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The Spatiotemporal Characteristics and Interactions between Urban Expansion and Tidal Flat Dynamics: A Case Study of Three Highly Urbanized Coastal Counties in the Southeastern United States

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Abstract: Tidal flats are widely recognized as sentinels of coastal environment change, and are also the guardians for beachfront communities. As a result of urban expansion, tidal flats have increasingly received environmental pressures and the surrounding ecosystem has been functionally downgraded. However, the existing studies could not provide an effective method to identify and quantify the interactions between urban areas and tidal flats, which is essential work particularly for the coastal preservations in the United States. Aiming at this environmental crisis, we proposed an approach which quantifies the change patterns from a spatiotemporal perspective. To justify the rationality and feasibility of this approach, this study selected three highly urbanized coastal counties in the southeastern United States as the study area. We analyzed the annual dynamics during 1985~2015, and the generated spatiotemporal regularities were used to identify and quantify the correlations between urban expansion and tidal flat dynamics. This study not only justified that the coastal urban expansion could considerably damage the environment of tidal flats, but also verified an effective approach to investigate the correlations between urban expansion and tidal flat loss on a large spatiotemporal scale.

Keywords: tidal flats; urban expansion; spatiotemporal correlation; coastal environment; land cover transition

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1. Introduction

The sediment-rich environments along the coast, which are dominated by tidal ranges and other hydrodynamic forces, are also known as tidal flats [1,2]. As the buffer zone between land and sea, tidal flats can largely attenuate the destructive forces from the ocean, which greatly protects the beachfront communities from hurricanes, tsunamis, and flooding [3,4]. Being the natural transitions between ocean and terrestrial ecosystems, tidal flats are also featured by temperature, salinity, acidity, and other physical or chemical conditions [5], and consequently become the homeland of a variety of species, including but not limited to shorebirds [6], fungus [7], plankton [8], and coastal fish [9]. Regarding the issue of climate change, tidal flats also play an important role in the prevention of global warming, because they have strong potential in carbon capture and storage [3]. For coastal residents, tidal flats also have tremendous economic importance because they provide favorable environments for fisheries [10] and aquaculture [11]. However, the environments of tidal flats are facing unprecedented challenges due to the intensification of human activities. On a global scale, tidal flats had lost 16.02% from 1984 to 2016 [12], which is about 20,000 km^2. In the conterminous United States (US), the constant shrinkage of tidal flats has irreversibly changed the coastal environment [13].

The conflict between human beings and the coastal environment urgently calls for public awareness, as well as effective collaborations between lawmakers, scientists, and local authorities. In particular, urban expansion is regarded as one of the major anthropogenic threats to the environment of tidal flats. According to a recent study [14], a total of 14 km^2 tidal flats in the Zhoushan Archipelago, China were urbanized during 1986 to 2017, which contributed 4% of the urban growth during that period. Another study of Zhuhai, China [15] observed a more serious environmental crisis around the big city: tidal flats decreased by 67.2% during 1991~2018, which is about 19.3 km^2, due to the rapid expansion of urban areas. While the two studies have comprehensively examined a variety of land sources for urban expansion, they both lack the focus on the spatiotemporal change patterns exclusively between new urban areas and tidal flats. Indeed, it is worthwhile to further investigate this issue: as the counterforce of the damaged environment, natural hazards pose risks to the coastal communities, and the highly populated urban areas are especially more vulnerable [16].

Meanwhile, some scientists notified the environmental degradation of tidal flats due to human activities, and accordingly contributed innovative studies to visualize this crisis by utilizing geospatial methods. For example, Li et al. (2020) [17] used Google Earth Engine (GEE), a high-performance geospatial cloud computing platform [18], to implement an assessment of tidal flat loss in the Yangtze River Delta, China from 1974 to 2018. In addition to land reclamation, the study found that the reduced sediment supply could also cause large-scale losses of tidal flats. The supply of sediments in this area is heavily driven by the hydrodynamic regime [19], which could be greatly modified by navigation projects and other artificial constructions [17]. On the other hand, the study of the Yellow River Delta, China [20] confirmed that industrial equipment and facilities, such as oil bumps, are tremendously destructive to tidal flats in the surrounding areas. The above studies verified that human activities could indirectly affect the environments of tidal flats; however, the direct interactions between urban areas and tidal flats could barely be observed, since the large clusters of tidal flats are far from the major cities in these two regions. Therefore, it is necessary to select a better place to conduct the study, where both the direct and indirect interactions between urban areas and tidal flats can be clearly observed and analyzed.

In addition, a couple of studies should be highlighted, since they both provide substantial and insightful discussions regarding the land cover conversions from tidal flats to urban areas. The case study in Zhoushan Island, China [21] monitored the urbanization process and mechanism during 1995~2011, through which they found significant urban encroachment on tidal flats (10.6 km^2). Accordingly, the study utilized numerous factors to evaluate the ecological consequences, including net primary productivity, carbon sequestration and oxygen production, nutrient cycling, crop production, and habitat quality. On the other hand, the case study of Singapore [22] found that tidal flats had reduced from 33 km^2 (in 1922) to 8 km^2 (in 1993), and further dropped to 5 km^2 (in 2011). With respect to the reclamation plan as well as the spatial distribution of existing tidal flats, the authors projected the degradation of coastal ecosystems in three forms: (1) shrinking area, (2) increasing fragmentation, and (3) encroachment by urban expansion. Apparently, the core concepts of these two studies are ecological projections and sustainable planning, while the spatiotemporal analyses for the interactions between tidal flats and urban area are relatively weak.

More importantly, the existing studies are limited to the individual cities, which could not draw a picture to visualize and analyze the land cover conversions at the nationwide level. In addition, these studies mostly focused on Asian cities, which may not be applied to the rest of world due to the differences in socioeconomic and natural backgrounds. It is worthwhile to implement follow-up studies for the US, since it has the eighth longest coastline in the world [23]. Furthermore, nearly a quarter (24.92%) of the nation's population lives in the 100 most densely populated counties of the conterminous coastal US [24], which only contributes 2% of the nation's total area. The high population density aggravates the conflicts between humans and the environment, which poses a critical challenge to the sustainable developments in coastal areas.

Regarding these knowledge gaps, the objectives of this study are to propose and verify an effective approach, which could identify and quantify: (1) the spatiotemporal change patterns of urban areas and tidal flats; and (2) the correlations between them. The details of implementations are demonstrated in Section 2, and the generated results are illustrated in Section 3. Finally, we explore the information behind the identified results, discuss the environmental consequences and possible solutions, and determine the details of future works in Section 4.

2. Materials and Methods

2.1. Study Area

In this study, three highly urbanized coastal counties were selected to test the proposed framework, which will lay a solid foundation for the spatiotemporal assessments throughout the whole country. As illustrated in Figure 1, the three selected counties are in the southeastern US, including Charleston County in South Carolina (Charleston, SC), Chatham County in Georgia (Chatham, GA), and Duval County in Florida (Duval, FL). According to the official census results in 2020 [24], there were 350,209 residents in Charleston, SC, 265,128 residents in Chatham, GA, and 864,263 residents in Duval, FL, which makes them the third, fifth, and seventh most populated counties of their home states. All three counties are seated in the major cities of this region (Charleston, Savannah, and Jacksonville), so the intensified human activities would unavoidably affect the coastal environments. Under such circumstances, urban wastes [25] and groundwater extraction [19] have been confirmed as destructive powers which may undermine the ecological functionalities of the surrounding areas. Particularly, the new urban areas bring in unprecedented environmental pressures to the local environment, which needs to be profoundly explored and discussed.

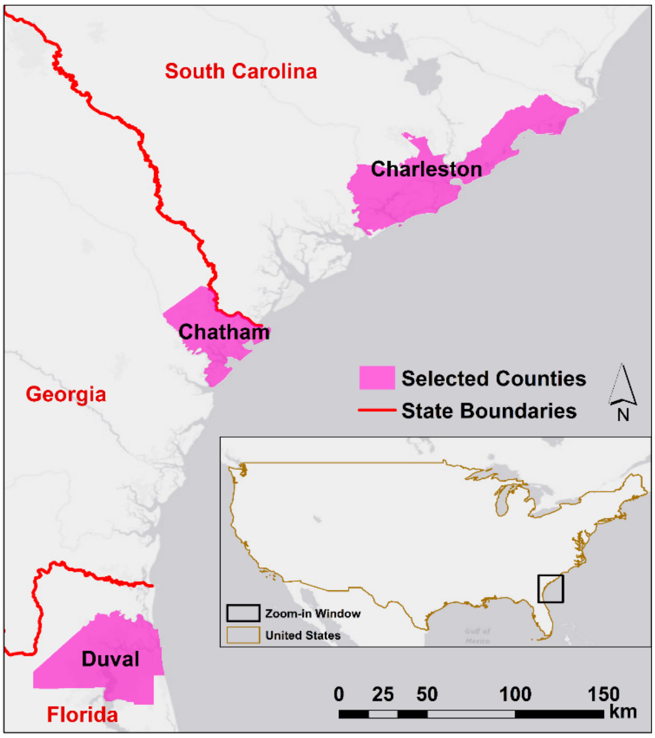

Figure 1. The study area consists of three coastal counties in the southeastern US, which are Charleston, SC, Chatham, GA, and Duval, FL. (The World Light Gray Basemap is used as the background, which is provided by Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS User Community.)

In addition, the three selected counties are located along the coast with unique environmental settings: a tidal flat system of more than 3168 km^2 from South Carolina to the northeastern corner of Florida [26], which is characterized by numerous sounds, estuaries, as well as the twice-daily ebb and flow of the tides [27]. According to Peel et al. (2007) [28], the entire study area is classified as a humid subtropical climate zone. With the abundant precipitation, the interaction between groundwater and tidal flats can be very active, which directly impacts the local ecosystem and the daily lives of coastal residents [29]. The unique environments make the three counties ideal places to identify and quantify the spatiotemporal change patterns of urban area and tidal flats, as well as the interactive dynamics between them.

2.2. Data

One primary dataset used in this study is a 30 m annual map collection of urban extents in the conterminous US from 1985 to 2015 [30]. Around 460,000 Landsat images were used in that study, which were preprocessed and segmented into four groups according to the year of acquisition (1985~1992, 1992~2001, 2001~2011, and 2011~2015). The National Land Cover Database (NLCD) [31,32] archives the land cover maps in different periods throughout the US, which provides worthwhile references for urban mapping before 2011. Additionally, the potential urban clusters after 2011 were delineated according to a set of nighttime light images given by the Visible Infrared Imaging Radiometer Suite [33]. For each one of the four groups, a temporal segmentation approach [34] was applied to the time series dataset of Landsat images, which delineates the pixels with respect to the year of urbanization. Acknowledging the limitations of NLCD availability, a hierarchical strategy was developed to implement a change vector analysis, which delineates the urbanized areas at the cluster level throughout the entire study period. Finally, the proposed framework was realized through GEE, and the mapping products obtained a satisfactory overall accuracy (around 90%, with the 1-year tolerance strategy) [35].

The second primary dataset is a 30 m annual map collection of tidal flat areas in the conterminous US from 1984 to 2020 derived from the authors' previous study [13], and the map frames from 1985 to 2015 are used in this study. A random forest classification model was proposed based on the spectral change patterns of satellite images, which was quantified by 30 predictor variables. In addition, the sample points under five classes (permanent water, tidal flats, barren grounds, vegetated lands, and artificial surfaces) were collected as the ground truth data, which were used for training the classification model and validating the resultant maps. Finally, the proposed model was realized through GEE, which produced the annual maps of tidal flats with an acceptable overall accuracy (84.4%). To improve the reliability, it is necessary to postprocess the tidal flat mapping product in two aspects. First, the unlikely tidal flats in waterbodies should be masked by the Global Surface Water dataset [36]. This dataset was derived from the Landsat 5, 7, and 8 images acquired between 1984 and 2020, and provides a global map of the water occurrence with the spatial resolution of 30 m. Every pixel on this map has an integer value (water frequency) between 0 and 100, and the tidal flat pixels falling within 98 or higher-scored areas should be masked since they are considered as permanent water [13]. Furthermore, the annual map collection of urban extents [30] was used to mask the unlikely landward tidal flats in the corresponding years.

Aside from the two primary datasets, this study used a shoreline shapefile provided by the National Oceanic and Atmospheric Administration [37] to create a two-sided distance buffer of 2 km along the coast (coastal buffer for short). With this buffer, it was easier to identify, quantify, and analyze the interactive dynamics between urban areas and tidal flats.

2.3. Methods

A workflow was proposed to implement the research tasks in this study (Figure 2). As mentioned, the unlikely tidal flat pixels are masked by two datasets, which are Global Surface Water and Urban Extents. The preprocessed dataset of tidal flat distribution, as well as the dataset of urban extents, were used for spatiotemporal assessments. In particular, the coastal buffer was used to capture the spatiotemporal change patterns near the seashore.

As we generated the spatiotemporal patterns of urban expansion and tidal flat dynamics, we could further explore the interactions between them. The details of implementation are as follows.

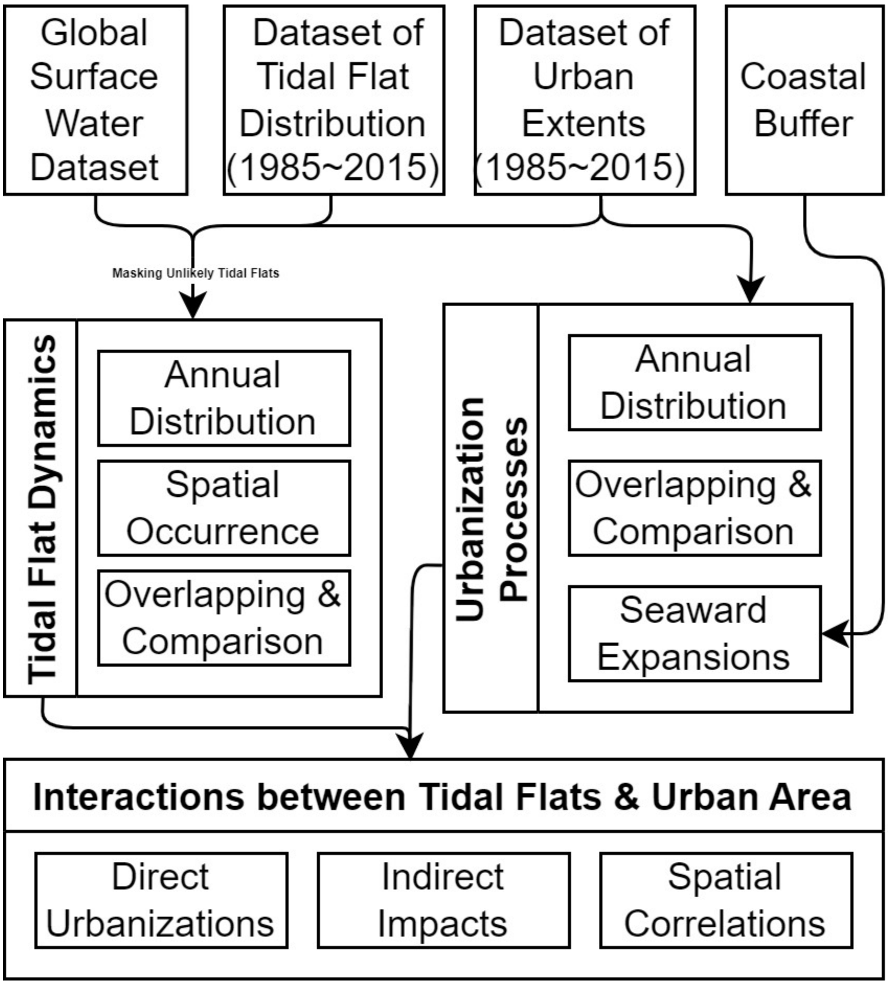

Figure 2. The overall framework for analyzing the spatiotemporal dynamics of tidal flats and urban extents, as well as the interactions between them, from 1985 to 2015.

2.3.1. Tidal Flat Dynamics

The spatiotemporal assessments for tidal flat dynamics were conducted from three aspects, including annual distribution, spatial occurrence, and overlapping comparison. To better observe the spatial distribution patterns on the map, the pixel values were converted to area (in km^2) and summarized by longitudes and latitudes, which were visualized as line charts along map edges (map-edge summary for short). The details are as follows.

1. Annual distribution: As a preliminary consideration of dynamic analysis, it is necessary to summarize the temporal change patterns of tidal flat areas. The data were organized by year and county, then illustrated as line chart. Based on this chart, we observed the evolutionary trends and the years of significantly larger or smaller areas than the subsequent years. Accordingly, the further explorations were conducted by referencing the related studies, which explains the geographical backgrounds behind the identified temporal change patterns in each county.
2. Spatial occurrence: Another preliminary consideration is to map the distribution of tidal flats in the three counties. Every county has 31 annual maps (binary images) of tidal flats from 1985 to 2015, where the raster value of 1 represents tidal flats and the raster value of 0 represents non-tidal flats. The Raster Calculator provided by ArcGIS was used to sum up all these binary images, which derives the occurrence map of

tidal flats. On the generated map, the pixel values vary from 0 (without occurrence) to 31 (always occurrence), which visualizes the spatial patterns of tidal flat distribution during the three decades [13,38,39]. Additionally, the pixel values were divided by 31 and visualized as map-edge summaries, which gives the annual average area of tidal flats with respect to longitudes and latitudes. Accordingly, we found the peaks from these map-edge summaries, which highlights the locations and quantifies the intensities of tidal flat clusters.

3. Overlapping and comparison: An in-depth inspection of spatiotemporal dynamics was given by overlapping and comparing the maps of tidal flats in the subsequent years [13,39]. A total of 30 comparison results were generated from the annual maps from 1985 to 2015, where tidal flat pixels in the previous year appearing as non-tidal flat pixels in the latter year were regarded as erosions, and accretions in the reverse cases. In addition, the pixels appearing as tidal flats in two consecutive years were considered as preservations. The results of this comparison were summarized as bar charts, in which the annual areas of the three events (erosion, accretion, and preservation) were separately visualized and analyzed. Additionally, this comparison was conducted between the annual maps of every ten years (1985 vs. 1995, 1995 vs. 2005, and 2005 vs. 2015), and the spatial distribution of the areas of the three events were visualized on maps. Likewise, the spatial patterns given by the generated maps were displayed as map-edge summaries, in which the accretions contribute to positive values, and the erosions contribute to negative values, and the preservations correspond to zeroes.

2.3.2. Urbanization Processes

Meanwhile, the procedure of urban expansion from 1985 to 2015 also needed to be inspected, which was conducted from both temporal and spatial perspectives. Particularly, we are interested in the urban expansions near the seashore, which calls for an extra assessment. The details are as follows.

1. Annual distribution: Likewise, the temporal analysis of urban expansion was based on a line chart, which summarizes the urban area by year and county. Accordingly, we identified the periods of rapid developments in every single county and compare the urban expansion rates between different counties.
2. Overlapping and comparison: To visualize the spatial distribution of urban expansion, an overlapping comparison was conducted between the annual maps of urban extents in every ten years (1985 vs. 1995, 1995 vs. 2005, and 2005 vs. 2015). The result was labelled in different colors with respect to the ten-year windows, which allows to find the new urban areas of different periods. Additionally, the new urban areas of different ten-year windows were quantified by the map-edge summaries, in which the peaks identify the intensive urbanizations during the corresponding periods.
3. Seaward expansions: Aiming at the nearshore zone, an extra assessment was conducted which summarizes the temporal patterns of the urbanization process in the three counties. For every county, the coastal buffer was applied to the 31 annual maps of urban extents, which derives the newly urbanized lands in every year within the three decades. These new urban areas are regarded as seaward expansions, which were summarized as a line chart with respect to year and county. It highlights the rate of urbanization on or adjacent to the coast, which further provides a reference for the assessments of interactions between urban areas and tidal flats.

2.3.3. Interactions between Tidal Flats and Urban Areas

The urbanization in the nearshore zone poses a critical challenge to the environment of tidal flats, which not only occupies the ecological space (direct impact) but also jeopardizes the surrounding area (indirect impact). Thus, the interactions between urban areas and tidal flats were assessed from two aspects, including the direct urbanizations and indirect impacts. In addition, it is necessary to visualize the clusters of new urban areas and tidal flat losses on the maps, which helps to understand the spatial correlations between them. The details are as follows.

1. Direct urbanizations: From the results of overlapping comparisons in Section 2.3.1, we extracted the tidal flat erosions by year and county. For every year, we found the overlaps between the new urban areas and tidal flat erosions, which refer to the direct urbanizations on tidal flats. The results were organized by year and county, and then summarized as a table.
2. Indirect impacts: Based on the maps of seaward expansions (Section 2.3.2), we created the buffers of different distances (200 m, 500 m, and 1 km) around the new urban areas. The three distance buffers were applied to the map of tidal flat erosions in the corresponding year, which generated the area of erosions with respect to the distance to the new urban areas. The result was organized by year and buffer zone (within 200 m, 200 to 500 m, and 500 m to 1 km), which was visualized as line charts and used to quantify the indirect impacts on the surrounding areas.
3. Spatial correlations: In this part, we implemented two overlapping comparisons between the maps in the initial year (1985) and latest year (2015). The first comparison was for tidal flats, and the second one was for the urban extents. Again, we are only interested in the nearshore zones, so the coastal buffer wase applied to the urban extents and extracted the seaward expansions during the three decades. The two results of overlapping comparisons were visualized on the maps, from which we observed the spatial correlations between the clusters of new urban areas and tidal flat losses. In addition, there was a pair of parallel map-edge summaries: one was for the seaward urban expansions, and another one was for the area changes of tidal flats.

3. Results

3.1. Tidal Flat Dynamics

The temporal changes of tidal flat areas in the three counties are summarized and visualized in Figure 3. Apparently, Charleston, SC, has the largest tidal flats (544.87 km^2 on annual average), followed by Chatham, GA (343.46 km^2 on annual average), and Duval, FL (89.49 km^2 on annual average). The ratio of the standard deviation to the mean, which is also known as the coefficient of variation (CV), is used to evaluate the degree of fluctuation. In this regard, the tidal flat areas in Charleston, SC (CV = 0.079), and Chatham, GA (CV = 0.084) are much more stable than that in Duval, FL (CV = 0.281). In particular, Figure 3 shows that Charleston, SC, in 1992 and 2003, Chatham, GA in 1992, and Duval, FL, in 1992 and 1994 had unusually low areas of tidal flats. Moreover, the tidal flats in all three counties demonstrated significant trends of shrinkage from 2005 to 2015 (p-values < 0.05), as verified by Mann–Kendall test [40,41].

The results of overlapping comparison, which details the areas of three events by year and county, are provided in Figure 4. Regarding the annual average areas of erosion, preservation, and accretion, it follows the ratios of 21:100:20 in Charleston, SC, 17:100:16 in Chatham, GA, and 52:100:48 in Duval, FL. Compared with the other two counties, Duval, FL, demonstrates outstandingly larger area shares of erosion and accretion. On the other hand, the area of preservation in Duval, FL (CV = 0.345), is significantly less stable than those in Charleston, SC (CV = 0.096), and Chatham, GA (CV = 0.099). The results of overlapping comparison echo the findings from Figure 3, which confirms that Duval, FL, has exceptionally higher active tidal flats than the two other counties. Another interesting finding is that, in every individual county, the area shares of accretion and erosion are considerably close to each other. This means that the accretion and erosion in the early years would be greatly offset by the erosion and accretion in the following years, and therefore would not significantly impact the overall area of tidal flats for a long period of time.

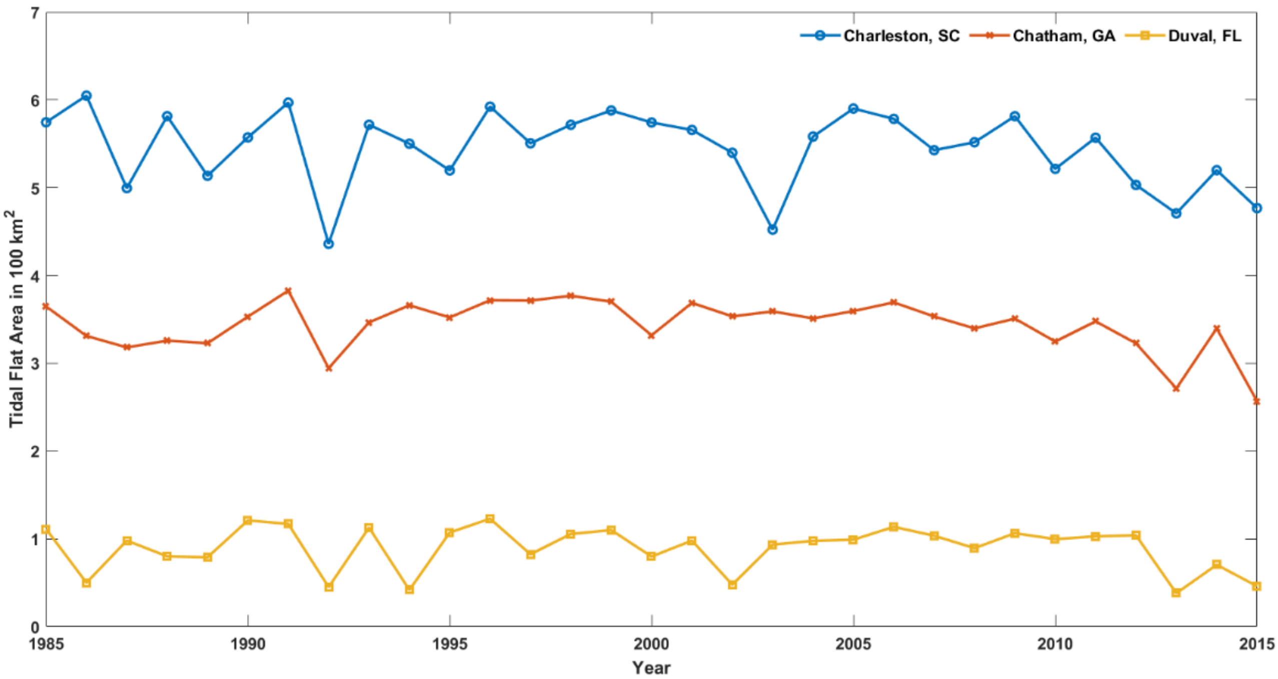

Figure 3. The annual distribution of tidal flat area in the three counties.

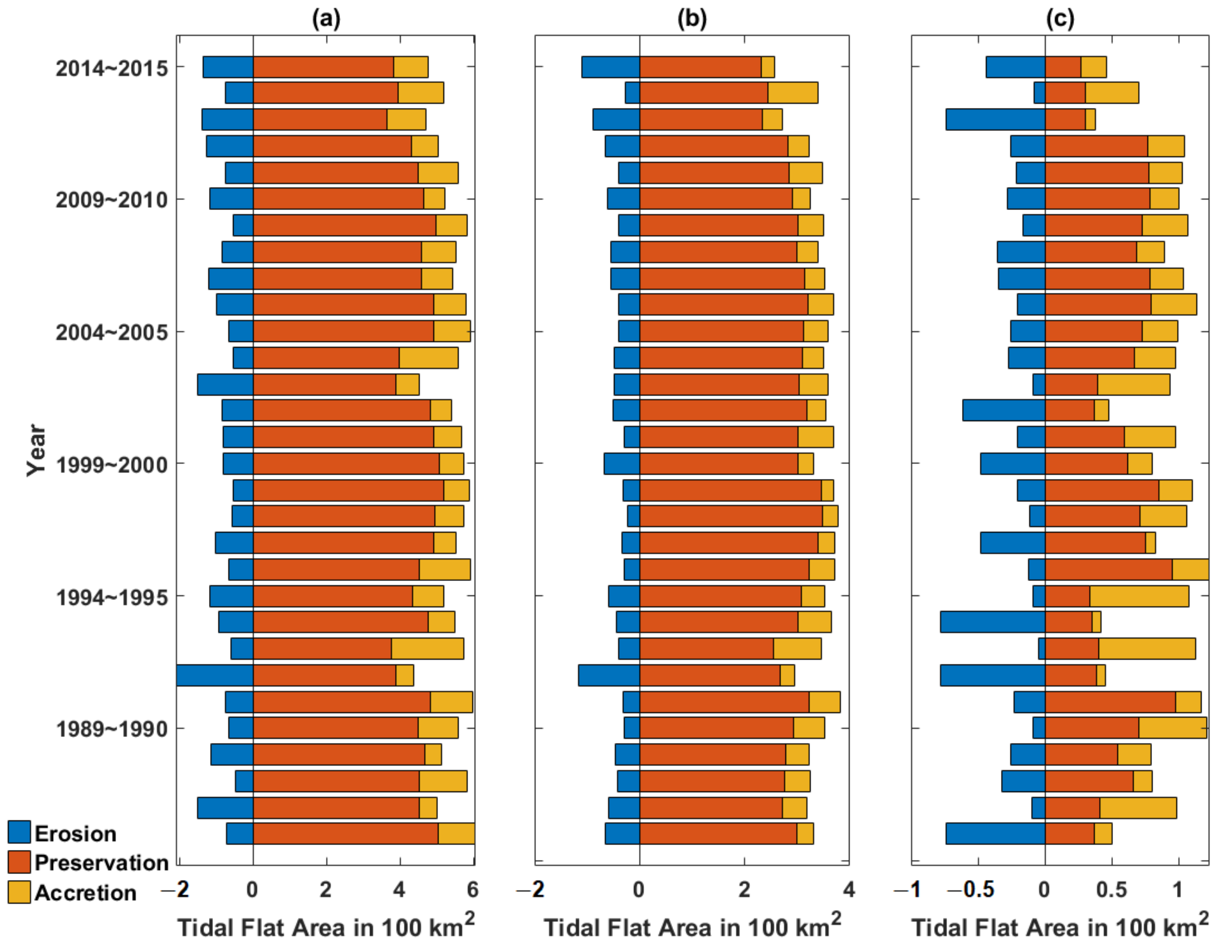

Figure 4. The annual distribution of tidal flat erosion, accretion, and preservation areas in (**a**) Charleston, SC; (**b**) Chatham, GA; and (**c**) Duval, FL.

The occurrence maps of tidal flats in the three counties, as well as the longitudinal and latitudinal summaries of annual average area, are illustrated in Figure 5. According to the maps, the clusters of tidal flats are not only well distributed along the coast, but also extended to the inlands along with the sinuous rivers. The longitudinal and latitudinal summaries suggest that tidal flats are intensively distributed in Charleston, SC, and Chatham, GA (line chart peaks reach up to 20 km^2), while the distribution in Duval, FL, is less intensified (line chart peaks reach up to 10 km^2). On the other hand, the mean durations of tidal flats in Charleston, SC (20.66 years), and Chatham, GA (22.04 years) are significantly longer than that in Duval, FL (15.32 years). Regarding the frequency, the most common values in Charleston, SC, and Chatham, GA, are both 30 years, while it is 1 year in Duval, FL. The tidal flats in Duval, FL, demonstrate shorter durations and more active dynamics than the two other counties, which is consistent with the findings from Figures 3 and 4.

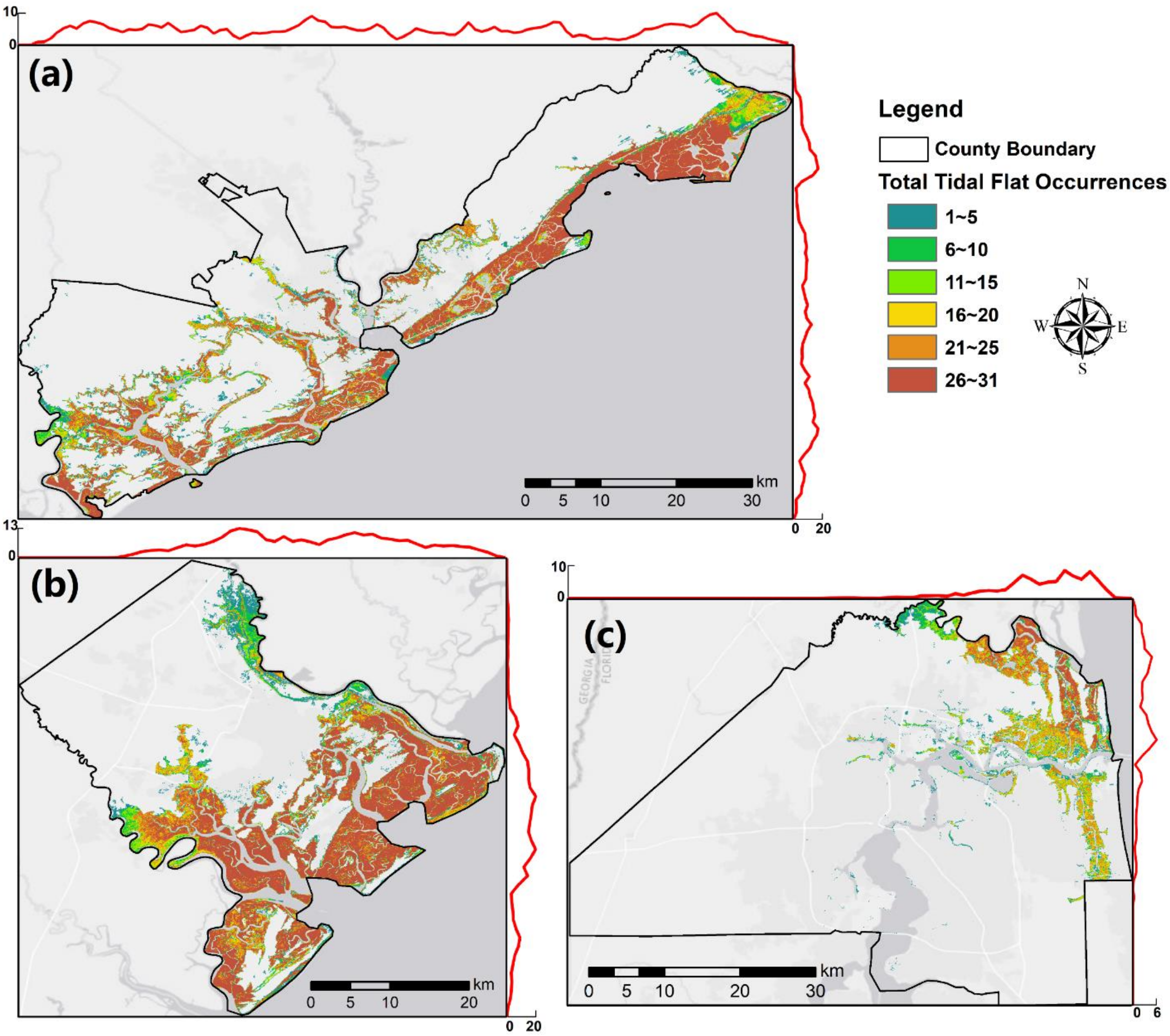

Figure 5. The spatial distribution of total tidal flat occurrences (in year) in (**a**) Charleston, SC; (**b**) Chatham, GA; and (**c**) Duval, FL. The annual average areas (in km^2) summarized by latitudes and longitudes are visualized as line charts along map edges. (The World Light Gray Basemap is used as the background, which is provided by Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS User Community.)

The results of overlapping comparisons between the tidal flat maps of every ten years are given in Figure 6. In Charleston, SC, the areas of preservation are 440.87 km^2 from 1985 to 1995, 439.70 km^2 from 1995 to 2005, and 414.47 km^2 from 2005 to 2015. The area of preservation contributes the largest portion of this county, and therefore the maps in

Figure 6a–c are overwhelmingly covered by orange color. In the same county, the areas of erosion are 133.63 km^2 from 1985 to 1995, 79.94 km^2 from 1995 to 2005, and 175.65 km^2 from 2005 to 2015, while the areas of accretion are 78.77 km^2 from 1985 to 1995, 150.42 km^2 from 1995 to 2005, and 62.23 km^2 from 2005 to 2015. Therefore, the dynamics during the period of 1985~1995 and 2005~2015 are dominated by erosions, while the period of 1995~2005 is a recovery process dominated by accretions. The southwestern portion of the county, which is featured by the network of the river and creeks, is a typical area that experienced this erosion–accretion–erosion procedure. As shown in the line chart, this area corresponds to the major valleys in Figure 6a,c, while contributes the major peaks in Figure 6b. Another active area is the northeastern portion in this county, which had significant erosions during the period of 2005~2015 and contributes major valleys in the line charts of Figure 6c (-4 km^2 in the longitudinal summary and -5 km^2 in the latitudinal summary).

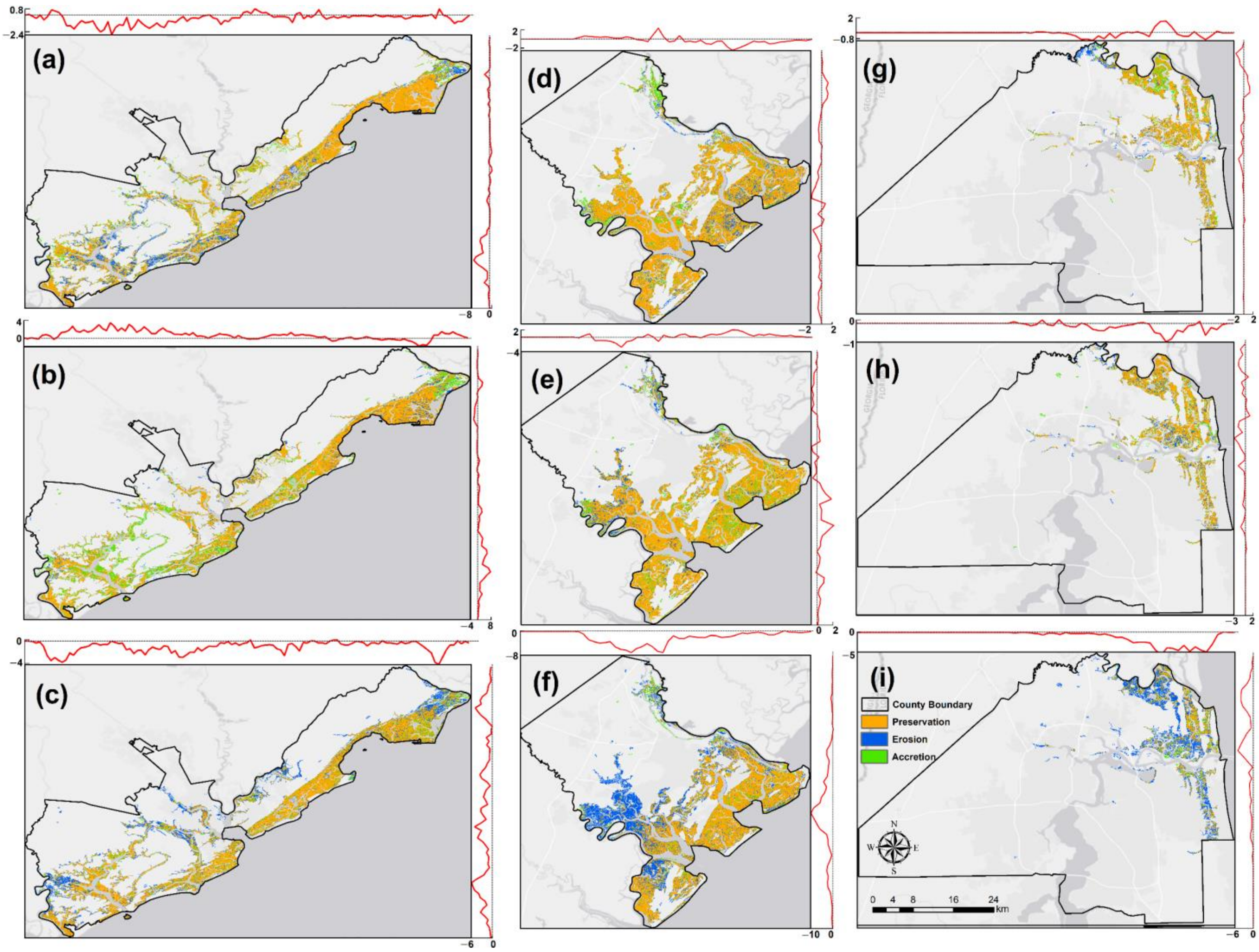

Figure 6. The spatial distribution of tidal flat area changes in Charleston, SC (**leftmost column**), Chatham, GA (**middle column**), and Duval, FL (**rightmost column**), between 1985 and 1995 (**top row**); 1995 and 2005 (**middle row**); and 2005 and 2015 (**bottom row**). The area changes (in km^2) summarized by latitudes and longitudes are visualized as line charts along map edges. (The World Light Gray Basemap is used as the background, which is provided by Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS User Community.)

The tidal flats in the two other counties were in stable states during the periods of 1985~1995 and 1995~2005, and therefore the tidal flat areas in Figure 6d,e,g,h are dominantly colored in orange (preservation). However, both counties have significant clusters of erosions during the period of 2005~2015, as illustrated by Figure 6f,i. During this period, the erosions in Chatham, GA, are intensively distributed around the upper reaches of the river and creeks. Likewise, the landward portion of tidal flats in Duval, FL, had experienced a significant shrinkage from 2005 to 2015. The intensive erosions in the inland area during the recent years is a warning sign of environmental crisis, which is a focus in the following discussions.

3.2. Urbanization Processes

The temporal dynamics of urban expansion in the three counties are summarized and visualized as Figure 7. The largest urban area belongs to Duval, FL, which is tremendously larger than the urban areas in two other counties. However, Chatham, GA, observes the fastest expansion throughout the three decades (34.13%), followed by Charleston, SC (26.65%), and Duval, FL (23.45%). The further observation focuses on the average annual expansions, which identifies the fastest consecutive expansions in every individual county. The result shows that Charleston, SC, has experienced the fastest expansion from 2002 to 2007, with the annual average rate of 1.10%. Similarly, the fastest consecutive expansions in the two other counties occurred between 2002 and 2008, which are, on annual average, 2.12% in Chatham, GA, and 1.20% in Duval, FL.

The overlapping comparisons were conducted based on the urban maps of every ten years, and the results are illustrated in Figure 8. All three counties have considerably large area of urbanized lands in the starting year (1985), which is surrounded by small land patches urbanized in the following three decades. Compared with the first decade, the two later decades demonstrate higher peaks in the line chart summaries, which is consistent with the findings from Figure 7 and confirms that all three counties have experienced an unprecedented rapid progress of urban expansion. Apparently, the newly urbanized lands in Chatham, GA, are intensively distributed on the inland side, and Duval, FL, also has considerably urbanized the inland area during the three decades. However, there are still some new urban areas located within the nearshore zone, including the northeast side of Charleston, SC, southwest side of Chatham, GA, and east side of Duval, FL. These newly urbanized land patches are small but not negligible, because they may directly impact the environment and distribution of tidal flats.

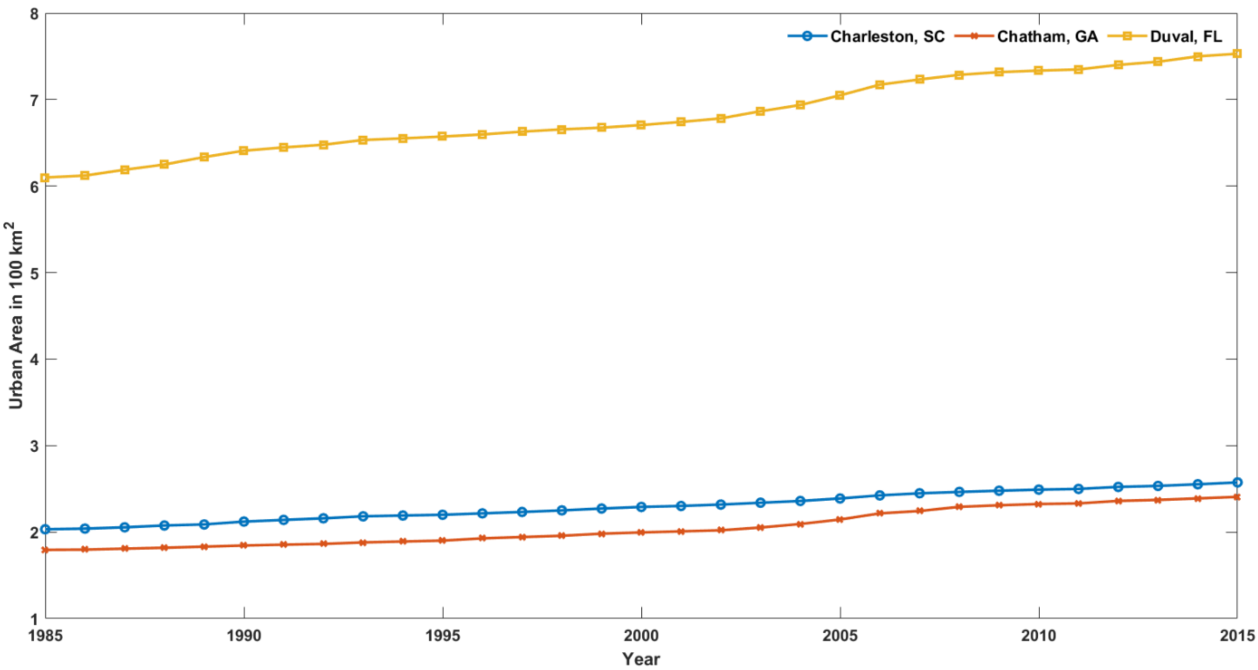

Figure 7. The annual distribution of urban area in the three counties.

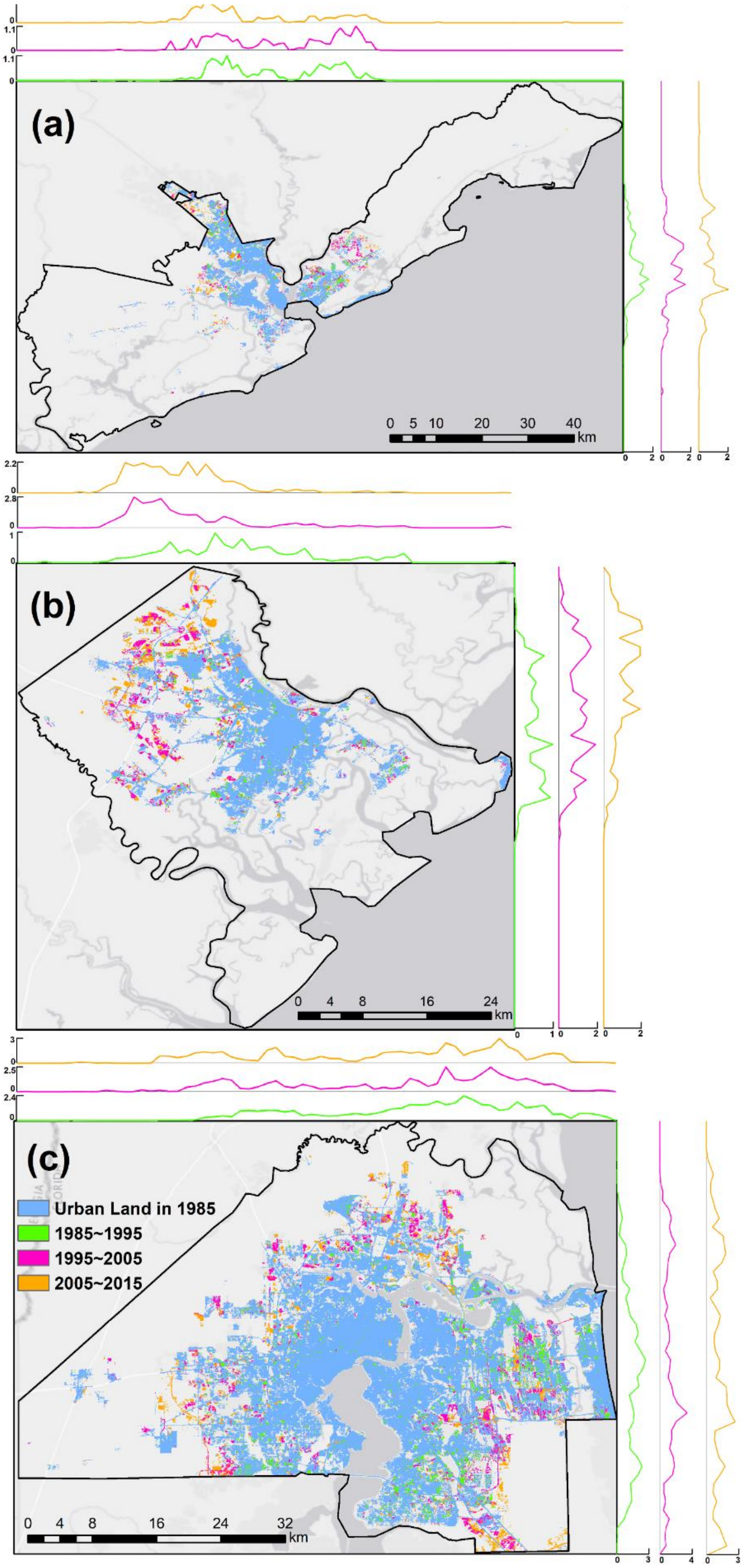

Figure 8. The spatial distribution of urban expansion in (**a**) Charleston, SC, (**b**) Chatham, GA, and (**c**) Duval, FL, between 1985 and 1995 (green); 1995 and 2005 (pink); and 2005 and 2015 (orange). The area changes (in km^2) summarized by latitudes and longitudes are visualized as line charts along map edges. (The World Light Gray Basemap is used as the background, which is provided by Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS User Community.)

To better quantify the process of urbanization within the nearshore zone, the coastal buffer was applied, and the newly urbanized area in the three counties are summarized and illustrated in Figure 9. Regarding the total area of newly urbanized lands, Duval, FL, contributes the largest share throughout the three decades (43.66 km^2), followed by Charleston, SC (32.13 km^2), and Chatham, GA (15.29 km^2). While the highest peak in Duval, FL, falls between 1986 and 1990, the sped-up progress from 1998 to 2006 indicates a more intensive urbanization and therefore attracts greater attention. Meanwhile, Charleston, SC, and Chatham, GA, also demonstrate long-lasting peaks from 2000 to 2006, which confirms a rapid and consecutive development within the coastal area of both counties.

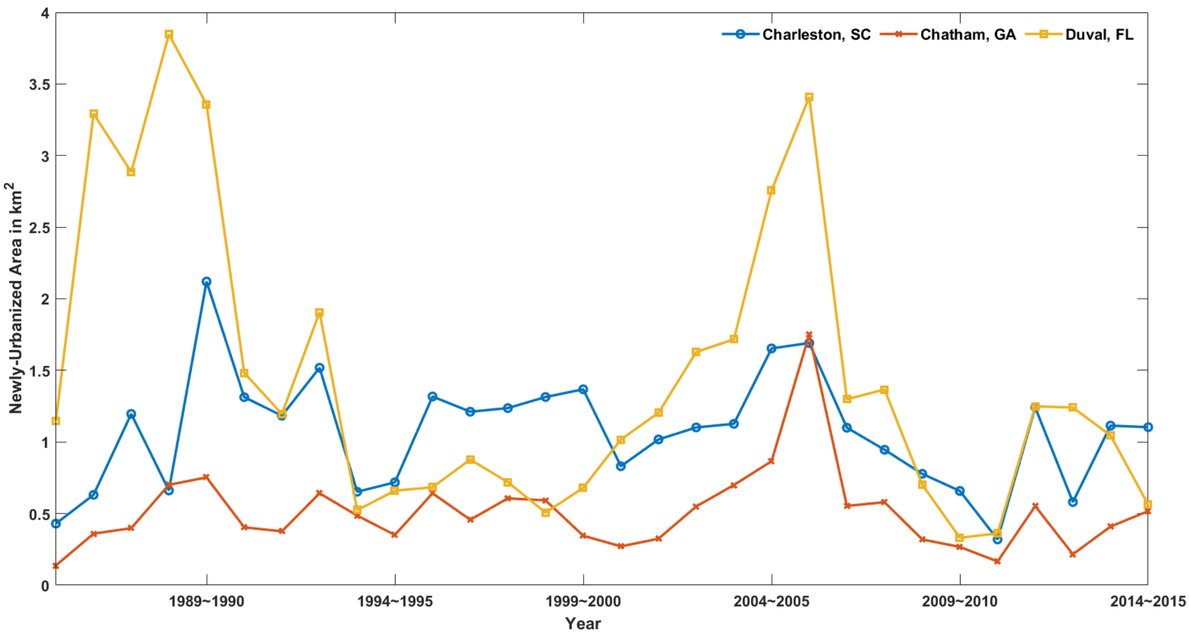

Figure 9. The annual distribution of newly urbanized lands which locate within 2 km of the coast in the three counties.

3.3. Interactions between Tidal Flats and Urban Areas

Since a tidal flat is an important land source for urban expansion, we summarized the details by year and county, and the results are given in Table 1. Regarding the information given by Figure 9, it turns out that tidal flat had contributed considerable shares of land for urban expansion throughout the three decades, which are 30.47% in Charleston, SC, 39.90% in Chatham, GA, and 22.12% in Duval, FL. Particularly, tidal flats had contributed more than half of the lands for new urban areas during 2010~2011 in all three counties, which are 70.42% in Charleston, SC, 77.17% in Chatham, GA, and 55.22% in Duval, FL. According to Table 1, there are three unusually high records in Charleston, SC, which correspond to the periods of 1986~1987, 1991~1992, and 1995~1996. In particular, 97.86% of the new urbans were derived from tidal flats during the first period (1986~1987), which is the greatest single-year contribution throughout the three decades. The other two periods also observed considerable shares of tidal flat contributions, which are 51.41% during 1991~1992, and 51.37% during 1995~1996. As mentioned, the highest contribution by tidal flats occurred in Chatham, GA, and Table 1 shows a stable rate of tidal flat urbanization during the three decades (CV = 0.422). In particular, there are five periods in which tidal flats have more than two-thirds of the contribution to new urbans, which are 1985~1986 (86.93%), 1991~1992 (80.38%), 1994~1995 (90.51%), 2010~2011 (77.17%), and 2012~2013 (89.58%). By contrast, Duval, FL, has the least stable rate of tidal flat urbanization among the three counties (CV = 0.571), with the peaks during 1985~1986, 1991~1992, and 2011~2012 emphasizing the rapid expansion of urban area towards the shoreline.

Table 1. The annual distribution of newly urbanized tidal flats in the three counties (in km^2).

Current Year [1]	Charleston, SC	Chatham, GA	Duval, FL
1986	0.24	0.12	0.47
1987	0.62	0.04	0.08
1988	0.14	0.14	0.18
1989	0.25	0.14	0.17
1990	0.16	0.11	0.12
1991	0.23	0.11	0.35
1992	0.61	0.30	0.46
1993	0.03	0.18	0.03
1994	0.31	0.21	0.32
1995	0.09	0.32	0.05
1996	0.68	0.11	0.13
1997	0.18	0.12	0.31
1998	0.14	0.14	0.07
1999	0.17	0.18	0.24
2000	0.17	0.11	0.15
2001	0.25	0.14	0.17
2002	0.35	0.11	0.32
2003	0.18	0.29	0.04
2004	0.11	0.19	0.14
2005	0.19	0.15	0.38
2006	0.40	0.26	0.18
2007	0.38	0.19	0.31
2008	0.31	0.20	0.26
2009	0.21	0.16	0.17
2010	0.20	0.10	0.17
2011	0.23	0.13	0.20
2012	0.28	0.19	0.23
2013	0.35	0.19	0.45
2014	0.23	0.07	0.15
2015	0.49	0.31	0.15

[1] The period of annual comparison is between the current year and its previous year.

The area of tidal flat erosion was classified by the distance to new urban areas, and then we calculated the area ratios of tidal flat erosions to the corresponding distance buffers, which is known as the intensity of erosion. The result was further summarized by year, and then visualized as Figure 10. Throughout the three decades, the overall intensity of erosion within 200 m, 200 to 500 m, and 500 m to 1 km are 2.52%, 1.95%, and 1.59%, which suggests that farther places from the new urban areas have lower intensified erosion of tidal flats. On the other hand, the Person's test [42] verified the high correlations between the results within the 200 m buffer and 200 to 500 m buffer (r = 0.932), as well as the 200 to 500 m buffer and 500 m to 1 km buffer (r = 0.910). These strong correlations further endorsed the regularity between distance and intensity, since it works for different urbanization patterns in different years.

The results of overlapping comparison within the coastal buffer, which gives the area changes of tidal flats and urban areas during the three decades, are visualized in Figure 11. In Charleston, SC (Figure 11a), the newly urbanized lands are intensively distributed in the middle part of the county, which corresponds to the eastern and western wings of the City of Charleston. The intensified urban expansion results in the peak up to 2 km^2 in the longitudinal summary, as well as the peak up to 4 km^2 in the latitudinal summary. The cluster of tidal flat erosions is also identified from the same area, which corresponds to the valley up to -2 km^2 in the longitudinal summary, and the valley up to -2 km^2 in the latitudinal summary. Likewise, the new urban areas in Chatham, GA (Figure 11b), are distributed along the north, east, and south edges of the City of Savannah. In particular, the new urban areas on the southern side of the city contribute a peak up of 1 km^2 to the longitudinal summary, as well as a peak of 2 km^2 in the latitudinal summary. Meanwhile, a huge cluster of tidal flat erosion appears at the center of the map, which greatly overlaps the new urban areas and corresponds to the major valleys in both longitudinal (up to -8 km^2) and latitudinal (up to -10 km^2) summaries. Compared with the two other counties, Duval, FL (Figure 11c), is a more typical case of land interactions between tidal flats and urban areas. It has numerous new urban patches distributed around the river estuary and seaside, which heavily overlap the erosions of tidal flats. As a result, the estuary area corresponds to the major valleys in the summaries for tidal flats (up to -5 km^2), as well as the major peaks in the summaries for urban areas (up to 2.5 km^2).

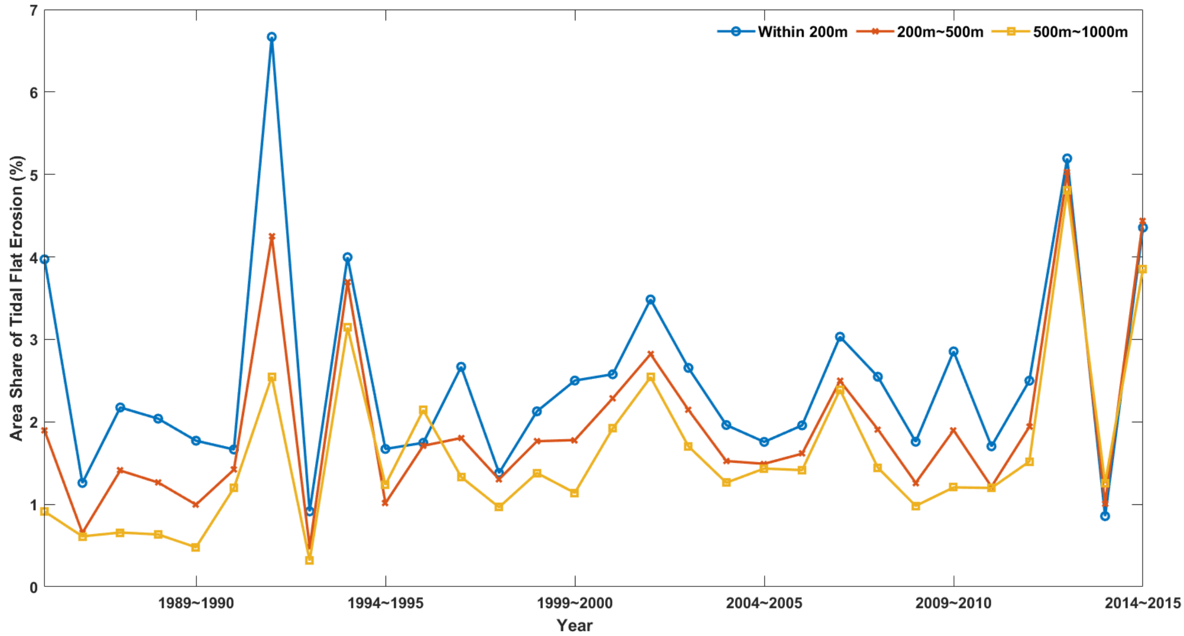

Figure 10. The intensity of tidal flat erosion around the seaward-expanded urbans.

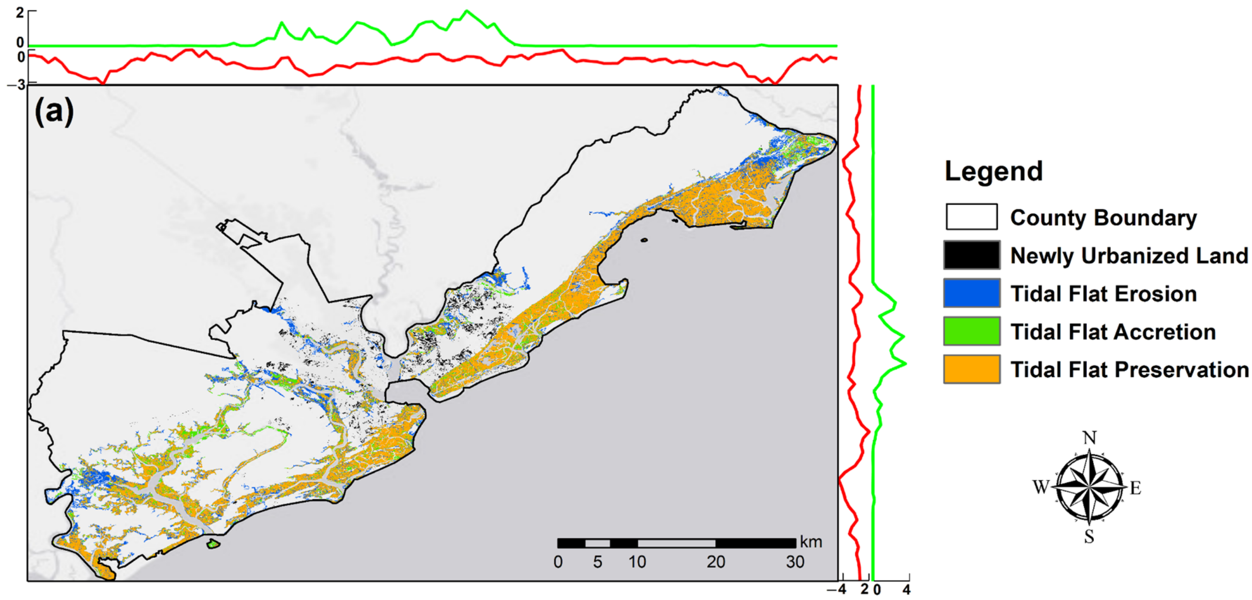

Figure 11. *Cont.*

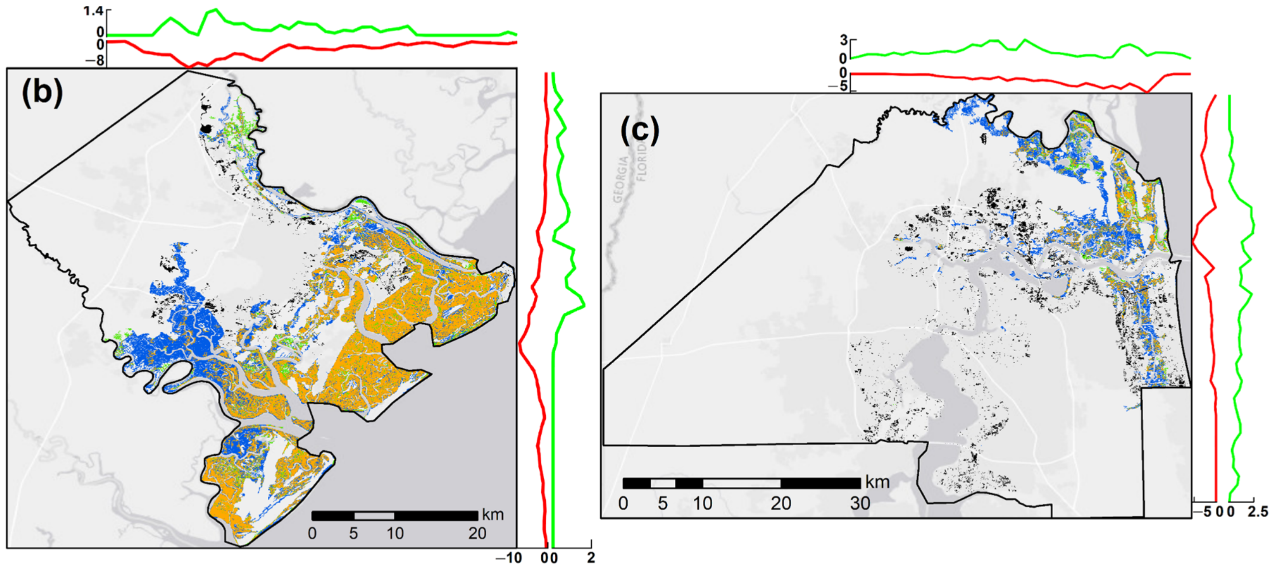

Figure 11. The spatial distribution of urban expansion and tidal flat dynamics from 1985 to 2015 within 2 km of the coast in (**a**) Charleston, SC, (**b**) Chatham, GA, and (**c**) Duval, FL. The area changes (in km^2) of tidal flats (in red) and urban extents (in green) are summarized as line charts along map edges. (The World Light Gray Basemap is used as the background, which is provided by Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS User Community.)

4. Discussion and Conclusions

In this study, we separately assessed the spatiotemporal dynamics of tidal flats and urban areas in Charleston, SC, Chatham, GA, and Duval, FL, from 1985 to 2015. Then, the tidal flat losses, which are directly or indirectly associated with urban expansion in the three counties, were identified and quantified from a geospatial perspective. As one of the earliest attempts to investigate the spatiotemporal correlations between tidal flats and urban areas, this paper verifies and highlights the conflicts between the intensified human activities and coastal environments. More importantly, the approach used in this paper could be revised and applied to the entire US, through which we could identify and summarize more diversified spatiotemporal regularities and further make contributions to sustainable urban planning and eco-friendly policymaking for coastal communities. In this section, we first summarize the identified spatiotemporal patterns and seek the reasonable explanations from peers' studies (Section 4.1). Then, we consider the environmental consequences of the rapid urbanizations of tidal flats, and explore some possible solutions suggested by other studies (Section 4.2). Finally, we discuss the limitations of this study and determine the directions of the future works (Section 4.3).

4.1. Explanations for the Identified Patterns

The environment of tidal flats is sensitive to climate changes. Since the maintenance of tidal flats highly relies on the stable supply of fresh water, severe drought has been confirmed as a major threat to the coastal environment [43]. It may explain some extreme low records of tidal flat annual area. For example, Figure 3 shows a constant shrinkage of tidal flats in Charleston, SC, from 1999 to 2003, which overlaps a period of widespread drought throughout the coastal area of South Carolina [44]. On the contrary, too much water is not good news either: tidal flats can be inundated by the high-tide flooding, which is common during El Niño periods [45]. From 2009 to 2010, El Niño brought unusually high precipitation to Charleston, SC, and there was a higher-than-average rainfall in Chatham, GA also [46], which may explain the shrinkages of tidal flats in these two counties. For the tidal flat cluster in Duval, FL, the south portion has significantly short duration (Figure 5c), which was also an erosion-dominated area from 2005 to 2015 (Figure 6i). According to the urban map (Figure 8c), this cluster locates between the City of Jacksonville and its satellite cities along the Atlantic Coast. Therefore, tidal flats in this area are under the pressure from urban expansion, which is from both the eastern and western sides. In particular, the western side had been rapidly urbanized during the three decades (Figure 11c), which gives Duval, FL, the largest new urban areas within 2 km of the coast (Figure 9).

Duval, FL, has much smaller tidal flats than the other two counties (Figure 3), while it has the largest newly urbanized area towards the seashore (Figure 9). Compared with the two other counties, Duval, FL, has a less stable environment of tidal flats (Figure 4), which calls for a higher level of public awareness and concern. Meanwhile, some suburbs in the two other counties have also been rapidly urbanized, including the eastern and western wings of the City of Charleston (Figure 8a) and southwestern side of the City of Savannah (Figure 8b). As verified by Figure 10, these urbanizations would also considerably affect the surrounding tidal flats, and the closer places would receive higher environmental pressures. Therefore, we not only observed the spatial overlaps between new urban areas and tidal flat erosions, but also the much larger erosion clusters in the surrounding areas (Figure 11). Moreover, we found that the constant shrinkage of tidal flats (Figure 3) is hysteretic to the accelerated process of urbanization in the coastal area (Figure 9). As emphasized by a relevant study [47], the hysteresis effect also exists in the restoration and management of ecosystems, and severe damages may result in irreversible changes. Therefore, it takes time to observe the follow-up ecological effects of urban expansion in recent years, and the tidal flats in the three counties urgently need a sustainable plan of management in response to the rapid expansion of urban areas.

4.2. Environmental Consequences and Possible Solutions

The absence of tidal flats makes the coastal communities more vulnerable to natural hazards, which is the environmental consequence of unsustainable development. With the baseline in 2010, Vousdoukas et al. (2020) [48] conducted a long-term projection for the storm-induced coastal erosions at a global scale. As projected, most coastlines will retreat 30 to 50 m by 2050, and more than 100 m by 2100. Particularly, the Atlantic Coast of the southeastern US, in which the study area is located, will experience more serious land losses than the rest of world (more than 100 m by 2050, and approximately 200 m by 2100). Meanwhile, the coastal flooding will become more serious than ever. According to a projection for the study area [49], severe floods will be more frequent as time goes by, and the level of historical 100-year floods will increase by 2 m at the end of the 21st century. Essentially, a recent study [50] concludes that the reclamation of tidal flats aggravates the risk from storms and therefore is regarded as a primary source of increased flood risks. Located along the Atlantic Coast of the southeastern US, the study area is usually exposed to the hurricanes, which will be more frequent and serious in the coming decades [51]. For the sake of coastal residents, it is urgent to seek a solution with respect to both environmental resilience and sustainable development.

It is challenging to restore tidal flats in highly urbanized areas, and we found some insightful ideas from the successful experiences in the rest of world. A case study in Taean County, South Korea [52], assessed the changes of tidal flats before and after the construction of Hwangdo Bridge, which connects Anmyeon Island and Hwang Island. In 1982, an inland dike was constructed in this area, which had blocked the seawater circulation for three decades and consequently damaged the tidal flat ecosystem in the surrounding area. The inland dike was replaced with a bridge in 2011, which resumed the hydrodynamic regime and the stable and sufficient supply of sedimentation. As a result, the tidal flats gradually expanded, and the associated ecosystem was restored. Moreover, the case study of Singapore [53] demonstrates higher initiative of sustainable development. As claimed by that study, the ecological engineering on artificial shorelines would be a practical solution. The core concept is to leave sufficient space for the landward migration of tidal flats, which prevents the effects of coastal squeeze due to sea level rise [54,55]. In other words, the environmental pressure on tidal flats comes from two aspects, which are urban expansion from inland and sea level rise from the ocean. While it is challenging to stop the inundation process driven by sea level rise, a more practical solution is to limit the urbanization near the shoreline, and thus the tidal flats would be more flexible to migrate towards the inland area.

4.3. Limitations and Future Work

The core concept of this paper is to justify the rationality and feasibility of a proposed approach. In this regard, the spatiotemporal analysis is just the secondary objective, which does not cover too many pages. In the following work, we will expand the study area to the entire US, and conduct in-depth analyses based on the resultant spatiotemporal patterns. For example, we could compare the map-edge summaries of tidal flat/urban changes of the same place but different periods (Figures 6 and 8). Assisted by the map-edge summaries, we will also quantify and compare the clusters of new urban areas and tidal flat losses (Figure 11). Moreover, the previous studies [12,13,39,56] verified that the map-edge summary would better fit the studies on large spatial scales, which suggests that we could identify more diversified information from the entire US. According to the intensity of urbanized lands, the coastal counties in the US would be classified into several levels. The dynamic analyses and correlation tests would be separately conducted for each level, and the results of different levels would be synthesized and compared.

It is also important to compare our analytical results with those of our peers, which will be addressed in our upcoming paper. Since our work is one of the earliest studies which focus on the spatiotemporal correlations between urban expansion and tidal flats in the US, there are not many directly relevant studies for us to compare and validate. However, we did find some other studies which indirectly related to our work. For example, we noticed that the US Geological Survey (USGS) has recently released a new version of NLCD [57], which provides the land cover maps of 30 m resolution with 16 classes in 2001, 2004, 2006, 2008, 2011, 2013, 2016, and 2019. The new urban areas would be classified accordingly, and we could further quantify and compare the rates of tidal flat losses surrounding the new urban areas of different land cover types. In addition, the USGS has released a dataset which projects the land cover changes in the conterminous US until 2100 [58,59]. The summarized rates of tidal flat losses would be applied to this dataset, through which we could predict the tidal flat losses until the end of the 21st century.

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