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Research Paper

New York City 2100: Environmental justice implications of future scenarios for addressing extreme heat

Maya Dutta[a], Pablo Herreros-Cantis[b,c,d], Timon McPhearson[d,e,f], Ahmed Mustafa[d], Matthew I. Palmer[a], Mika Tosca[g], Jennifer Ventrella[d], Elizabeth M. Cook[h,*]

[a] *Department of Ecology, Evolution, and Environmental Biology, Columbia University, New York, NY, USA*
[b] *Basque Centre for Climate Change (BC3), 48940, Leioa, Spain*
[c] *Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona (UAB), Cerdanyola del Vallès, Spain*
[d] *Urban Systems Lab, The New School, New York, NY, USA*
[e] *Cary Institute of Ecosystem Studies, Millbrook, NY, USA*
[f] *Stockholm Resilience Centre, Stockholm University, and Beijer Institute of Ecological Economics, Royal Swedish Academy of Sciences, Stockholm, Sweden*
[g] *Solarpunk Project, Chicago, IL, USA*
[h] *Environmental Science Department, Barnard College, 3009 Broadway, New York, NY, USA*

HIGHLIGHTS

- NYC stakeholders co-produced future scenarios for urban resilience to extreme heat.
- Business-as-usual land development reinforces existing environmental injustices.
- Co-produced green infrastructure scenario increased heat mitigation by 108%
- Co-produced green infrastructure scenario increased flood mitigation by 55%
- Anticipatory urban planning can address climate resilience and environmental justice.

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ABSTRACT

Climate-driven hazards, such as extreme heat or precipitation, are threatening the current and future livability of New York City (NYC) and disproportionately affecting low-income communities and communities of color. To envision future climate resilience, government stakeholders and researchers co-produced future scenarios for 2100 in response to climate hazards for NYC during participatory workshops in Fall 2021. A commonly co-produced strategy included urban green infrastructure (UGI) because of its potential to retain runoff and provide cooling benefits. We ask, what are the potential environmental justice implications of ecosystem services provisioned from UGI distribution in the co-produced NYC future scenario compared to a business-as-usual future scenario? To analyze potential outcomes and tradeoffs, we integrated spatially-explicit UGI strategies into simulated land use and cover models. We then assessed two ecosystem services (flood and heat mitigation) using the spatially-explicit tool Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST). We explored potential environmental justice implications by comparing the provision of ecosystem services to sociodemographic indicators within census block groups between scenarios. Presently, ecosystem services are disproportionately lower for communities of color, including predominantly Asian, Black/African-American, and Hispanic/Latino communities. In future scenarios we found ecosystem service provision will decrease within these communities under business-as-usual land development. The future scenario co-produced for extreme heat resilience, however, shows an increase in overall provisioning across NYC, including in neighborhoods with a high proportion of people of color. Our results show that co-produced future scenarios can be used to inform strategic future planning for inclusive adaptation decisions to improve future climate resilience and justice.

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* Corresponding author.
E-mail address: ecook@barnard.edu (E.M. Cook).

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1. Introduction

1.1. Climate change, environmental justice, and the future of cities

Climate-driven hazards threaten the current and future livability of cities, with marginalized communities facing disproportionate risk and vulnerability (Dodman et al. 2022; Pelling & Garschagen 2019). The resilience of cities to climate hazards—such as extreme heat or precipitation—is uniquely challenged by density and diversity of people, infrastructure, and landscapes interacting with legacies of unjust land use (Frantzeskaki et al. 2019; Hölscher et al. 2019). In response, cities are implementing strategies to adapt to extreme climate events (Chu & Cannon 2021). The efficacy, however, depends on a city's ability to integrate equity and uncertainty into planning given urban areas face a range of plausible futures with varying implications for climate resilience and justice (Balk et al. 2022; Grabowski et al. 2023).

Climate projections indicate a high likelihood of increased frequency, intensity, and duration of weather-related hazards (Dodman et al. 2022; Solecki & Rosenzweig 2019). Impacts of climate hazards—ranging from health and financial burdens to the loss of lives and homes—are not experienced equitably (NYCEM 2019; Ratcliffe et al. 2020). In U.S. cities, urban development rooted in racial-capitalism and settler-colonialism, undergirding practices including redlining, zoning, and public housing distribution (Rothstein 2017), has produced unjust cities. From an environmental justice lens, unjust cities, in part, entail a disproportionately high exposure to environmental hazards yet simultaneously lower allocation, function, and quality of greenspaces for communities of color and low-income communities (Hoover & Lim 2021; Nyelele & Kroll 2020; Schell et al. 2020; Taylor, 2014). Environmental justice in cities is uniquely shaped, amplified, and challenged by density, spatially varied land use, and limited affordable resources (Wamsler, Brink, & Rivera 2013). Despite these legacies, planning efforts do not systematically explore potential future justice implications of climate planning decisions (Anguelovski 2016).

To equitably address the impacts of future hazards, cities must take an integrative, anticipatory approach to long-term climate resilience and justice planning (Chu & Cannon 2021; Muñoz-Erickson et al. 2021). Anticipatory planning provides cities the opportunity to explore future scenarios—plausible and coherent future visions—that integrate systems thinking through co-production. Co-production entails a process for diverse stakeholders with pluralistic values—often including scientists, urban designers, decision-makers, and/or community members—to engage in planning, envision what future scenarios look like and how to implement them (Iwaniec et al. 2020a, 2020b; Pereira et al. 2018). Future-oriented planning is a tool to move past perceived present constraints, uncertain cycles of political will and "business-as-usual" scenarios, where cities continue on current trajectories without intentional shifts towards normative or radically transformative goals or values (Muñoz-Erickson et al. 2021). In an effort to address injustices, anticipatory planning can consider future unknowns, identify pathways to reach desired outcomes, and explore potential outcomes and unintended tradeoffs of decisions to allow for adjustment (Berbés-Blázquez et al. 2023).

1.2. Urban green infrastructure and ecosystem services

Given the complex challenges climate change brings to cities, management often incorporates strategies with potentially wide-reaching benefits (Frantzeskaki et al. 2019; Hölscher et al. 2019). One increasingly popular multifunctional strategy to enhance climate resilience includes urban green infrastructure (UGI) (Grabowski et al. 2022; Gómez-Baggethun & Barton 2013; Hansen et al. 2015). UGI integrates ecological and technological-engineered infrastructure (Grabowski et al. 2023) through the restoration, connection, and/or design of green space to provide benefits to human well-being (Herreros-Cantis & McPhearson 2021; McPhearson 2022). UGI is conceptualized in diverse ways and, depending on desired outcomes, can consist of green roofs, tree canopies, and parks with diverse features (Francis and Jensen, 2017; Langemeyer et al. 2015; Matsler et al., 2021; Nyelele et al. 2019). UGI is particularly appealing due to its ability to provide benefits to people, referred to as ecosystem services. For example, runoff retention and cooling can be increased through the implementation of UGI. Ecosystem services have become an important framework to plan and measure the climate resilient benefits of UGI (Geneletti et al. 2020; Hansen et al. 2015). Current UGI, however, may not be enough to cope with climate change (O'Neill et al. 2022).

Environmental justice research suggests past unjust urban development practices are associated with present spatially embedded disparities of UGI in cities (Schell et al. 2020). Studies in New York, San Antonio, and Chicago found communities of color and/or low income communities have less access to UGI, such as tree canopy (Nyelele & Kroll 2020), and associated ecosystem services, such as flood and heat mitigation (Yi et al., 2019; González et al., 2022; Herreros-Cantis & McPhearson 2021). There is a need to increase equitable distribution, quantity, and quality of ecosystem services for current and future generations (Yi et al. 2017; Nyelele et al. 2019).

UGI's capacity to locally supply ecosystem services makes it a relevant strategy to advance environmental justice, prevent future harm, and lessen severity of climate hazards (Hoover et al. 2021). Yet, despite recorded environmental injustices, municipal planning and prioritization approaches for UGI do not systematically consider its spatially-explicit, future justice implications following implementation, often attributed to lack of adequate governmental mechanisms (Chu & Cannon, 2021; Hoover et al. 2021; Hoover et al. 2023; Grabowski et al. 2023). In the near-term, municipal climate-related investments are prioritized among a broader scope of other capital investments, where a multitude of factors at the present time must coalesce for a project to be funded, designed, and implemented. In this context, justice-oriented UGI planning often focuses on whom the project would benefit if implemented today, rather than through its asset life. Yet, understanding the future spatialities of UGI implementation is important so as to not magnify existing inequities or produce new injustices. Understanding future UGI can help preemptively plan to mitigate green gentrification, where implementation absent of other interventions can push out communities due to rising costs and changing neighborhood character (Jimenez & Maantay 2023). Given the inequitable distribution of UGI from past decisions (Schell et al. 2020), we must comprehensively plan and implement UGI to provide ecosystem services to lessen current and future injustices (Kabisch and Haase 2014; Rigolon et al. 2018).

2. Research objectives

Our research aims to understand how the anticipatory planning of a multifunctional land use strategy—UGI—can contribute to alleviating environmental injustices and mitigating climate hazards in cities. We ask: what are the potential environmental justice implications of ecosystem services provisioned from UGI in a co-produced future scenario compared to a business-as-usual future scenario? We answer this by: (1) assessing capacity of UGI to provision flood and heat mitigation across current (2016), business-as-usual, and co-produced for climate resilience future (2100) scenarios using spatially-explicit models; (2) assessing the change of ecosystem service provisioning from UGI between current and alternative future scenarios; and (3) assessing the potential environmental justice tradeoffs of ecosystem services across current and alternative future scenarios.

3. Methods

3.1. Co-producing future scenarios in New York city

We use New York City (NYC) as a case study. NYC is the most populous city in the United States, with over 8.8 million residents in a

Table 1

Co-produced goals and strategies to address heat resilience envisioned by participants in co-production workshop (Fall 2021). Each strategy that addressed spatially explicit land cover was translated into an additional modeling rule for the cellular automata (CA) land use land cover (LULC) model. Modeling rules describe the transition rules for every 4x4m cell from one land cover (e.g., mixed use urban) to another (e.g., open space).

Co-produced heat resilience goals for 2100	Strategies to address goals as described by participants in visioning workshop	Translation of spatially explicit strategies into LULC modeling rules
(1) Eliminate heat related illness and mortality, and (2) Minimize and reuse waste heat sources and at same time maximize city green and blue infrastructure (vegetation and water features)	**Increase green corridors along roadways** – 50% of street parking spaces are repurposed by 2025 to green space/street trees – No private street parking by 2035 – Reclaim curb space for green infrastructure (less parking, fewer cars) by 2035	1. Narrow streets by adding green corridor. Allow transition to urban green/forests corridors along streets by 2030; allow 8 m for green corridors on streets <4 lanes and 4 m corridors on 2 lane streets
	Increase water features for evaporative cooling (misters or ponds) – 15% of neighborhood space includes water features	2. Allow transition from vegetation classes to water in medium and low density residential (minimum area set to 5x5m (25 m^2))
	Ensure that all New Yorkers are well-served by green and efficient public transit – Expanded access to people-based, better networked public transit – Car free zones (financial district), 80% reduction in truck traffic – Bike infrastructure prioritized over private cars with >50% travel lanes for bikes – More subways, Bus Rapid Transit, & better network	3. Car free zones created by transition from streets/ impervious to green space (park) –- prioritize major intersections >4 lanes near major transit hubs; include intersections in all boroughs
	Increase green infrastructure throughout city, especially heat vulnerable areas – By 2025, funding for street trees, green roofs, & green infrastructure in vulnerable areas – By 2030, 2% city budget to green space – By 2035, new street tree bed designed for stormwater capture – By 2040, reclaim curb space for green infrastructure (less parking, fewer cars) – By 2050, 50% increase in street trees – By 2060, 90% of roof space is green or solar – By 2065, all street tree beds include stormwater capture – Increase green space & natural infrastructure (including green facades) by 50%	4. In addition to rule 1 (above), increase transition to green space from urban/residential, increase forest patches along roadways/street corridors to represent 50% increase of street tree, increase transitions to urban green roofs (using statistical regression based on lot size & income for where green roofs are likely to happen)
	Increased shade / canopy cover throughout city – Update codes to include shade requirements in new construction, plazas, open space – 50% of open space is shaded	5. In addition to rule 4 (above), transition from open space to forested for shade.
	Target neighborhoods based on NYC Heat Vulnerability Index (HVI) and map*	6. Start with HVI neighborhoods for green space transitions. In 2050, open transitions to full city. – apply this to rule for increase in street trees – increase in water features – increase in transition from urban to green space

* HVI data publicly available: https://a816-dohbesp.nyc.gov/IndicatorPublic/data-features/hvi/.

total area of 783.73 km^2 making up five boroughs (Manhattan, Queens, Bronx, Brooklyn, and Staten Island). Climate hazards pose a risk to NYC, including flooding and extreme heat (NYCEM 2019). The New York Panel on Climate Change (NPCC) high range projections suggest mean annual temperatures could rise by more than 3.5 °C and mean annual precipitation could increase by 17% by the 2050s (Braneon et al. 2024; González et al. 2019).

To envision a future NYC resilient to climate hazards, we collaborated with the NYC Mayor's Office of Climate and Environmental Justice to lead the NYC Climate Adaptation workshop series. Local, state, and federal NYC government stakeholders from 24 agencies (Supplementary Material (SM) Table 1) attended five 2.5-hour virtual workshops in Fall 2021 consisting of anticipatory planning activities to address climate resilience. We invited government representatives specifically with the goal to bridge silos and foster cross-agency climate resilience and adaptation discussion and planning. Through these workshops, participants co-developed six future scenarios for NYC 2100 to address climate hazards, including one addressing extreme heat. The goal of scenario building was to envision positive and resilient futures, different from typical business-as-usual approaches, by radically transforming social, ecological, and built infrastructure for a long-term, future NYC. The year 2100 was chosen to create an uncommon space for more transformative, long-term visioning and goal setting that isn't constrained by current circumstances. Following methods in Iwaniec et al. (2020a) and Cook et al. (2022), in the first workshop, participants worked in small groups (approximately six people representing diverse agencies/sectors, plus a trained facilitator who guided the activities) to define long-term goals for their scenario in 2100 (e.g., eliminate heat-related illness and mortality by 2100). In the following workshop, participants continued to work in the same small groups and used backcasting approaches to co-develop implementation strategies (e.g., expand UGI throughout vulnerable neighborhoods) needed to achieve their scenario's goals (Box 1). The remaining workshops focused on activities to refine the details on spatial locations, timelines, and governance approaches to achieve the goals (Table 1) as well as engage collective feedback from other groups. In this paper, we assess the extreme heat scenario as heat is the deadliest climate-related hazard in New York City (Matte et al. 2024), and UGI has measurable benefits for cooling in cities.

Box 1

Workshop participants co-developed a vision of NYC in 2100 that is resilient to rising temperatures and extreme heat. The future scenario addresses two main goals of (1) eliminating heat-related illness and mortality, while (2) minimizing and reusing waste heat sources and maximizing UGI. Heat-related illness is reduced through micro-cooling centers, regulations for outdoor workers and indoor temperatures, and increased community health programs. The scenario maximizes the UGI and water features, including 50% shaded open space and 50% more green corridors by 2100, reclaimed curb space for tree canopy, 25% of neighborhood space includes water features, and 90% of retrofit and new roof space is green or solar by 2060. The scenario minimizes new energy use by reducing or reusing heat waste (e.g., from air conditioning) due to updated building codes, passive or low-energy building design and materials, and required green roof retrofits (more details and timelines can be found in Cook et al. 2022).

3.2. *Future land use land cover simulations*

In order to explore outcomes of the envisioned future, projections of land use and land cover (LULC) were simulated for the co-produced 2100 heat scenario and a 2100 business-as-usual scenario. Following methods from Mustafa and colleagues (2018, 2021), the projections are simulated from a multi-objective Markov Chain Monte Carlo (MO-MCM) cellular automata (CA) model, which divides the spatial area into a grid of cells and each cell's LULC evolves over discrete annual time steps based on predefined rules and the states of neighboring cells. The base CA model was trained with data from 2002 and 2016 MapPLUTO land use classifications at a 4-m spatial resolution to estimate the rate of change from one land use state to another at each timestep. The model also accounts for population and geophysical variables, such as elevation, slope, and road networks, that were generated at or resampled to 4-m resolution to align with MapPLUTO data (SM Table 2).

Building on this base CA model, the models for business-as-usual (BAU) and the co-produced scenarios project future LULC change. The BAU scenario was modeled as a baseline or point of comparison for the co-produced scenario in 2100 (similar to Ahmadisharaf et al. 2020; Bolliger et al. 2008). The BAU model represents a continuation or extrapolation of recent (2002–2016) LULC trends—projected to 2100—based on the quantity of changes from one land use class to another and the spatial locations of observed changes (Fig. 1, panel 1). The co-produced scenario LULC projections also build upon the base CA model, but incorporate additional modeling rules that represent the heat-related spatially explicit strategies developed during the workshop. The scenario's co-produced timelines were used to determine the transition rates of respective changes and modeling rules, following methods from Ortiz et al. (2021). The additional modeling rules account for biophysical (e.g., 30% increase in tree cover along roadways by 2100) and/or infrastructure changes (e.g., repurpose 50% street parking by 2030). (Fig. 1, panels 2–4; Table 1).

Both the BAU and co-produced models are simply projecting future LULC changes. In our case, the model does not aim to predict how NYC will look in the future, as it does not capture future socio-political dynamics, such as gentrification, nor incorporate demographic projections or potential climate change influences to the LULC, such as sea level rise. However, the LULC models allow us to explore the consequences of potential decisions on the distribution of future ecosystem services (described in section 2.2). The output of scenario modeling consisted of LULC maps for each scenario, consisting of 14 types for the 2100 BAU and 18 types for the 2100 heat scenario, where an additional four types were included to differentiate buildings with green roofs (SM Fig. 1).

3.3. *Ecosystem service assessment*

We assessed the capacity of UGI in NYC to supply two ecosystem services: flood and heat mitigation. To quantify this, we used the Integrated Valuation of Ecosystem Services 3.12.0 (InVEST) toolset (Natural Capital Project 2022), a spatially-explicit open-source modeling software that provides biophysical estimations of ecosystem service supply. InVEST for urban ecosystem services have been thoroughly presented in other studies such as Hamel et al., 2021. Here, we briefly describe its use and functioning and provide extended materials in SM 1.1 and 1.2.

3.3.1. *Flood mitigation*

The InVEST Urban Flood Risk Mitigation model calculates the capacity of UGI to retain runoff during a specific storm event (Natural Capital Project 2022). Based on land use characteristics across NYC including runoff potential (SM Table 3; USDA 2004) and soil type, we calculated the m^3 of runoff retained during a 24-hour, 5-inch (127 mm) rain event, as an example of a present extreme (approximately a 100-year event) storm (SM Section 1.1; González et al. 2019). Each scenario's raster output (4-m pixels representing runoff retention volume in m^3) was aggregated by averaging values within the census block groups (CBG) to compare runoff retention and sociodemographic variables.

3.3.2. *Heat mitigation*

The InVEST Urban Cooling model calculates the capacity of urban green infrastructure to cool the surrounding area. For this model, land use class characteristics on shade, evapotranspiration, albedo, and distance from large greenspaces (SM Table 4) were used to model the heat mitigation index (HMI). HMI is a unitless measure that represents cooling capacity and represents the proportional capacity of a pixel to cool relative to the maximum urban heat island effect observed in NYC (SM Section 1.2; Natural Capital Project 2022). The output rasters (4-m pixels representing HMI) were aggregated and averaged to the CBG scale to compare the HMI and sociodemographic variables.

3.4. *Environmental justice indicators*

To evaluate environmental justice and ecosystem services in New York City, we aggregated 2020 sociodemographic variables (SM Table 5) at the CBG scale, the smallest shared spatial scale among sociodemographic variables. We recognize demographic distributions may change by 2100, however most population projections are short-term, do not always incorporate sociodemographics, and do not exist at a fine enough spatial scale for meaningful analysis (Balk et al. 2022). Thus, future population projections add another layer of uncertainty to our analysis. Instead, we evaluate how future land cover and UGI changes by 2100 may impact current community demographics. Furthermore, municipal UGI planning largely considers present populations for implementation justification—rather than future populations—allowing us to provide realistic methodology.

New York City has 6391 inhabited CBGs; we compiled information from both the decennial census and American Community Survey (ACS) estimates (Herreros-Cantis and McPhearson, 2021). With the 2020 census, we calculated the proportion of individuals living in a CBG identifying as white, Black and/or African-American, Hispanic and/or Latino, and Asian (the predominant racial/ethnic categories) using the Tidycensus package in R (4.1.2). Using the 2016–2020 ACS 5-year estimates (U.S. Census Bureau n.d.) and Tidycensus package (Walker & Herman 2023) in R (4.1.2), we compiled and calculated the proportion

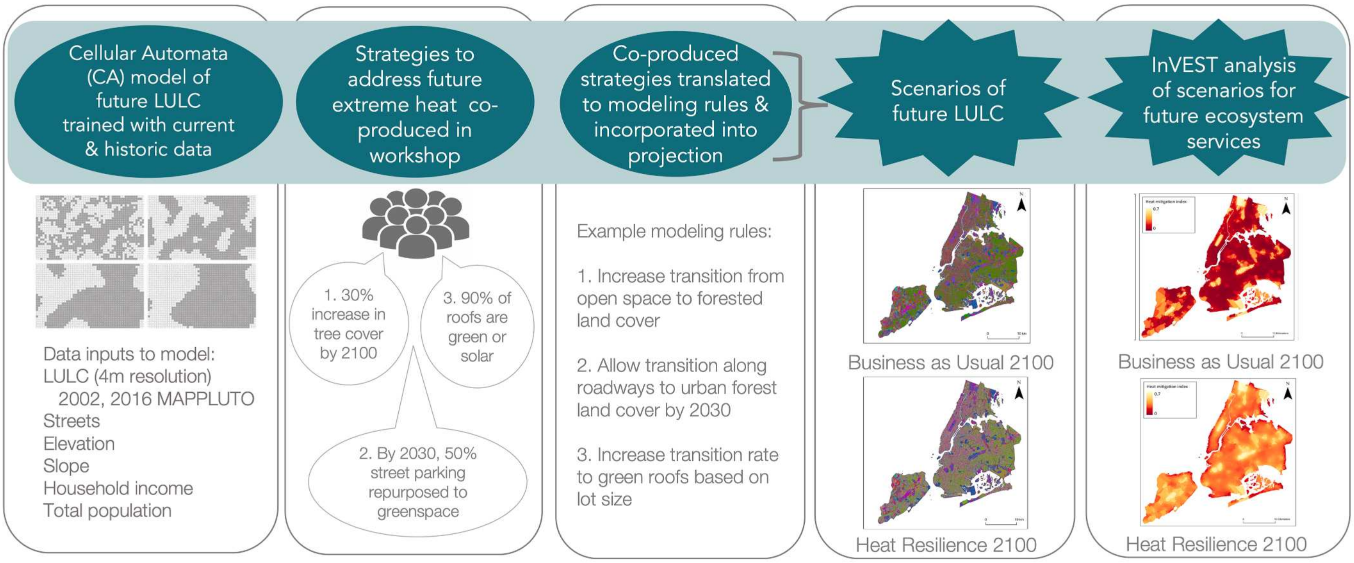


Fig. 1. Schematic of developing the future scenario LULC outputs and InVEST analysis of future ecosystem services. The multi-objective Markov Chain Monte Carlo (MO-MCM) cellular automata (CA) LULC model was trained (following Mustafa et al 2018) with 4-m resolution LULC data, along with other baseline data, to project the 2100 Business-as-Usual LULC output. Additional modeling rules were added based on the co-produced strategies to address heat resilience in order to project the 2100 Heat Resilience LULC output. The LULC outputs feed into Urban InVEST ecosystem service models. Additional details on LULC classes in SM Fig. 1 and how workshop strategies were translated into modeling rules in Table 1.

of individuals per CBG for the remaining sociodemographic variables: percent in poverty, female-headed households, uninsured health coverage, no internet access, low educational attainment, and renters (SM Table 5). All data were incorporated into the geographic boundaries of NYC CBGs obtained from the TIGER/LINE database via the U.S. Census Bureau (n.d.).

3.5. *Environmental justice implications of ecosystem services*

We evaluated the environmental justice implications of flood and heat mitigation across scenarios by assessing how sociodemographic variables predict ecosystem service distribution in NYC through stepwise regression modeling. Ordinary least squares (OLS) and geographically weighted regression (GWR) models can be employed as an exploratory mechanism to examine how particular sociodemographic indicators correlate with environmental benefits or burdens (Gilbert & Chakraborty 2011; Schwarz et al. 2015; Yu et al. 2023). The OLS regression models represent global relationships of environmental justice across a dataset, in our case highlighting the subset of sociodemographic variables important in predicting ecosystem services regardless of spatial distribution. The second step GWR provides additional understanding of how citywide relationships, as established in the OLS, may vary across space.

For the stepwise modeling, we first conducted a Spearman's correlation test to explore relationships between the predictor sociodemographic variables (Yi et al., 2019). If two sociodemographic predictors showed a relationship of 0.5 or greater, the two variables were not initially included in the same regression model (Shaw et al. 2023). We then employed ordinary least squares (OLS) regression models, using a forward and backward stepwise approach and selecting the model with the lowest Akaike Information Criterion (AIC). We added sociodemographic variables previously removed due to correlations equal to or greater than 0.5 and kept them in the model if the AIC of the model decreased and the variance inflation factors (VIF) did not exceed 5 (Snee, 1973). OLS are based on an assumption of stationarity and homogeneity–or, that the global parameters behave identically across the study area (Mennis 2006). The OLS best fit models served to identify the combination of sociodemographic variables that best explained the range of ecosystem service values across NYC. Given the co-production process focused on making NYC more heat resilient as a single geographic region, this analysis provides us information on the factors that impact citywide justice and ecosystem service outcomes.

To account for the spatial variability within the study region, we followed the OLS with a GWR. We conducted a local Moran's *I* test on the OLS models and confirmed spatial autocorrelation across the scenarios—indicating the global OLS models and their associated environmental justice predictors may vary across NYC. Therefore, we also employed GWR using the spgwr package (Bivand & Yu, 2022) in R (4.1.2) to explore local variability within NYC. The OLS regression equations are the basis for this process where GWR analyzes a given regression equation separately across optimal numbers of CBGs within NYC, defined using an adaptive kernel (Gilbert & Chakraborty 2011).

3.6. *Change in environmental justice implications*

We assessed tradeoffs between scenarios by comparing the changes in ecosystem service provisioning between the present and future scenarios and their potential implications for environmental justice. We created "delta maps" showing the difference in current to future service provisioning capacity (e.g., 2016 raster − 2100 BAU raster for each ecosystem service) and calculated the mean delta value at the CBG level. Comparisons were conducted between 2016 and BAU and 2016 and the heat scenario. We then conducted a Spearman's correlation test to explore a baseline of association with sociodemographic variables, culminating in a forward and backwards stepwise OLS regression using the same AIC and VIF approach as stated above. We focused on citywide relationships for this analysis to explore the overall trends in temporal changes.

4. Results

4.1. *Spatial distribution of ecosystem services*

4.1.1. *Flood mitigation*

Our results show spatial variations in the capacity of UGI to mitigate flooding during an extreme storm (5-in. over a 24-hour period, Figs. 2 & 3) across scenarios. While the mean runoff retention in CBGs across NYC does not vary drastically between 2016 NYC and 2100 BAU NYC (0.33-

m^3 to 0.34-m^3), the 2100 co-produced heat scenario mean runoff retention increases by 55%, to 0.58-m^3, compared to 2016 Table 2). The majority of CBGs do not drastically change positively or negatively in runoff retention between 2016 and 2100 BAU NYC (mean = 0.00+/-0.07-m^3; Table 2), whereas the majority of CBGs increase (mean = 0.25+/-0.1-m^3; Table 2) in runoff retention capacity from UGI between 2016 and 2100 co-produced heat scenario.

4.1.2. Heat mitigation

Our results show the capacity of UGI to mitigate heat in NYC varies spatially (Fig. 2) and between scenarios (Fig. 4). Where heat mitigation index is a unitless measure of cooling from vegetation on a scale from 0 to 1, and represents the proportional capacity of a CBG to cool relative to the maximum urban heat island effect observed in NYC, the spatial distribution of highest heat mitigation in NYC occurs in and surrounding large green spaces (such as Central Park in Manhattan and Forest Park in Queens). While the mean is 0.11 for both 2016 NYC and 2100 BAU NYC, the mean is 108% higher at 0.37 for the 2100 co-produced heat scenario (Table 2). In this co-produced scenario, HMI values are more evenly distributed compared to that of the other scenarios.

Comparing 2016 and 2100 BAU NYC, the majority of HMI values do not change across CBGs (Fig. 4). The range of changes across CBGs are at a greater magnitude gained than lost (Table 2). On the other hand, the majority of CBGs increase in HMI values between 2016 NYC and the 2100 co-produced scenarios (mean = 0.27+/-0.06; Table 2). A handful of CBGs on the boundaries of NYC, such as in Jamaica Bay and Staten Island, appear to make up the majority loss of heat mitigation capacity (Fig. 4).

4.2. Regressions for ecosystem service spatial associations

Our results illustrate unique associations between environmental justice and the distribution of ecosystem services in each scenario as well as change in provisioning between current and future scenarios. In total, our analyses resulted in 10 best fit relationships, as identified in the stepwise approach (five per ecosystem service, Table 3). Each best fit model had a different combination of environmental justice indicators (SM Section 2), where collectively all variables included in this study were significant in at least a subset of the models (Table 3). The most common indicators in the models included percent Asians, which predicted service provision in all the models, and percent renters and population density which were significant in all but two models (Table 3). Poverty, female-headed household, and no high school diploma were the least common variables in the best fit models.

Globally, the positive or negative relationship and magnitude of coefficients varied across models (Table 3). The 2016 and 2100 BAU heat mitigation OLS models contained the largest positive coefficients for the variables white, Hispanic/Latino, and Black/African-American (SM Table 6). Overall, sociodemographic variables related to racial/ethnicity were most commonly predictors across scenarios. Notably, the adjusted R^2 values for all OLS models are relatively small (Table 3, SM Table 7), indicating the environmental justice variables predict only up to 10% of variation in the ecosystem service models at the citywide scale. Our analyses illustrate relationships between environmental

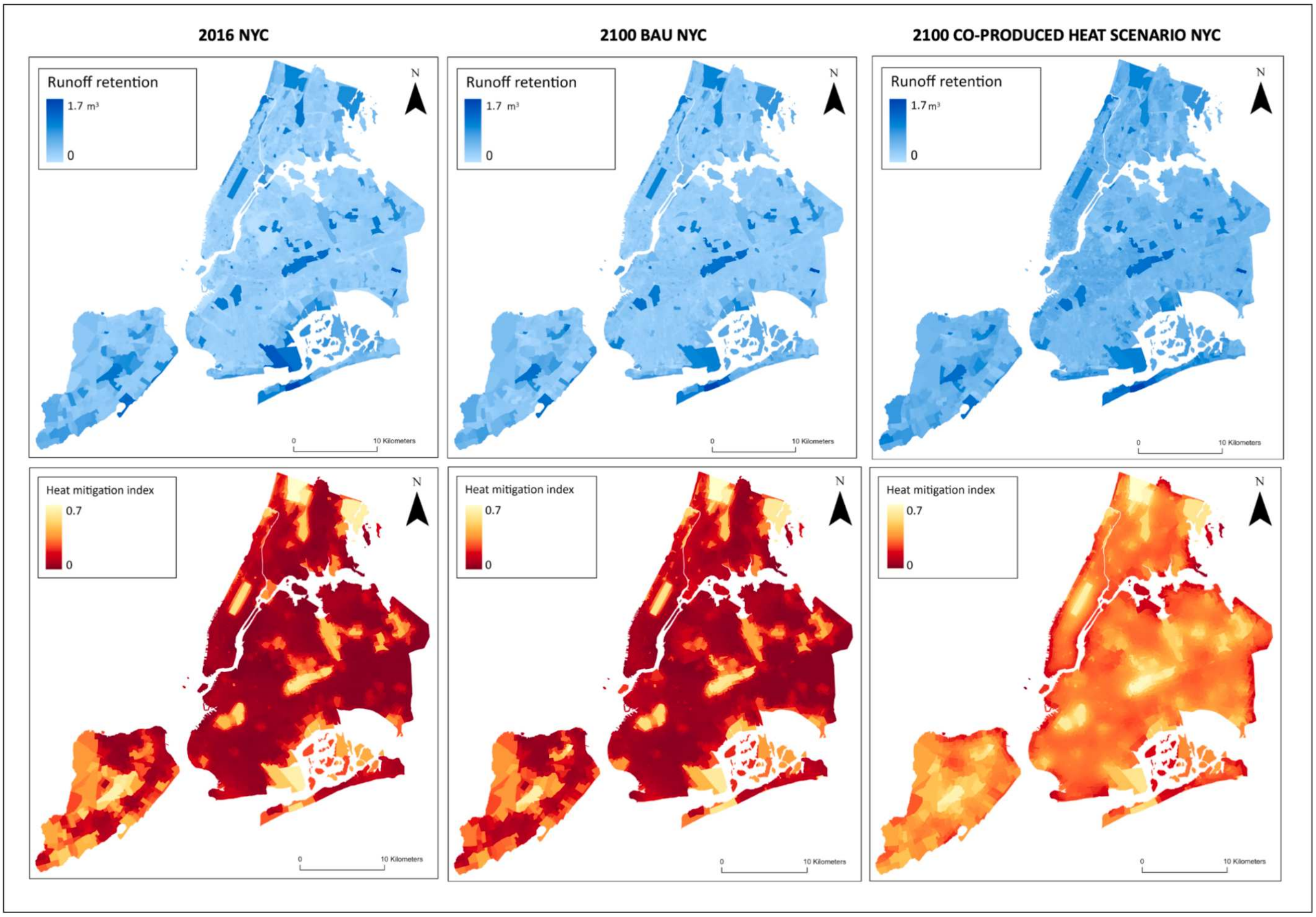
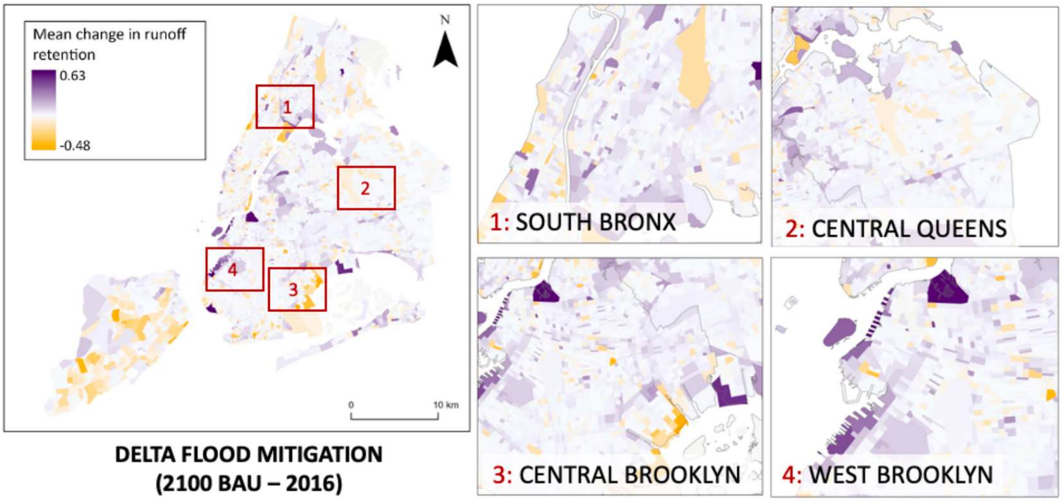
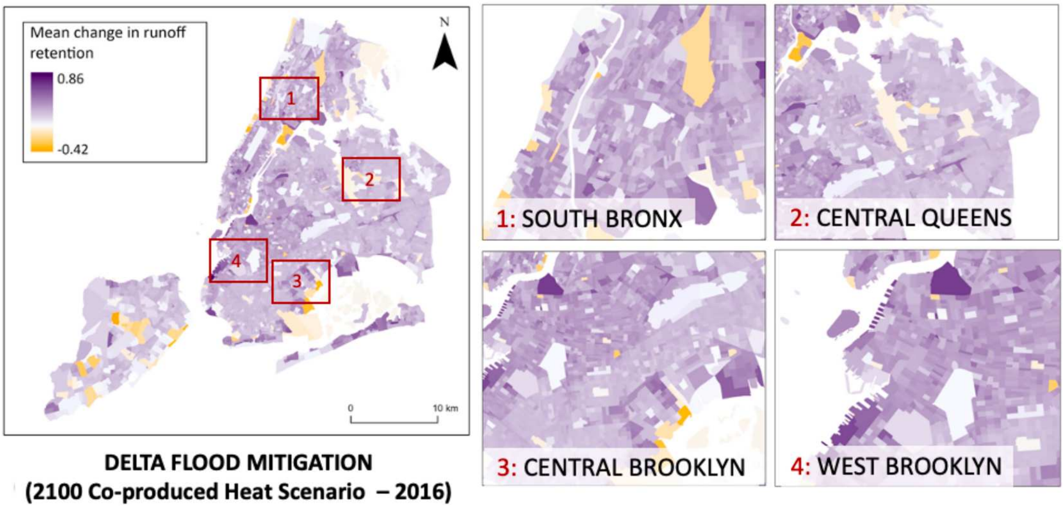


Fig. 2. Distribution of runoff retention (m^3, top panel) and heat mitigation (unitless, bottom panel) provisioned by UGI across three NYC scenarios (NYC in 2016, BAU in 2100, and co-produced scenario to address heat in 2100). Data presented as census block group's average runoff retention or heat mitigation capacity per 4-m^2 pixel.



DELTA FLOOD MITIGATION
(2100 BAU – 2016)



DELTA FLOOD MITIGATION
(2100 Co-produced Heat Scenario – 2016)

Fig. 3. Change in mean runoff retention capacity across census block groups between 2016 NYC and 2100 BAU NYC (top panel) and between 2016 NYC and 2100 co-produced heat scenario (bottom panel). Negative values (orange) indicate a lower capacity of ecosystem services in the future, and positive values (purple) indicate higher future capacity. Zoomed in areas (clockwise) highlight key NYC neighborhoods with service change and varying predominant demographics, including 1: predominantly Hispanic/Latino and Black/African-American; 2: predominantly Asian; 3: predominantly Black/African-American; 4: predominantly white. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

justice and ecosystem services, but indicate sociodemographics are not the main drivers of provisioning at the citywide scale.

To better understand how the global regression models varied across space, we used geographically weighted regressions (GWR) to explore the spatial heterogeneity of relationships between ecosystem services and sociodemographic variables across NYC. The GWR models for flood and heat mitigation did not fully account for spatial clustering in the models, however, they did reduce the spatial dependence in the residuals from the OLS models in most cases and improved performance (global R^2) across models (Table 4). Specifically, the GWR models detected locally varying associations across space given the global regression models identified through the OLS approach. Our results show a range of spatially strong and weak associations (local R^2) for both ecosystem services across CBGs per scenario (Fig. 5, SM Table 8). Overall, the GWR models most strongly predict flood (adjusted $R^2 = 0.57$) and heat (adjusted $R^2 = 0.92$) mitigation in the 2100 co-produced scenarios, compared to their respective 2016 and BAU scenarios (Table 4). Given stepwise process, similar environmental justice predictors are important in the GWR models as the OLS models (SM Table 8). However, the GWR results highlight spatial variation, where for example the strongest relationships (highest R^2) for flood mitigation and sociodemographic variables occur in coastal areas of south Brooklyn and Queens and northern Manhattan and the Bronx (Fig. 5). The strong relationships between heat mitigation and sociodemographic variables are more evenly distributed across NYC (Fig. 5). Across GWR models, the range of coefficients (SM Table 8) is greatest for the race/ethnicity variables, compared to other sociodemographic variables, such as no education, renter, and health insurance status. This coefficient range highlights how race/ethnicity groups may specifically experience high variation in access to UGI throughout the city in a given scenario. For example, while some Asian communities would be associated with higher access to UGI from the proposed strategies in the co-produced scenarios, there will be other locations where Asian communities will experience lesser access to UGI given land use changes.

5. Discussion

The increase in frequency and severity of climate-driven hazards in cities necessitates the strategic planning and implementation of solutions that benefit the communities and locations most at risk (Chu & Cannon 2021). Urban climate resilience efforts, however, rarely take a long-term planning approach or develop shared, positive visions to then explore potential tradeoffs ahead of implementation (Cook et al. 2022; Iwaniec et al., 2020a; Meerow 2020). Our research seeks to fill this gap by assessing how the anticipatory planning of UGI can contribute to both the alleviation of environmental injustices and climate hazard

Table 2
Descriptive statistics of ecosystem services and environmental justice indicators across census block groups. For the rows describing change in ecosystem services between 2016 and 2100 scenarios, negative values indicate a reduction of future service capacity, while positive indicates an increase in capacity.

	Min	Max	Mean (Std. dev)
(1) Flood mitigation (m^3)			
NYC 2016	0.1	1.66	0.33 (0.1)
2100 NYC BAU	0.07	1.69	0.34 (0.09)
2100 NYC Heat	0.07	1.69	0.58 (0.13)
BAU − 2016	−0.48	0.63	0 (0.07)
Co-produced heat scenario − 2016	−0.42	0.86	0.25 (0.1)
(2) Heat mitigation index (unitless)			
NYC 2016	0.03	0.68	0.11 (0.08)
2100 NYC BAU	0.04	0.7	0.11 (0.08)
2100 NYC Heat	0.09	0.74	0.37 (0.07)
BAU − 2016	−0.19	0.5	0.01 (0.03)
Co-produced heat scenario − 2016	−0.07	0.53	0.27 (0.06)
(3) Environmental justice indicators			
Asian proportion (%)	0	94	15 (18)
Black/African-American proportion (%)	0	91	20 (25)
Female-headed household (%)	0	100	35 (17)
Hispanic proportion (%)	0	96	28 (22)
No high school diploma, >age 25 (%)	0	42	3 (4)
No internet subscription at home (%)	0	100	13 (12)
Population density (people per CBG)*	4	8541	1311 (609)
Poverty (%)	0	100	13 (15)
Renter (%)	0	100	63 (29)
Uninsured rate for health insurance (%)	0	100	6 (7)

* CBGs with population density zero were removed from analysis.

mitigation in NYC. Our results highlight, however, not all communities may benefit equally given planned strategies, indicating need for additional planning interventions to address remaining environmental justice challenges.

Similar to other research assessing the present inequitable distribution of ecosystem services in NYC (Herreros-Cantis & McPhearson, 2021; Nyelele & Kroll, 2020; Nyelele, Kroll, & Nowak, 2019), we found present day (2016) ecosystem service provisioning in NYC is inequitably distributed. Communities of color and low-income communities are, overall, associated with lower access to ecosystem services provisioned by UGI, whereas wealthier and/or whiter communities have disproportionately high access. Given present day injustices and a predicted increased frequency and severity of climate hazards (González et al. 2019; Matte et al. 2024; Solecki & Rosenzweig 2019), it is critical to understand how future development and anticipatory planning may alleviate or reinforce these qualities.

Our twofold citywide and spatially-explicit regression analyses provide novel information on ecosystem service access and distribution across communities and among outcomes of potential future planning decisions. The results provides critical information needed to identify tradeoffs and avoid unwanted implication through comprehensive analysis prior to implementation. At a citywide scale, our results highlight how often racial/ethnic categories and renter status (a proxy for poverty) matter most for predicting service provision and changes in access today and in the future, depending on what action is taken. This is critical for planners and policymakers because decisions are typically informed given citywide trends observed. Yet, our spatially-explicit analyses highlight the importance of exploring how citywide trends vary among neighborhoods to avoid a narrative that perpetuates a monolithic experience of environmental injustice. For decision-makers identifying where to implement change under minimal resources, our results help answer where and for whom this can be done to ensure the biggest benefits are realized both citywide and locally.

More specifically, at the citywide scale comparing present (2016) and the future BAU scenario in 2100, our results reveal the average change for both heat and flood mitigation is zero. This suggests while UGI and associated services increased in some locations of the NYC BAU scenario, those services similarly decreased elsewhere, leading to no overall citywide cumulative change in service provisioning. Importantly, our results illustrate certain sociodemographic groups are associated with less and diminishing access to provisioning given BAU. Our citywide models on change in UGI from 2016 to BAU reveals Black/African American communities experience a loss in flood mitigation while Asian communities are associated with a loss in both flood and heat mitigation. We additionally see a loss in services for those without internet and health insurance. Our results exploring change between 2016 and BAU suggest such a development trajectory would not alleviate injustices and may exacerbate or reconfigure the uneven distribution of provisioning for some groups. Notably, the frequency, intensity, and cycles of recurring extreme hazards in NYC is expected to increase and systematically increase the overall vulnerability of NYC communities over time (Solecki & Rosenzweig 2019; Gallina et al. 2016). In this sense, our results may underestimate the severity of future hazards and over emphasize the capacity of UGI to provide ecosystem services during future extreme events.

However, comparing present (2016) and the co-produced, future scenario in 2100 at the citywide scale illustrates the promise of intentional, anticipatory planning for future climate resilience. The co-produced scenario reveals an average increase in both flood and heat mitigation in NYC. Interestingly, heat mitigation is greater than flood mitigation from UGI, suggesting variability of UGI to provide climate benefits. Overall, this work highlights how cross-sectoral, anticipatory planning can target a specific challenge in order to gain benefits for climate resilience overall and especially advances for extreme heat mitigation goals. Yet, still, those changes in climate resilience between present day and the co-produced future have divergent implications for communities. For example, Asian communities and those without internet or high school would lose access to flood services on average citywide while female-headed households, renters, those without health insurance, and predominantly white communities would gain access. On the other hand, for heat mitigation, we found a disproportionate increase in access for renters (proxy for poverty), predominantly Asian and Black/African-American communities, and those without internet. Overall, the citywide analyses indicate not all communities will benefit equally and the multidimensional nature of vulnerability. Overlapping systems of oppression and inequality, including limited economic, political, land, and social power, often contribute to climate vulnerability (Malin & Ryder 2018). While our analyses do not fully capture intersectional identities, the inclusion of a broader suite of environmental justice variables adds nuance in exploring how interlocking systems of oppression in NYC can harm communities through spatial access now and in the future. Planners and policymakers should consider these dimensions in cross-sectoral, anticipatory planning, design, implementation of future UGI for climate resilience.

Our spatially-explicit analyses reveal how citywide relationships as explored above vary locally—providing critical data for those decision-makers seeking where and for whom to implement UGI. In 2016, strong inverse relationships between environmental justice variables and ecosystem services may be indicative of underlying historic inequities and processes embedded in the urban fabric, such as redlining or disinvestment, still driving environmental injustices and present distribution of UGI (Hoover & Lim 2021). These are strategic locations for UGI interventions to lessen environmental injustices and inform where implementation could be prioritized today. Those areas with weaker associations between sociodemographic variables and service provision may be indicative of already succeeding, ongoing justice-based UGI interventions, such as increased greenspace within NYC Housing Authority properties or low-income areas. As we see in both the 2100 BAU and co-produced scenarios, the strength of relationships between environmental justice and ecosystem services vary over space—highlighting the redistribution of UGI may not fully disentangle past injustices. The outcomes of the co-produced heat resilience scenario can be a good starting point for planners to reevaluate where and when UGI

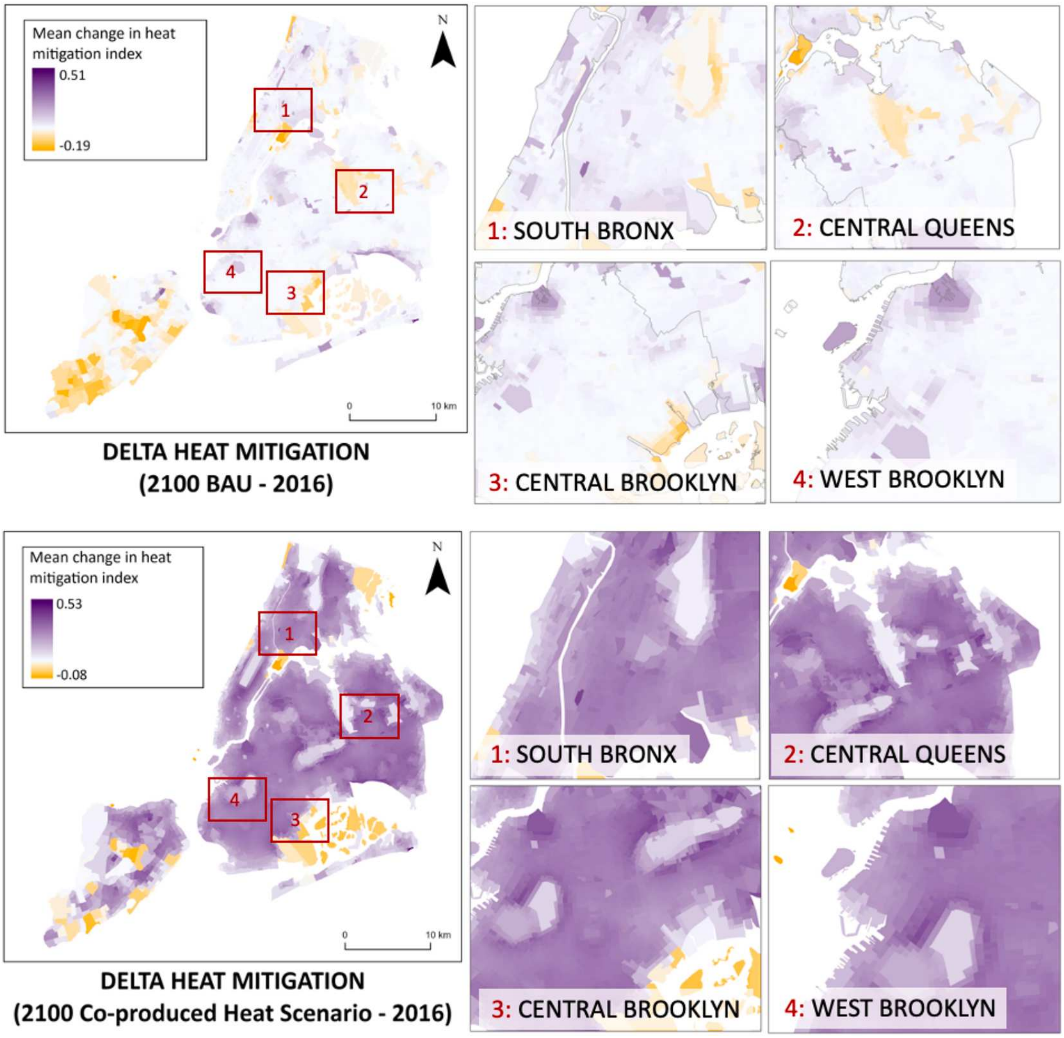


Fig. 4. Change in mean heat mitigation index capacity across CBGs between 2016 NYC and 2100 BAU NYC (top panel) and between 2016 NYC and 2100 co-produced heat scenario (bottom panel). Colors and insets as defined in Fig. 3.

implementation policies could occur, such that future planning decisions do not simply reconfigure injustices.

Previous studies primarily explore current or near term, but not long-term future, environmental justice implications of ecosystem services. Herreros-Cantis and McPhearson (2021) identified ecosystem service supply–demand mismatch for current populations in NYC. Additional studies have linked legacies of residential segregation to current inequitable allocation of green space (Rigolon et al. 2018) and tree canopy (Nyelele & Kroll 2020) for NYC communities of color. González and colleagues (2022)—applying InVEST models to explore current ecosystem services in the Chicago region—similarly found that communities of color were associated with fewer ecosystem services. Near-term future studies in Atlanta and San Antonio found that BAU scenarios projected to 2050 also reinforce existing inequities (Sun et al., 2018; Yi et al., 2019). In contrast, our research is novel as it builds on a participatory planning process and assesses the ways co-produced land use strategies for heat resilience may alleviate environmental injustices, which can act as a tool for decision-makers to assess locations that may require an adjustment in UGI implementation to avoid unwanted implications.

5.1. Planning considerations

NYC has institutionalized and prioritized climate resiliency planning and policy through multiple avenues within agencies. Past extreme hazard events, such as Hurricane Sandy in 2012, Post Tropical Cyclone Ida in 2021, and heat waves in the summer of 2022, which led to the loss of lives and property in NYC, have affirmed the salience of resilience planning. PlaNYC, NYC's climate plan updated every four years (NYC MOCEJ 2023), references UGI as a strategy to increase climate resilience. Though NYC maintains strong ambition for UGI—its planning, implementation, or maintenance is not consistently, or systematically, prioritized alongside citywide nor local variations in environmental justice implications. For example, the NYC Parks Community Parks Initiative and MillionTreesNYC (NYC Parks 2023a; 2023b), had social vulnerability served as a factor in implementation. Yet, Garrison (2021) showed MillionTreesNYC did not sufficiently prioritize underserved communities to a measurable degree due to the legacies of maldistributed greenspace. Future research and strategies must bridge theories of environmental justice into practice by forecasting potential implications–both citywide and locally–ahead of implementation to manage tradeoffs, redirect resources, or, at the very least, support transparent governance and communication (Garrison 2021). For example, future PlaNYCs can set the precedence for actionable environmental justice by convening stakeholders from multiple sectors in participatory settings and utilizing frameworks and participatory methodologies, such as ours, for anticipatory and spatially strategic planning with metrics to assess potential outcomes prior to implementation.

Anticipatory planning is critical to assess and limit unwanted tradeoffs. Settings to convene agencies across a wide range of

Table 3

Relationships between ecosystem service models and environmental justice variables for each best fit OLS model. Red arrows indicate negative relationships (as population variable increases, ecosystem service provision decreases) and green indicate positive (population variable and ecosystem service provision increases together). Thick arrows indicate absolute value of coefficients ≥ 0.1 and thin arrows indicate absolute value of coefficients < 0.1; coefficient values in SM Table 5. Variables not included in best fit models are blank. FHH = female-headed households, NHS = no high school diploma, P = poverty, R = renter, NHI = no health insurance, NI = no internet, A = Asian, BAA = Black and/or African-American, HL = Hispanic and/or Latino, W = white, PD = population density.

Model	Adjusted R^2	FHH	NHS	P	R	NHI	NI	A	BAA	HL	W	PD
Flood mitigation												
2016	0.06	↑	↑		↓			↓		↓	↑	↑
2100 BAU	0.04		↑		↓		↓	**↓**	↓	↓	↓	↓
2100 co-produced heat scenario	0.06	↑			↑		↓	↓				↓
2100 BAU minus 2016	0.06	↑			↑		↓	↓		↑	↓	↓
2100 co-produced minus 2016	0.10	↑	↓		↑	↑	↓	↓			↑	↓
Heat mitigation												
2016	0.08				↓	↓	↓	↑	**↑**	**↑**	**↑**	↑
2100 BAU	0.09				↓	↓	↓	↑	↑	**↑**	**↑**	
2100 co-produced heat scenario	0.03			↓		↓	↓	↓	↓	↑		↓
2100 BAU minus 2016	0.04			↑	↑	↓	↓	↓	↓		↓	↓
2100 co-produced minus 2016	0.05				↑	↑		↑	↑			↓

Table 4

GWR model performance: Adjusted R^2 and AICc scores for the flood and heat mitigation.

GWR Model	Adjusted R^2	AICc
Flood mitigation, 2016	0.40	−14328.17
Flood mitigation, 2100 BAU	0.18	−13295.43
Flood mitigation, 2100 co-produced	0.57	−12509
Heat mitigation, 2016	0.87	−25318.9
Heat mitigation, 2100 BAU	0.65	−19827.78
Heat mitigation, 2100 co-produced	0.92	−24616.81

responsibilities in this context is essential given segmented municipal responsibilities. For example, urban greening has been linked to the rising rents and displacement of Black and low-income residents (Anguelovski 2016). Yet, agencies with the greatest capacity to implement UGI are distinct from agencies who can invest in complimentary social infrastructure. We emphasize the need to implement UGI alongside programs including community-led planning initiatives, affordable housing options that serve the most economically burdened individuals, and green jobs development and training, to ensure comprehensive climate resiliency and justice strategies that empower communities that both need and want these investments. Our study presents a methodology for assessing how UGI could advance distributional justice, but also informs and challenges decision-makers to consider where additional policy interventions may need to take place such that equitable investments do not simply reconfigure vulnerable communities over time (Jimenez & Maantay 2023).

There are additional important planning considerations in ensuring research contributes to alleviating environmental injustices practically. First, the results do not represent or necessarily serve as a proxy for the lived experience of the communities studied. While UGI is an important strategy to manage climate hazards (Gómez-Baggethun & Barton 2013), there are diverse values, needs, and preferences between UGI and individuals, which must be acknowledged and prioritized during planning (Grabowski et al. 2023; Hoover et al. 2021; Meerow 2020). Future scenario co-production therefore must authentically engage and include local communities (Hoover & Lim 2021). Additionally, ecosystem service valuations of biophysical units, if taken out of context, risk portraying UGI as neutral or disproportionately technocratic (Meerow 2020). Municipal planning and implementation of UGI is inherently political, with the capacity to spatialize and reify race-based inequities in cities. Future scenario analyses can therefore seek to address these nuances by further involving local communities in the evaluation of UGI interventions so that relevant quantitative and qualitative metrics are considered. For example, other studies have highlighted participatory mapping (Hoover & Lim 2021) and/or multicriteria decision modeling approaches (Kremer et al. 2016), which allow stakeholders to assign social-ecological weights across spatial layers for ecosystem service models to best represent, value, and assess tradeoffs for communities.

5.2. Research limitations

We assess ecosystem service capacity using spatially-explicit InVEST

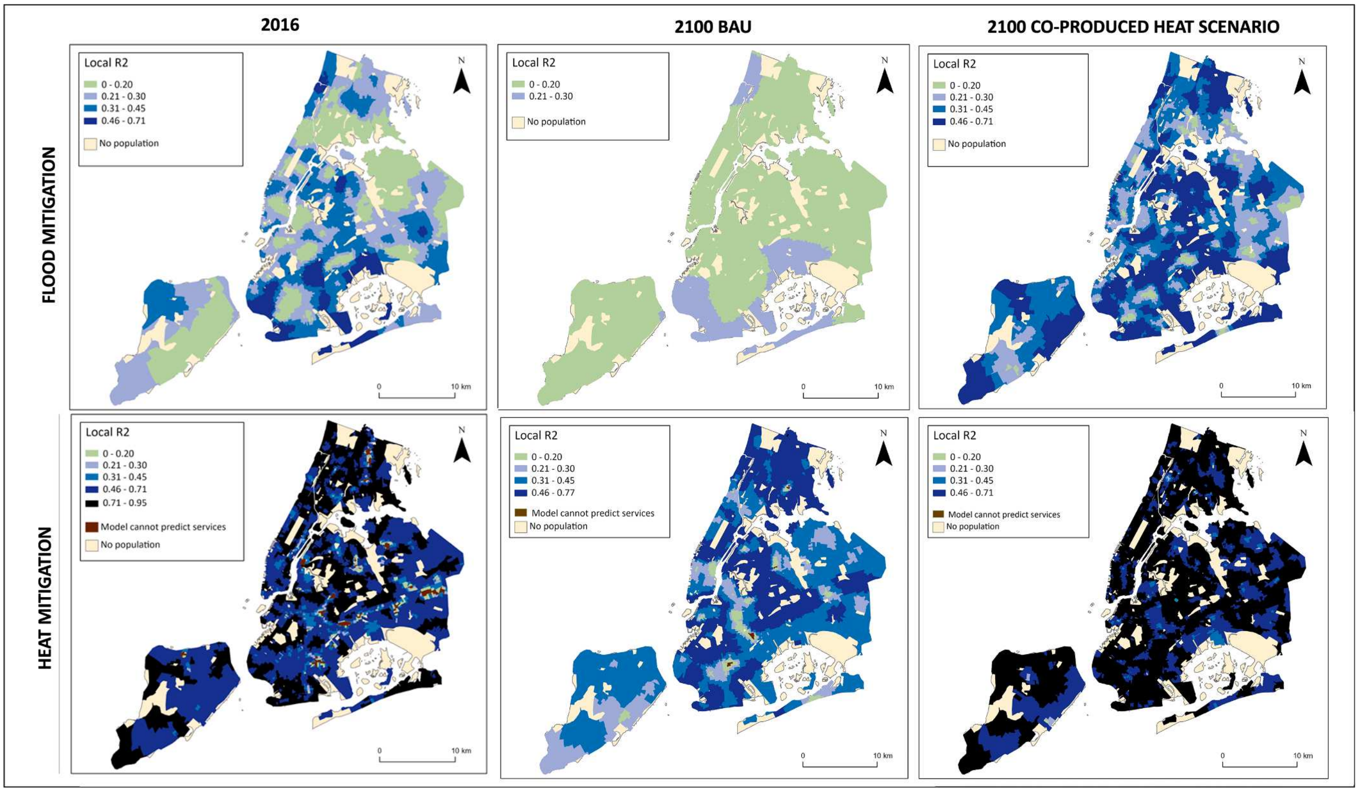


Fig. 5. Local R^2 for the geographically weighted regression models of flood mitigation (top panel) and heat mitigation (bottom panel) provisioned by UGI across three NYC scenarios (NYC in 2016, BAU in 2100, and co-produced scenario in 2100). Green represents lowest local R^2 (0–0.2) and darkest blue the highest local R^2 (0.71–0.95). Beige/brown contain no population or data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

models. The models illustrate benefits of UGI, but are simplifications of more complex urban processes and do not represent comprehensive planning tools. Similarly, the models do not explore the greater dimensions of a city's social and built infrastructure that can contribute to both an amplification of ecosystem services (McPhearson et al. 2022) and alleviation of climate hazard risk and injustice. Yet, the suite of InVEST and comparable models and methods are commonly used in urban ecosystem service assessments (Kremer et al. 2016; Hamel et al. 2021; Ochoa & Urbina-Cardona 2017) and can be easily implemented in other cities' planning and decision-making. Our methodology overcomes challenging barriers of more accurate but intensive models such as a lack of expertise, data requirements, and efficiency, which often impedes their use (Hamel et al. 2021).

Limitations in data resolution lead to assumptions and uncertainties. Specifically, data availability and spatial resolution of inputs to InVEST varied. Additionally, we used sociodemographic data from the 2020 census and 2016–2020 ACS 5-year estimates (U.S. Census Bureau n.d.) for assessing environmental justice implications in 2100 scenarios. There will be demographic shifts due in the future (Balk et al. 2022), and census data already has limitations, where low-income households and communities of color are undercounted (O'Hare 2019). We use the 2020 sociodemographic information as both a proxy to understand potential implications for future communities, and a practical use of how local governments use the sociodemographics of today to plan and implement UGI investments extending into the future.

6. Conclusion

Climate resilience and adaptation planning in cities rarely engages in cross-sectoral, long-term planning and transformative visioning. Moreover, it is critical to examine the future implications of the envisioned initiatives and the potential to mitigate future climate challenges and to do it equitably. Our study provides a New York City-wide and spatially-explicit understanding of the potential environmental justice implications of ecosystem services provided by UGI. Specifically, we explore how the provisioning of ecosystem services varies across BAU and a co-produced scenario integrating land use strategies developed in a participatory process by cross-agency decision-makers through positive visioning for climate resilience. In linking ecosystem services, environmental justice, and future planning through a geospatial lens, we illustrate that access to ecosystem services varies across development trajectories and is not spatially just or temporally constant. Results indicate that, overall, communities of color and low-income communities do not have equitable access to ecosystem services from UGI at present. And while BAU development may potentially further marginalize these communities through an exacerbated loss of access, co-produced land use strategies responding to extreme heat may minimize expected loss or even alleviate current injustices. Furthermore, identifying future spatial implications by comparing results with present day and spatially-explicit analyses on where and which communities are experiencing unjust distribution provides critical information for decision-makers to evaluate tradeoffs and revise strategies ahead of implementation to maximize efficacy. Many programs fail to implement participatory planning or evaluate the efficacy of land use strategies as they relate to environmental justice in their planning process—leading to what can exacerbate injustices and amplify climate risk in communities already bearing disproportionate burden. With this study, we bring future environmental justice goals to the forefront and illuminate how they can analytically be assessed and prioritized using spatial analyses to drive informed decision making. With these insights, the anticipatory planning of urban green infrastructure can identify planning pathways to achieve climate resilience and justice goals and best serve the location-based needs of communities now and in the future.

CRediT authorship contribution statement

Maya Dutta: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing - original draft, Writing - review and editing. **Pablo Herreros-Cantis:** Writing – review & editing, Methodology, Formal analysis. **Timon McPhearson:** Writing – review & editing, Resources, Methodology, Investigation, Funding acquisition, Data curation. **Ahmed Mustafa:** Writing – review & editing, Validation, Software, Methodology, Formal analysis, Data curation. **Matthew I. Palmer:** Writing – review & editing, Supervision. **Mika Tosca:** Writing – review & editing, Supervision. **Jennifer Ventrella:** Writing – review & editing, Methodology, Investigation, Data curation. **Elizabeth M. Cook:** Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

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.

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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.2024.105249.

Data availability

Data will be made available on request.

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