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Modeling present and future ecosystem services and environmental justice within an urban-coastal watershed

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HIGHLIGHTS

- Present and future carbon sequestration and storage modeled in urban-coastal setting.
- Land loss from sea level rise projected to concentrate in low lying coastal habitats.
- Projected losses in carbon sequestration, aboveground and belowground carbon storage.
- Urban trees and forested areas predicted to sequester and store the most carbon.
- Coupled ecosystem services with socio-economic data to assess environmental justice.

ABSTRACT

Globally, urban-coastal areas are expected to experience substantial landscape shifts as a result of climate change induced sea level rise. Such changes will impact valuable ecosystem services. We employed sea level rise projections and land cover change mapping to develop a model which quantified present-day carbon sequestration, aboveground carbon storage, and belowground carbon storage ecosystem services and predicted the impact of sea level rise and accretion through 2100 on future ecosystem services in the urban-coastal Jamaica Bay, New York (USA) watershed. Our model predicted that future carbon sequestration, aboveground carbon storage, and belowground carbon storage potential in our watershed will be significantly impacted in wetlands and natural coastal-fringe habitat and have losses up to 0.16%, 15%, and 51%, respectively. We paired our present-day ecosystem services model results with data on socio-economic need (access to open space and poverty level of each census tract in the watershed) and used multivariate clustering analysis to identify clusters in which planning and restoration may help to address issues of ecological conservation and environmental justice. Our work addresses the need for better understanding of urban-coastal ecosystem service flows and the potential impact of future landscape change on these services. Our results provide support to increase coastal resilience through informed design, planning, and management of these ecologically and socially significant landscapes.

1. Introduction

Ecosystem services are defined as the direct and indirect benefits to human well-being that are derived from ecosystems and ecosystem function (Gómez-Baggethun & Barton, 2013). The ecosystem service framework may be used to assess present-day function, monitor change over time, and inform future planning, conservation, and restoration to maximize the ecosystem function and services generated at multiple scales (Daily, 1997).

Realizing the promise of its application, ecosystem service science has received increasing attention in recent years and a growing cadre of scientists have become involved in assessing and mapping ecosystem services (Turner et al., 2013; Wilkerson et al., 2018). Despite these research efforts, gaps in our understanding of the assessment and application of ecosystem service valuation and modeling remain (Bennett, 2017). In particular, research of urban ecosystem services remains understudied and constitutes a domain of high priority for future research (Hurley & Emery, 2018). To date, much of the urban ecosystem service research has focused on regional landscape changes (Hou et al., 2020). However, a need has arisen for deeper understanding of the ecosystem service flows of the urban core to direct urban planning and management (Elmqvist et al., 2015). Locally generated ecosystem services benefit urban quality of life and can be integrated into planning strategies to promote livability, sustainability, and resilience (Gómez-Baggethun & Barton, 2013).

Confronted by intense human development and the impacts of global

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climate change, the urbanized coast represents a dynamic and high priority landscape. Urban development on coastlines has become more intense and extensive and the coastal urban population is increasing (United Nations, 2017). Further, urban areas have been shown to have patterns of inequities related to open space provision and park spending at various spatial scales (Rigolon et al., 2018). Coastal cities and the environmental and social services generated by these landscapes are globally relevant and significant.

The ecosystem services of coastal cities are particularly vulnerable and are confronted with multiple pressures on ecosystem function. Coastal cities are often bounded by urban development and water (a phenomenon called "coastal squeeze") and are thus vulnerable to pressures from climate change, including mean sea level rise (SLR) (Smart et al., 2021), and local SLR, which includes subsidence (Restrepo-Ángel et al., 2021). It is expected that SLR will increase coastal erosion (Leatherman et al., 2000) and when combined with changing temperature and precipitation, alter the composition and structure of coastal habitat and biota (Meixler et al., 2020). The resulting loss of species and habitat will generate a net loss of associated ecosystem services and an uneven distribution across space and demographics causing gaps in environmental justice (Kremer et al., 2013).

Environmental justice is defined as the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies (Maantay et al., 2010). The goal of addressing environmental justice inequities, often through policies and regulations, is to create environmental equity: the concept that all people should bear a proportionate share of environmental pollution and health risk and enjoy equal access to environmental amenities (Harner et al., 2002). Many factors relate to urban environmental justice. Among them are often measures of the environment (e.g. ecosystem services provision) and demography (e.g. poverty levels, access to open space) (Browne et al., 2022; Sims et al., 2022). An understanding of the inequities related to environmental justice can address the issue of disadvantaged communities and assist regional planning organizations, environmental-justice networks and scholars, and state and federal agencies in affecting change and adopting more fair and equitable practices going forward (Herreros-Cantis et al., 2020).

Modeling of present-day conditions and future scenarios educates people of the existing value of their urban-coastal landscape and provides planners with spatially explicit decision-making tools (Elmqvist et al., 2015). Recent research has identified the value of combining ecosystem services analysis with socio-economic data to identify areas of varying environmental and social need which help to address issues of ecological conservation and environmental justice (e.g., McPhearson et al., 2013a) particularly in urban areas (Kremer et al., 2016a). There is great utility in expanding upon such efforts (Sikor, 2013). In doing so we may not only quantify future ecosystem service flows, but also spatially identify where to implement conservation and restoration efforts to maximize ecosystem and public services and rectify environmental justice inequities.

Addressing these topics of interest and need, our research asks: *How will projected relative SLR impact the flow of ecosystem services, in particular, carbon sequestration and carbon storage, in a highly utilized urban-coastal watershed?* And, *how can our ecosystem services results be coupled with socio-economic data to identify sites of varying levels of environmental justice for planning and restoration purposes?* In answering these questions, we present a model generated in the urban-coastal ecosystem of Jamaica Bay, New York, an area defined by intense urbanization and ecological value (Hartig et al., 2002) and predicted to be significantly impacted by and vulnerable to local SLR (Hopper and Meixler, 2016; NPCC, 2019). Further, historic power dynamics in the city have resulted in inequitable and unjust urban land use decisions (Rosan, 2012). There is a recognized need to understand how climate change will impact the city and affect measures of environmental justice to better direct mitigation actions going forward (Solecki et al., 2021).

We modeled carbon sequestration and carbon storage services generated from both built and natural landscapes under present-day (2020) and future (2050, 2080, and 2100) conditions. Then, we demonstrated the use of our ecosystem service model results in parallel with socio-economic data to identify areas of varying environmental and social need in terms of environmental justice. Traditionally, commonly used ecosystem service models such as i-Tree (Nowak et al., 2018) do not estimate urban carbon values by specific land use and greenspace type. However, recent research has found significant differences in carbon sequestration and carbon storage within these types (Pregitzer et al., 2021). Consequently, we used specific categories (e.g., urban trees, maritime forest/shrub) when modeling future scenarios and impacts on ecosystem services. Ultimately, our research and modeling methodology has the potential to inform future design, planning, and management of the Jamaica Bay watershed and other urban-coastal landscapes—some of the fastest growing environments in the world (Barragán & de Andrés, 2015).

2. Methods

2.1. Study site

Our ecosystem service model was applied to the Jamaica Bay watershed, which is a 321 km^2 area located on the southwestern shore of Long Island, New York (40.6178° N, 73.8425° W). Located in both the Queens and Brooklyn boroughs, the watershed is defined by densely populated urban landscape immediately adjacent to coastal fringe habitat, including wetlands and upland zones (McPhearson et al., 2013b). Jamaica Bay has a long history of urbanization and reduction of natural habitat (Gornitz et al., 2001). A mapping analysis showed that the bay lost half of its vegetated islands between 1924 and 1999 (Hartig et al., 2002), resulting in a 95 % carbon storage loss between 1885 and 2019 (Pace et al., 2021), with the rate of loss increasing over time (Hartig et al., 2002). Recent land cover data reveal that 55 % of the Jamaica Bay watershed is characterized by urban infrastructure and impervious cover, including buildings, roads, railways, and impervious surfaces (Natural Areas Conservancy, 2014). The Jamaica Bay watershed is characteristic of the entire urban northeast which is experiencing pressures from urbanization, SLR, storm surge, and invasive species (Johnson et al., 2020). Due to the inaccessibility of data, our analysis excluded areas of the watershed located in Nassau County, New York (Fig. 1).

We developed a multi-scenario model to quantify the impacts of land loss from projected SLR on the ecosystem services of our Jamaica Bay urban-coastal landscape. Model components included: SLR projection and land cover change modeling; ecosystem service quantification; and spatial analysis of ecosystem services and socio-economic data to map environmental justice.

2.2. Sea level rise projection and land cover change modeling

Similar to previous urban ecosystem service models (e.g., McPhearson et al., 2013a), land cover figured prominently in our SLR mapping and quantification of ecosystem services. High-resolution (1 m × 1 m) land cover data were obtained from the Natural Areas Conservancy (NAC) (2014), which had reclassified local LIDAR data to correspond to the land cover types included in the National Land Cover Database. When compared to other land cover data, the NAC dataset was better able to capture the heterogeneity of the urban landscape. We reclassified the NAC land cover data into ten categories using ArcGIS Desktop 10.8.1 (ESRI, 2022) to group similar habitat types based on corresponding ecosystem service values identified in peer reviewed literature: buildings, roads/railroads, other paved surfaces, bare soil, urban trees, urban grass/shrub, coastal grassland, wetlands, maritime forest/shrub, and water. Reclassified bare soil consisted of NAC categories containing the

Fig. 1. The Jamaica Bay, New York watershed is located in the southwestern portion of Long Island in the boroughs of Queens and Brooklyn, and in Nassau County. Modeling was limited to the Queens and Brooklyn boroughs due to data availability (red outline). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

words bare soil or sand barrens; urban grass/shrub consisted of the NAC category maintained lawn/shrubs; coastal grassland consisted of NAC categories dune and coastal grassland/shrubland and Eastern coastal beach; wetlands consisted of NAC categories that included the words swamp, aquatic vegetation, marsh, wet meadow, wet prairie, or tidal flat; maritime forest/shrub consisted of NAC categories that included the words forest, plantation, floodplain, or shrubland (other than maintained lawn/shrubs as mentioned earlier); urban trees consisted of the NAC category other tree canopy. Buildings, roads/railroads, other paved surfaces, and water categories remained the same in the reclassified land cover data. The reclassified land cover data were then used in all scenarios of future SLR projections to predict loss or gain of ecosystem services.

Located on the Long Island coast, the Jamaica Bay watershed is subject to climate change related impacts, including relative SLR (Gornitz et al., 2001). In the greater New York City region *relative* SLR, which includes both a rise in water elevation and local subsidence, is expected to exceed global averages as a result of local subsidence and compaction (Gornitz et al., 2001) and interactions between ocean currents, isostatic adjustment, and eustatic SLR (Abadie et al., 2020). We calculated land loss due to SLR using a static "bathtub" coastal flooding modeling technique (NPCC, 2019, Chapter 5) based on the NPCC (2015) SLR Projections (Table 1) and a digital elevation model (DEM) for the region (NYC DCP, 2015) with a 1 m × 1 m resolution. Our process was based on the methodology performed in the most recent NPCC report (2019) and assumed that floodwaters will move landward until they reach an equivalent topographic elevation. Note that in 2019, the NPCC tested the accuracy of their 2015 predictions and stated: "This report confirms the use of the NPCC (2015) SLR projections for decision-making" (NPCC, 2019). Using Python 2.7.18, for each SLR projection year (2050, 2080 and 2100) and each projection likelihood (10th, 25th, 75th and 90th percentile), we selected all areas from the DEM within the watershed that would be inundated and reclassified those areas as water in the land cover data. In addition, we created a map of present-day conditions (2020) using the 10th percentile projection likelihood values for 2020 from NPCC (2015) based on the analysis in 2019 that the most recent observed trends show that sea level at The Battery at the southern tip of Manhattan has continued its upward rise at around the 10th percentile projection since the 2015 NPCC report was issued (NPCC, 2019). Our analysis process involved thirteen scenarios; present-day conditions plus

Table 1
New York City sea level rise projections for the years 2050, 2080 and 2100 relative to 2000–2004, based on six components that include global and local factors, where percentiles (10th, 25th, 75th and 90th) represent the likelihood of occurrence. For example, 10th percentile projections represent 90% probability of occurring (New York City Panel on Climate Change 2019).

Year	NPCC (2015) Sea Level Rise Projections (m)			
	10th Percentile	25th Percentile	75th Percentile	90th Percentile
2050	0.20	0.28	0.53	0.76
2080	0.33	0.46	0.99	1.47
2100	0.38	0.56	1.27	1.91

twelve predicted SLR scenarios (for the years 2050, 2080 and 2100 and the 10th, 25th, 75th and 90th percentiles). Note, we performed an additional quantification of ecosystem services given SLR as well as accretion. Methods and results can be found in Appendix A; Python scripts available upon request.

2.3. Ecosystem services quantification

We calculated three categories of ecosystem services provided by the Jamaica Bay watershed: carbon sequestration, aboveground carbon storage, and belowground carbon storage. We undertook an extensive literature search to identify coefficients for the rates of ecosystem service flows for each of the ten land cover types. Where possible, coefficients were derived from research local to the Jamaica Bay watershed; when local data were not available, regional or national studies were used (Table 2; Appendix B for detailed explanations of coefficient derivation).

Using Python 2.7.18, we inserted the coefficient value (Table 2) for each of the three ecosystem services (carbon sequestration, aboveground carbon storage, and belowground carbon storage) into each cell of the present-day land cover data, based on the cell's land cover type. At the watershed scale, for each ecosystem service, coefficients for each land cover type were multiplied by the number of cells of that land cover type and then by the cell area to arrive at present-day total predicted carbon sequestration, aboveground carbon storage, and belowground carbon storage for the watershed. Combinations of projected SLR were used to map scenarios of future land loss or gain and the corresponding changes in land cover type abundance. The resultant land cover maps were used to calculate changes in ecosystem service flows for the watershed based on changes in total area represented by each of the land cover types. For each future scenario, the total land area for each cover type was summed and the associated ecosystem service values calculated following the methodology used for the present-day scenario. It is important to note that our focus was on impacts of SLR thus this model assumes no other changes to the landscape from 2020, including any projected urbanization or alteration to landform or land cover (i.e., increased development or future restoration and park development).

Table 2

Ecosystem services coefficients for carbon sequestration, aboveground carbon storage, and belowground carbon storage by land cover type. Land cover types with coefficients that don't apply (N/A) were not included in the analysis.

	Carbon sequestration (kg C/m^2/yr)	Carbon storage	
		Aboveground (kg C/m^2)	Belowground (kg C/m^2)
Buildings	N/A	N/A	3.8[a]
Roads/railroads	N/A	N/A	3.8[a]
Other paved surfaces	N/A	N/A	3.8[a]
Bare soil	N/A	N/A	3.8[a]
Urban trees	0.12[b]	7.3[b]	10.5[c]
Urban grass/ shrub	0.09[d]	0.18[e]	0.16[d]
Coastal grassland	0.06[f]	0.18[g]	0.58[h]
Wetlands	0.08[i]	0.44[j]	0.95[j]
Maritime forest and shrub	0.05[k]	5.0[l]	9.0[m]
Water	0.05[n]	N/A	0.007[o]

a) Pouyat et al., 2006; b) Nowak et al., 2018; c) Downey et al., 2021; d) Jo and McPherson, 1995; e) McPhearson et al., 2013a; f) Patrick et al., 2014; g) Zavaleta and Kettley, 2006; h) Ryals et al., 2014; I) Hill and Anisfeld, 2015; j) Teal and Howes, 1996; k) Bridgham et al., 2006; l) Smart et al., 2020; m) Brown et al., 2001; n) Duarte et al., 2005; o) Postlethwaite et al., 2018.

2.4. Spatial analysis of ecosystem services and socio-economic data to map environmental justice

Following ecosystem services quantification, a series of analyses were conducted to identify areas of concentrated ecosystem services and socio-economic need. When combined, such areas may inform where to target planning and restoration activities and rectify environmental justice inequities.

Areas of socio-economic need were defined using two interrelated metrics: access to open space and poverty level of each census tract in the watershed. Our choice of variables was based both on alignment with previous studies' findings and on recent political focus in relation to ecological conservation and environmental justice. We first mapped the accessibility of each census tract to open space through a set of criteria established by a New York City mandate. The mandate in part orders that by the year 2030, every city resident be within a 10-minute walk or 0.5 miles (0.8 km) of park space (PlaNYC, 2007). In addition, research has shown that there is considerable heterogeneity in racial groups' access to open space (Sims et al., 2022) which makes this variable an important factor in terms of environmental justice. We used New York City land use data from the Primary Land Use Tax Lot Output (MapPLUTO, release 21v4) provided by the NYC DCP (2022) to identify areas classified as open space in the Jamaica Bay watershed (e.g., those classified by building code as open space, parks/recreation facilities, or playgrounds; and by zoning district as parks). Additionally, we obtained tract level data from the United States Census Bureau (2022) from which access origin points (e.g., centroids for each tract) were generated in ArcGIS Pro 2.8.1 (ESRI, 2022). We then used the Near tool in ArcGIS to calculate the distances between each tract centroid point and each open space polygon while using the search radius feature to limit matching features to only those within a 0.8 km buffer (10-minute walk). All the areas of open space within the buffered distances of each centroid point were then summed, determining the total open space area 0.8 km from the center of each census tract (e.g., access to open space). Note that entire park areas were summed even if only a small portion of the park was within the 0.8 km buffer.

In addition to open space access, our analysis of socio-economic need included the percent of the population within each census tract classified as below the poverty level as reported in the 2019 American Community Survey-five-year estimates on poverty status for the past 12 months (United States Census Bureau, 2022). Poverty level has been cited as one of the most important variables in terms of environmental justice specifically in urban environments (Harner et al., 2002). Poverty remains a big issue within New York City with nearly 18 % of residents living in poverty and just over 40 % living in or near poverty (The City of New York, 2021). Only census tract polygons with existing poverty data were retained in our analysis (N = 765).

To identify areas of concentrated ecosystem services, we converted our raster ecosystem services data to point centroids and statistically tested for clustering of points with values representing summed total carbon sequestration, total aboveground carbon storage, and total belowground carbon storage for all combinations of year and SLR projections using Moran's I in ArcGIS Pro 2.8.1 (ESRI, 2022). To accomplish this process, we converted raster data to point data by aggregating the raster cells (using a cell factor of 200 to overcome memory limitation issues given our high-resolution datasets). Once clustering was established, we performed optimized hot spot analysis on all combinations of year and SLR projections. Optimized hot spot analysis evaluates the characteristics of input features to create a map of statistically significant hot and cold spots. In our optimized hot spot analysis the input features were total carbon sequestration rates for a particular year and SLR projection and these values were used to create a map showing statistically significant spatial clusters of high values (hot spots) and low values (cold spots). We repeated the optimized hot spot analysis for total carbon sequestration for each year and SLR projection and performed the same process to create maps of total aboveground carbon storage and total belowground carbon storage for each year and SLR projection as well. Additionally, we tested for clustering of open space areas alone using an Average Nearest Neighbor analysis, and access to open space (e.g., summed areas of open space available within a 0.8 km walk from each census tract centroid) and poverty level in each centroid using Moran's I. Again, once clustering was established, optimized hot spot analyses were performed on access to open space and poverty spatial datasets.

Finally, we demonstrated the use of Multivariate Clustering analysis using a K-means clustering method and optimized seed locations to generate five clusters based on the present-day scenario using total carbon sequestration per census tract normalized by tract area, access to open space, and poverty level as analysis fields in ArcGIS Pro 2.8.1 (ESRI, 2022). Analysis of the optimal number of clusters indicated a high pseudo F-statistic for five clusters indicating that this strategy would be highly effective at distinguishing the features for our variables of interest without adding complexity that would make the results difficult to interpret. We repeated the process swapping total aboveground carbon storage and total belowground carbon storage per census tract, normalized by tract area, for total carbon sequestration in turn.

3. Results

3.1. Sea level rise projection and land cover change modeling

Our model predicted that SLR would cause substantial land loss in our study watershed (Fig. 2). For all projections, SLR-induced land loss was concentrated in low lying coastal habitats, specifically wetlands and coastal grasslands, while upland habitat was not predicted to be impacted until late in the century under extreme SLR projections (Table 3). Wetlands were expected to be impacted, even under the most conservative estimates of SLR. By the 2050s, between 5.76 % and 35.29 % of present-day wetlands were projected to be lost to SLR (Table 3).

Coastal grasslands, such as those found at the National Park Service site Floyd Bennett Field, were predicted to be moderately impacted by 2050s across all scenarios (1.01–7.14 % losses in area relative to the present-day scenario), with impacts increasing by the 2080s (2.00–18.28 % losses). Maritime forest/shrub were not expected to be substantially impacted until the 2080s (up to 5.51 % losses for the most extreme projection) and track similarly to bare soil in terms of area lost (up to 6.60 % losses by the 2080s for the most extreme projection). Urban trees and urban grass/shrub also tracked similarly to each other and resulted in small predicted losses except under the most extreme projections (up to 2.09 % and 2.51 % losses by 2100, respectively). Areas of impervious surfaces, which define the built landscape, were not expected to lose considerable land due to SLR until 2100 under the most extreme projections (up to 3.44 % losses) (Table 3). Gains in water area were predicted to be 0.97–6.23 % of present-day area by the 2050s and 2.90–23.83 % by 2100.

3.2. Ecosystem services quantification

The loss of coastal habitat has significant implications for ecosystem services in the Jamaica Bay watershed. Ecosystem service coefficients for carbon sequestration ranged from 0.05 to 0.12 kg C/m^2/yr with urban trees sequestering the most carbon and maritime forest/shrub and water sequestering the least (Table 2). Aboveground carbon storage coefficients covered a broader range from 0.18 to 7.30 kg C/m^2 with urban trees again at the high end of the scale and urban grass/shrub and coastal grasslands at the low end (Table 2). Belowground carbon storage coefficients covered an even broader range from 0.007 to 10.50 kg C/m^2 with urban trees again at the high end of the scale and water at the lowest end (Table 2).

Thus, it was not surprising when viewing the modeled total sequestered carbon, aboveground carbon storage, and belowground carbon storage values for the Jamaica Bay watershed by land cover type across years and SLR projections without accretion that urban trees were the land cover type with the highest expected values for all three ecosystem service types (Fig. 3a,b,c; Appendix Ca,b,c). Annual urban tree carbon sequestration values were predicted to be 0.04 Tg C/yr for the watershed with little change across time or SLR projection. Water (0.04–0.05 Tg C/yr) and urban grass/shrub (0.03 Tg C/yr) represented similarly high land cover categories with water surpassing urban trees in terms of carbon sequestration by the year 2100 under the most extreme SLR projections. Wetlands (0.01 Tg C/yr), maritime forest/shrub (<0.01 Tg C/yr), and coastal grasslands (<0.01 Tg C/yr) were predicted to sequester lower levels of carbon in the watershed, respectively (Fig. 3a; Appendix Ca). Over time, most land cover types were expected to retain fairly consistent carbon sequestration services with just slight decreases in performance by the year 2100 under the most extreme projections of SLR. However, wetlands tended to decrease and water tended to increase in predicted carbon sequestration with time and SLR (Fig. 3a). Total present-day carbon sequestration for the watershed was predicted to be 0.1273 Tg C/yr, ranging from 0.1257 − 0.1276 Tg C/yr across all years, with losses in services up to 0.16 % under future scenarios (Appendix Ca). Interestingly, the scenario with the lowest total carbon

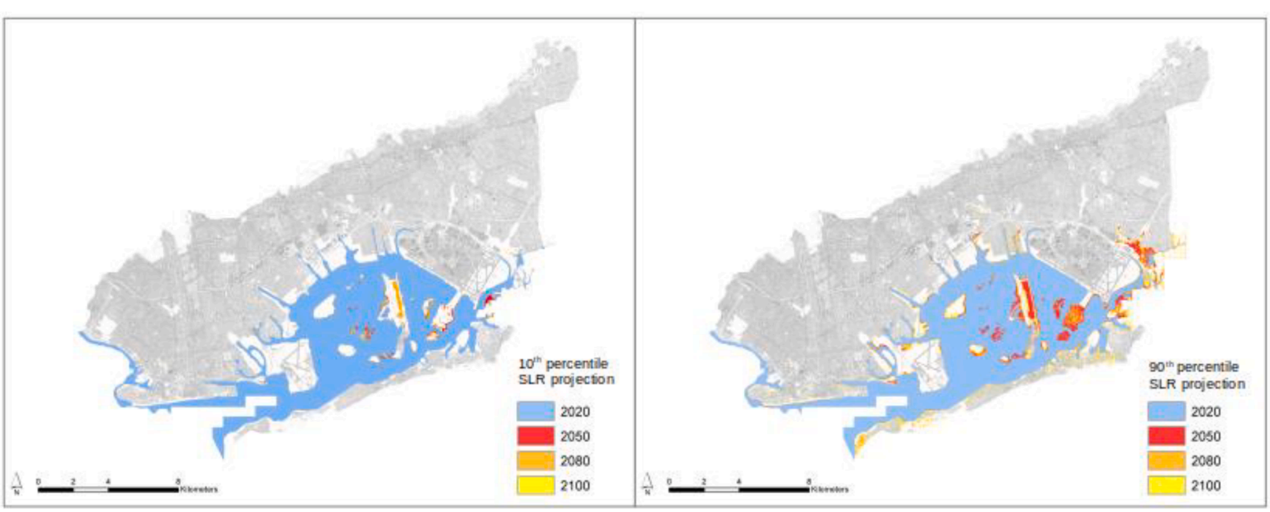

Fig. 2. Sea level rise 10th percentile projections (left) and 90th percentile projections (right) for the Jamaica Bay, New York watershed. Color bands delineate decadal projections (2020, 2050, 2080, and 2100). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Present-day area (km^2) and percent (%) of total study area values for 2020, and area (km^2) and percent (%) change in land loss or water gain based on projected sea level rise, not including accretion, by the years 2050, 2080 and 2100 (relative to 2020) for each land cover type. Impervious surface includes roads, railroads, and other paved surfaces. Summary values are given as total area (km^2) and percent area (%) for 2020 and as total predicted land area lost (km^2) and average predicted percent land area lost (%) for sea level rise projections by the years 2050, 2080 and 2100.

		Buildings		Impervious Surface		Bare Soil		Urban Trees		Urban Grass/Shrub		Coastal Grassland		Wetlands		Maritime Forest/Shrub		Water		Summary values	
		(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)
2020		50.07	15.58	106.39	33.10	7.88	2.45	32.47	10.10	33.97	10.57	2.42	0.75	10.66	3.32	8.42	2.62	69.12	21.51	321.40	100
2050 SLR	10th	0.00	−0.01	−0.02	−0.01	−0.01	−0.10	0.00	0.00	0.00	−0.01	−0.02	−1.01	−0.61	−5.76	0.00	−0.01	0.67	0.97	−0.67	−0.86
	25th	−0.01	−0.02	−0.02	−0.02	−0.01	−0.16	0.00	0.00	0.00	−0.01	−0.04	−1.60	−0.98	−9.18	0.00	−0.02	1.07	1.55	−1.07	−1.38
	75th	−0.02	−0.04	−0.05	−0.05	−0.06	−0.71	0.00	−0.01	−0.02	−0.05	−0.10	−4.04	−2.43	−22.82	−0.01	−0.18	2.69	3.90	−2.69	−3.49
	90th	−0.03	−0.07	−0.08	−0.07	−0.13	−1.70	−0.01	−0.02	−0.04	−0.11	−0.17	−7.14	−3.76	−35.29	−0.07	−0.88	4.30	6.23	−4.30	−5.66
2080 SLR	10th	−0.01	−0.02	−0.03	−0.03	−0.02	−0.21	0.00	−0.01	−0.01	−0.02	−0.05	−2.00	−1.65	−15.49	0.00	−0.04	1.77	2.56	−1.77	−2.23
	25th	−0.01	−0.03	−0.04	−0.04	−0.04	−0.46	0.00	−0.01	−0.01	−0.04	−0.08	−3.24	−2.14	−20.09	−0.01	−0.09	2.34	3.38	−2.34	−3.00
	75th	−0.07	−0.13	−0.13	−0.12	−0.20	−2.59	−0.02	−0.05	−0.06	−0.18	−0.25	−10.32	−5.47	−51.34	−0.15	−1.82	6.35	9.19	−6.35	−8.32
	90th	−0.35	−0.70	−0.83	−0.78	−0.52	−6.60	−0.11	−0.34	−0.23	−0.67	−0.44	−18.28	−6.40	−60.02	−0.46	−5.51	9.34	13.52	−9.34	−11.61
2100 SLR	10th	−0.01	−0.02	−0.04	−0.03	−0.02	−0.29	0.00	−0.01	−0.01	−0.03	−0.06	−2.49	−1.86	−17.45	0.00	−0.05	2.01	2.90	−2.01	−2.55
	25th	−0.02	−0.04	−0.05	−0.05	−0.06	−0.79	0.00	−0.01	−0.02	−0.06	−0.10	−4.29	−2.54	−23.82	−0.02	−0.22	2.82	4.08	−2.82	−3.66
	75th	−0.16	−0.31	−0.34	−0.32	−0.33	−4.16	−0.04	−0.13	−0.12	−0.36	−0.35	−14.32	−6.07	−56.94	−0.30	−3.53	7.71	11.15	−7.71	−10.01
	90th	−1.49	−2.97	−3.66	−3.44	−1.23	−15.67	−0.68	−2.09	−0.85	−2.51	−0.72	−29.71	−6.76	−63.41	−1.08	−12.78	16.47	23.83	−16.47	−16.57

sequestration rate was 2100 with 75th percentile SLR projections and the highest was 2100 with 90th percentile SLR projections. Presumably this increase in carbon sequestration was due to the higher possible rates of carbon sequestration in water compared to the surfaces lost (e.g., paved surfaces) due to SLR.

Aboveground carbon storage for the watershed was again predicted to be highest for urban trees (2.50–2.55 Tg C) with lower levels for maritime forest/shrub (0.40–0.45 Tg C), urban grass/shrub (0.06–0.07 Tg C), wetlands (0.02–0.05 Tg C), and coastal grasslands (<0.01 Tg C) (Fig. 3b; Appendix Cb). Over time, all land cover types were expected to retain consistent aboveground carbon storage services with just slight decreases in performance by the year 2100 under the most extreme projections of SLR (Fig. 3b). Total present-day aboveground carbon storage for the watershed was predicted to be 3.13 Tg C, ranging from 2.98 to 3.13 Tg C across all years, with losses in services up to 15 % under the most extreme future scenarios (Appendix Cb).

Total belowground carbon storage was also predicted to be highest for urban trees (3.59–3.67 Tg C) with lower levels for other paved surfaces (2.52–2.61 Tg C), buildings (1.99–2.05 Tg C), roads/railroads (1.68–1.74 Tg C), maritime forest/shrub (0.71–0.82 Tg C), bare soil (0.27–0.32 Tg C), with lowest levels for urban grass/shrub (0.06 Tg C), wetlands (0.04–0.11 Tg C), coastal grassland (0.01–0.02 Tg C), and water (0.01 Tg C) (Fig. 3c; Appendix Cc). All land cover types were expected to retain consistent belowground carbon storage services over time with just slight decreases in performance by the year 2100 under the most extreme projections of SLR (Fig. 3c). Total present-day belowground carbon storage for the watershed was predicted to be 11.39 Tg C, ranging from 10.88 to 11.39 Tg C across all years, with losses in services up to 51 % under the most extreme future scenarios (Appendix Cc). Across the three ecosystem services, belowground carbon storage was most greatly impacted by SLR.

3.3. Spatial analysis of ecosystem services and socio-economic data to map environmental justice

Analysis of clustering of carbon sequestration, aboveground carbon storage and belowground carbon storage using Moran's I indicated significant clustering for all year and SLR projection combinations (z-score = 12.78–14.52, $p < 0.0001$, Index = 0.04; z-score = 38.18–39.60, $p < 0.0001$, Index = 0.12–0.13; z-score = 17.03–18.19, $p < 0.0001$, Index = 0.05, respectively). The greatest clustering of hot spots (those with 99 % confidence) for carbon sequestration were near the shorelines to the east and west of the opening to the bay and at three spots near the interior shoreline of the bay (Appendix Da). Aboveground carbon storage displayed the greatest clustering in the locations most inland in the watershed (Appendix Db). Belowground carbon storage also clustered in inland areas of the watershed and in two locations along the shoreline on the western end of the bay (Appendix Dc).

Significant clustering of open spaces, based solely on location, was evident (Average Nearest Neighbor z-score = −21.46, p-value < 0.0001, Average Nearest Neighbor ratio = 0.56) with the majority of the open spaces in the coastal areas on the shores around the bay and in the interior of the bay on the islands of the Gateway National Recreation Area. Access to open space was similarly clustered (z-score = 40.99, $p < 0.0001$, Index = 0.31) with most access in the neighborhoods of Flatbush, Fort Hamilton, Marine Park, Gerritsen Beach, and Mill Basin in Brooklyn, and Woodhaven and Brooklyn Manor in Queens.

Analysis of percent impoverished census tracts indicated significant clustering (z-score = 41.94, $p < 0.0001$, Index = 0.32) with more poverty in the areas of Coney Island, Borough Park, and Brownsville in Brooklyn. Less impoverished neighborhoods were clustered in the areas of Flatlands in Brooklyn and Queens Village in Queens.

Results of the Multivariate Clustering analysis of summed areas of open space within an 0.8 km buffer of each census tract, poverty level of each tract based on the 2019 census, and total sequestered carbon per census tract normalized by the census tract area for the watershed given

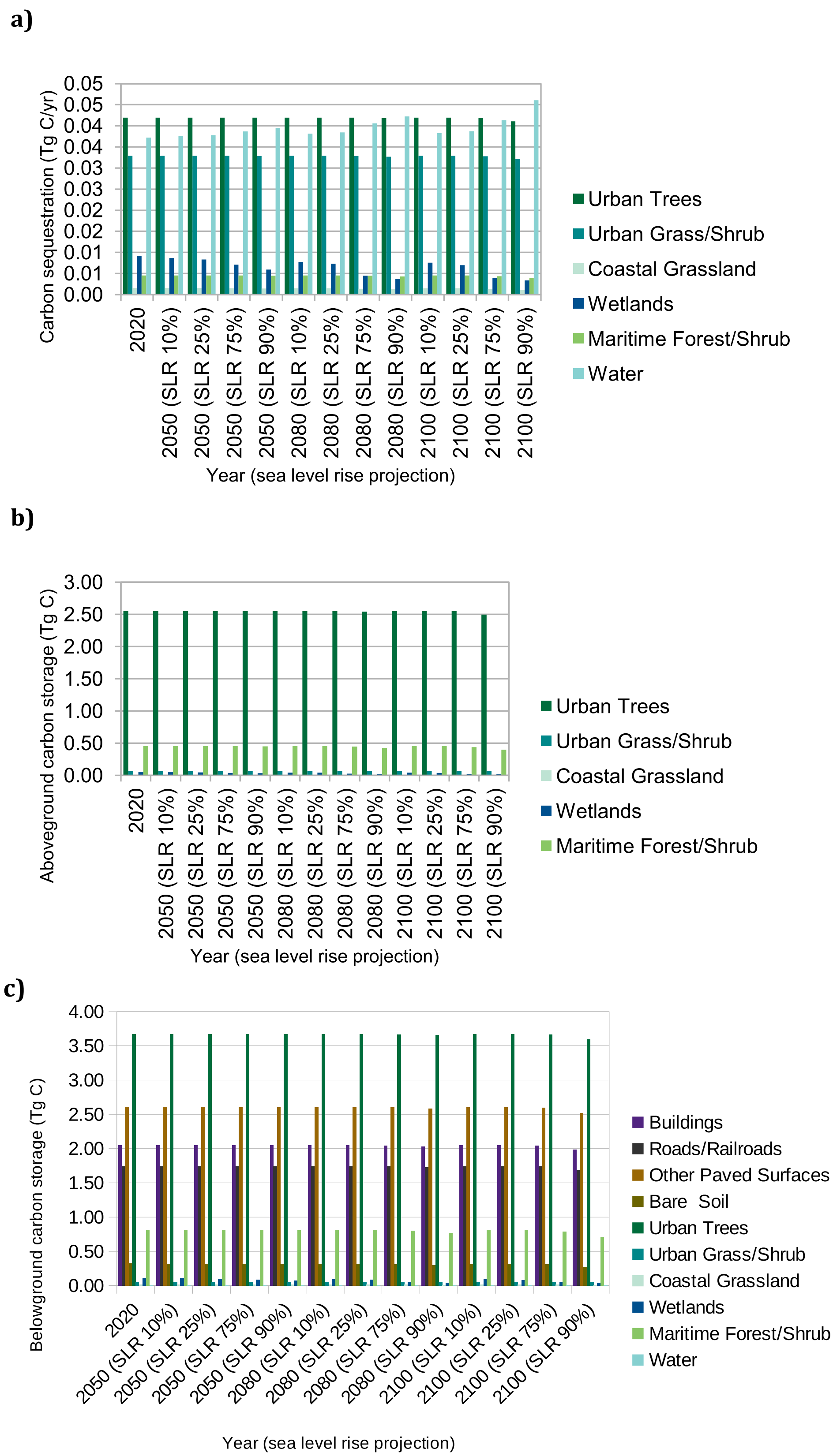

Fig. 3. Predicted (a) total sequestered carbon (Tg C/yr), (b) total aboveground carbon storage, and (c) total belowground carbon storage (Tg C) for the Jamaica Bay, New York watershed by land cover type for present-day 2020 conditions and 2050, 2080, and 2100 under 10th, 25th, 75th, and 90th percentile sea level rise projections not including accretion.

present-day conditions revealed five classes of clusters (Fig. 4a). Access to open space proved to be the best metric at discriminating among clusters ($R^2 = 0.77$). Poverty was also effective at discrimination ($R^2 = 0.69$); sequestered carbon was least effective ($R^2 = 0.46$). Few census tracts existed with the most ideal combination of metrics (high ecosystem services, high access to open space, and low poverty). Thus, they did not garner their own cluster category for any of the Multivariate Cluster analyses. However, one cluster was identified with moderate levels of sequestered carbon and low poverty but low access to open space (brown areas; N = 267; Fig. 4a). These areas were mostly located in the eastern side of the watershed. Another cluster identified areas with high sequestered carbon; however these were in places with high rates of poverty and low access to open space (light blue; N = 12). These locations were in Dyker Heights, Saint Albans and sparsely scattered throughout the watershed. These areas represent neighborhoods with yards housing ample urban trees and vegetation with good capacity for carbon sequestration in census tracts without substantial access to open space. Clusters representing low levels of all three metrics (dark blue; N = 302) indicate areas with economic resources but with low access to open spaces and subsequent loss of carbon sequestration potential. These were quite numerous and were located in the western and central parts of the watershed further from the water. Clusters with high access to open space but low carbon sequestration and low poverty (pink; N = 55) were sparsely located close to the coastline or near large parks like Prospect Park in Brooklyn. These locations have significant built infrastructure or cover with low carbon sequestration potential (e.g., pavement, grass and water as opposed to trees and wetlands). Finally, clusters were identified that were low in carbon sequestration potential and in access to open space and were moderately impoverished (grey; N = 129). These represented areas most in need of attention and were located quite numerously in the western and central parts of the watershed furthest from the coastline. Vacant lots (NYC DCP, 2022) were abundant (N = 9248) in each cluster category and many are directly adjacent to existing open space areas.

Multivariate Cluster analysis with aboveground carbon storage in place of sequestered carbon demonstrated access to open space to be considerably more effective at discriminating among clusters ($R^2 = 0.90$) than the previous analysis using carbon sequestration. Poverty was somewhat effective at discriminating among clusters ($R^2 = 0.63$); aboveground carbon storage was least effective ($R^2 = 0.32$). Results from this Multivariate Cluster analysis revealed some overlap in cluster categories with those described earlier (Fig. 4b). Areas with open space but poor aboveground carbon storage capacity (pink; N = 48) were in many of the same locations as seen with cluster modeling using carbon sequestration as the ecosystem service variable. Clusters representing opportunities for planning and restoration (e.g., those with low carbon storage potential, low access to open space, and high (red; N = 91) or moderate (grey; N = 307) poverty levels) were fairly numerous and widespread throughout the western and central parts of the watershed. Clusters with low aboveground carbon storage, moderate levels of access to open space, and low poverty occurrence (light green; N = 58) represented areas with moderate open space but in which the open space didn't result in increased predicted aboveground carbon storage. Locations in this cluster were fairly sparse and were found mostly around Dyker Heights in Brooklyn and in the central part of the watershed furthest from the coastline. Lastly, areas with high aboveground carbon storage capacity, low access to open space, and low poverty (orange; N = 261) appeared frequently in the eastern and western interior tracts throughout the watershed.

Multivariate Cluster analysis with belowground carbon storage, access to open space, and poverty as analysis factors yielded results that indicated belowground carbon storage as most effective at discriminating among clusters ($R^2 = 0.76$); access to open space performed similarly ($R^2 = 0.71$) with poverty a bit lower ($R^2 = 0.56$). The results from this cluster analysis yielded some similar categories of clusters to those described earlier and a few new ones (Fig. 4c). Areas with high

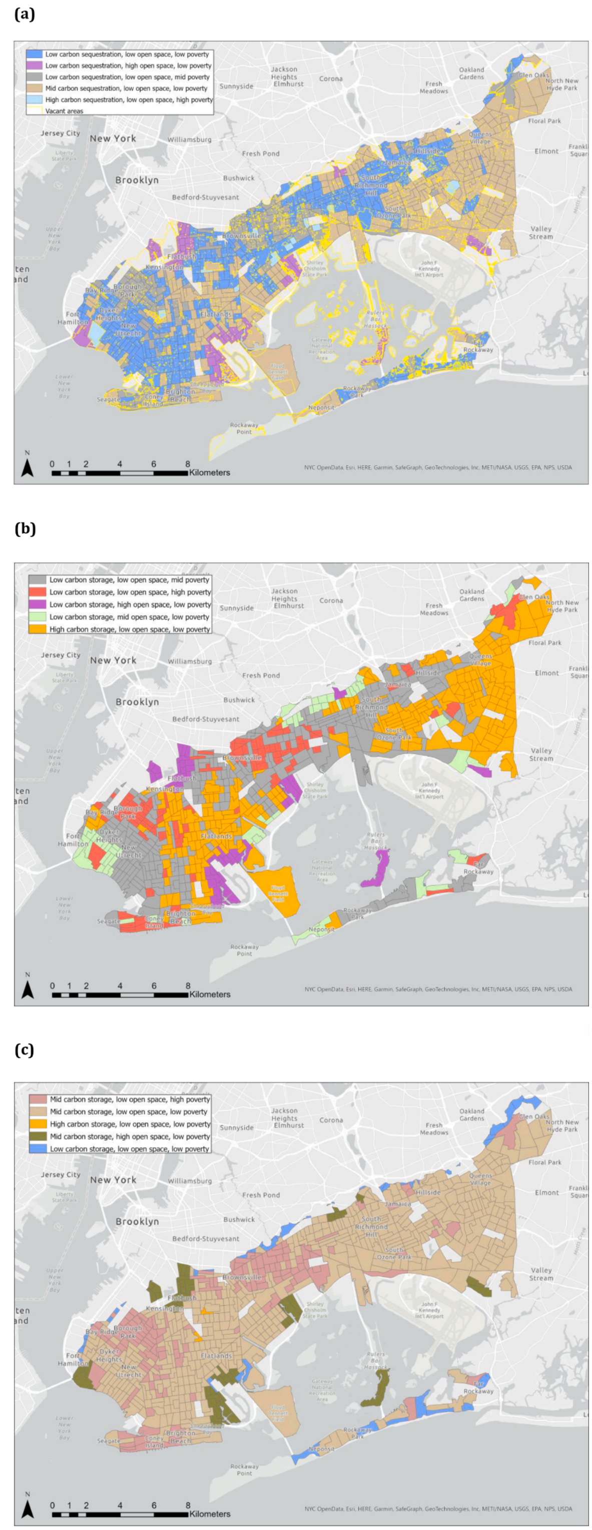

Fig. 4. Multivariate Clustering analysis of summed areas of open space within a 0.8 km buffer of each census tract, poverty level of each tract based on the 2019 census, and ecosystem services for the Jamaica Bay, New York watershed for present-day 2020 conditions. Yellow outlines denote vacant areas. Panels (a), (b) and (c) show total carbon sequestration, total aboveground and total belowground carbon storage, respectively for ecosystem services. Areas with moderate ecosystem services, high access to open space, and low poverty (forest green) are high functioning; areas with low ecosystem services, low access to open space, and high poverty (red) are opportunities for planning and restoration. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

belowground carbon storage capacity, low access to open space, and low poverty (orange) were very rare (N = 2) and only seen in two interior locations in the watershed. Locations with low values for all three factors (dark blue; N = 47) were primarily found along the watershed border furthest from the bay and on the Rockaway Peninsula. As seen earlier, one fairly ubiquitous cluster (N = 524) identified areas with moderate levels of belowground carbon storage and low poverty but low access to open space (brown). This cluster was somewhat in contrast with the cluster representing moderate levels of belowground carbon storage and high poverty with low access to open space (rose; N = 141) due to its differing level of poverty. These locations were also somewhat numerous and were found in the western and central interior parts of the watershed. Finally, the cluster with locations representing moderate levels of belowground carbon storage, substantial access to open space, and low levels of poverty (forest green; N = 51) represented high functioning locations. These were somewhat sparsely found in locations along the coastline and the outer margins of the watershed.

4. Discussion

Our study aims to address the need for increased research on the provision of urban-coastal ecosystem services in changing landscapes, coupled with socio-economic data to evaluate consequences for environmental justice. Our study is unique in providing a multidimensional understanding to better manage historically undervalued natural areas in urban-coastal landscapes (Pregitzer et al., 2021).

4.1. Sea level rise projection and land cover change modeling

Our model, demonstrating climate-induced SLR and land cover impacts on carbon sequestration and storage ecosystem services in Jamaica Bay, provided perspective on local coastal vulnerabilities. Key findings from the model illustrated great exposure and limited adaptive capacity of ecosystems and services in urban-coastal environments to predicted changes. In particular, our model identified wetlands as a land cover feature contributing valuable ecosystem services, while under the greatest threat from SLR. We predicted that by 2100, wetland area in Jamaica Bay will decrease 17 % to 63 % based on 10th to 90th percentile projected SLR, respectively. Wetland loss and increased flooding risk due to SLR are not just local concerns; global SLR projections predict that 20 % to 90 % (low and high SLR scenarios, respectively) of the present-day coastal wetland area will be lost by 2100 (Schuerch et al., 2018). Loss of this vulnerable landscape has the potential to impact 40 % of the global population living within 100 km of a coastline (United Nations, 2017).

The implications of the predicted wetland loss for the Jamaica Bay study area are vast and will likely result in increased flooding, accelerated erosion, decreased carbon sequestration and storage potential, and habitat loss for wildlife species (Li et al., 2018). With the added pressure of SLR, increased use of green infrastructure and urban planning tools will be critical for guarding against loss of ecosystem services to climate change. Additionally, preserving and restoring land cover features of high value can secure benefits and play a key role in urban planning and policy development.

4.2. Ecosystem services quantification

A key finding from our study, in terms of ecosystem services quantification, is the extent of the impact that loss of wetland and other natural habitats is predicted to have on carbon cycling. The loss of these habitats has implications not just on ecosystem services but also in terms of social equity and environmental justice and begs the question: can we create new natural area upland habitat to compensate for these losses and if so, how can we locate these greenspaces in places that also address issues of social equity? Not all greenspaces are equal and those with greater ecosystem and social value might be at greatest risk for being lost. Specific to our study area, for many New Yorkers, urban natural areas are the only natural lands that people get to experience (Auyeung et al., 2016). This presents a planning challenge in conserving areas or thinking about the types of habitats that can replace those lost to SLR.

We predicted that total aboveground carbon storage and total belowground carbon storage will decrease 15 % and 51 %, respectively, in the Jamaica Bay watershed by the year 2100 given high rates of sea level rise due in large part to high (up to 63 %) predicted losses of wetlands and other natural coastal habitats. Should these results become reality, the implications would be detrimental to the future of carbon abatement as wetlands sequester and store carbon in their soils for periods of hundreds to thousands of years if undisturbed (Artigas et al., 2015). While wetlands comprise only 5–8 % of the Earth's surface, they store approximately 20–30 % of the global carbon pool (Bridgham et al., 2006).

With lost wetlands and other natural coastal habitat, the Jamaica Bay watershed will become more dependent on urban trees and urban grass/shrub as drivers of carbon sequestration. The rate at which sequestration operates is species and region dependent. For the Jamaica Bay watershed, we estimated total present-day carbon sequestration at 0.13 Tg C/yr. Fortunately, urban-coastal habitat boasts several of the most efficient carbon sequestering land cover types (urban trees, urban grass/shrub, and wetlands) with storage capacities that are comparable to native forests (Pouyat et al., 2006). Additionally, urban vegetation, soils, and even built infrastructure are carbon sinks (Pouyat et al., 2006). We estimated present-day total aboveground carbon storage at 3.1 Tg C and total belowground carbon storage at 11.4 Tg C for the Jamaica Bay watershed with spatial variation in the provision of ecosystem services across the watershed, a geographic phenomenon also found by Kremer et al. (2016b) in New York City.

Both aboveground and belowground carbon storage capacities in the Jamaica Bay watershed were predicted to be reduced through time, though the services of upland land cover (e.g., urban trees and maritime forest/shrub) should help to moderate the impacts of SLR. Urban trees and maritime forest/shrub are responsible for much of the aboveground carbon storage in the Jamaica Bay watershed. As a result, the impacts of SLR on aboveground carbon storage were less prominent than impacts to belowground carbon storage where wetlands and coastal grasslands play a larger role. However, long term research shows that maritime forest/shrub areas experience a loss of biomass and shift in community assembly when threatened with SLR and storm surge (Woods et al., 2021) with subsequent likely impacts on carbon sequestration and storage potential (Breithaupt et al., 2020), succession (Woods et al., 2021), and invasion by species such as *Phragmites australis* (Bhattarai & Cronin, 2014).

Some research has shown that accretion may help to compensate for land losses to SLR (Hill & Anisfeld, 2015) and thus potentially mitigate changes in ecosystem service flows over time. However, such responses may be variable across sites and dependent upon plant communities. By our calculations, accretion appeared to have limited capacity to reverse land loss in our watershed (Appendix A).

4.3. Spatial analysis of ecosystem services and socio-economic data to map environmental justice

Our models found that access to open space was very effective at discriminating among features in multivariate clustering analysis when used in combination with poverty and carbon sequestration and even more effective when aboveground carbon storage was used in place of carbon sequestration. It is challenging to determine exactly why we found these results but we submit that access to open space (summed areas of open space available within a 0.8 km walk from each census tract centroid) is a continuous variable, unlike percent poverty level, and thus may have provided more variability and power when used to discriminate among features in multivariate cluster analyses. Aboveground carbon storage and carbon sequestration are also continuous variables but both are fairly limited in their ranges and were weak at discriminating among features; however, belowground carbon storage, a metric with a wider range of possible values, was quite effective at discriminating among features providing more evidence for our theory.

Specifically, our models were able to identify, at the census tract scale, neighborhoods with low levels of predicted carbon sequestration or aboveground carbon storage, limited access to open space, and moderate to high levels of poverty (grey locations in Fig. 4a,b; red locations in Fig. 4b). In short, these are the areas predicted to be in high need. Spatially, these locations are further from the coast and more densely concentrated in Brooklyn than in Queens. The spatial distribution of these clusters is possibly driven by the availability of low income housing in these areas. This high need category of clusters represents opportunities for planning and restoration actions such as urban tree plantings, wetland restoration, increased access to open space, poverty relief programs and more. The inclusion of vacant lots to the spatial analysis may help to further identify where an infusion of resources may assist in conversion of these lots to open spaces which, in turn, would increase ecosystem services provision and enable additional access to open space in currently impoverished neighborhoods.

Our models also identified locations with moderate predicted belowground carbon storage potential, high access to open space, and low levels of poverty (forest green locations in Fig. 4c). In short, these are the areas predicted to be demonstrating success from an ecosystem services and socio-economic perspective. Spatially, these locations are along the coast or located in areas with adjacent parks (e.g. Prospect Park in Brooklyn). The spatial distribution of these clusters is possibly driven by the locations of vast areas of open space (e.g. Gateway National Recreation Area) alongside census blocks with low populations. This category of clusters of high environmental and social value represents challenges for planners and land managers who will need to guard against loss of open space land to development through conservation action. With increased open space acquisitions and wise management of current holdings these locations may shift to even higher levels of belowground carbon storage capacities. Their intermediate success may serve as a model for neighborhoods struggling to increase ecosystem services provision, access to open space, and reduction in poverty.

We demonstrated the use of Multivariate Cluster analysis with present-day data but this analysis could be repeated for future scenarios with predicted ecosystem services, predicted access to open space, and predicted poverty levels to simulate a variety of scenarios such as increased investment in open space through land acquisition, impacts of climate change, or economic shifts in neighborhoods.

4.4. Current and future land use planning and suggested actions

Current and future land use planning receives a lot of attention in the NYC DCP. Currently, across Brooklyn and Queens, many communities have been designated as resilient neighborhoods (Canarsie, Gerritsen Beach, Sheepshead Bay, Old Howard Beach, Hamilton Beach, Broad Channel, Rockaway Park and Rockaway Beach) in which planners have identified changes to zoning and land use to support the continued vitality of the areas, reduce the risks associated with coastal flooding, and ensure the long-term resiliency of the built environment (NYC DCP, 2022). The planning department is also promoting affordable housing preservation and development, encouraging economic development, creating pedestrian-friendly streets, and introducing new community resources to support the long-term growth and sustainability in the East New York neighborhood.

Our study results are directly applicable for future urban-coastal land use planning in this region. Landscape and urban planners can use the results of our study to identify important locations in which to respond to the effects of climate change and environmental justice in the following generalized ways: 1) clusters near the coast that the model identified as moderate to high in ecosystem service provision and with high access to open space are good quality locations; from a planning perspective these are low priority in terms of near-term need but action should be taken to mitigate long-term potential impacts. These areas are likely to be locations with natural vegetation and low population density which are expected to experience increased impacts from SLR. These areas are currently performing well but may be prioritized for actions that promote storm surge wave attenuation and/or coastal vegetation expansion (NPCC, 2019) to mitigate long term SLR impacts. Such actions may include cultivation and protection of salt marshes (Möller et al., 2014) and local assisted expansion of coastal upland vegetation such as grasslands and maritime shrubland/successional maritime forest (Meixler et al., 2020). For instance, our results may help to inform the plan for Broad Channel and Gerritsen Beach such that areas with increased projected SLR impacts are left undeveloped or encouraged to return to more natural habitat; 2) clusters near the coast that the model identified as low in ecosystem service provision and with low access to open space are high need locations; from a planning perspective these are high priority in terms of near-term need and action should also be taken to mitigate long-term potential impacts. These areas, many of which are under current development and have been classified as resilient neighborhoods, are also likely to experience the adverse affects of SLR and may be prioritized for strategic relocation programs for people currently living in floodplains (NPCC, 2019) coupled with restoration of the coastal land to more natural habitat and changes to zoning and land use designations. For instance, in Rockaway Park and Rockaway Beach, our results may help to identify locations where zoning and land use changes would help to increase resilience to flooding; 3) inland clusters that the model identified as low in ecosystem service provision and with persistent socio-economic issues are high need locations; from a planning perspective, these are high priority in terms of near-term need but are less at risk for long-term potential impacts than are coastal locations. These locations are candidates for neighborhood-based climate adaptation projects such as open space land acquisition, particularly in areas with currently vacant land, greenspace quality improvement projects (Herreros-Cantis and McPhearson, 2021; Hoover et al., 2021), affordable housing preservation and development, and economic development/anti-poverty programs. For instance, our results may help to find vacant lots in the East New York neighborhood that might be candidates for conversion to open space; or the model may locate low income areas where affordable housing may be developed with access to currently existing open space; and 4) inland clusters with moderate to high ecosystem service provision and low socio-economic need are high functioning locations; from a planning perspective, these are low priority in terms of near-term need and are less at risk of long-term potential impacts than are coastal locations. These areas may have been so successful due to former urban-coastal planning initiatives that involved continued local ownership of adaptation responses and application of collective actions across space and over time (Hurlimann et al., 2014). In our watershed, Sheepshead Bay, Canarsie, and Gerritsen Beach have been designated as resilient neighborhoods; our model may be used to identify locations within the inland parts of these neighborhoods where cooperative action may help to preserve the high quality of these areas.

Our findings suggest that programmatic, social, engineering, and nature-based adaptive initiatives will be important to urban planning efforts that aim to successfully respond to climate change in ways that are socially and environmentally sustainable (Kremer et al., 2016b; NPCC, 2019) and assist in determining candidate locations for these initiatives.

4.5. Limitations and future research

There are a variety of limitations inherent in modeling ecosystem services at the watershed scale. Due to its scale, our model must oversimplify complicated ecological interactions in aboveground and belowground vegetation and soil which may alter the ecosystem services predictions. Temporally, we projected over a long time span which allows room for variables not included in our model to change the development direction of factors of interest. Also, our model only considers static impacts of SLR on ecosystem services and not flooding and coastal inundation, which would affect areas well beyond sea level and may have a significant impact on urban tree growth and mortality (Hallett et al., 2018). Similarly, our model assumed no changes to the landscape (e.g. development, restoration, management) other than SLR. Additionally, there are limitations in using ecosystem services coefficients from other studies since, despite our attempts to use local and regional values, microscale differences in land use and land cover distributions could impact carbon sequestration rates and storage amounts (Kremer et al., 2016b). Terrestrial and wetland ecosystems will shift to marine ecosystems when flooded in the future. We used a coefficient of 0.007 kg/C to reflect the belowground carbon stored in marine ecosystems (Postlethwaite et al., 2018) however this might be a low estimate. Uncertainties exist surrounding coefficient rates and values (Chmura, 2013) and thus ecosystem services coefficients can vary depending on the source utilized. Further, estimates are skewed by sampling protocol (Pregitzer et al., 2021). For instance, our model doesn't consider carbon values from downed woody debris, litter, and standing deadwood; specific site type understanding is needed, but not necessarily available, and this understanding will have impacts on measured carbon benefits and scenario planning (Pregitzer et al., 2021). Our calculations of distances from census tract centroids to open space locations use euclidean distance metrics instead of the street network that people would follow if walking, cycling or driving. Our calculated values thus likely underestimate the actual distances to open space locations. However, as we were calculating a single open space access metric for the entire census tract centroid, a euclidean distance based value would suffice. Finally, data do not exist to determine the true accuracy of our model projections and thus validation remains a great future challenge. It is our expectation that data will become available in the future for these purposes. While acknowledging the limitations and assumptions that went into our model estimations, we note that others have used similar approaches (McPhearson et al., 2013a; Kremer et al., 2016b) and that our estimates still reveal the potential for SLR to impact urban-coastal ecosystem services. Further research in this area is necessary.

Opportunities to elaborate on our research objectives could incorporate additional environmental impacts in calculating ecosystem services including tidal ranges, storm surge, and extreme winds, factors that have been observed in Jamaica Bay (Swanson & Wilson, 2008). Additionally, a broader suite of ecosystem services could be modeled including air pollutants and urban species movement and function as a result of climate change (Kremer et al., 2016b; Meixler et al., 2020). For our socio-economic assessment, additional variables could be included from the United States Census Bureau's American Community Survey such as age structure, educational attainment, and disability. Understanding directions of change allows management to strategize appropriate responses at scales which promote ecosystem resilience. Also related to scale, fine-scale census blocks or blockgroups may be used in place of census tracts to gain a more nuanced understanding of socio-economic function at appropriate scales for local planning and management across the watershed.

5. Conclusions

Urban ecosystems are important in terms of provision of ecosystem services, yet historically they have not been adequately incorporated into landscape and urban governance and planning for resilience (McPhearson et al., 2015). Our model was designed to estimate present and future carbon sequestration and storage in an urban-coastal watershed across a varied landscape of cover types. We found that sea level rise induced land loss was predicted to be concentrated in low lying coastal habitats and that future losses in carbon sequestration, aboveground, and belowground storage potential will be up to 0.16 %, 15 %, and 51 %, respectively. Urban trees and forested natural areas were predicted to sequester and store the most carbon. Our ecosystem services results coupled with socio-economic data identified clusters for climate change mitigation and enhanced environmental justice. Our model provides a structure that can be adapted for any coastal city or heterogeneous landscape given the availability of regional ecosystem services coefficients. Continued use of models such as ours will be imperative to identify high value landscapes and areas for conservation, restoration, creation of inland wetland habitat, and natural resource management. Our work thus provides a viable strategy for urban planning to address environmental justice inequities and improve urban-coastal resilience.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2022.104659.

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