2014) could reduce the adaptive capacity of these rural communities. In counties where projected deaths exceed projected births and the population growth is positive, the balance is maintained by positive net migration. For example, in Beaufort County the population is projected to grow at 0.1% in 2020 and projected population deficit (births minus deaths) is 1100, while the in-migration rate then is expected to be 2.5% and is projected to increase to 3.7% in 2030 and 4.4% in 2036.

To put the future growth and migration rates in context with nearby urban counties, the population of Wake County is projected to grow by 24% in 2020 and the in-migration rate is expected at 16%. Although Beaufort and Dare counties show positive in-migration rates for the future, we hypothesize that in-migration rates may shift depending on the state of the local economy. If the local economy is impacted negatively by sea level rise and saltwater intrusion through impacts to natural ecosystems, agricultural landscapes, and human infrastructure, then in-migration rates could also be negatively affected. Two APP counties Tyrrell and Hyde where more than 80% of the projected populations will be located in areas of inundation risk, could experience catastrophic flooding by 2100 under 1.8 m sea level rise (Hauer et al., 2016).

Although a weak workforce and an aging population often limit economic growth in rural areas (Wall and Marzall, 2006), government agencies and non-governmental organizations contribute to capacity building through support of local industries and project implementation (Fig. 2, #5). There is some evidence that local programs (e.g., Smith, 2012) help maintain a viable workforce despite market difficulties, as a strong sense of place can foster an unwillingness to leave. For example, ecotourism initiatives such as Red Wolf Coalition on the APP could work to increase visitation, augment incomes, and provide job opportunities for local youth (North Carolina Institute of Emerging Issues, 2015). Workshops on fishing, tourism, and agricultural practices help build partnerships between government, communities and industries to promote economic development and stronger communities. In fact, stakeholders in the region have identified ecotourism as a key—but as of yet unrealized—economic development initiative (Peroff et al., 2017). Thus, tourism development is not a fail-safe adaptation strategy, as climate related changes to the natural environment and associated physical alterations affect nature-based tourism demand (Mendelsohn and Markowski, 1999), as well as visitor perceptions of risk and uncertainty (de Freitas, 2003d; Scott et al., 2007).

Previous research concerning sea level rise impacts on the ecological and social systems of coastal North Carolina considers the nexus of problems, policy and politics to create a "policy window" (e.g., Fig. 5 in Poulter et al., 2009). However, the optimal "policy window" described by Poulter et al. (2009) seems to have passed. This is largely attributed to a major political shift in the North Carolina state legislature, which Dow et al., (2013) documented as "a shift in the state's political climate and increased skepticism and hostility toward climate-related efforts among elected officials at the state and, in some cases, local level" (p. 1238). Specifically, the North Carolina legislature instituted a four-year moratorium in 2012 on regulations and long-range planning related to sea level rise until additional climate model projections were analyzed and considered (Allen et al., 2018). More recently, the North Carolina Coastal Resources Commission published an update to their 2010 report that illustrates differing rates of sea level rise and uses a 30-year period projection (as opposed to the more common 2100 projection date), with a 5-year reassessment cycle to increase confidence in forecasts (North Carolina Coastal Resources Commission, 2015).

Despite the challenges facing climate adaptation planning efforts in coastal North Carolina, stakeholders have mobilized ad-hoc networks to plan for climate change and sea level rise (Dow et al., 2013). Stakeholder participation through outreach activities with goals of data collection and localized planning for climate adaptation can be better served in provisioning of ecosystem services through the SES framework presented in this paper, which previous studies have not addressed in the APP.

4. Risk perceptions and the implications for decision-making

Land-use decisions and preferences for specific management activities are determined by a multitude of factors such as socio-economic characteristics, personal preferences, market (and non-market) drivers, peer influence and level of emotional involvement (Lerner et al., 2014). The process of decision-making related to climate change adaptation entails consideration of several complex factors, many of which affect intuition, emotions, and values, as well as understanding of risks associated with climate change impacts (Adger et al., 2009). Social and environmental interactions influence the way humans derive ecosystems goods and services from the landscape. In turn, these interactions and impacts on land-use and management activities dictate the range of available responses to climate change and sea level rise. Therefore, human decision-making is susceptible to the manner in which options are presented as well as the perceived risk, which is known as the framing effect (Tversky and Kahneman, 1981).

Because the risk perceptions of stakeholders living on the APP have only been minimally examined (e.g., Jurjonas and Seekamp, 2018), we present a synthesis of the risk perception literature on sea level rise, saltwater intrusion, and climate change for general categories of stakeholders (i.e., communities, landowners, agricultural industry, government agencies and non-governmental organizations). We also synthesize implications of the risk perceptions on decision-making and resilience of social-ecological systems (Table 1). To better understand the implications of decision-making in the APP, it is important to understand that stakeholders' climate change risk perceptions are intricately linked to socioeconomic factors (Fothergill and Peek, 2004; Donner and Rodriguez, 2008; Heltberg et al., 2009). For example, poor and rural communities may perceive climatic hazards as risky but are less likely to buy insurance to prepare against the risk (Fothergill and Peek, 2004). The reluctance to protect against coastal hazards is often linked to limited or poor understanding of climate risks (Kunreuther and Pauly, 2006; Mattingly, 2008; Webber and Fisher, 2008); however, effective communication of risk from flooding and prior experience with flooding impacts (Peacock et al., 2005; Petrolia et al., 2013; Mills et al., 2016; Shao et al., 2018) influence risk perceptions and have led to willingness by homeowners to purchase flood insurance (e.g., Shao et al., 2017). When farmers perceive low or no risk due to climate change, there is less support of adaptation either by the government or individuals (e.g., Arbuckle et al., 2013; Prokopy et al., 2015). As such, the shift in risk perceptions is only likely after farmers are directly affected by climate change impacts (Prokopy et al., 2015). For example, the risk perception of farmers affected by drought driven saltwater intrusion in Netherlands was determined by the experience of prior droughts (van Duinen et al., 2015v).

Our synthesis illustrates, for example, that stakeholders who do not perceive any risks to climate change, sea level rise, or saltwater intrusion are less likely to make any proactive decisions about adaptation strategies; consequently, their decisions would likely impact policy implementation, economic structure and ecological sustainability of the region. For example, hardened shorelines are less effective in providing protection during hurricanes (Smith et al., 2017) and the decision to establish living shorelines in coastal North Carolina indeed protected the shoreline during Hurricane Matthew in 2016 (Smith et al., 2018). The lack of proactive decision-making stemming from low risk perception of stakeholders would then negatively affect the freshwater resources in the APP (Fig. 2, arrow 8). A recent study has shown that public officials in 20 North Carolina coastal counties are willing to take adaptive action against climate change if they perceive climate change as a threat (e.g., Bulla et al., 2017). With this in mind, specific efforts are needed in regions vulnerable to sea level rise and saltwater intrusion that communicate climate change risks to local stakeholders. These efforts should include adaptation measures that clearly link future climate change projections and the specific hazards to which different types of stakeholders will be exposed. If such communication is paired with data collection (e.g., focus groups) or outreach (e.g., workshops) efforts, then stakeholders may subsequently become more engaged in local adaptation decision-making specifically or public governance generally (Vogel et al., 2007; Moser, 2014).

A better understanding of SESs and specific vulnerabilities of system components to sea level rise is essential to foster informed adaptation planning and decision-making. Different land-use practices have varying levels of vulnerability to both long-term and episodic environmental disturbances such as inundation and saltwater intrusion. By changing land-use practices and the underlying social mechanisms in managed landscapes such as the APP, vulnerabilities to climate change, sea level rise, or saltwater intrusion may decrease thereby enhancing the ecological system and the quality of ecosystem services (Fig. 2, arrow 6). However, reducing these vulnerabilities requires understanding of actions that minimizes the trade-offs between meeting immediate human needs and maintaining the capacity of ecosystems to provide ecosystem services into the future (Foley et al., 2005), which will be particularly challenging in complex systems like the APP.

5. Applicability to other rural coastal regions

Although existing implementation of adaptation and mitigation strategies to deal with sea level rise appears limited to major urban centers of the world (Hallegatte and Corfee-Morlot, 2011; Lane et al., 2013b), the SES framework presented here, which uses APP as a case study, is applicable to other rural coastal regions. While specific resource-dependent industries or the demographic makeup of another rural coastal region may vary from the APP, the linkages and feedbacks between human communities and ecological processes in the SES framework outlined in this paper are relevant. A recent estimate suggested that approximately 90% of the low-lying coastal land are found in rural areas, with South Asia, Sub-Saharan Africa and East Asia accounting for most of this coastal land (Barbier, 2015). Unlike the rural coastal regions of the developing world, which do not have adequate resources to protect against coastal hazards (Barbier, 2015), APP farmers and towns have received government subsidies to protect against coastal hazards. Yet, the potential for such subsidies to decline or be eliminated is being documented (Craig, 2018; Neal et al., 2018), which could reduce the adaptive capacity and expose rural coastal communities like the APP to risks of marine and coastal resource degradation, such as those documented in several rural coastal regions around the developing world (e.g., Barbier, 2015).

In the United States, minority rural coastal populations are either already exposed to or are expected to bear the brunt of sea level rise impacts (Maldonado et al., 2013; Hardy et al., 2017; Hardy and Hauer, 2018; Marino, 2018). While the displacement of the residents on Isle De Jean Charles in Louisiana is driven by sea level rise and land use change (Maldonado et al., 2013) and likely experienced similar feedbacks in the SES framework we outlined, the condition of the APP residents is not yet as dire. Yet, the resilience of many rural, marginalized coastal communities has been eroded through time (Adger et al., 2005) and with over half of the affected coastal communities in the United States being home to socioeconomically vulnerable rural communities (Dahl et al., 2017), equity in resource distribution and an array of adaptive responses—particularly ones that preserve community cohesion (Adger et al., 2012)—are needed to prepare against physical exposure of sea level rise and bolster adaptive capacity. Thus, in the coming decades sea level rise and its impacts on rural, low-lying coastal communities, like those of the APP, will continue to threaten the functioning of the SES and the ability of already socially vulnerable communities to thrive.

While we do not argue that we should ignore the present focus on the plight of the urban coastal systems that support large populations and critical infrastructure, we recommend that adaptation measures to prepare against sea level rise, flooding and saltwater intrusion are also needed for rural parts of low-lying, coastal regions. Our study illustrates the potential for collaborations between rural coastal communities, governments, and other organizations to adapt and prepare for sea level rise. These adaptations and preparations can yield positive feedback (Fig. 2, arrow 6) to improve the ecological system and further reduce the vulnerability of the social system. The SES framework presented

Table 1
Summary of risks and perceptions of rural stakeholders, implications for decision-making, and possible impacts to the coastal social-ecological systems. Sea level rise, climate change and social-ecological systems are denoted by SLR, CC and SES respectively.

Stakeholders	Risks/Perceptions of SLR (CC)	Implications for Decision Making	Possible/Current Impacts to SES	References
Communities	1. Limited or poor understanding of risks	1. People may choose not to invest in insurance policies to protect against flooding, hurricanes etc.	1. Post-disaster economic distress and increased environmental and economic vulnerability	1. Tversky and Kahneman 1974; Kydland and Prescott, 1977; Kunreuther and Pauly, 2006; Mattingly, 2008; Webber and Fisher, 2008.
	2. Climate change is not dangerous; it will not affect me	2. Priorities might focus other community infrastructure before adaptation or social issues	2. Planning might not be designed for adaptation	2. Rapaport et al., 2015; Leiserowitz, 2005.
Landowners	1. Extant Adaptation or Mitigation Strategies are inadequate or unknown	1. Adaptation is not prioritized as an individual strategy	1. Adaptation strategies may need updates	1. Ludy and Kondolf, 2012.
	2. Climate Denial	2. Adaptation and resilience planning will not be supported or adopted and it will be difficult to finance	2. Increased vulnerability as development continues on the coast	2. Dang et al., 2014; Corry and Jorgenson, 2015.
	3. Lack of Agency	3. Planning will not be considered a viable solution	(3. Lack of preparedness for coastal hazards	3. Lazrus, 2012.
Agriculture	1. No threat to local agriculture	1. Fear of admittance due to increased policy restrictions, results in mitigation of current issues and no plans for adaptation	1. Increased vulnerability due to absence of adaptation strategies	1. Arbuckle et al., 2013; Prokopy et al., 2015.
Government	1. Agencies work toward adaptation on public land and help farmers adapt to SLR related impacts	1. Strategies for adaptation and resilience are employed through subsidies and governmental management	1. Increased preparedness through management of ecosystem transitions	1. Titus et al., 2009; Mawdsley et al., 2009.
	2. Politicization causes differences in risk perception within the government	2. Progress made toward adaptation planning could be lost with political change	2. Failure to implement lasting strategy	2. Eriksen et al., 2015.
Non-Government Organizations	1. Mitigation efforts are necessary	1. Key areas are identified and prioritized for mitigation	1. Increased preparedness	1. Mcleod et al., 2010.
	2. Living shorelines mitigate storm surge	2. Projects are implemented to install oyster, sea grass, and reef habitat	2. Coastal areas have improved resilience	2. Swann, 2008; Smith et al., 2018.

here necessitates interdisciplinary research and highlights the importance of mutual learning amongst stakeholders in other low-lying rural coastal regions.

6. Conclusions

In this paper, we presented a conceptual model of the social and ecological impacts of sea level rise in rural, low-lying coastal areas, contextualizing our discussion by describing the current challenges facing the APP region of eastern North Carolina. Our synthesis of sea level rise impacts to hydrological, ecological and social systems of the APP demonstrates the coupling between the social and ecological systems. Whereas previous research has primarily focused on the impacts of sea level rise to urban coastal regions, rural contexts like the APP face a different set of vulnerabilities given their socioeconomic functioning, particularly with respect to their dependence on natural resources. The discussion of these vulnerabilities in the SES framework allows for the consideration of dynamic feedbacks between diverse ecological and social components (Fig. 2).

Climate change, sea level rise and their associated impacts on rural, low-lying coastal communities, like those of the APP, will continue to threaten the functioning of the SES. Although programs to support the adaptive capacity of such rural areas exist, we strongly believe that a greater impetus towards developing meaningful understanding of diverse stakeholders' risk perceptions and targeted policies from the local and state agencies will further enhance their ability to plan for drastic change. The feedbacks between ecological and social systems, coupled with the high degree of uncertainty associated with many climate scenarios, necessitate dynamic, adaptive responses and management decisions. A conceptual SES framework such as this provides a lens through which the implications of sea level rise, saltwater intrusion and related phenomena can be observed and evaluated for rural, low-lying coastal communities.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2018.10.006.

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