Population and Environment
https://doi.org/10.1007/s11111-019-00315-8

ORIGINAL PAPER

No landward movement: examining 80 years of population migration and shoreline change in Louisiana

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Abstract

Louisiana lost nearly 5,000 km^2 of its coastal land area due to relative sea level rise (including local, regional, and global factors driving relative sea level change) since 1932, mirroring both the hazards associated with sea level rise and the time horizons of sea level rise impacts expected this century. This represents an opportunity to examine the relationship between long-term population changes and shoreline change. Based on detailed land change data for the period 1932–2010 and a small area population estimation technique for the period 1940–2010, we examine intra-parish population changes in relation to shoreline changes for the one million plus residents living in the ten coastal parishes of Louisiana. We find that since 1940, only two of the ten coastal parishes exhibited landward population movement, which we define as movement perpendicular to the shoreline, exceeding 1 km. Three parishes exhibited seaward population movement in excess of 1 km. Overall, we find very little net intra-parish landward population movement for the region. Our findings suggest that coastal Louisiana's historical population has not moved in concert with observed shoreline encroachment. We also find a potential tipping point related to population migration when a neighborhood loses at least 50% of its land area. Our findings suggest that this lack of landward population movement could be attributable to either localized adaptation strategies or migrations to other landward areas.

Keywords Louisiana · Hurricane Katrina · Sea level rise · Adaptation · Migration · Coastal populations · Landward migration

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The data and code that supports this analysis are available in the supplementary materials.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11111-019-00315-8) contains supplementary material, which is available to authorized users.

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Introduction

Estimates of the population that could be affected by climate-driven sea level rise (SLR) by 2100 range from 187 million (Nicholls et al. 2011) to over 1 billion people (Neumann et al. 2015) making SLR a major impact of climate change. Twentieth century examples of abandonment, retreat, relocation, and/or resettlement due to land loss in coastal regions have already occurred (Connell 1990; Gibbons and Nicholls 2006; Steel 2011; King 2017) and may offer insights into the potential future experiences of populations that would be displaced by future SLR. Examining these historical analogs is key to avoiding a "no-analog future" (Fox 2007) due to climate change impacts, guiding the development of cohesive, effective public policy.

Hypotheses regarding population migration due to SLR undertaken in the absence of governmental intervention suggest incremental landward (defined as movement away from the shoreline) migration to nearby destinations. Döös (1997) and Kahn (2014) hypothesize that SLR will spur migration toward landward areas. Curtis and Schneider (2011) and Hauer (2017) hypothesize that SLR in the USA will likely spur migration that crosses administrative boundaries toward more landward counties (or parishes in the case of Louisiana), though not limited to *just* landward counties. It is possible some people may make more local moves toward higher ground or toward more landward locales within their present county. Despite these well-formed hypotheses, little, if any, empirical work has examined population movements in relation to shoreline changes due to SLR in mainland communities.

Three widely cited examples of island abandonment in the twentieth century, Holland Island, St. Kilda Island, and the Carteret Islands (Connell 1990; Gibbons and Nicholls 2006; Steel 2011), form the backbone for understanding relocation due to SLR for island communities. However, these are poor analogs for understanding the potential relocation or resettlement of mainland communities for several reasons. Mainland communities have additional options unavailable to island communities, such as relocating landward with the shoreline (Döös 1997). Additionally, conventional wisdom suggests that abandonment must occur if adaptive measures are not undertaken (Döös 1997; Nicholls et al. 2011), but only one historic precedent, Holland Island (Gibbons and Nicholls 2006), was abandoned by choice and not facilitated with a managed relocation. Lastly, the islands are sparsely populated communities and are likely unrepresentative of the millions at risk of displacement in mainland areas (Strauss et al. 2015; Hauer et al. 2016). Therefore, these examples offer little insight into the theories of landward migration discussed above, and better analogies for the current situation in US coastal communities could be developed. Between 1932 and 2016, coastal Louisiana lost 1,866 mi^2 (4,833 km^2) in land area—representing a decrease of 25% of the 1932 land area (Couvillion et al. 2017)—due to relative SLR. We define land loss due to relative SLR as global sea level rise plus all other factors driving local to regional sea level changes that affect local land elevation relative to local sea level including a suite of natural and anthropogenic processes such as land loss due to oil and gas canaling, damming of the Mississippi reducing sediment loading and accretion, polar ice sheet gravity fingerprints, and glacial isostatic adjustment, among others (Craig et al. 1979; Gagliano et al. 1981; Boesch et al. 1994; Barras et al. 2003; Mitrovica et al. 2009; Olea and Coleman Jr 2013; Peltier 2004). This land loss presents an ideal situation for exploring the relationship of coastal population movement threatened by SLR and their changing shorelines for three primary reasons. First, the land loss mirrors both the hazard associated with SLR and the time horizons of SLR impacts expected this century. Second, Louisiana's one million plus coastal residents represent a population facing widespread land loss that is orders of magnitude larger than any other historically threatened population studied in the literature (Connell 1990, 2016; Gibbons and Nicholls 2006; Steel 2011). Lastly, local residents' complaints to local officials on coastal land loss have historically fallen on deaf ears (Boesch et al. 1994; Boesch 2006; Burley et al. 2007; Yusuf et al. 2016), which allows us to examine population level movement responses largely in the absence of policy interventions.

Assessing population migration patterns via small area demographic change, the ideal scale at which to investigate population responses to relative SLR in Louisiana, is difficult to quantify over time due to the problems of the modifiable areal unit problem (Cromley et al. 2009). The US Census Bureau redraws many sub-parish and sub-county Census delineated units at each decennial census limiting analysis to larger areas with relatively stable boundaries. Additionally, the USA was not fully tracted until Census 1990, limiting historical examinations of small area demographic change to just 1990, or to the major cities tracted prior to 1990, such as New York and Chicago. This forces most demographers to focus on small area population forecasts rather than population hindcasts (Swanson et al. 2010; Smith et al. 2006; Hauer et al. 2016).

This paper addresses these gaps and examines the relationship between long-term shoreline change and population growth/decline patterns in coastal Louisiana as an analog for understanding population responses to relative SLR in mainland communities. We combine detailed land change data, a small area estimation technique based on the Hammer Method (Hammer et al. 2004) for the period 1940–2010, and geostatistical techniques to investigate how each coastal parish's population has moved in response to shoreline movement caused by relative SLR. To assess population "movement," we measure the distance that each parish's weighted mean population center has changed in decadal increments. We ask three fundamental questions relating to population movement: Has coastal Louisiana's population moved landward, which we define as perpendicular to the shoreline, corresponding with shoreline encroachment from relative SLR? What is the relationship between land loss and population growth/decline within neighborhoods (i.e., Census Block Groups)? and; What threshold, if any, of land loss might be associated with large population declines?

Scholars have identified the investigation of possible tipping points as important avenues of research (Bardsley and Hugo 2010; Black et al. 2011a; McLeman 2011) and we contribute to this conversation with empirical analysis of population change in concert with land change in coastal Louisiana. Our analysis identifies possible thresholds related to land loss that might be associated with population declines.

Background

Adaptation to sea level rise

SLR is one of the most written about and best understood implications of climate change (IPCC 2014). Detailed research has sought to identify the specific communities at risk (Wu et al. 2002; Martinich et al. 2013; Hauer et al. 2015) and numerous scholars have provided guidance and assessments for local adaptation planning (Lutsey and Sperling 2008; Titus et al. 2009). Recently, highly localized estimates and projections of populations at risk to SLR have been of significant interest (Lutz et al. 2007; Rowley et al. 2007; Plyer et al. 2010; Curtis and Schneider 2011; Hauer et al. 2015; Hardy and Hauer 2018) and the implications of SLR-driven migration on population landscapes beyond coastal zones are starting to be understood (Hauer 2017). The behaviors deployed to adapt to climate change have long been studied (Smit and Skinner 2002; Berrang-Ford et al. 2011), but the research surrounding the migration behaviors of mainland populations related to SLR have tended to be theoretical rather than empirical (Döös 1997).

Coastal residents' responses to shoreline erosion and relative SLR broadly fit three categories: shore protection, accommodation, and relocation (Titus et al. 2009; Nicholls et al. 2011; King 2017). Socioeconomic and environmental conditions can dictate the response (or even a mixture of responses) employed to cope with rising seas (Gornitz 2013). Protection primarily consists of infrastructure solutions such as dikes, levees, seawalls, and other "hard armoring" techniques or beach renourishment as "soft armoring techniques." Individuals can also employ a wide variety of adaptation techniques through accommodation. For instance, garages can replace many ground floor spaces in homes preventing high-water events from passing through more expensive to repair living areas. Florida building codes require minimum housing elevations above the crown of the road, reducing the risk of catastrophic flooding from hurricanes (Dehring 2006). Important roads can be raised if localized flooding becomes too burdensome on local residents and businesses.

Relocation and/or resettlement is an option for sparsely developed areas and can be undertaken when protection and accommodation are either ineffective or too costly. Managed relocations have been undertaken before, as seen on St. Kilda Island in Scotland in the 1970s (Steel 2011), and have begun more recently for the community of Isle de Jean Charles in coastal Louisiana (Simms 2016; King 2017).[1] Resettlement brings with it many challenges. The costs of relocation will vary widely and will be borne by the property owners in an unmanaged, or ad hoc retreat, or by the public at large through a government-managed relocation with estimates for managed

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[1] Despite the use of the term "retreat" in much of the literature on climate change adaptation (Titus et al. 2009), many coastal communities do not use the term "retreat" to describe their plans to relocate. Retreat signifies a reactive effort that ignores the complex social and cultural toll of relocating, whereas the terms "relocation" or "resettlement" are more empowering and proactive, especially when community led (Center 2015); these latter terms acknowledge both "ends" of the process involved with leaving one place and moving to another.

relocations upwards of \$100,000 to \$1 million per person (Huntington et al. 2012; Hino et al. 2017).

Materials and methods

We examine coastal Louisiana's population movements in relation to observed relative SLR effects on Louisiana's shoreline by using the US Geological Survey's (USGS) Land Area Changes in Louisiana data set (Couvillion et al. 2011). These data collate 17 data sets of historical surveys, airborne and satellite data, and consistent change criteria to track landscape change in Louisiana between 1932 and 2010 with land loss measured at 30-m and 60-m resolutions, depending on the time period. While some landlocked Louisiana parishes (governing units that are essentially equivalent to US counties within the US Census) experienced land loss since 1932, we consider only census block groups in parishes adjacent to the Gulf of Mexico for this analysis as the land loss in these parishes is significantly greater than in the landlocked areas. We aggregate all land loss/gain over the time period into single loss/gain categories.

Coastal Louisiana

The wetlands in coastal Louisiana comprise the seventh largest delta on Earth and are an environmentally fragile ecosystem, accounting for 90% of the coastal wetland loss in the USA (Couvillion et al. 2011) (Fig. 1). Currently, Louisiana is losing 10.8 mi^2 (28 km^2) per year or the equivalent of one American football field per 100 min (Couvillion et al. 2017).

The factors driving land loss due to relative SLR in coastal Louisiana are well-documented phenomena (Craig et al. 1979; Burley et al. 2007; Couvillion et al. 2011). As mentioned above, a host of processes—both natural and anthropogenic—

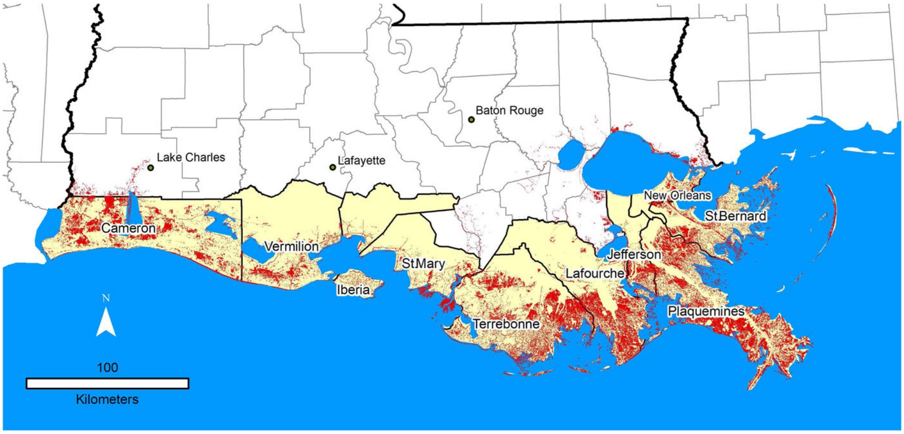

Fig. 1 Study area parishes are colored in tan. Red areas indicate land loss due to relative SLR between 1932 and 2010

are responsible for this loss and include tropical cyclones, natural erosion from waves, dredging, building oil and gas pipeline networks, flood-control practices such as diversion canals, and local to regional patterns of SLR (Craig et al. 1979; Burley et al. 2007); even global SLR has natural and anthropogenic processes driving it, although anthropogenic forces have dominated since the 1950s (Marcos et al. 2017). The leveeing of the Mississippi River and the fragmentation of coastal land area due to diminished sediment supply and the complicated networks of oil and gas pipelines have altered the natural accretion of sediment in the coastal area, causing much of the area to slowly sink, lose land area, and increase vulnerability to disastrous storm surges. While research on the attribution of natural/anthropogenic forces to this land loss is important, for our purposes, we make no direct distinction between natural/anthropogenic in our analysis. We are not examining the causes of the land loss but rather how these changes relate to population movements.

During the same period of observed land loss (1932–present), the population in coastal Louisiana boomed. Between 1940 and 1980, the region saw its population increase by approximately 95.0%, growing from 752,651 people in 1940 to 1,465,340 in 1980. Since 1980, the population in coastal Louisiana has slowly decreased, declining from 1,465,340 in 1980 to 1,419,167 in 2000. The effects of Hurricanes Katrina and Rita on population changes in 2005 are well known (Thiede and Brown 2013; Curtis et al. 2015) and are a contributing factor to the population decline in the region after 1980.

With 70+ years of both population and land classification data, the time horizons for land loss in coastal Louisiana mirror the time horizons for projected SLR impacts in the 21st century. Louisiana's one million plus coastal residents represent a population facing widespread land loss that is orders of magnitude larger than any other historically threatened population studied in the literature (Connell 1990; Gibbons and Nicholls 2006; Steel 2011). Moreover, coastal Louisiana is one of the areas most threatened by relative SLR in the USA. Many coastal Louisiana parishes could see over 50% of their populations directly impacted by 1.8 m of SLR by the end of the century (Hauer et al. 2016).

Housing units

We overcame the issue of the mutability of sub-parish units to produce spatio-temporally contiguous housing estimates by using a modified Hammer Method (Hammer et al. 2004; Hauer et al. 2016) to produce estimates by census block groups (CBG) for the period 1940–2010. By creating historic small area housing estimates we are able to investigate population movement within coastal parishes. Equation 1 demonstrates the modified Hammer Method for estimating the number of housing units in CBGs.

$$\hat{H}_{ij}^{v} = \left(\frac{C_j^v}{\sum_{i=1}^{n} \sum_{t=1939}^{v-1} H_{ijt}^{v}} \right) \cdot \sum_{t=1939}^{v-1} H_{ijt}^{v} \quad (1)$$

where:

C_j^v is the number of HUs in parish j counted in census taken in time v

H_{ij}^{v} is the number of HUs in block group i in parish j based on the "year structure built" question in the U.S. Census American Community Survey (ACS)

v is the set of time periods $v \in \{1940, 1950, 1960, 1970, 1980, 1990, 2000, 2010\}$

Thus, to estimate the number of housing units in block group i in parish j for the year 1970, for example, the number counted in parish j according to the 1970 census (C_j^{1970}) is divided by the number of HUs in parish j, as estimated in the ACS, for the period 1939-1969 $\left(\sum_{i=1939}^{1969} H_j^{1970}\right)$ and multiplied by the number of HUs estimated in the ACS in block group i for the same period $\left(\sum_{i=1939}^{1969} H_{ij}^{1970}\right)$. This is repeated for each decade until the most recent time period. These estimates of HUs for each CBG provide the key input needed to convert an estimate of HUs into an estimate of total population.

Data for historically estimating the housing units come from two main sources. First, the ACS 2008–2012 estimates provide the "year structure built" data as well as the 2010 boundaries for the CBGs. Houses that are destroyed or demolished, become uninhabitable, or converted to non-residence uses would not be present in the ACS data as they would not have "survived." Any use of just the ACS data would result in an underestimation of historical housing units. To overcome this, we use a second data source, the actual historical count of populations and housing units for each parish, to proportionally adjust the ACS housing unit estimates. This data come from digitized records available on the Census Bureau's website for reach decennial census.[2] By creating historic small area population estimates we are able to investigate population movement within coastal parishes. A longer discussion of the Hammer method is available in the Supplementary Materials.

Housing Units to Population

To estimate population at time t (P_t), Eq. 2 is applied to convert an estimate of HUs to an estimate of population.

$$P_t = H \cdot PPHU \tag{2}$$

where H is the number of housing units and $PPHU$ is the persons per housing unit. The two variables required to calculate the $PPHU$ are known only for each historical census at the parish level, thus the $PPHU$ for each CBG must be estimated. Keeping in the same tradition as Hammer, we utilize the known variability in current decadal CBG geography for $PPHU$ to backcast $PPHU$ for prior decades based on this variability using a double-rake proportional fitting algorithm (Deming and Stephan 1940). The first rake occurs by proportionally adjusting each CBG's $PPHU$ value and the second rake occurs by ensuring the sum of the CBG populations equal the parish's historical count of population.

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[2] For 1940 to 1990, data can be found at http://www.census.gov/prod/cen1990/cph2/cph-2-1-1.pdf. Census 2000 data can be downloaded through American FactFinder.

Equation 3 demonstrates the historical calculations of population for each CBG for any given time period.

$$P_{ij}^{'v} = \frac{P_j^v}{\sum\left[\left(\frac{PPHU_{ij}^{2010}}{PPHU_j^{2010}} \cdot PPHU_j^v\right) \cdot \hat{H}_{ij}^v\right]} \cdot \hat{P}_{ij}^v \tag{3}$$

The $PPHU$ in CBG i in parish j in 2010 is denoted as $PPHU_{ij}^{2010}$ while the $PPHU$ observed in parish j in historical time v is denoted as $PPHU_j^v$. The initial $PPHU$ estimate for each CBG is computed as the ratio of the PPHU in CBG i in parish j in 2010 to the PPHU in parish j in 2010 multiplied by the observed PPHU in parish j in historical time period v. This initial estimate of historical PPHUs are then multiplied by the estimated number of Housing Units as estimated from Eq. 1 ($\hat{H}_{ij}^v$) in historical time v to create an initial estimate of population. These are then summed to the parish level and proportionally adjusted based on the observed population of a parish from historical time period v. By simply dividing the estimated population by the estimated number of housing units, we will generate $PPHU$ for any given time period ($P_{ij}^{'v}/\hat{H}_{ij}^v$). This provides us with variable $PPHU$ estimates for each CBG for each time period in any given parish. This makes it possible to produce a historical time series of population and housing units at the CBG geography with consistent boundaries for a period of 1940–2010 and with unique $PPHU$ values for each time period.

To estimate the historical population in block group i in parish j in time 1970, for example, one would first divide $PPHU_{ij}^{2010}$ by $PPHU_j^{2010}$ and then multiply by the PPHU in parish j in historical time v ($PPHU_j^{1970}$). In essence, this creates a raked $PPHU$ value in historical time v. This raked $PPHU$ value is then multiplied by the output from the Eq. 1 ($\hat{H}_{ij}^{1970}$), and summed to parish j. This creates an estimated population in time v that is raked a second time ($P_j^{1970}/\hat{P}_j^{1970}$) and multiplied by the estimated population in each member block group ($\hat{P}_{ij}^{1970}$).

Limitations

There are several limitations in using these approaches that we acknowledge. These limitations include (i) assumptions that the relative distribution of housing in each year-built period (i.e., 1939–1970) represents the actual proportional allocation of housing in that period. For example, if block group i contains 10% of the housing units built between 1939 and 1970 in parish j, as observed in the ACS, Hammer's method assumes that block group contains 10% of the counted housing units from Census 1970. (ii) The methods rely heavily on the accuracy of the reported age distribution (year structure built) of the housing stock. Errors due to misreporting or age heaping can significantly impact the results. Additionally, the method we ouline above relies on relatively low "churn" of the housing stock. Any homes that are destroyed and rebuilt will bias estimates toward more recently built structures. And (iii) we are limited to only examining absolute numeric changes. If there is a compositional change in the population (ie, educated in-migrants); if there are aspects of rural gentrification occuring; we cannot detect it with our methods.

Despite these limitations, previous research supports our methodological approach. First, regarding the appropriateness of proportional fitting to small area demographic analysis—limitation (i)—scholars have successfully employed proportional fitting methods to sub-county and sub-parish geographies with great success for a number of years (Beckman et al. 1996) with Wong (Wong 1992) even encouraging their use for small area geographic analysis. Evaluations of the errors associated with proportional fit estimates of Census Tracts and CBGs demonstrate consistently low errors (Wong 1992; Beckman et al. 1996; Choupani and Mamdoohi 2016; Rose and Nagle 2017) giving us confidence in the quality of our own sub-parish proportionally fit historical estimates. The more recent evaluations of sub-county and sub-parish proportional fitting utilize ACS data—the same data source we use—finding acceptably low errors. Second, regarding low "churn" of the housing stock— limitation (ii)—it is possible that the devastating hurricanes that hit Louisiana over the past few decades could cause our estimates to be biased toward more recently built structures. However, the proportional fitting approach ensures that sub-parish housing unit estimates always sum to the observed housing units in the historical period. Thus, only if the "churn" occurs in a significantly uneven geographic pattern should this be a concern. While this is possible, we believe it unlikely in light of the stability of our results below.

Measuring Population Movement

Population in a given CBG or parish could continue to grow while the land area is shrinking. We measure population movement by using a geostatisical approach consisting of two steps. First, to determine if a parish experienced movement of its population, we employ the use of a weighted mean center of the population, given as the weighted average of the x and y centroid coordinates of all of the block groups in a parish. Here, our weight is given as the total population of a block group for each decade between 1940 and 2010. With a 2010 mean population center as our starting point, movement of the population is measured as a shift in the mean center relative to the shoreline. Positive distances, or distances that increase, are defined as more landward movement while negative distances, or distances that decrease, are defined as more seaward movement. The weighted mean center is given as:

$$\bar{X}_w = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}, \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i} \tag{4}$$

To measure landward movement of the population relative to the coastline, we first simplify the US coastline using the $simplify\_shape$ function from the $tmaptools$ package in R. $simplify\_shape$ uses the Visvalingam algorithm to modify the area metric by underweighting the effective area of points at the vertex of more acute angles. This step is undertaken to remove extemporaneous abutments present in the Louisiana coastline (Fig. 2). Next, we determine the Euclidean distance from each mean center in each time period to each parish's nearest simplified coastline.

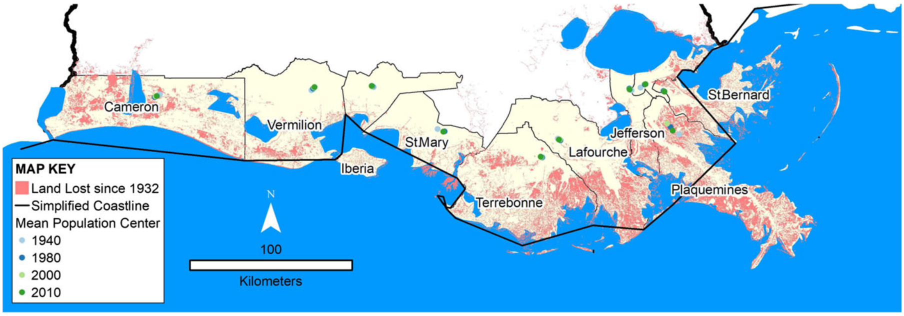

Fig. 2 Land loss due to relative SLR and population movement for coastal Louisiana, 1940–2010. Areas in red indicate land lost since 1932. The mean population centers for 1940, 1980, 2000, and 2010 are also included

Results

The ten-parish region saw its population increase by 483,575 persons between 1940 and 2010 while simultaneously losing approximately 4,000 m^2 of land area due to relative SLR (Table 2). Thus, coastal Louisiana continued to see population growth despite nearly unprecedented land loss over time horizons mirroring those predicted for SLR in the 21st century.

Has coastal Louisiana's population moved landward, corresponding with shoreline changes from relative SLR?

Overall, we observe no robust landward population movement in eight of the ten coastal parishes with only Jefferson and Terrebonne parishes exhibiting landward movement in excess of 1 km (Figs. 2 and 3). Three coastal parishes exhibited seaward movement in excess of 1 km between 1940 and 2010—Cameron, Orleans, and St. Bernard (Fig. 2). These parishes have population movements that draw the population center closer to the encroaching shoreline. For the region as a whole, the mean centers were approximately 31.5 km from the shoreline in 1940 and were 30.6 km from the shoreline in 2010—demonstrating no substantial landward movement across the aggregated study region.

Plaquemines Parish observed the greatest landward population movement between 1940 and 2000, moving nearly 10 km landward in conjunction with experiencing the greatest land loss due to relative SLR in coastal Louisiana. This landward movement was likely the result of both the prolific land subsidence in Plaquemines and the continued suburbanization of New Orleans, pushing more people into the northern part of the Parish. However, between 2000 and 2010, Plaquemines Parish's population center moved over 10 km seaward representing a rapid and dramatic shift in its population coinciding with the extraordinary, and well-documented, demographic changes caused by Hurricanes Katrina and Rita through population displacement (Sastry 2009; Hori et al. 2009; Gutmann and Field 2010). Our methods can only detect the numerical changes in population and their possible correlates. We are unable

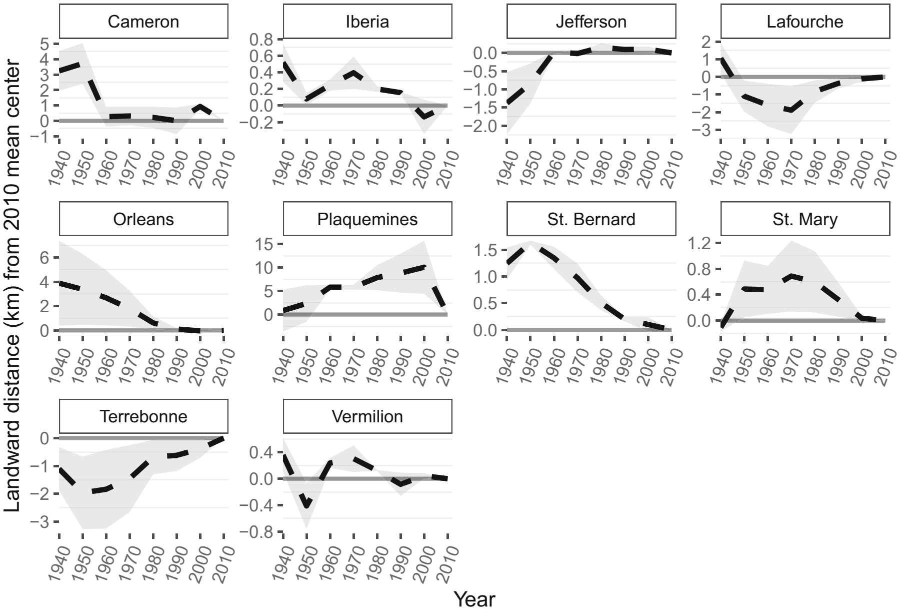

Fig. 3 Distance in kilometers from the 2010 mean center population for Coastal Louisiana parishes, 1940–2010. Positive distances or distances that increase reflect landward population movement, negative distances or distances that decrease reflect seaward population movement. The shaded area is the 90% confidence interval. Lines below the 0 line indicate a mean center that is more seaward of the 2010 mean center while lines above the 0 line indicate a mean center that is more landward of the 2010 mean center. For example, Cameron Parish's 1940 mean center is approximately 3 km more landward than the 2010 mean center, suggesting seaward movement of Cameron's housing stock

to directly isolate the causes nor the contribution the varying causes might have on the movement (e.g., land subsidence, suburbanization, and tropical cyclones). It is the likely confluence of a variety of factors that has spurred the movement in Plaquemines (Fig. 4).

Landward population movement is present in Plaquemines Parish, however, with the parish experiencing the greatest relative SLR. Other parish populations could also move landward as their communities continue to subside. Jefferson, Terrebonne, and Vermilion parishes exhibit much smaller landward movements, but may increasingly move landward as relative SLR continues.

What is the relationship between land loss and population growth/decline?

Approximately one-third of CBGs experiencing land loss also experienced population decline since 1980 (58 out of 161) meaning that nearly two-thirds of CBGs that are losing land area grew in population (Table 1). The relationship is inverted for the CBGs that did not experience land loss, where nearly 75% of the CBGs experiencing no land loss declined (753 out of 1024). Over 90% of CBGs experiencing population declines since 1980 did not experience land loss (753 out of 811).

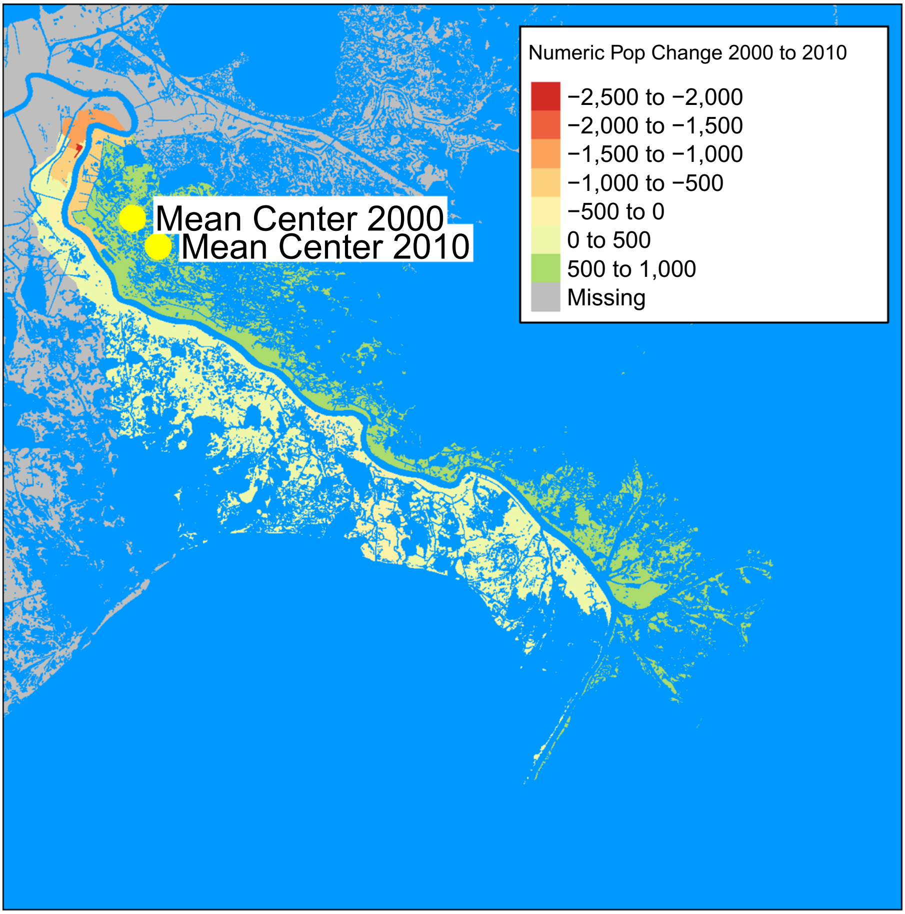

Fig. 4 Population change in Plaquemines Parish, 2000–2010. The declining populations in the northern part of the parish and the population growth in the southern part led to the seaward movement of the mean population center

Table 1 Land and population loss in coastal Louisiana, 1980–2010 by Census Block Group. CBGs without land area were excluded from the land loss/no land loss/decline/no decline categories

	Land loss	No land loss	Total
Pop. decline	58 36%	753 73.5%	811
No pop. decline	103 64%	271 26.5%	374
TOTAL	161	1024	1185

What threshold, if any, of land loss leads to abandonment?

We observe a relatively strong relationship between land loss and population decline since 1980 as land loss increases (Fig. 5 and Table 2). In all CBGs experiencing land loss (*n*= 161), approximately 30% also experienced population declines. As the amount of land loss experienced in a CBG increased the likelihood of a CBG experiencing decline also increased. Half of the CBGs that experience greater than 50% land loss also went into population decline, rising to 60% of these CBGs when over 55% of the land area disappeared.

Taken together, these results suggest a possible "tipping point" near 50% of land loss before the majority of CBGs go into population decline. It bears repeating that population decline could be tied to numerous other effects aside from relative sea level rise and shoreline encroachment, but these results demonstrate a potential relationship.

Discussion

Coastal populations will face increasing threats from climate change in the coming decades and beyond. Our empirical work offers a quantitative examination of population movement in relation to relative SLR, or long-term, slow-onset environmental change in mainland areas. We observe very little landward population

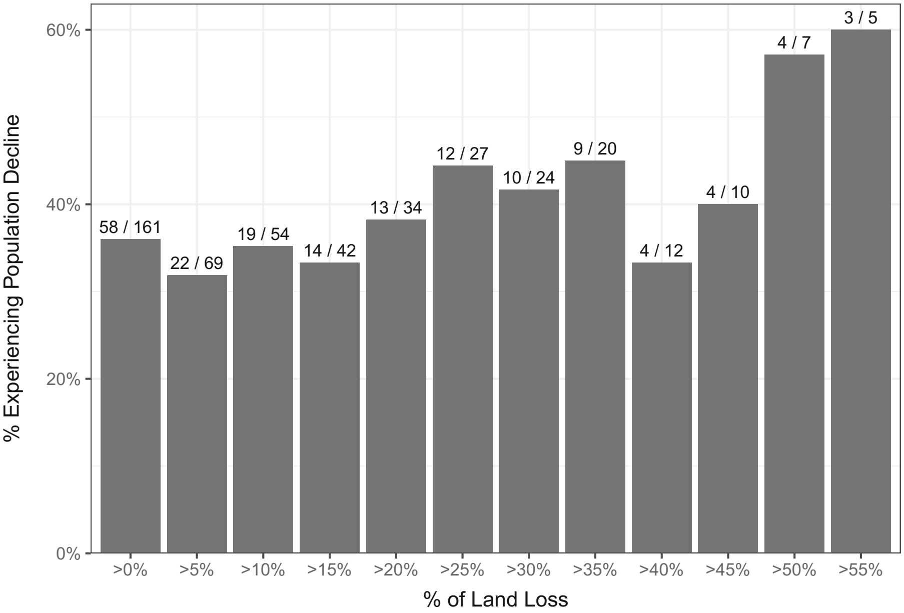

Fig. 5 Percent of block groups experiencing population declines between 1980 and 2010 by the amount of land loss since 1940. The numbers above the bars reflect the number experiencing decline and the number of block groups in that land loss category

Table 2 Population change, land loss, and landward movement, 1940–2010

Parish	Population 1940	Population 2010	% chng 1940-2010	km2 1932	km2 2010	% Land lost 1932-2010	Distance to Shore-line 1940 (km)	Distance to Shore-line 2010 (km)	Landward move-ment 1940-2010 (km)
Cameron	7,203	6,839	−5%	3,541	2,875	−19%	37.3	34	−3.3
Iberia	37,183	73,240	97%	1,518	1,448	−5%	24.5	24	−0.5
Jefferson	50,427	432,552	758%	870	681	−22%	28.7	30.1	1.4
Lafourche	38,615	96,318	149%	2,971	2,372	−20%	57.8	56.8	−1
Orleans	494,537	343,829	−30%	473	403	−15%	23.7	19.8	−3.9
Plaquemines	12,318	23,042	87%	2,512	1,326	−47%	33.6	32.7	−0.9
St. Bernard	7,280	35,897	393%	1,272	873	−31%	13	11.8	−1.2
St. Mary	31,458	54,650	74%	1,497	1,409	−6%	21.8	21.9	0.1
Terrebonne	35,880	111,860	212%	3,481	2,546	−27%	48.6	49.7	1.1
Vermilion	37,750	57,999	54%	3,113	2,911	−7%	25.8	25.4	−0.4
Total	752,651	1,236,226	64%	26,824	22,295	−17%	31.5	30.6	−0.9

movement, in opposition to hypothesized migration responses (Döös 1997) and rational "self-preservation" models (Kahn 2014).

The lack of landward population movement coupled with continued population growth suggests two possible options. First, in-situ adaptation is likely occurring due to the "immobility paradox" (Findlay 2011) (where people favor "holding the line" rather than relocating). Relocation is typically the second option, as people will adjust their behavior before they adjust their location. Migration is costly in terms of financial and social capital and deep rooted cultural ties. Our results suggest that the population in coastal Louisiana is not moving landward and, considering our results in conjunction with relative population stability, residents appear to favor "holding the line," echoing many findings in the literature of other communities facing environmental migration pressures (Zhang et al. 2004; Findlay 2011; Maldonado 2015). Accommodation efforts have been employed in Louisiana for decades and include voluntary home elevation, deployment of floating docks, and a replacement of older structures with more resilient ones (Bailey et al. 2014). However, when people do stay it may not be a choice, as the capacity to mitigate vulnerability by relocating requires having overcoming several socio-cultural and political economic obstacles that are frequently beyond the control of many households and communities (Thomas et al. 2018). Remaining increases risks to health and safety (Maldonado et al. 2013), and could ultimately require additional measures to address increasing vulnerability (Black et al. 2011a, b).

Historical small area population data is virtually non-existent in the USA as the US Census Bureau completely tracted the USA only in 1990. To overcome this issue, we applied a novel method of population estimation. The absence of sub-parish population data makes it impossible to determine the accuracy of these estimates, but previous assessments of similar methods have proved quite accurate (Hauer et al. 2015; Hauer et al. 2016). The lack of substantial landward population movement in some parishes could be methodologically driven rather than empirically driven. Landward population movement could have occurred *within* block groups rather than *between* block groups, but with little to no historical data, geographies smaller than block groups are virtually impossible to examine at this scale. We also cannot detect compositional changes in the population nor can we detect population "churn" due to our limitation of absolute numeric population change. Despite these limitations, we believe our analysis accurately describes the historical population distribution and mean population movements of the parishes in coastal Louisiana.

Additionally, we only investigate population movement within coastal parishes. Landward retreat via out-migration to more distant, landlocked communities is still possible, similar to the population redistribution that occurred after Hurricanes Katrina and Rita (Hori et al. 2009; Curtis et al. 2015). Although we did not examine such historical migration destinations due to the very limited linked historical origin-destination migration data that exists in the USA, the findings from our study provide an insight into the population movements in Louisiana's coastal parishes in relation to relative SLR. The mechanisms behind environmental migration could be tied to other effects of relative SLR such as economic losses, changes in fisheries, or damage to infrastructure (Black et al. 2011a, b) or reasons completely unrelated to environmental change. It might not be direct impacts from shoreline retreat that lead to landward population movement, but rather a combination of direct and associated effects—effects long noted in the environmental migration literature (Black et al. 2011a, b).

The approach we demonstrate in this paper allows for investigations of historical small area demographic changes in relation to gradual environmental changes caused by a changing climate. We believe that the coupling of historical small area estimates with other climate-related hazards such as droughts or changing precipitation regimes to jointly investigate climate change analogs and demographic change is a fruitful approach for future research. We imagine that such extensive, broad scale, modeling of climatic change along with demographic change may offer insights into where more intensive qualitative social science research could be conducted. The tools of more intensive, place-based research are capable of examining the socio-environmental relationships observed in approaches such as our model-based approach, providing detailed explanations into why people adapt in place or relocate.

Acknowledgments Support for RDH was provided by the National Socio-Environmental Synthesis Center (SESYNC) under funding received from the National Science Foundation (Award #DBI-1639145).

Data availability All data generated and analyzed and all R code needed to replicate these results are available in the supplementary material.

Compliance with Ethical Standards All experiments complied with ethical standards in the USA.

Conflict of interest The authors declare that they have no conflict of interest.

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