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Understanding climate gentrification and shifting landscapes of protection and vulnerability in green resilient Philadelphia

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ABSTRACT

As resilience strategies become a prominent orthodoxy in city planning, green infrastructure is increasingly deployed to enhance protection from climate risks and impacts. Yet, little is known about the social and racial impacts of such interventions citywide. In response, our study uses a quantitative and spatial analytical approach to assess whether interventions we call “green resilient infrastructure” (GRI) protect social groups traditionally most at risk and/or least able to adapt to climate impacts – or conversely, if the aggregate effect is maladaptive and inequitable outcomes (i.e. shifting vulnerability or climate gentrification). First, we performed a pre-post test of GRI siting distribution relative to socio-ecological vulnerability in Philadelphia neighborhoods. Second, we examined gentrification trends in relation to GRI siting and whether these interventions contribute to increasing the socio-ecological vulnerability of historically marginalized populations. Our findings point to a strong negative association between GRI siting and increased minority population, and a strong positive association between GRI siting, gentrification, and reduced minority population. The paper contributes to a better understanding of siting inequities and urban climate injustice dynamics and offers a new conceptual frame for critical urban adaptation research and practice of the pathways that shape uneven and unjust outcomes.

1. Introduction

As strategies to “build resilience” gain urgency and prominence in city planning, green infrastructure – rain gardens, green roofs, bioswales and climate-proof parks – are much heralded as a win-win solution for enhanced urban climate protection and security. These green climate adaptations are often highlighted for their economic and neighborhood attractiveness co-benefits in order to boost political salience and financial feasibility. Yet, as social-ecological resilience is frequently framed in the context of reducing vulnerability to “natural” disasters and extreme events, it is thus decoupled from the political-economic landscape of cities' historic and ongoing patterns of uneven and unsustainable growth. In this sense, urban adaptation may be repackaging “business as usual” land use planning practices that deprioritize the protection and security of vulnerable and minority residents, and reproducing uneven landscapes of social-ecological vulnerability.

In this paper we bring the critical adaptation planning and social-ecological resilience literature together with recent scholarship

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on urban green inequities and climate gentrification in order to analyze the extent to which green and resilient interventions protect vulnerable groups, or, on the contrary, result in new inequities and insecurities. Using data from Philadelphia, we examine how neighborhoods' social, racial, and real estate characteristics change over time in relation to the siting of green and resilient infrastructure, with a focus on processes of gentrification and increased vulnerability. Here, we seek to test whether social-ecological vulnerability is addressed by green and resilient infrastructure siting or if uneven conditions are reproduced, paradoxically rendering historically marginalized populations more vulnerable and less secure, while benefiting more privileged new residents. This paper contributes new understandings on urban climate justice and injustice dynamics.

2. Theoretical foundations

2.1. From climate adaptation to urban resilience

With cities increasingly dedicating planning and funding efforts to climate adaptation (Aylett, 2015; Carmin et al., 2012; Hughes, 2015; Woodruff and Stults, 2016), their attention on reducing vulnerability to and preparing for ongoing (e.g., global warming) and sudden (e.g., flash flooding) environmental risks and impacts (Dodman, 2009; Hughes, 2015; Huq et al., 2007) has grown more nuanced. In some cases, these efforts are also geared toward addressing differential climate impacts vis-à-vis social vulnerabilities, unequal rights and entitlements (Bulkeley et al., 2014; Eriksen et al., 2015; Hughes, 2015; Ziervogel et al., 2017). As such, climate adaptation is being folded into a larger umbrella of resilience planning and broad-scale governance of urban capacities to cope with an array of social, economic and environmental risks (Woodruff et al., 2018).

"Resilience thinking" for governance and planning has come to be seen as a comprehensive and multi-scalar way of reducing vulnerability and improving the capacity of systems to cope with multiple and diverse shocks and chronic disturbances (Coaffee and Clarke, 2015; Friend and Moench, 2013; Wilkinson, 2012). This is accomplished through risk-diffusing self-organization and decentralization combined with redundancy and flexibility, and through multi-functional and diverse interventions that might prevent entire system failures resulting from one component or single point failure (Folke, 2006, 2016). Thus, some scholars and practitioners view resilience as a necessary critical step along the way to a deeper, more structural and systemic transformation of social-ecological relations (Pelling, 2011).

2.2. The shift from grey to green to green resilience

Many adaptation programs start out as or are even conceived as non-adaptation programs and then reframed and remarketed to gain buy in and support (Bassett and Shandas, 2010; Carmin et al., 2012). Today, as part of urban climate adaptation planning, cities in the global North are increasingly deploying green infrastructure (Meerow and Newell, 2017), especially existing green stormwater management tools (Liu and Jensen, 2018) toward a new goal of building climate resilience. These more flexible and socially-oriented means of addressing climate change impacts and urban environmental risks are increasingly preferred (Ahern, 2013) to repairing traditional grey infrastructure (e.g., underground sewer systems, seawalls or levies), in particular for their lower-cost.

Widely defined as an "interconnected network of green space that conserves natural ecosystem values and functions and provides associated benefits to human populations" (Benedict and McMahon, 2001, p. 5), green infrastructure (GI), such as parks, gardens, greenways or green roofs, is meant to achieve strong ecological *multifunctionality* while making cities more livable (Kabisch et al., 2016; Pauleit et al., 2011; Young et al., 2014). Among the manifold *co-benefits* of exposure to green spaces are those to health and wellbeing (Douglas et al., 2017; Triguero-Mas et al., 2015; Tzoulas et al., 2007) and to greater inclusiveness and social cohesion, especially through participatory and community-based greening (Connolly et al., 2013; Haase et al., 2017). Meanwhile, urban investment in green adaptive measures is touted as good economic sense based on demonstrated rises in real estate values (Heckert and Mennis, 2012; Immergluck, 2009) around greened spaces and to green job creation. In other words, urban green infrastructure is perceived as a *cost-effective* (Ahern, 2007), *pragmatic* approach for resilience planning (Lennon and Scott, 2014; Palmer et al., 2015) making it more politically feasible to implement.

Despite claims that green infrastructure provides city decision-makers with a "no-regrets solution" to climate adaptation (Mees and Driessen, 2011), a "win-win" with the lowest tradeoffs, the jury is still out as to who benefits (Anguelovski et al., 2016; Gould and Lewis, 2018; Haase et al., 2017). Indeed, there is growing evidence that the benefits of adaptation flow primarily to entrenched political and economic interests (Sovacool et al., 2015) and that "competitive resilience" strategies may generate concentrated protection zones (Teicher, 2018). Even though mapping and modeling tools help identify hotspots for GI investment (Kremer et al., 2016; Meerow and Newell, 2017), GI siting-decisions may lead to perverse outcomes for vulnerable residents despite efforts to ensure equal distributions (Heckert and Rosan, 2018; Mabon and Shih, 2018). Displacement and gentrification are especially virulent social impacts that undermine calls for socially and ecologically transformative aims (Chu et al., 2017).

2.3. From critical climate adaptation to climate and resilience gentrification

Research on green and environmental gentrification has shown that new green amenities and environmentally revitalized brownfields can create conditions favorable to the exclusion and displacement of the most vulnerable residents (Dooling, 2009; Essoka, 2010; Pearsall, 2010). This work draws away the neutralizing veneer of technocratic and economic valuation approaches to infrastructural siting decisions (Finewood et al., 2019) and exposes how urban sustainability planning can contribute to gentrification and displacement via redevelopment strategies that revalorize stigmatized neighborhoods (Checker, 2011; Gould and Lewis, 2017). Green beautification tactics may even be perceived by socially vulnerable groups as "green locally unwanted land uses (green LULUs)" (Anguelovski, 2016).

While scholarly research on climate adaptation and climate justice has engaged with questions of equity and vulnerability of low-income populations (Carmin et al., 2012; De Sherbinin et al., 2007; Huq et al., 2007), most of this attention has been focused at the global or national scale (Bulkeley et al., 2014), with the idea of a double inequity or double injustice: the poorest groups or nations, least responsible for climate change are those made most vulnerable to its impacts (Füssel, 2010; Gough, 2011). The poor are also often faced with a third injustice in which they are the least likely to benefit from climate adaptation and mitigation efforts while paying disproportionately for them (Anguelovski et al., 2016; Roberts and Parks, 2007).

At the city-scale, the uneven terrain of urban adaptive and protective infrastructure remains relatively under-examined (Shi et al., 2016). There is an under-problematized and depoliticized promotion of green and resilient solutions as inherently good and beneficial for all (Anguelovski et al., 2018a; Brown, 2014; Fainstein, 2015; Ziervogel et al., 2017), often overlooking historic and ongoing racial inequalities (Hardy et al., 2017). However, GI, such as trees, may even face the resistance of low-income and minority residents when histories of urban development and disinvestment give rise to the perception that they will be burdened with its maintenance (Carmichael and McDonough, 2019; Lyytimäki et al., 2008). Emerging studies on GI adoption by residents, even less costly ones, find that income is a significant barrier to uptake and implementation (Baptiste et al., 2015; Newburn and Alberini, 2016) contributing to uneven results. Indeed, GI siting may simultaneously have adaptive and maladaptive effects – protection in one urban area can generate more risk in another and disproportionately burden the most vulnerable residents (Barnett and O'Neill, 2010; Juhola et al., 2016). Recently, critical scholars are pointing out how these asymmetric outcomes compound deeply rooted environmental inequalities (Garrison, 2017) and generate green landscapes of pleasure and privilege for a few and new riskscapes for others (Anguelovski et al., 2018a; Connolly, 2018).

New empirical studies also link a high risk of sea-level rise with “climate gentrification” in elevated urban areas, and suggest that resilience investments may drive gentrification in more socially vulnerable neighborhoods (Keenan et al., 2018). Resilience gentrification might therefore represent a “dual process of urban greening and structural mitigation of climate change threats, [with] resilience [being] equated with wealth, and the sustainability class emerg[ing] as the new urban elite” (Gould and Lewis, 2018, p. 13). Gould and Lewis' argument suggests extending the existing research focus on increased property values to the actual displacement of (historically) marginalized peoples (Anguelovski et al., 2018a), and to the analysis of how the greening of cities paired with climate resilience actions may ignore and even undermine the long-term security and livelihoods of the most vulnerable residents (Ranganathan and Bratman, 2019; Zografos et al., 2014).

While recent scholarship on urban greening and climate adaptation problematizes security in terms of differential climate impacts or unequal protections or adaptive capacities, new studies have yet to (a) operationalize the impacts of climate protective land-use measures on human security at the city level in the context of green resilience gentrification, and to (b) investigate the specific forms and patterns of urban change that emerge. This paper is focused on addressing these gaps. In the next section, before delving into our research design, we present Philadelphia's green resilience efforts, as a critical case to examine green resilience planning, and possible resulting inequities and gentrification.

3. Philadelphia's green resilience turn

By the late 1990s, Philadelphia began considering new green landscaping measures to tackle chronic watershed issues in response to dramatic changes to U.S. Federal environmental regulations including cuts to grey infrastructure grants and fines for the breaching of stormwater limits (Environmental Protection Agency, 1994; Pollock, 1991; Tibbetts, 2005). Despite once having an avant-garde XIXth century combined sewer overflow system (CSS) (US Environmental Protection Agency, 2004), currently, during major storms experienced at least annually, the CSS allows pollution from storm-water runoff and wastewater overflow into the same streams from which drinking water is sourced. Coupled with the presence of vast non-porous surfaces, Philadelphia has also experienced frequent and costly flooding and expects a mid-century sea level rise of between one and three feet and an end-of-century sea level rise of between one and six feet (Phil. Office of Sustainability & ICF, 2015). Along with chronic subsidence due to sewer line breaks and the swelling of buried streams, Philadelphia's CSS has given rise to health and safety concerns for nearly the whole XXth century.

The Philadelphia Water Department (PWD), renamed Philadelphia Water (PW), has since the early 2000s embarked on a mission to tackle flooding, stormwater runoff, drinking water pollution, and wastewater overflow with green interventions that by the early 2010s became a major milestone in watershed planning in the United States (Liu and Jensen, 2018). The city's program created a broad scope of data collection methods, green stormwater practices, and citywide public-private partnerships to dramatically reduce 85% of the contamination in combined sewer areas (PWD, 2009), as well as to mitigate urban heat island effects and air pollution. In 2006, a major flood episode prompted a citywide sense of urgency to better control overflows (Madden, 2010). Their cost-effectiveness and multi-functionality in the context of reductions to federal grey infrastructure funding made GI especially appealing to the cash-strapped city.

Indeed, following decades of deindustrialization, suburbanization, population decline, and widespread land pollution and abandonment (Adams, 1991; Cooke, 2003), there was an effort in the early 2000s to promote green stormwater interventions for both beautification and better water management. When in, 2009, Philadelphia's mayor released the *Greenworks* sustainability plan, he declared that Philadelphia would become the greenest city in America and outlined a broad array of urban greening projects with particular emphasis on economic benefits to boost the city's revival. Two years later in 2011, Philadelphia adopted the signature *Green City, Clear Waters* (GCCW) plan (PWD, 2009),[1] setting in motion a 25-year citywide landscape-based approach to stormwater management, also claiming a host of economic advantages, at a lower cost to the city. Back then, Philadelphia was still a city in

[1] Also the Combined Sewer Overflow Long-Term Control Plan Update

recovery, with 40, 000 vacant lots, an ailing economy (Heckert and Mennis, 2012) and in some areas violent crime was rapidly rising (Brownlow, 2006); meanwhile, other areas that were faring better had started to gentrify (Hwang, 2016).

In this vein, the PW program claimed to provide co-benefits by: addressing a lack of attractive green spaces in schoolyards, improving residential and commercial streetscapes, revitalizing parks, and contributing to cleaning up its vacant lands which have been associated with crime and property value decreases (Heckert and Mennis, 2012). It also emphasized the benefits of reducing climate risks and impacts such as warmer and wetter weather and diminished air quality. Now, green infrastructure (GI) in Philadelphia has been associated with health and safety co-benefits, including lower rates of narcotics possession (Kondo et al., 2015), and increases to property values in moderately-distressed neighborhoods (Heckert and Mennis, 2012). Nevertheless, with real estate prices soaring in many central neighborhoods, advantages may not be experienced evenly or equitably by Philadelphia residents.

3.1. Philadelphia's green infrastructure programs for stormwater management

Many PW interventions prioritize high visibility projects and, wherever possible, complement ongoing greening programs, but are also selected based on individual leadership or community petitioning (Dalrymple, 2018; Heckert and Rosan, 2018; Madden, 2010). Specific green stormwater management practices include green roofs, rain gardens, bioswales, and tree trenches in combination with other non-vegetated "green" measures including pervious pavements and sub-surface infiltration tanks.[2] With this suite of tools, engineers may overcome most localized environmental and technical constraints (Christman et al., 2018; Philadelphia Water, 2015), in contrast to single GI intervention programs such as MillionTreesNYC and MillionTreesLA (Garrison, 2018), and facilitate their installation throughout the Combined Sewer System on both public and private lands.

The showcase Big Green Block project[3] completed in 2013 in West Kensington and Fishtown – 20 acres (approximately 8 ha.) of vacant land converted to include a LEED Platinum certified high school facility, dog park, athletic field, and new paths to local public transit – is one recent example of maximizing partnerships and visibility while capturing 95% of stormwater runoff from the area. It is also an example of the PW's partnership with groups like the Pennsylvania Horticultural Society to identify vacant lands[4] for new or improved green spaces. Similarly, the Green Parks[5] and Green Schools[6] programs partner with Philadelphia Parks & Recreation, local schools and others to utilize public green spaces, playgrounds, recreation centers and schoolyards to reduce overflows and climate risks.

Furthermore, as part of the Philadelphia Rain Check program,[7] small-scale products are offered to homeowners for purchase, such as rain garden kits and downspout planters, engaging private individuals in improving neighborhood aesthetics and property values while cost-sharing in reducing urban environmental risks. Lastly, stormwater management regulations for new development and major retrofits, as well as parcel-based stormwater fees and grants incentivize both residential and nonresidential properties to install green stormwater infrastructure (Mandarano and Meenar, 2017) and reduce impervious surface areas. In these ways, the GCCW program leverages private investment, which also raises the issues of income, land rights and capital as key constraints in the uptake of green resilience-building interventions (Baptiste et al., 2015; Newburn and Alberini, 2016), ones that will be reproduced as these programs continue unfolding.

3.2. A new climate adaptation plan with the same green tools

Growing Stronger: Toward a Climate Ready Philadelphia – released in 2015, became the first report on the city's climate change adaptation planning process which began in 2012 (Philadelphia Office of Sustainability, ICF International, 2015). The Mayor's Office of Sustainability (MOS) in partnership with the city's Climate Adaptation Working Group (CAWG), other city departments and external consultants created the report to identify climate risks and impacts and existing climate resilient strategies. The plan deploys many of the same green stormwater interventions in existence since the early 2000s as low-barrier adaptation options intended to reduce vulnerabilities and protect vulnerable populations.

In sum, Philadelphia has gained nationwide status as a model for wide-scale urban green stormwater infrastructure (Liu and Jensen, 2018) and seems to be successfully layering a new green and resilient identity over one of the most racially and economically segregated cities in the US. What has received little or no focus, however, is how the distribution of the nearly 1200 green stormwater interventions relates to shifts in Philadelphia's uneven landscape and who benefits from these ecological protections and amenities in the long run. We therefore argue that because identical green stormwater management tools were incorporated into Philadelphia's

[2] For comprehensive descriptions of the city's various GI tools, see: Philadelphia Water, "Green Stormwater Infrastructure Design Requirements and Guidelines Packet," Philly Watersheds. Philadelphia Water Department, May, 15, 2015, http://phillywatersheds.org/doc/GSI/GSI_Design_Requirements_&_Guidelines_Packet_5-15-2015.pdf. (accessed on July 26, 2019)

[3] For information about this particular Big Green Block, see: New Kensington Community Development Corporation, "About us: Big Green Block," http://www.sustainable19125and19134.org/about-us/big-green-block. (accessed on July 30, 2019)

[4] See: Philly Watersheds (PW), *Green Vacant Land*, http://www.phillywatersheds.org/green-vacant-land. (accessed on July 30, 2019).

[5] See: Philly Watersheds (PW), *Green Infrastructure Programs: Green Parks*, http://www.phillywatersheds.org/what_were_doing/green_infrastructure/programs/green-parks. (accessed on July 30, 2019).

[6] See also: Philly Watersheds (PW), *Green Infrastructure Programs: Green Schools*, http://www.phillywatersheds.org/what_were_doing/green_infrastructure/programs/greenschools. (accessed on July 30, 2019).

[7] For more about the Rain Check program, see: Philadelphia Water Department, *What is Rain Check?,*https://www.pwdraincheck.org/en/what-is-rain-check#whatisraincheck (accessed on July 30, 2019).

later adopted Growing Stronger climate adaptation program, a study like ours can provide key missing insights into how climate resilience programs using the same long-standing GI tools may encounter uneven and inequitable outcomes.

4. Research design

We designed this study as a spatial quantitative analysis of the effects of GRI on populations vulnerable to climate exposure and gentrification. We conducted, on the one hand, a cross-sectional analysis that studied social-ecological conditions before and after green resilient interventions to evaluate the equity of siting decisions; and, on the other hand, a longitudinal analysis that tracked socio-economic changes over time in relation to GRI siting to examine gentrification trends. Our goal was to understand the extent to which green and resilient interventions protect vulnerable groups, or result in new inequities and insecurities.

4.1. Green resilient infrastructure

Our principal explanatory variable is what we call “green resilient infrastructure” (GRI). Drawing on PW's preferred stormwater management practices, we defined GRI as all *surface-level*, *vegetated* interventions, installed to mitigate environmental risk or impact, and improve adaptive capacity in the context of climate change, while enhancing neighborhood attractiveness. In Philadelphia these included green roofs, rain gardens, wetlands, and tree trenches, among others[8] We, therefore, excluded sub-surface, or non-vegetated (grey) projects – those which are generally not visible and not green – such as permeable pavements, sub-surface infiltration trenches and rain barrels. Because our study is focused on the combination and intersection of green and resilient – where the goal was improved protection – we have not included all forms of existing green space. However, utilizing this definition, it became clear that GRI were sometimes implemented in *vacant lands, parks,* and *schoolyards.* To deal with this circumstance, we identified vacant lands, parks, or schoolyards where isolated GRI installations constituted upwards of 10% of the surface area. In such cases, we considered the entire green space to have been ostensibly transformed into GRI. Given the generally small size of GRI installations, this was a fairly conservative threshold. Out of 1172 GRI data points included in the study, only a few green spaces – 6 parks, 1 schoolyard and 72 vacant lots – met the 10% requirement. Overall, 26% of the total surface area of GRI is under public ownership; the remainder is privately-owned—although private GRI is largely implemented due to public mandate or assistance programs.

Our green spatial data collection extended between 2000 and 2016 – that is the period during which the PWD recorded new installations of green stormwater infrastructure. We selected polygon features meeting our “green” criteria from PWD Stormwater Management Practice (SMP) and *Rain Check* points to create a combined shapefile of all active stormwater GRI (up to 2016). These databases provided a detailed geographic inventory of every intervention, its subtype, installation date, ownership typology, and lifecycle status. Where only point data without surface area was available, − such as for planters and rain gardens of the Rain Check program – we used either exact dimensions to create a polygon or estimated areas of the GRI, both based on city data and descriptions of the infrastructure. This allowed us to preserve the count and the surface area per tract of ‘greened acres’. Next, we joined the city's vacant lands shapefile with the combined SMP and *Rain Check* file to identify and incorporate lots which received green stormwater features. Lastly, we selected parks from among the Philadelphia Parks & Recreation assets data, which included schoolyards, and followed a similar procedure.

4.2. Identifying sites of omission (SO) and sites of commission (SC)

To investigate how issues of equity and security pan out across green and resilient urban landscapes, we constructed two dependent variables: Sites of Omission (SO) and Sites of Commission (SC) – building upon and refining Anguelovski et al.'s (2016) classification of *acts of omission* that result in uneven and inequitable climate protection because the urban poor are “omitted” from interventions, and *acts of commission* that may worsen baseline social vulnerabilities over time, much of it because of gentrification or displacement of the urban poor.

Through our analysis, we identify tracts as SO when (a) tracts are highly vulnerable and do not receive GRI or/and when (b) tracts with wealthier, privileged populations (or where other economically valorized areas of cities, such as waterfronts, central business and historic districts exist) receive GRI without necessarily being most vulnerable to climate threats. In other words, Sites of Omission identify where higher social and ecological vulnerability neighborhoods have been neglected or deprioritized in relation to economically valorized areas. On the other hand, Sites of Commission include socially-underprivileged areas that received protection and subsequently gentrified or where GRI seemed to have contributed to a certain extent to the displacement of low-income and minority groups. Hence, SC may also refer to areas that gained low-income and minority groups over time but received little or no GRI while other areas received GRI and gentrified. They indicate new insecurities in the long-time place of residence, livelihoods, social ties and climate resilience of socially vulnerable populations. Therefore, the SO and SC variables are socio-ecological and politico-economic indicators of who benefits from or is disadvantaged by GRI – are they the socially and ecologically more, or less, vulnerable populations and areas?

[8] For comprehensive descriptions of the city's various GI tools, see: Philadelphia Water, “Green Stormwater Infrastructure Design Requirements and Guidelines Packet,” Philly Watersheds. Philadelphia Water Department, May, 15, 2015, http://phillywatersheds.org/doc/GSI/GSI_Design_Requirements_&_Guidelines_Packet_5-15-2015.pdf. (accessed on July 26, 2019).

4.2.1. Data selection for SO and SC

All census variables required for SO/SC analysis for 2000, and 2010 5-year estimates, were downloaded at the census tract level from the Geolytics database, and 2016 5-year estimates, from the American Community Survey (ACS). All data was normalized to 2010 census tract boundaries[9] to enable demographic comparison across three time periods (2000, 2010, and 2016) at the finest spatial resolution possible (Maantay, 2002). We decided to exclude 13 tracts out of 384 for having zero or low population and/or housing, and population loss due to unique factors such as Navy yard closure and airport expansion.

Our first outcome variable, Sites of Omission, requires identifying areas with high *social-ecological vulnerability* (SEV), which we define as the interlinked socioeconomic and biophysical factors (Bennett et al., 2016) relating to a local capacity to respond to stress or change. Vulnerability studies have recently paid much attention to the multiplicity, relationality and diversity of exposures and sensitivities in a more integrative and dynamic way (Adger, 2006; Bennett et al., 2016; Cinner et al., 2011; O'Brien et al., 2007; Pearsall, 2010; Taylor, 2015; Turner et al., 2003; Turner, 2016). Following this trend, we conceptualize SEV by considering the disparities in exposure to climate hazards across the urban landscape in relation to disparities in the susceptibility of Philadelphia residents to those shocks and stresses.

We selected census variables for Sites of Omission guided by empirical research on social vulnerability to environmental hazards, including the Social Vulnerability Index (SoVI) (Cutter et al., 2003), Climate Resilience Screening Index (CRSI) (Summers et al., 2017), and Social Vulnerability Index (SVI) (Flanagan et al., 2011) of the US Centers for Disease Control (CDC). We calculated population percentages at the tract-level for each of the following categories of demographic indicators: residents living in poverty, unemployed, non-Bachelor's degree holders, aged over 65, single-parents, of minority background (Black and Hispanic), and with limited English language proficiency. We call this combined variable "social vulnerability" (SV).

Next, using Philadelphia's open data portal,[10] we collected spatial data and calculated percent surface area per census tract on several bio-physical environmental variables –Combined Sewer System (CSS) area, FEMA 100-year floodplain and impervious surfaces data updated in 2004. While location in CSS area was the main criteria in municipal GRI siting decisions, this, together with flood plain and impervious surface data,[11] captures urban biophysical/bioenvironmental aspects that were important to GRI siting and therefore to identifying and locating "ecological vulnerability" (EV) throughout Philadelphia.

Our second outcome variable, Sites of Commission pertains to pathways of *green resilience gentrification* which we define as a change in population such that an area gains in wealthy and/or less vulnerable populations (while losing more vulnerable populations), and in which private rental real estate values rise in conjunction with actions taken to mitigate climate and environmental risks. The definition and operationalization of gentrification varies across studies and landscapes (Freeman and Braconi, 2004; Newman and Wyly, 2006; Owens, 2012; Phillips and Smith, 2018). In Philadelphia, income (PEW Charitable Trusts, 2016), and education and property value-based (Ding et al., 2016) variables have been applied to identify gentrification.

For this study, we operationalized gentrification in Philadelphia tracts as combined tract increases[12] in median gross rent, residents earning above the citywide median income, White residents, and residents with a college degree (or higher) and a parallel decrease in Black and Hispanic residents. This meant that our analysis captured more change than other local gentrification studies and therefore more neighborhoods were found to be gentrifying. Because of the historical significance of "race" and racism behind practices of segregation, redlining and suburbanization underlying Philadelphia's uneven development patterns (Beauregard, 1990; Brownlow, 2006), the racial dimension of gentrification is particularly important to understanding in a novel and more fine-grained manner the distribution and impact of new development patterns of green and protective infrastructure.

4.3. Analytical strategy

Overall, we aimed at spatially analyzing the impacts of reducing climate risks through urban GRI on social-ecological vulnerabilities (SEV) and in relation to gentrification trends at different periods of time. To achieve this aim, we examine, first, the distribution of new green and resilient infrastructure at different points in time relative to social and ecological vulnerabilities; and second, the relationship between this distribution and the processes that render historically marginalized populations more vulnerable and less secure, while benefiting more privileged populations.

While the precise causal role of GRI relative to other potential drivers of gentrification is an important consideration, it is not an explicit or direct part of this analysis. Rather, we highlight the extent to which GRI, despite intentions otherwise, become enmeshed in deeper processes of urban change and the creation of environmental insecurity through uneven resilience. In doing so, we illuminate the interplay between social and ecological riskscapes in a way that challenges technocratic site selection and spatial planning approaches to account for a more complex set of considerations. It is, we argue, less a question of causality, and more one of how, when, and where urban greening becomes inexorably linked with social change such that interventions like GRI are both cause and consequence.

[9] In cases where the normalization process appeared to have created large discrepancies across years in a tract's population, we reapportioned the tracts to allocate population counts more evenly.

[10] The open data portal can be found at: OpenDataPhilly, https://www.opendataphilly.org/ (accessed on July 30, 2019).

[11] Areas that have higher impermeability have less green and are more likely to be ecologically vulnerable.

[12] For demographic variables, percent change is given as the increase or decrease in percentage points for a specific variable during a given period

Table 1
Social-Ecological Vulnerability (SEV) matrix according to SEV score.

Social Vulnerability (SV) score \ Ecological Vulnerability (EV) score	< 3	3 - 4	> 4
< 3	**LL**		**LH**
3 - 4		**M**[a]	
> 4	**HL**		**HH**

L = Low; H = High; M = Moderate; SV precedes EV (i.e. LH = Low SV, High EV).

[a] In this case only one of either SV or EV needed to equal 3 or 4. The other variable could have been equally moderate or of low or high value.

4.3.1. GRI and sites of omission

First, we used a quantitative spatial approach to identify *sites of omission* (SO) in GRI plans and interventions. Here, we address the first sub-study question: Which areas receive GRI by 2010 and 2016, relative to social-ecological vulnerabilities? Because GRI data is tracked annually, whereas census data provides a snapshot in time at larger intervals, we performed a pre-post study to describe tracts before and after GRI went in. We assessed SEV in 2000 and 2010, as pre-GRI starting points, and in 2010 and 2016, as post-GRI endpoints. We then looked for associations between spatial accumulation/clustering of GRI and changes in SEV over time.

To do so, we built 5 social-ecological type indicators representing varying combinations of high (scores > 4) and/or low (scores < 3) social and ecological vulnerabilities in census tracts. For example, if a tract scored < 3 for social vulnerability, but > 4 for ecological vulnerability, it was classified as a Low SV-High EV tract, abbreviated as LH. Table 1 explains how the scores were calculated for each SEV type and their abbreviations (LL, LH, HL and HH) which are later referenced in our maps. We included a fifth indicator for tracts with moderate levels of social or ecological vulnerability (M): if either score, but not necessarily both, was in the middle range (3–4), then the tract was classified as moderate. Two types of tracts were classified as Sites of Omission: tracts that received little or no GRI but had high SEV (HH) and tracts with low levels of social and ecological vulnerability (LL) that gained in GRI.

4.3.2. GRI and sites of commission

In order to analyze the extent to which the implementation of GRI is associated with green resilience gentrification, we identified tract level changes over time in socioeconomic indicators of gentrification and compared them with concentrations of GRI in the same tracts.

First, we identified which tracts could be gentrified, or were “gentrifiable” tracts at the start of each study period (2000 and 2010). Gentrifiable tracts had to have a median household income below the citywide median in 2000 and 2010. In a second step, gentrifiable tracts were examined for gentrification trends during the following time periods: 2000–2010, 2010–2016 and the overall 2000–2016 period. We chose the overall city-level rate of gentrification to provide a comparison point from which to interpret degree of gentrification at the tract-level. Indicators that changed according to our criteria received one point and were subsequently added together to obtain a composite score, with a maximum of six demographic or real estate changes possible (Anguelovski et al., 2018b). For example, if median rent grew faster than the citywide median change, a gentrifiable tract received one point toward its composite gentrification score.

Five tract typologies emerged from this analysis: non-gentrifiable, gentrifiable-non-gentrifying and three sub-types for gentrifiable-gentrifying tracts. These were highly gentrifying (scoring 5 or 6), moderately gentrifying (scoring 3 or 4) and low gentrifying (scoring 1 or 2). We then summarized the average GRI counts and average GRI percent area for each typology to examine which tracts had the highest concentrations and numbers of GRI.

5. Results

5.1. Sites of omission: who received GRI and who did not?

5.1.1. SEV in 2000 and GRI investment from 2000 to 2010

First, our analysis from 2000 to 2010 reveals that areas that tended to receive the highest average number (0.95 per tract – note

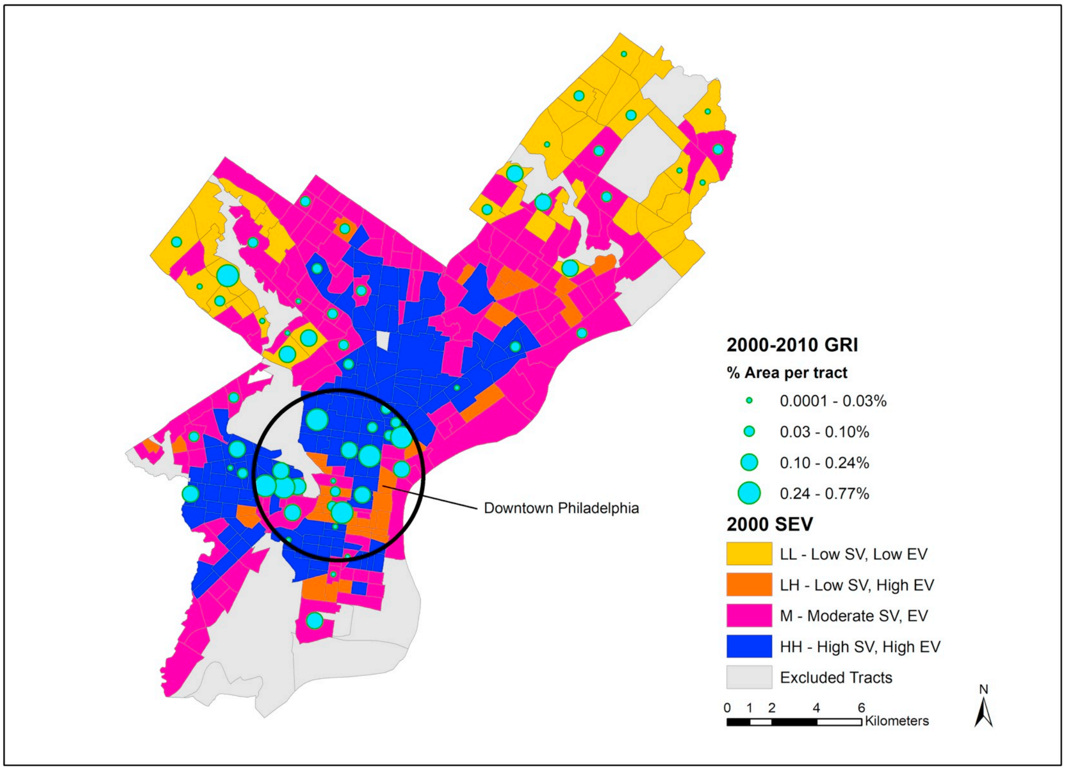

Fig. 1. Sites of Omission, SEV in 2000 and GRI from 2000 to 2010, in the City of Philadelphia.

Table 2
Summary results of GRI accumulation according to SEV type at different start and endpoint years of the study (highest average values are bolded).

	SEV Type	Average # GRI[a]	Average % GRI[a]	% tracts with no GRI
2a.	SEV 2000	GRI 2000–2010		
	LL	**0.95**	**0.029%**	58.5%
	LH	0.24	0.014%	90.2%
	M	0.40	0.013%	84.4%
	HH	0.48	0.022%	85.7%
2b.	SEV 2010	GRI 2011–2016		
	LL	1.15	0.076%	55.9%
	LH	2.73	**0.113%**	27.5%
	M	**2.91**	0.074%	46.1%
	HH	1.86	0.070%	49.6%
2c.	SEV 2000	GRI 2000–2016		
	LL	1.93	0.075%	43.9%
	LH	2.76	**0.112%**	41.5%
	M	**3.22**	0.088%	45.4%
	HH	2.67	0.103%	37.4%
2d.	SEV 2016	GRI 2000–2016		
	LL	2.46	0.116%	38.5%
	LH	**4.30**	**0.160%**	27.3%
	M	3.08	0.080%	40.8%
	HH	2.17	0.084%	47.9%

[a] GRI averages by SEV type include tracts with 0 values for GRI.

that the average is below one because many years in this time period tended to have zero GRI) and average percent area (0.029%) of GRI in the same period were those that were simultaneously the least socially and ecologically vulnerable (LL) at the beginning of the time period (see Fig. 1 and Table 2a). The second highest average number of GRI (0.48 per tract) (with a similar average surface area of 0.029%) was located in areas with the highest social and ecological vulnerability (HH), but these sites tended to cluster exclusively

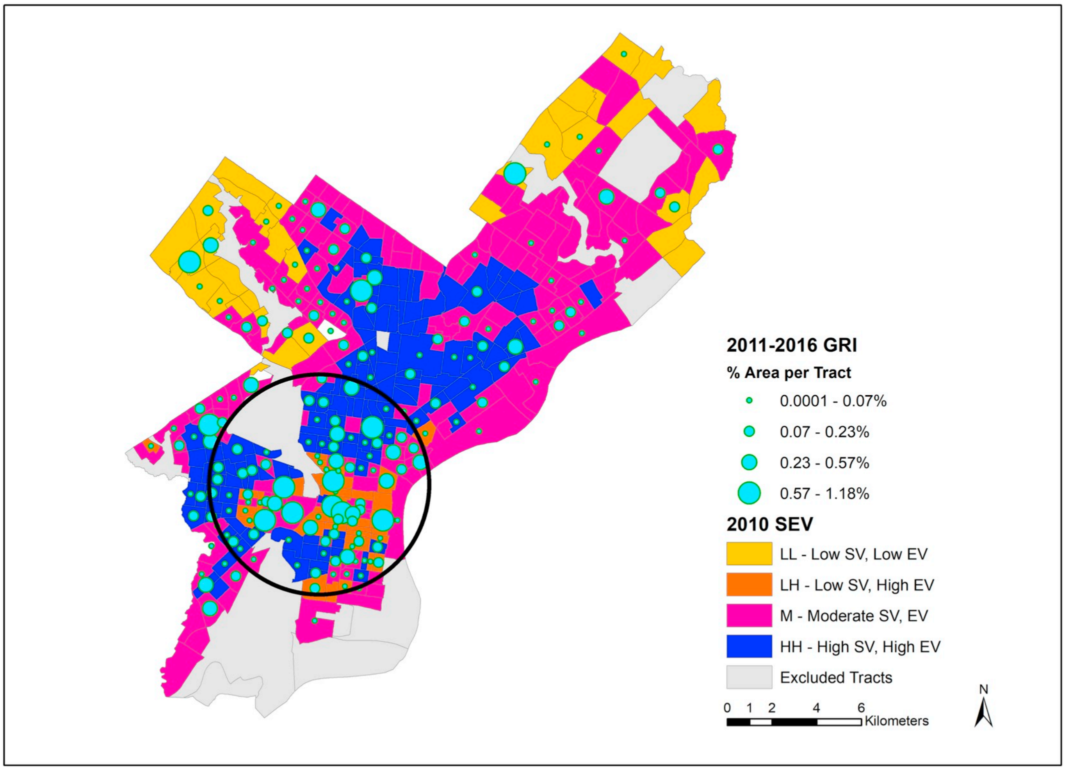

Fig. 2. Sites of Omission, SEV in 2010 and GRI from 2011 to 2016, in the City of Philadelphia.

around the city center (downtown) in the neighborhoods of Center City, Rittenhouse, University City, Powelton, West Kensington and Fishtown. Generally, less vulnerable populations received the most GRI and more vulnerable populations received GRI only if they were close to the business district and downtown.

5.1.2. SEV in 2010 and GRI investment from 2011 to 2016

Second, from 2011 to 2016, areas that tended to receive the greatest average number of GRI (2.91 per tract) were those that had moderate (M) social and ecological vulnerability at the beginning of the time period (see Fig. 2, Table 2b). This may be explained by the downspout planters, offered by the Rain Check program which began in 2012. They are small in area (estimated at roughly 0.5 m^2) but could quickly impact the total count of interventions in a tract. However, in terms of percent area of GRI, tracts with a combined low social vulnerability and high ecological vulnerability (LH) tended to receive the most protection (0.113% area on average). Conversely, the highest overall vulnerability tracts – high social and high ecological vulnerability (HH) – had the lowest percent area of GRI (0.070%), fewer numbers of interventions (1.86) and overall less protection. Ecological vulnerability gained increasing focus for GRI in later years, but social vulnerability remained a low priority.

5.1.3. SEV in 2000 and 2016 and GRI investment from 2000 to 2016

Lastly, for the overall period (2000–2016), we observe (Fig. 3, Table 2c) that the tracts that would accumulate the greatest percent area of GRI (0.112%) were those which started with a low social and high ecological vulnerability (LH) in 2000, while tracts with moderate SEV (M) in 2000, would receive the highest number of GRI (3.22). Tracts with high SEV (HH) in 2000 were close behind. By the end-point of the time period (2016) (Fig. 4, Table 2d), areas which had accumulated the most GRI in count and percent area (4.3 and 0.160%) were those which had become low social and high ecological vulnerability (LH) tracts, surpassing high SEV tracts (HH) with twice the number and percent area of GRI (2.17 and 0.084%), $p < .05$. The discrepancy in GRI siting between HH areas and LH areas grew from 2000 to 2016. Therefore, in the overall period, high ecological vulnerability was a better predictor of GRI, but so was low social vulnerability. By 2016, 48% of the highest socially and ecologically vulnerable tracts (HH) were left behind with no GRI while among the least socially and ecologically vulnerable tracts (LL) only 38.5% had zero.

5.2. Sites of commission: how did areas receiving GRI (or not) change over time?

5.2.1. Gentrification trends in Philadelphia

Among the 371 tracts studied from 2000 to 2016, 188 were eligible to gentrify at the start of the study period, with median

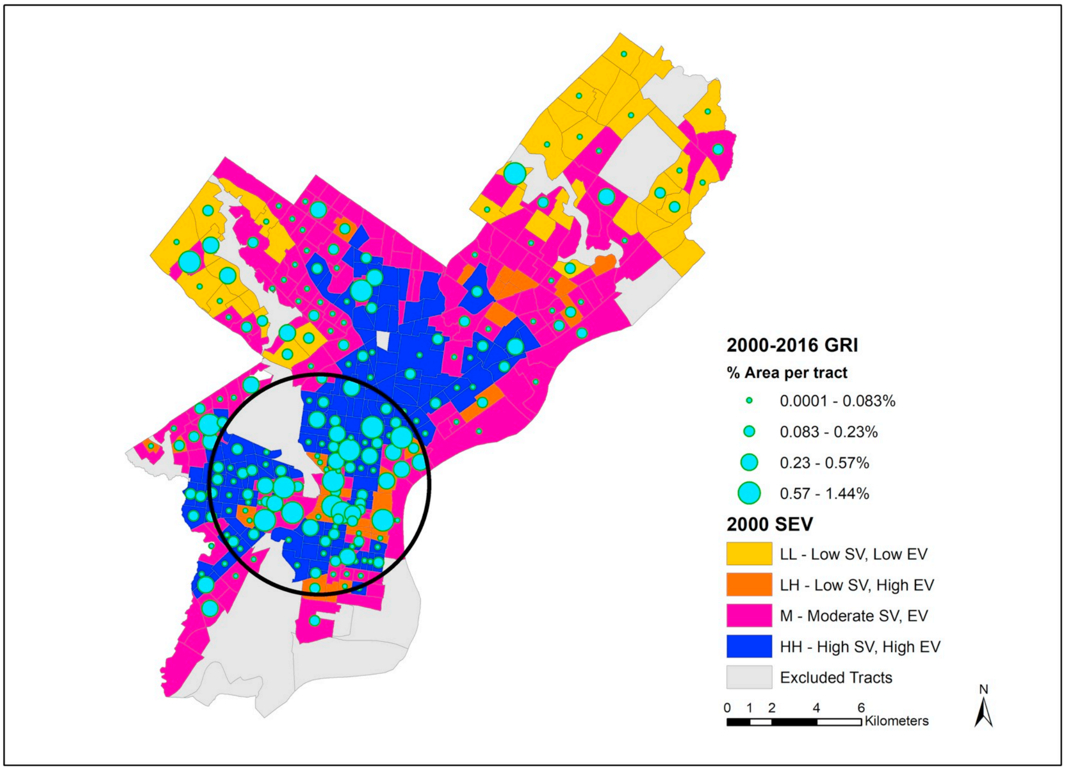

Fig. 3. Sites of Omission, SEV in 2000 and GRI from 2000 to 2016, in the City of Philadelphia.

incomes below the 2000 citywide median. A total of 47 tracts received a composite gentrification score of 5 or 6 and met all or nearly all the criteria to be considered highly gentrifying. We further stratified the tracts as "moderately gentrifying" for those which scored 3 or 4 (94 tracts), "low gentrifying" for those which scored 1 or 2 (54 tracts) and "non-gentrifying" for those which scored 0 (186 tracts). The large number of tracts (141) experiencing moderate or high gentrification from 2000 to 2016 and their relative spatial concentration (Moran's I z-score: 15.87, *p*-value: 0.00) seems to indicate a great deal of flux in and around downtown neighborhoods with concentrated gentrification, such as University City, Spruce Hill, Woodland Terrace, Point Breeze, Callowhill, Brewerytown, West Kensington, Ludlow and Center City-Chinatown (see Fig. 5).

5.2.2. Gentrification observed with GRI siting from the overall period of 2000 to 2016

Fig. 6 demonstrates that green resilience interventions from 2000 to 2016 are tightly enmeshed with processes that generate Sites of Commission through the correlation with gentrification in Philadelphia. The 47 tracts with the highest composite gentrification scores of five or six (see Table 3a), received both the overall highest average number of GRI interventions (9.8 per tract) and the highest average percentage of GRI area (0.40% of the tract) from 2000 to 2016. This amounts to a 4 to 5 times higher average percent GRI than in the lowest and non-gentrifying tracts. These highly gentrifying tracts with high GRI were concentrated mostly in the neighborhoods of Southwest Centre City, University City, North Philadelphia East and West, and Brewerytown. In general, the higher the count or percent area of GRI, the higher the gentrification score of a tract. The bivariate association between GRI and gentrification score was highly statistically significant ($p < .05$).

5.2.3. Gentrification observed with GRI siting from 2000 to 2010 and from 2011 to 2016

We also divided the time period into 2000–2010 and 2011–2016 to test whether the announcement and adoption of the *Green City, Clean Waters* plan between, 2009 and 2011, and the subsequent increase in GRI interventions, also correlated with gentrification trends. We found that in the first period (Table 3b), GRI and gentrification showed strong positive correlations, just as they did in the overall period. The highly gentrifying areas (scores of 5 or 6) by 2010 had received the highest percent area (0.06%) and the highest number (1.3) of GRI. However, in the second period (Table 3c), from 2011 to 2016, more GRI (5.7 interventions and 0.19% area) were invested in the moderately gentrifying areas. The highly gentrifying areas were close behind in percent area (0.18%) and number (4.67) accumulated. Further analysis below helps shed light on why this may be.

5.2.4. Which came first: gentrification or GRI?

We also tested if GRI, sited from 2000 to 2010, was correlated with subsequent gentrification (Table 3d), and further tested the

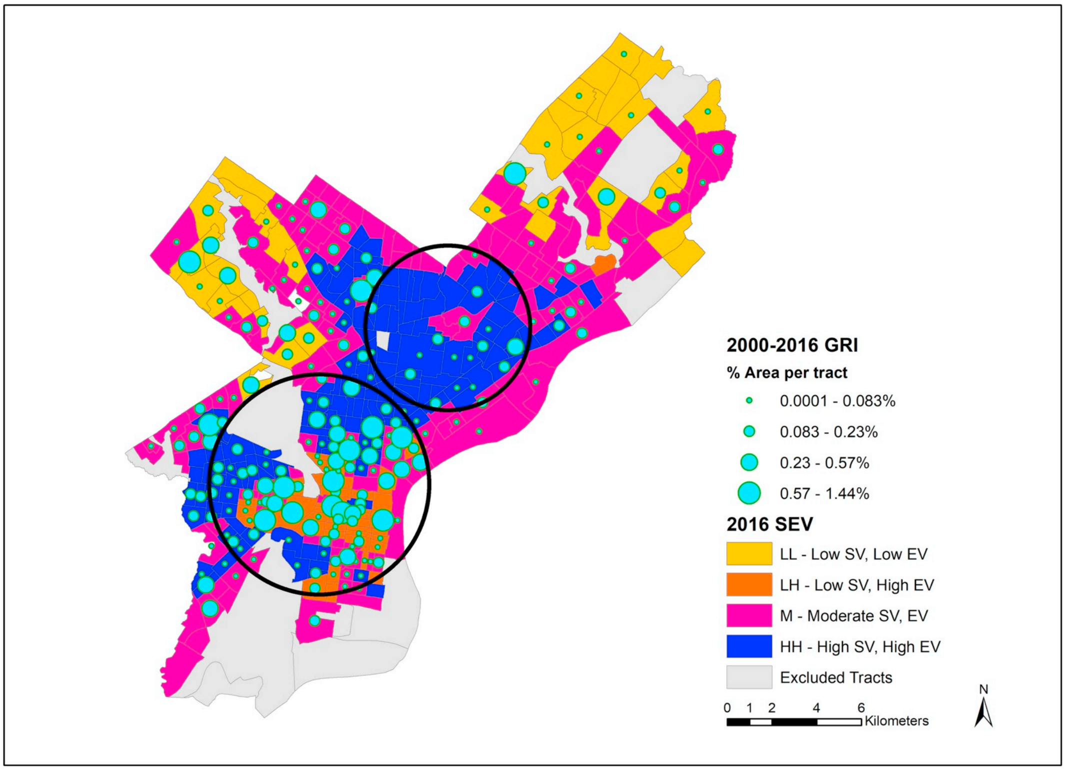

Fig. 4. Sites of Omission, SEV in 2016 and GRI from 2000 to 2016, in the City of Philadelphia. By 2016, the upper encircled area has grown more socially vulnerable and received relatively little to no GRI.

reverse proposition: whether gentrification in the first period was correlated with subsequent GRI siting (Table 3e). Indeed, the strongest positive correlations appear for gentrification in the first period (2000 − 2010) and GRI siting in the second period (2011–2016, see Fig. 7, Table 3e). This was the case for both average number (6.2) and average percent area (0.26%) of GRI. Results indicate GRI 3 times higher in number and 4 times higher in percent area than those found in non-gentrifying tracts. In other words, GRI tends to be sited in neighborhoods that were gentrifying in the previous period, showing that it is likely both cause and consequence of gentrification – it is likely integrated with and intensifies processes of gentrification.

We found that GRI siting in the first period (2000–2010) tends to precede moderate levels of gentrification in the second period (2011–2016), more so than preceding high gentrification levels (see Table 3d) for both average number (1.5) and average percent area (0.07%). Viewed in combination with the results in Table 3c, which also found higher levels of GRI in moderately gentrifying tracts from 2011 to 2016 (5.72 and 0.19%), these findings suggest that increasing amounts of GRI went to tracts that were highly gentrifying in the first period but in which gentrification had slowed to moderate levels by the second period.

5.2.5. Does earlier gentrification correlate with overall GRI or does earlier GRI correlate with overall gentrification?

Lastly, GRI in the first period strongly correlates with gentrification in the overall time period (see Table 3f) - increasing amounts of GRI see increasing degrees of gentrification. The reverse, however, is also true (see Table 3g) wherein increasing degrees of gentrification in the first period correlate with more GRI in the overall period. These findings may reflect the strong correlation between the two key variables, regardless of directionality, when both are considered over the whole study period. Green resilience gentrification may not occur subsequently to GRI siting – as we have defined Sites of Commission – but in conjunction with it, possibly generating a snowball effect, in which economically valued areas and more privileged residents are better protected at the expense of – and leading to the greater insecurity of – already more vulnerable residents.

5.2.6. Changes in minority populations/income and GRI siting from 2000 to 2016

Finally, we examined tracts that increased in concentration of socially vulnerable populations over time and had little to no GRI – the corollary to trends above where areas receiving GRI gentrified. These are also Sites of Commission because we may observe an increased concentration of more socially vulnerable groups in less protected areas and/or a worsening of conditions. We did not measure for absolute change in populations; rather we tested for our hypothesized association of a negative correlation between percent minority/low-income residents and percent White/higher-income populations.

Fig. 8 (left) shows the change in Black population from 2000 to 2016. The darkest red areas, totaling 24 tracts, represent an

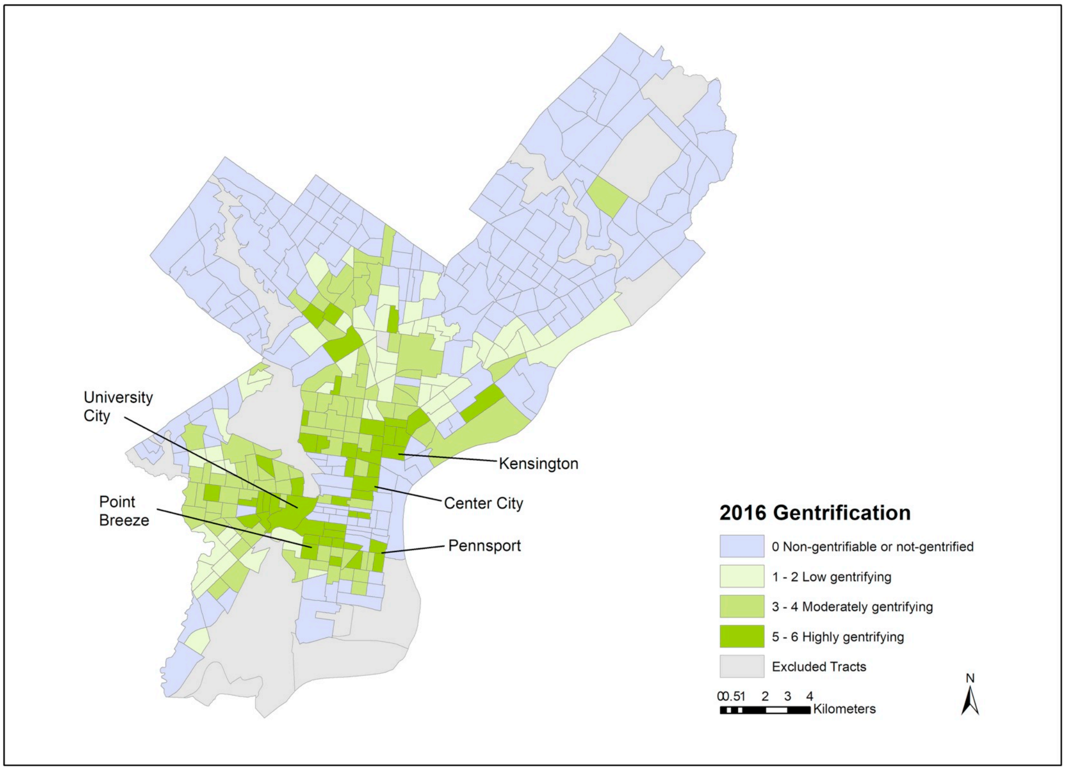

Fig. 5. Gentrification in Philadelphia 2000–2016.

increase of 20–48 percentage points in Black residents. The blue areas represent a decrease in Black population during the time period, with most between 0 and 20%. We can observe an increase in percentage of Black residents where relatively few GRI have been installed and a decrease in the percentage of Black residents where high numbers of GRI cluster. These results were strongly significant for a negative association between GRI and Black population ($p < .01$). Similar results were found for Hispanic residents (Fig. 8, right). On the contrary, there was a strong positive association between high-income/White residents and GRI, especially in the overall period ($p < .01$). Table 4 shows Pearson correlation coefficients for GRI by year and by each of four gentrification demographic variables, pertaining to race/ethnicity and income, across the 371 census tracts in Philadelphia. Sites of Commission in the more economically valued neighborhoods of Philadelphia to which whiter and wealthier residents have increasingly moved are paralleled by increases in the percentage of lower-income and minority residents in under-protected, less climate-resilient areas.

6. Interpretation and discussion

In this paper, we responded to calls for a better understanding of how adaptation or climate resilient infrastructure play out in the lives of socially vulnerable residents. We have sought to test whether green and resilient infrastructure siting addresses social-ecological vulnerability or if such practices reproduce uneven conditions, rendering historically marginalized populations actually more vulnerable to climate impacts and risks and less secure, while benefiting more privileged new residents.

Our study indicates that green resilience infrastructure in Philadelphia are not being sited or accumulating in such a way as to benefit the most socio-ecologically vulnerable residents. Had the landscape of social vulnerability remained unchanged from 2000 to 2016, residents with high social vulnerability would have almost equally benefited over time. However, residential stability did not occur in Philadelphia: As our analysis of gentrification and GRI shows, most of the benefits of protective infrastructure have gone to areas with wealthier, whiter and better educated residents over time. It is possible that green resilience investments and improvements made these areas more attractive and seemingly less risky (or more secure) for those newcomers.

However, our results also strongly suggest that early gentrifiers have themselves attracted or created the protections we see in these areas by 2016 – GRI is most likely both cause and consequence of gentrification in Philadelphia. It is thoroughly entwined in the processes of social change that are occurring.

During this period, marked by extreme gentrification in the city center, the numbers of Black and Hispanic lower-income residents declined in gentrifying resilience-invested areas while they increased in neighborhoods where GRI investments did not occur in the most recent period. This leads us to suggest that a dually – simultaneously or parallel – unjust process of omission and commission may be occurring alongside the planning, provision and siting of resilience investments in Philadelphia. On the one hand, climate protective infrastructure is becoming concentrated in wealthier and economically valued areas over other ecologically vulnerable,

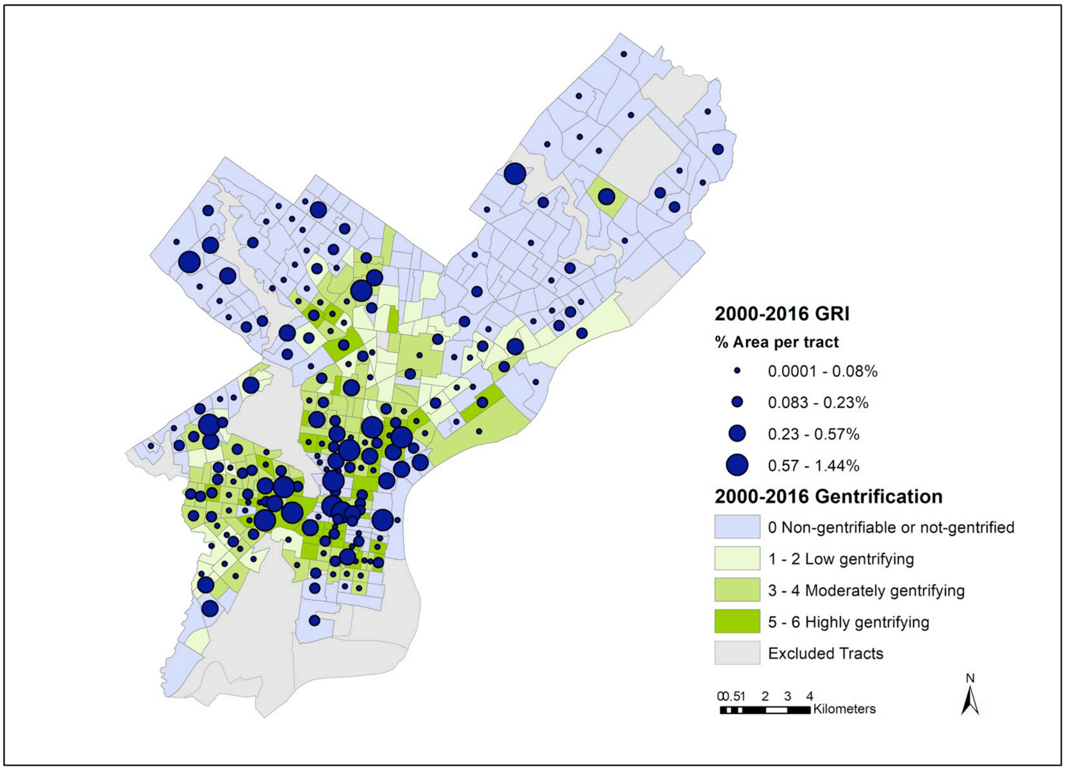

Fig. 6. Green Resilience Gentrification in Philadelphia: Sites of Commission, Gentrification and GRI 2000–2016.

less favored areas; while on the other hand, minority and low-income residents have shifted from wealthy areas and are increasing in green resilience dis−/under-invested neighborhoods. This means that the landscape of vulnerability in Philadelphia shifted, but also that a new social-ecological riskscape and environmental insecurity shaped by resilience-building measures emerged.

6.1. Climate protection inequities in addressing socio-ecological vulnerabilities

As we first examined whether the most socio-ecologically vulnerable tracts were receiving GRI protection or not, our findings indicated that ecologically vulnerable areas were targeted for GRI from 2000 to 2016, but with a strong preference for less socially vulnerable areas. Here there may be two factors at work. Before the passage of the *Green City, Clean Waters* plan, as with other 'early adapters' (Chu et al., 2016), Philadelphia's watershed engineers may have taken an experimental approach that required some degree of 'learning by doing' and a strategy of deploying demonstration projects in neighborhoods with the lowest implementation risks, as well as the highest potential to achieve visibility (Bulkeley and Castán Broto, 2013) and boost political salience (Madden, 2010). In this scenario, engineers and planners would have seized on opportunities for inter-agency partnerships and ad-hoc initiatives proposed by private and community leaders (Anguelovski et al., 2014; van den Berg and Coenen, 2012) leading possibly to siting in centrally-located, higher income neighborhoods with strong private investment interest and potential.

However, even with the later passage of the *Green City, Clean Waters* plan in 2011, neighborhoods with low social vulnerability continued to be better protected by more recent GRI siting. Here, procedural justice issues may be structuring siting decisions such that less vulnerable neighborhoods are more capable of attracting and maintaining protective infrastructure, as opposed to high social vulnerability neighborhoods with a legacy of disinvestment and privatization of urban service provisions (Heynen et al., 2006). For example, the Philadelphia *Rain Check* program tends to privilege homeowners (Bulkeley et al., 2014) – that is traditionally higher-income residents – and individualizes the responsibility to adapt to those able to (Dauvergne, 2016; Zografos et al., 2016), in particular, those with the budget, time, space and physical ability to make and maintain their homes in a greener, more resilient condition (Heckert and Rosan, 2018; Mandarano and Meenar, 2017). In neighborhoods where residents do not have the income or capital to invest in these projects, they may lose out on GRI investment and protection, with this uneven outcome reproduced as another green resilient inequity over the program's continuation.

Furthermore, the strong clustering of GRI in the city center and in and around downtown university campuses, which have been sites of concentrated public and private investment in recent years (PEW Charitable Trusts, 2016), suggests that these economically-valued districts are being unequally protected, and possibly at the expense of more socio-ecologically vulnerable neighborhoods such as Olney and parts of Lawndale, Oxford Circle and Hunting Park. As Mandarano and Meenar point out (Mandarano and Meenar, 2017, p. 11) in Philadelphia, "regulations mandating private sector investment in [GRI] prompt the inclusion of [GRI] projects in

Table 3
Gentrification Composite Scores and GRI concentrations (Counts and Percent Area).

		Composite gentrification score	Tract typologies	Average GRI count by tract typology	Average % GRI by tract typology
3a	Does 2000-2016 GRI correlate with Gentrification in the same period?	0	[a]Non-gentrifying	2.36	0.080%
		1–2	Low gentrifying	4.87	0.120%
		3–4	Moderately gentrifying	5.88	0.208%
		5–6	Highly gentrifying	**9.8**	**0.400%**
			r value:	*0.9706***	*0.9776***
3b	Does 2000-2010 GRI correlate with Gentrification in the same period?	0	[a]Non-gentrifying	0.35	0.013%
		1–2	Low gentrifying	0.78	0.030%
		3–4	Moderately gentrifying	1.13	0.040%
		5–6	Highly gentrifying	**1.3**	**0.060%**
			r value:	*0.9508***	*0.9824***
3c	Does 2011-2016 GRI correlate with Gentrification in the same period?	0	[a]Non-gentrifying	2.36	0.069%
		1–2	Low gentrifying	2.11	0.110%
		3–4	Moderately gentrifying	**5.72**	**0.192%**
		5–6	Highly gentrifying	4.67	0.184%
			r value:	*0.7825*	*0.9027**
3d	Does 2000–2010 GRI correlate with 2011–2016 Gentrification?	0	[a]Non-gentrifying	0.4	0.013%
		1–2	Low gentrifying	0.44	0.010%
		3–4	Moderately gentrifying	**1.54**	**0.069%**
		5–6	Highly gentrifying	0.72	0.046%
			r value:	*0.4766*	*0.7243*
3e	Does 2000–2010 Gentrification correlate with 2011–2016 GRI?	0	[a]Non-gentrifying	2.04	0.064%
		1–2	Low gentrifying	4.23	0.108%
		3–4	Moderately gentrifying	4.66	0.135%
		5–6	Highly gentrifying	**6.24**	**0.256%**
			r value:	*0.9353**	*0.9620***
3f	Does 2000–2010 GRI correlate with 2000–2016 Gentrification?	0	[a]Non-gentrifying	0.34	0.013%
		1–2	Low gentrifying	0.7	0.019%
		3–4	Moderately gentrifying	1.02	0.053%
		5–6	Highly gentrifying	**2.34**	**0.076%**
			r value:	*0.9590***	*0.9920****
3g	Does 2000–2010 Gentrification correlate with 2000–2016 GRI?	0	[a]Non-gentrifying	2.38	0.077%
		1–2	Low gentrifying	5.01	0.132%
		3–4	Moderately gentrifying	5.79	0.178%
		5–6	Highly gentrifying	**7.55**	**0.316%**
			r value:	*0.9433**	*0.9769***

[a] Non-gentrifying tracts included both non-gentrifiable tracts whose median incomes were above the citywide median, and gentrifiable tracts that did not gentrify. There were 183 non-gentrifiable tracts in 2000 and 181 in 2010.
*** Indicates significant at $p < 0.01$.
** Indicates significant at $p < 0.05$.
* Indicates significant at $p < 0.10$.

development, but do not shift the location of development." This reliance on private investment for protection and adaptation generates new Sites of Omission, leading to maladaptation and new landscapes of unequal socio-ecological vulnerability.

The city's climate resilience model may further assume that the economic (i.e. increasing real-estate values) and the hedonistic (i.e. beautification, recreation) are equally beneficial for all social groups. Overlooking the terrain of unequal and entrenched power dynamics among social and racial groups and the potentially contested space onto which new green technologies enter (Connolly, 2018; Finewood et al., 2019), technocratic approaches ensure that more powerful actors will benefit most from "urban ecological security" (Hodson and Marvin, 2009).

6.2. *Climate protection: a new pathway toward green resilience gentrification?*

In our study, we found a significant positive correlation between GRI clustering and highly gentrifying neighborhoods in Philadelphia from 2000 to 2016. The discrepancy between GRI clustering in highly gentrifying tracts versus non-gentrifying tracts was 3 to 1 on average for the number of interventions and 4 times the amount of "greened acres", Philadelphia's metric for green resilience infrastructure. We also found that the fastest gentrifying neighborhoods in the 2000s received the highest quantities and concentrations of GRI in the most recent years.

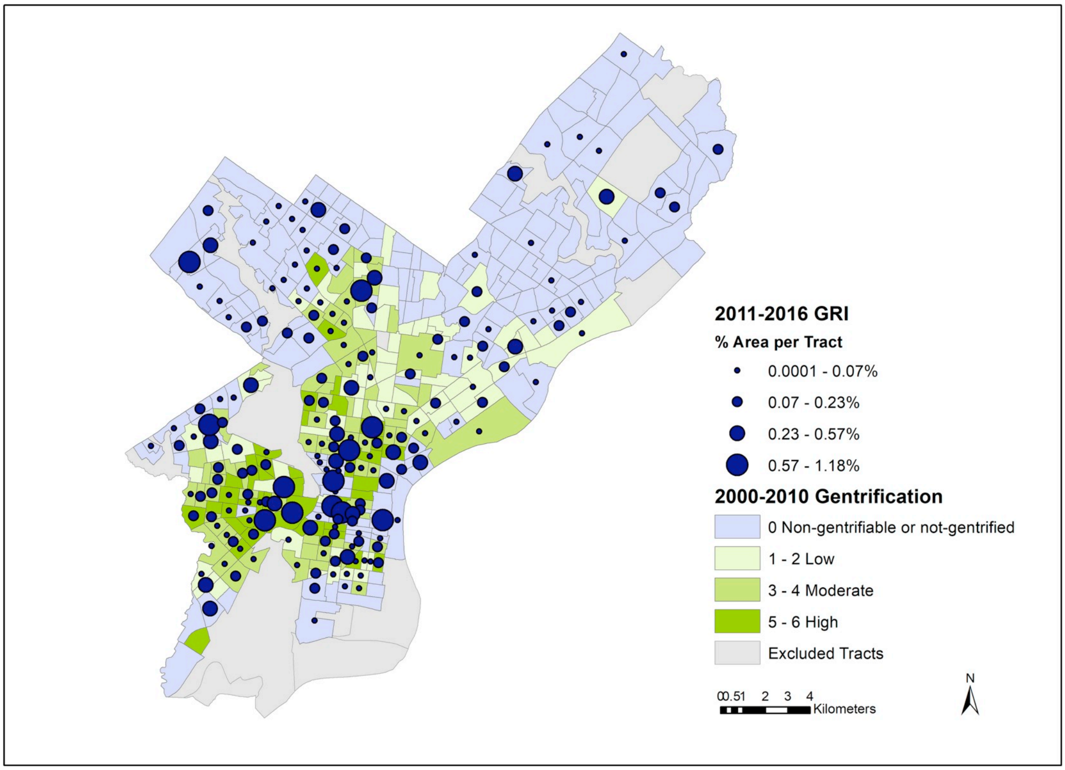

Fig. 7. Green Resilience Gentrification in Philadelphia: Sites of Commission, Gentrification 2000–2010 and GRI 2011–2016.

Our interpretation builds on nascent critical climate adaptation (Anguelovski et al., 2016), green gentrification (Anguelovski et al., 2018b; Checker, 2011; Curran and Hamilton, 2012; Gould and Lewis, 2017), and climate gentrification (Keenan et al., 2018) scholarship. By leaving open the direction of association between GRI and gentrification, our results suggest an important nuance – that gentrification correlates strongly with GRI and may also facilitate or accelerate climate protective infrastructure. It is a two-way relationship characterized by the embeddedness of social and ecological processes rather than a linear causation pathway. The Philadelphia case therefore indicates a new bidirectional pathway not yet described in the climate gentrification literature, one in which public-private investment in climate protection in gentrifying neighborhoods results in new ecological enclaves for privileged White/high-income residents. Those residents then reinforce those enclaves by drawing further investment after gentrification, thus producing a new geography of risk in the city.

Moreover, by including a racial component, our approach produced a key finding. In Philadelphia, racial composition tends to be the strongest predictor of which areas receive GRI, suggesting that race plays a key role in siting, even more so than socioeconomic and real estate variables (Mohai and Saha, 2015). Such results advise extending the analysis of gentrification conceptualized solely as increased property values or as changes in the proportion of highly educated residents, to investigating which social and racial groups of residents benefit from green climate resilience strategies over the short and mid-term and whose long-term security and livelihood is undermined. Older discriminations, lurking in past zoning decisions, infrastructural investments, and housing affordances, may continue to haunt present-day decisions (Mohai et al., 2009).

Thus, our study contributes to better understanding climate gentrification as a process of climate *protection* gentrification and climate injustice. Fig. 9 presents a framework for understanding its pathways and implications by extending the theoretical development of sites of omission and commission that emerged from the analysis. Although we have not measured displacement – further research is needed – these results nonetheless point to trends that Black and Hispanic residents in Philadelphia seem to be shifting into less protected areas (future sites of commission should they gentrify with the siting of new GRI), and corroborate other findings that Philadelphia is re-segregating as minority middle-income neighborhoods grow more fragile with higher rates of eviction and foreclosure and declining incomes and employment (Reinvestment Fund, 2017). This re-segregation is thus marked by a new form of social-ecological polarization that arises from, on the one hand, an unequal distribution of environmental protections and possibly, on the other hand, a lack of social protections to prevent displacement. Even if physical displacement is always difficult to demonstrate in gentrification studies (Easton et al., 2019), the arrival of wealthier and whiter residents and the frequent next step (or accompanying step) of cultural and political gentrification (Hyra, 2015, 2017; Prince, 2014) signifies potential losses of social cohesion and political power, which are also key in urban adaptation and in harnessing adaptation projects and/or resources (Graham et al., 2016; Zografos et al., 2016). Therefore, coupled with patterns of gentrification, resilience efforts can lead to new landscapes of environmental insecurity and injustice by class and race characterized by increased livelihood insecurities, new climate protected enclaves for the privileged, privatized resilience, maladaptation and climate protection segregation.

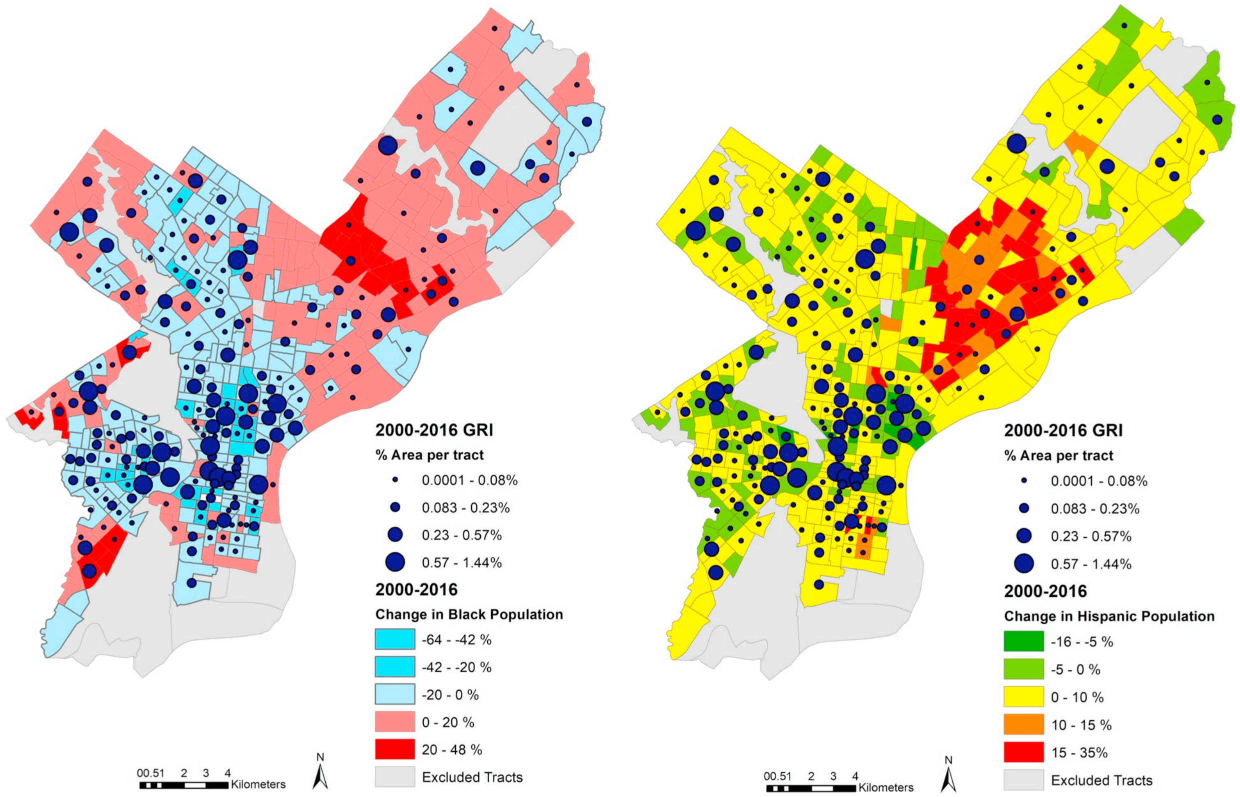

Fig. 8. GRI and Change in minority residents, Black (left) and Hispanic (right), 2000–2016 - Sites of Commission.

6.3. Policy implications: new pathways and methodologies for a more just green climate protection

Using a spatial quantitative analysis, we attempted to uncover mechanisms by which environmental inequalities of climate protection occur and perpetuate. Environmental inequalities today cannot be reversed by simply replacing "hazards" with "green amenities", while leaving entrenched social, racial, and economic hierarchies untouched. We suggest here a process that re-couples an understanding of historic drivers of uneven geographies to the social-ecological model and to resiliency planning and explicitly ties a longitudinal approach to social-ecological vulnerability by integrating questions of gentrification and environmental and climate justice.

Based on our study, this requires 1) to evaluate social and ecological vulnerability across urban landscapes to ensure that green infrastructure not only builds resilience equitably, but is justice enhancing by prioritizing neighborhoods with higher socio-ecological vulnerability; 2) to analyze neighborhoods for vulnerability to gentrification/displacement and identify intersectional drivers of climate injustice; 3) to proactively put in place anti-gentrification and anti-displacement measures before projects are underway; and 4) to prioritize community-driven climate resilience approaches so that they can be responsive in real time to social-ecological processes and ensure that benefits belong to vulnerable residents.

To do so, GRI programs must carefully consider race, socioeconomic and real estate factors - among others - in addition to environmental and climate ones (Ranganathan and Bratman, 2019), and to go beyond techniocratic, colorblind approaches to building resilience as they may subordinate alternative aspirations, politics and forms of knowledge (Finewood et al., 2019; Hardy et al., 2017). They should work closely with local organizations to prioritize GRI's wider adoption by lower-income residents, including fully subsidizing community driven efforts. They should also advocate alongside these organizations for protections ensuring that residents in long disinvested areas can stay in place if they choose. GRI programs can assist by endorsing tax breaks or incentives

Table 4
Pearson correlation coefficients for selected gentrification variables by GRI siting period among census tracts in Philadelphia (n = 371).

GRI siting period	Gentrification period	High-income residents	White (non-Hispanic)	Black (non-Hispanic)	Hispanic
2000–2016	2000–2016	0.173***	0.153***	−0.142***	−0.170***
2000–2010	2010-2016	0.036	−0.011	−0.016	−0.163***
2011–2016	2000–2010	0.170***	0.09	−0.162***	−0.136***

*** Indicates significant at $p < 0.01$.

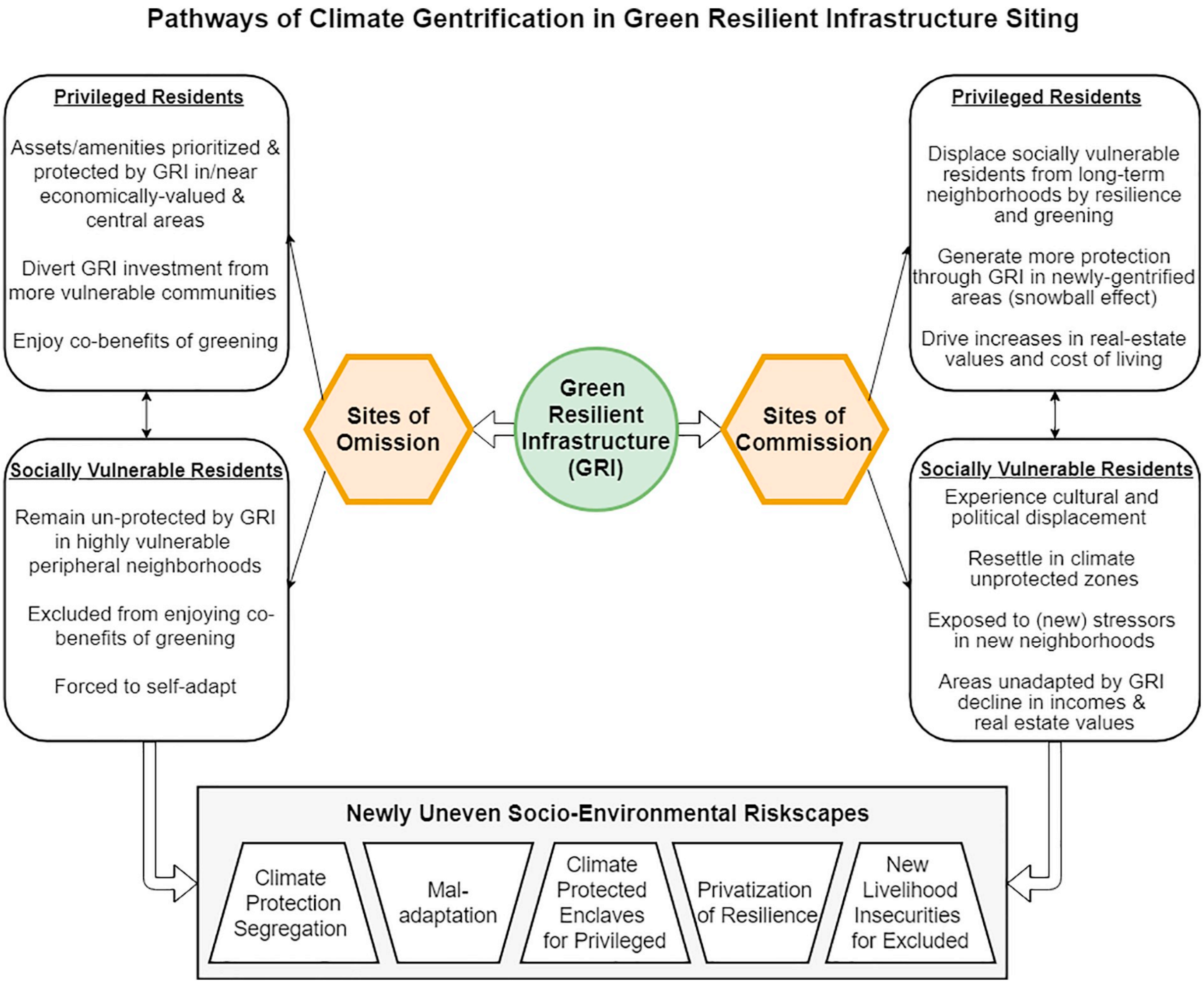

Fig. 9. Pathways of climate protection gentrification in green resilient infrastructure siting.

to low-income homeowners designed to keep housing costs and repairs (including green upgrades) down (Immergluck and Balan, 2018) and support a series of citywide community land trusts around GRI cluster areas or large-scale climate protection projects (i.e. waterfront resiliency redevelopments) which can secure long-term affordability and stability for lower-income residents (Anguelovski, 2014; Thompson, 2015). They can further call for other complementary housing affordability, tenants' rights and land rights policies, which also help preserve social networks and important local cultural institutions and symbolic places (Wolch et al., 2014). This also means advocating against the hazardous features of so-called community development programs that largely benefit wealthier homeowners and developers (i.e. federal opportunity zones and long-term city tax abatements on all new construction and major renovations). These policies increase vulnerability to gentrification and displacement, reduce city resources and therefore hinder their ability to ensure climate protection for socio-ecologically vulnerable areas.

Lastly, there is real opportunity for GRI programs and partners to participate in more transformative urban climate justice and reparations efforts. For example, by allying with and promoting low-income and minority community-driven efforts, cities can boost local workforce development and minority owned businesses as part of a broader Green New Deal, labor reform or other green climate economy initiatives. Beyond infrastructure itself, any work that strengthens local organizational networks, social ties and place attachments is more likely to benefit long-lasting climate resiliency and justice (Graham et al., 2016).

7. Concluding reflections and future research directions

In sum, we found that shifting patterns of vulnerability in correlation with gentrification created new urban riskscapes in which low-income and minority residents were shifted into conditions of heightened socio-ecological insecurity. Based on findings in Philadelphia, green resilient infrastructure is enmeshed in these processes, creating new urban conditions for the privileged and enlarged social risk (insecurity) for vulnerable populations – a key missing consideration of land use planning and decision-making.

Therefore, future research is needed to understand the social and political barriers to adopting green resilient interventions in high vulnerability neighborhoods, including residents' perceptions of and resistance to resilience projects (Kaika, 2017) and their association of green resilience projects with locally unwanted land uses (green LULUs) and indicators of wealth, whiteness and status. People have indeed different perceptions of social-ecological risk and security shaped by confrontations within unequal power dynamics and rooted ultimately in uneven conditions and possibilities for flourishing and thriving.

A research agenda that engages with the politics of resiliency and adaptation planning is needed to better understand these dynamics. Future research should also examine the politics by which green resilient infrastructure siting decisions are made in the complex inter-agency and planning configurations of the city (Connolly, 2018; Pellow, 2000) and consider the political economy of drivers behind the clustering of protective infrastructure in new “resilience zones” (Teicher, 2018).

In future research we intend to examine vulnerability to future green resilience gentrification in correlation with private investment and new development as well as adaptive capacity to gentrification. Resilience carries with it a notion of security that suggests protection from the harms of future hazards (Vale, 2014) – including those that are more and less predictable – such as gentrification and its well-known social, cultural, and economic impacts. Future research could also try to unpack whether and why some more socially and ecologically vulnerable neighborhoods may succeed in acquiring green and resilient protection and yet stave off gentrification and displacement. These potential examples of social-ecological resilience are not well known or understood.

Building resilience in a context of uneven (unequal) conditions thus means confronting uneven socio-ecological riskscapes, vulnerabilities, and increased insecurities vis-à-vis people's long-time place of residence, their social ties and livelihoods, combined with new exposure to extreme weather events, so that today's green climate interventions and other environmental benefits do not become tomorrow's undesirable outcomes for the politically and economically less powerful and more vulnerable.

Declaration of Competing Interest

The authors have no conflicts of interest to declare.

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