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Climate gentrification and green infrastructure in the U.S. Great Lakes region: Engaging with heat exposure and adaptation policy

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ABSTRACT

Climate risks can pose significant challenges and create adaptation policy instruments in response. Green infrastructure has played a pivotal role in enhancing adaptation or minimizing maladaptation in the context of climate risks. In this work, we 1) identify climate gentrification dynamics with two hypotheses and 2) examine the role of green infrastructure as a climate policy effort in the dynamics of gentrification and climate adaptation/maladaptation to heat exposure within the U.S. Great Lakes region and four metropolitan cities between 2010 and 2019. Drawing on temporal and spatial effects, our findings suggest that green infrastructure efforts can play a vital role in adaptation/maladaptation policy intervention for addressing climate gentrification effects. Our work is a preliminary study examining the complex relations between climate, society, and policy.

1. Introduction

How do climate change or climate risks, as forms of urban challenges or opportunities, transform urban space that may include gentrification, segregation or inequality, and social or physical infrastructure? And, how can we overcome the challenges by enhancing climate adaptation or reducing maladaptation? Numerous attempts have been made to answer these inquiries (e.g., Anguelovski et al., 2019; Keenan et al., 2018; Kim & Park, 2023). At the interface of climate science and public policy, our findings show that intersections of heat exposure and adaptation policy can contribute to the dynamics of climate gentrification as a proxy for adaptation/maladaptation. In addition, our work shares the potentials of green infrastructure as a policy effort to enhance climate adaptation and minimize maladaptation.

In the name of climate gentrification, Keenan et al. (2018, p. 4) addressed the dynamics of gentrification following the assumption that, “climatic influences will increasingly play an important role in the weighted factors driving investment and locational decisions of households, investors, and financiers.” Climate gentrification also exposes built environment and social and economic dynamics under climate change or climate relevant risks (Tedesco et al., 2022; Wang et al., 2023). The dynamics especially include (social) vulnerability that can serve as both contributors and outcomes of social inequalities or climate injustice (Cutter et al., 2003; Kim et al., 2018), disproportionate burdens of disaster risk (Cutter 2017) and unequal exposure to climate risks (Wisner et al., 2004). In line with the nexus of people and place within the urban climate vulnerability (Wilhelmi & Hayden, 2010) and the perspectives of heat racism, heat gentrification, and heat justice (Anguelovski et al., 2025), Wilson and Chakraborty (2019) and Mitchell and Chakraborty (2015) demonstrated that the extent of human loss or damage caused by climate change, especially heat risks, can run parallel to (social) vulnerability, climate change adaptation measures, and health issues.

Ecosystem-based adaptation tools or practices have been adopted to reduce the vulnerability to climate risks. Together with various adaptation forms of green infrastructure, ecological structure, and others, their effectiveness or benefits have been examined and revealed in the context of climate change (e.g., Gaffin et al., 2012; Kim et al., 2022; LaFrombois et al., 2023). However, such benefits can be linked with the green gentrification pattern proposed by Anguelovski et al. (2019),

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Wolch et al. (2014), Shokry and Anguelovski (2022), among others. Some communities have experienced increases in housing value, caused by an influx of wealthier individuals drawn to green infrastructure, resulting in the displacement of original residents. In addition to the adaptation perspectives, Juhola et al. (2016, p. 139) through the feedbacks of maladaptation, argued that policy or measure as action can influence affected entities depending on the types of maladaptation that embrace “rebounding vulnerability, shifting vulnerability, and eroding sustainable development.” In this sense, our work conceived green infrastructure as adaptation or maladaptation measures by seeking out climate gentrification dynamics (including socioeconomic vulnerability) and green infrastructure outcomes to embrace the intersections of climate, society, and policy.

Prior studies (e.g., Anguelovski et al., 2019; Blok, 2020; Harper, 2020; Keenan et al., 2018; Kim & Park, 2023; Shokry, 2022; Shokry & Anguelovski, 2022; Thompson et al., 2023) have paid greater attention to theoretical connections of (social) vulnerability, urban gentrification, sustainability, equity or justice, resilience, green infrastructure, and migration in accordance with the types of climate impacts (e.g., sea level rise, storms, flooding) and the extent of climate risks. Keenan et al. (2018) and others (e.g., Taylor & Aalbers, 2022; Thompson et al., 2023) highlighted that the climate gentrification pattern can be revealed through the pathways of investment and settlement (relocation) (or climate risk-rent dynamics) by climate change impacts.

Despite prior efforts, few studies have empirically examined the dynamics of climate gentrification aligned with the concrete framework of scenarios of housing vacancy (displacement) and housing value as drivers of gentrification outcomes and the extent of specific climate impacts. Further, little research has been conducted in heat-vulnerable regions to address the potential role of green infrastructure as adaptation/maladaptation efforts in the dynamics of climate gentrification over time.

Our work to integrate heat exposure and adaptation policy in the context of climate risks contributes to applying the dynamics of climate gentrification and identifying the potentials of green infrastructure as policy efforts for climate adaptation/maladaptation. From the perspectives of intersections of climate, society, and policy, we build on an empirical study with the U.S. Great Lakes region over the past 10 years. Considering the climate risk mechanisms of ‘before’ and ‘after’ and ‘with’ and ‘without’ heat exposure, our work attempts to achieve two research aims. First, we will examine climate gentrification dynamics using two hypotheses-based research phases (i.e., housing value-gentrification, housing vacancy-gentrification) using temporal effects and spatial differentials. Second, we will identify the role of green infrastructure as a climate adaptation/maladaptation instrument in the context of heat exposure and climate gentrification within four selected counties, home to metropolitan cities, across the U.S. Great Lakes region.

This manuscript is organized into five sections. Following the introduction, related literature is reviewed that addresses the dynamics of climate gentrification and the potential role of green infrastructure as adaptation or maladaptation instrument in the context of climate risks. The next section outlines the analytical framework of two research hypotheses, data sources, and empirical data employed in the U.S. Great Lakes region between 2010 and 2019. Following the empirical results, conclusions and a discussion summarizes our findings, policy implications, and study limitations (which give rise to future research needs).

2. Climate gentrification, green infrastructure, and climate risks

Climate change or relevant climate risks can create new policy instruments (interventions) for mitigation. Hamstead (2023), through the lens of climate urbanism and thermal insecurity, argued that the link of heat and health impacts can enhance heat mitigation strategies (e.g., early warning system, investment). Of the policy instruments, green infrastructure projects (green space, urban greening, urban greenery) have been conceived as a representative nature-based solution (e.g., Tozer et al., 2020), adaptation (or mitigation) policy (or planning) strategy (e.g., Mabon & Shih, 2018; Sanchez and Reames 2019), and sustainability perspectives on social and environmental justice (e.g., Chatzimentor et al., 2020; Geng et al., 2024; Kim et al., 2022). In reality, green infrastructure interventions have been adopted to reduce heat stress, urban heat island effects, flood related risks, and improve stormwater management and air quality (e.g., Davies & Lafortezza, 2017; Feyisa et al., 2014; Keenan et al., 2018; Kim et al., 2022; Pugh et al., 2012).

Connecting climate change impacts and sustainability, Brink et al. (2016) argued that ecosystem-based adaptation benefits can be meaningfully aligned with ecological structures (e.g., green space, wetlands, trees and parks), ecological functions, valuation, and management practices for climate related hazard risks. Meerow (2020) demonstrated that such benefits include 1) managing stormwater, 2) reducing social vulnerability, 3) increasing access to green space, 4) improving air quality, 5) mitigating the urban heat island effect, and 6) increasing landscape connectivity. Such multifunctional benefits of green infrastructure were also highlighted in the works of Hoover et al. (2023)’s rational categories of social, economic, hydrology, and ecology and Hansen and Pauleit (2014)’s multiple ecosystem services. Such benefits of green infrastructure can be tied to policy interventions (or policy measures) to enhance health justice (e.g., Kim et al., 2022), health care (e.g., Carmichael et al., 2019), green gentrification (e.g., Mendonça et al., 2024), climate change adaptation approaches (e.g., Ambrey et al., 2017; Emmanuel & Loconsole, 2015), green or thermal equity (e.g., Byrne et al., 2016; Kamjou et al., 2024; Nesbitt et al., 2019), green gentrification or environmental justice (e.g., Sax et al., 2022), and urban sustainability (e.g., Sánchez et al., 2018).

Several works (e.g., Geng et al., 2024; Grabowski et al., 2023; Haase et al., 2022; Heckert & Rosan, 2016; Rigolon & Németh, 2021; Zheng & Barker, 2021) focusing on the benefits of green infrastructure (or green regeneration) highlighted the equity or justice of the infrastructure through measurable context (e.g., access to green space) or others (e.g., quality of life, sustainable urbanization). In line with the work of Wolch et al. (2014)’s green space paradox in the process of climate adaptation, some communities (residents) are more likely to confront the negative (or positive) outcomes of green gentrification. Such outcomes take the form of increased property values, in-migration of wealthier individuals, and physical or socio-cultural displacement of long-time residents (Black & Richards, 2020; Kamjou et al., 2024; Oscilowicz et al., 2023; Scott et al., 2024; Shokry & Anguelovski, 2022). Shokry and Anguelovski (2022) argued that socio-cultural displacement due to greening or environmental amenities can lead to social concerns like social isolation and socio-environmental vulnerability.

Calling for “socio-spatial tensions in green infrastructure,” Angueloveski et al. (2018) suggested the negative or positive role of greening planning in growth, climate risks, and gentrification. Such dynamics of gentrification (e.g., low-carbon gentrification, eco-gentrification, ecological gentrification) or gentrification effects (outcomes) can be connected with climate change risks (e.g., Black & Richards, 2020; Bouzarovski et al., 2018; Dooling, 2009; Harper, 2020). Drawing on the disproportionate share of climate risks, Blok (2020, p. 2805) documented that green gentrification can be dealt with climate-sensitive notions and its influence on “socio-material inequality,” “environmental (in)justice” and displacement with multi-scalar (local, global) frames. Applying to hurricane-prone U.S. coastal cities, Kim and Park (2023) argued that residential displacement (migration) due to climate risk (flood risk) can give rise to climate gentrification as a form of demographic shift and social inequality. Thompson et al. (2023), with more attention given to the outcome of gentrification redefined climate gentrification as the links between climate hazards (e.g., flooding) and property values.

Incorporating with the works of Angueloveski et al. (2019) and Castán Broto and Robin (2021, p. 1) argued that “urban climate interventions can exacerbate preexisting dynamics of gentrification and displacements, notably through low-carbon interventions and green infrastructure projects." To accomplish the goal of urban green interventions, Anguelovski et al. (2018, 1065) documented that several policies and research schemes have existed as forms of the U.S. Environmental Protection Agency's (EPA) Green Infrastructure Program, Nature-Based Solutions, and Re-Naturing Cities. Linking climate change vulnerability among the urban poor with the gradual decline in green structure or service, Roy et al. (2018) highlighted the role of urban green service and innovative adaptation practice. Such approaches can be aligned with a balance between justice concerns with urban greening and climate risk reduction. Through the case of Taiwan's Taipei, Mabon and Shih (2018, 227) emphasized the "potential challenges to equity thinking when considering greenspace functions for climate adaptation."

Several works have paid more attention to green infrastructure as an adaptive response (adaptation policy) to climate change or climate change risks. For local adaptation, Krellenberg et al. (2014) highlighted the combined socio-environmental fragmentation and vulnerability to climate change that includes exposure, susceptibility, and coping capacity. Hsu, Sheriff, Chakraborty, & Manya, 2021 documented the disproportionate exposure to the intensity of urban heat islands. Incorporating adaptation and resilience to climate risks, Meerow and Newell (2017) argued the role of multifunctional green infrastructure in enhancing resilience.

Likewise, in considering cases of high temperatures, Norton et al. (2015) adopted a green infrastructure framework in planning for cooler urban landscapes. In addition to the capacity of green infrastructure, Matthews et al. (2015) argued that agency and institutional factors can be barriers in adapting to climate change. Chu et al. (2017) highlighted that climate adaptation action (option) should be required from an equity perspective and inclusive urban development by addressing the cases of ecological infrastructure or green infrastructure. Shokry (2022, p. 235) documented the imperative of green resilience (program) as climate adaptation efforts aligned with "social justice and anti-displacement measures."

Such perspectives can be connected with the statement that green infrastructure can be both adaptation and maladaptation to climate risks, depending on how the green infrastructure is developed/delivered and for whom. In addition to the adaptation, our work also applies maladaptation as the meanings of "impacts adversely on, or increases the vulnerability of other systems, sectors or social groups" (Barnett & O'Neill, 2010, 211), "benefits for households directly involved but negative externalities for others" (Scott 2024, 5), and outcomes of "an intentional adaptation policy or measure directly increasing vulnerability for the targeted and/or external actor(s), and/or eroding preconditions for sustainable development by indirectly increasing society's vulnerability (Juhola et al., 2016, p. 139)." Further, assessing adaptation option in the context of adaptation-maladaptation continuum to minimize the maladaptation risk, Reckien et al. (2023, p. 4) demonstrated that every adaptation intervention has "some potential for both adaptation and maladaptation." In this context, our work regarded green infrastructure as a proxy for adaptation/maladaptation. We also adopted the ideas of inequality, justice, and equity to minimize maladaptation and enhance adaptation due to climate gentrification. For an empirical analysis, our work employed the percentage of renters and income inequalities as socioeconomic vulnerability beyond the traditional socioeconomic variables.

Following Schlosberg's (2012) capabilities approach (with the perspectives of climate justice and sustainability), Agyeman's (2013) just sustainability, and Curran and Hamilton's (2012) just green enough, our work strives to embrace (social) vulnerability, the relationships between people and place, and climate justice within the dynamics of climate gentrification, green infrastructure, and adaptation policy. From an interdisciplinary perspective, our work provides some insights into the nexus of climate, society, and policy.

3. Research design and methods

3.1. Analytical framework, empirical variables, and data collection

Our attempt to advance heat exposure (as a form of climate exposure) and climate adaptation/maladaptation policy in the context of climate gentrification and green infrastructure allows us to follow two research phases in response to the spatial boundaries: (1) across the U.S. Great Lakes region and (2) within the selected four counties (incorporating four metropolitan cities) of the region.

Drawing attention to the (potential) role of green infrastructure effort (as climate adaptation/maladaptation option) in the dynamics of climate gentrification, our first research phase follows two hypotheses -based research procedures: (1) housing value effect (*Housing value-gentrification*) and (2) displacement effect (*Housing vacancy-gentrification*). Such a scenario-based empirical approach outlined in Fig. 1 addresses the temporal dynamics of gentrification effects and green infrastructure effort in the context of heat risks (heat exposure) across the U.S. Great Lakes region over a recent 10-year period. To account for the associations between green infrastructure efforts and gentrification effects, our work focuses more on climate risks and climate adaptation/maladaptation. Considering the research procedures, we specify the gentrification effect by the degree of heat exposure (as climate risk effect) and socioeconomic vulnerability. In addition, our work reflects the time spectrum (temporal aspects) through the climate risk mechanisms of 'with' and 'without' heat exposure.

The first hypothesis for our empirical work describes how green infrastructure effort works property value in accordance with the extent of heat exposure. The causal links also will be represented by a set of socio-economic vulnerability aspects (e.g., renter, household income, educational attainment, income inequality) and temporal dynamics (i.e., 5 year-long effect, 10 year-long effect). To proceed with the first hypothesis, we selected several empirical variables that imply specific attributes of climate effect, green infrastructure, property value, and socio-economic vulnerability aspects summarized in Table 1. Collected from the U.S. Census Bureau at the census track level over the study period, property value (*Housing value* variable) was selected as an outcome variable to identify the effect of green infrastructure and socioeconomic vulnerability on housing price. Measured by Normalized Difference Vegetation Index (NDVI) at the census track-level based on the data resource from the Landsat, green infrastructure effort (*Green infrastructure* variable) reflects the degree of greenness across the Great Lakes region over the 10 year period under consideration. Secured from the U.S. Census Bureau, socio-economic vulnerability variables include the percentage of renters (*Renter* variable), median household income level (*Income* variable), percent of population that is white (*White* variable), percentage of individuals with at least a bachelor's degree (*Education* variable), and income inequality level (*GINI* variable).

To measure the degree of climate risk, we first capture the number of days that represented heat and excessive heat (*Heat days* variable) at the county levels over the study period. Secured from the National Oceanic and Atmospheric Administration (NOAA), our work specifies the extent of the heat exposure as the form of binary measures (i.e., coded as '1' and '0'). The *Heat exposure* variable was measured by the assumption that a county experienced extreme heat and heat events rather than adopting an existing estimated real number of injuries and fatalities caused by heat events.

Following the first hypothesis, *Housing vacancy-gentrification* as a second empirical work allows us to illustrate the interplay of green infrastructure effort and property value in the context of displacement by green infrastructure and the degree of heat exposure. For the empirical hypothesis, we selected the rate of housing vacancy (*Housing vacancy* variable) as the outcome variable. By adopting five socio-economic vulnerability variables (i.e., *Renter*, *Income*, *White*, *Education, GINI* variables) and *Housing value* variable used in the first hypothesis, we advance the dynamics of gentrification. Our process depicted in

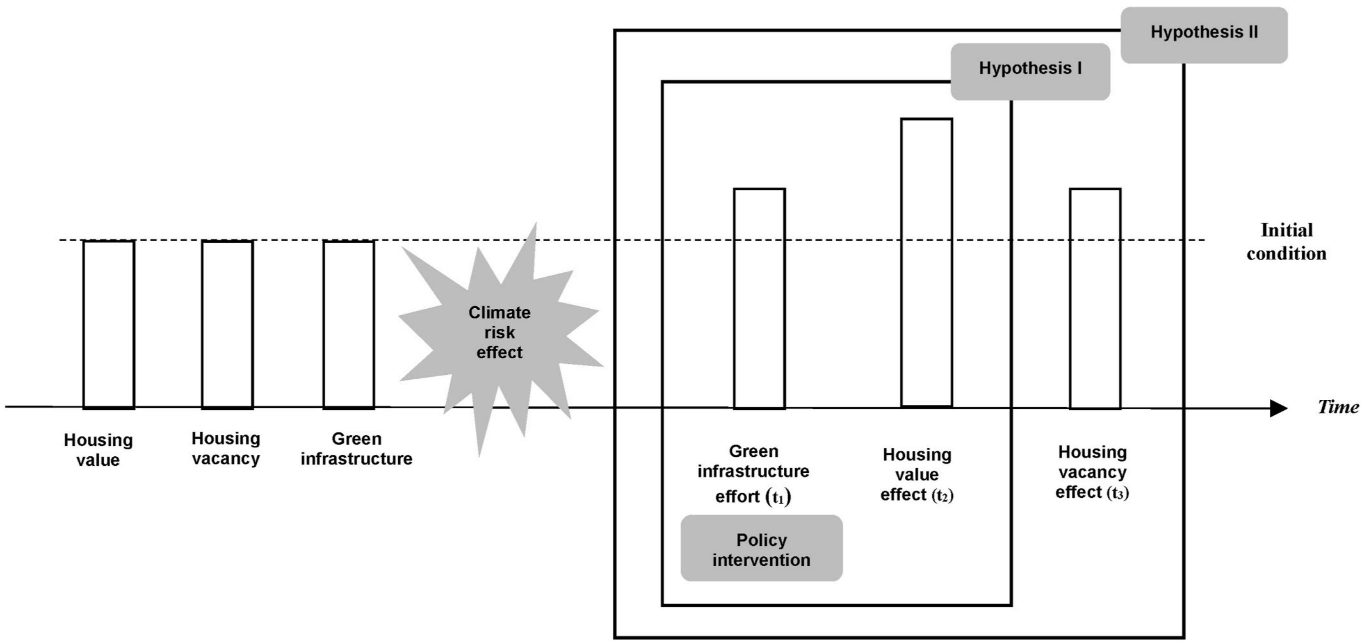


Fig. 1. Conceptual framework and two hypotheses of climate gentrification and green infrastructure effort.

Fig. 1 reflects a quantitative approach using a panel model with temporal effects.

To accomplish the goal of the second research phase, we paid more attention to the assumption that gentrification effect and green infrastructure effort can be applicable to the context of climate risks and micro-level spatial and temporal dynamics. Within the second phase, our work accounts for (1) temporal dynamics of gentrification effect by heat exposure and green infrastructure effort aligned with temporal effects, 5 year-long effect (2010–2015) and 10 year-long effect (2010–2019). And then we address (2) spatial dynamics with heat vulnerable regions as potential hotspots of heat risks (surrounding areas of four metropolitan cities) across the Great Lakes region. As to the potential heat vulnerable region (applied in the work of Kim et al., 2022), we selected Cook County (Chicago metropolitan city) in Illinois, Wayne County (Detroit metropolitan city) in Michigan, Milwaukee County (Milwaukee metropolitan city) in Wisconsin, and Cuyahoga County (Cleveland metropolitan city) in Ohio (see detailed in Section 3.2). Such an approach represented by temporal variation and spatial visualization can be meaningful to reflect the potential application of the first research approach. Further, our attempt is exploratory in embracing the complexity of climate gentrification effect and green infrastructure effort.

3.2. *Study area, heat risks, and green infrastructure*

In keeping with the works of Kim et al. (2020; 2022) on the impacts of green infrastructure on heat vulnerability, we also selected the U.S. Great Lakes region and urban areas within said region as our study area. The study area is considered ideal in identifying the intersections of climate and society that are conceived as climate vulnerable areas and socio-economic dynamics. The Great Lakes region depicted in Fig. 2 involves eight states (i.e., Minnesota, Wisconsin, Illinois, Michigan, Indiana, Ohio, New York, Pennsylvania), several metropolitan cities (e.g., Chicago, Detroit, Milwaukee, Cleveland), and 212 counties as administrative units. Like the work of Kim et al. (2022), we also selected 212 counties that reflect the buffer zone due to climate risk effects and “homogenous geographical attributes” of coastal effects of the Great lakes. Such selection also mirrors the historical experience on the heat events as was the case in Chicago in 1995. Klinenberg (2015) and other related studies described the severe health risks by heat risks. As summarized in Kim et al. (2022) and other relevant studies (e.g., Florida, 2017), the Great Lakes region and its cities revealed social and economic dynamics (e.g., economic inequality, racial disparity) and lower green infrastructure that can address the greater close integration of social vulnerability and environmental (in)justice with heat exposure (as climate risks).

As depicted in Fig. 2 (1), most metropolitan cities within the Great Lakes region revealed lower green infrastructure measured by the NDVI index at the census track-level between 2010 and 2019, as supported by the results of Kim et al. (2022). Specifically, lower levels of green infrastructure were exhibited in Cook county (Illinois), Milwaukee county (Wisconsin), Wayne county (Michigan), and Cuyahoga county (Ohio). Given the assumptions that regions with heat exposure require a high level of green infrastructure, we attempted to incorporate a lower level of green infrastructure into heat exposure status within the four counties (see Fig. 2 (2) and (3)). As a whole (a preliminary work), regions with heat exposure (because of estimated human damage) have lower green infrastructure as opposed to those without heat exposure (see (b) and (f) of Fig. 2(2); (d) and (h) of Fig. 2(3)). Such dynamics of our study area can be sufficient to offer some insights into climate adaptation/maladaptation policy effort as green infrastructure, particularly in the context of climate gentrification.

4. Results

4.1. *Temporal dynamics of green infrastructure effort and potential gentrification effect*

To examine the temporal variation of gentrification effects, we compared the 5 year-long effect with the 10 year-long effect in accordance with the heat exposure and green infrastructure effort summarized in Table 1. The degree of most variables concerned with climate risks and climate effect within 5 year-long effect showed an increasing trend compared to the 10 year-long effect. This implies that the extent of heat related climate risks over 2010–2015 was considerably more severe than during the last five years (2016–2019). Likewise, the extent of socioeconomic variables (i.e., *White* and *Education*) that represent lower social vulnerability to climate risks under the 5 year-long effect increased compared to the 10 year-long effect. The degree of socioeconomic vulnerabilities (i.e., *Renter*, *GINI* variables) increased under the

Table 1
Concept measurement and temporal effects.

Variable name	Definition/measurement	Data source	Units of analysis	Mean		SD		Range		
				5 year-long effect	10 year-long effect	5 year-long effect	10 year-long effect	5 year- long effect	10 year- long effect	
Climate risk variables										
Heat days	Number of days with excessive heat and heat (Days)	NOAA	County	0.529	0.386	1.070	0.916	0–5	0–5	
Heat exposure	Heat exposure status derived from *Heat days* variable (1 = if a county experienced heat day; 0 = otherwise)	Authors' calculation	County	0.234	0.177	0.423	0.382	0–1	0–1	
Socio-economic vulnerability variables										
Renter	Renter population (%)	US Census Bureau	Census track	27.77	28.42	18.68	18.88	0–100	0–100	
Income	Median household income (US$)			53,294	55,479	24,998	26,474	3589–241,513	3589–248,974	
White	White population (%)			73.98	73.62	29.65	29.46	0–100	0–100	
Education	Bachelor's degree and over (%)			26.13	25.14	18.29	53.33	0–100	0–100	
GINI	Gini index derived from household income	US Census Bureau	County	0.44	0.45	0.03	0.03	0.33–0.50	0.33–0.50	
Housing vacancy	Housing vacancy rate (%)	US Census Bureau	Census track	21.63	21.95	27.28	27.75	0–54.11	0–55.44	Outcome variable for Hypothesis II
Housing value	Property value (US $)			162,652	164,401	104,897	108,951	10,100–1,310,700	10,100–1,548,500	Outcome variable for Hypothesis I
Green infrastructure variable										
Green infrastructure	NDVI index	Landsat	Census track	0.249	0.250	0.072	0.074	−0.154-0.496	−0.161-0.512	

Note: units of analysis in parentheses.

10 year-long effect compared to the 5 year-long effect. Linked with the direct effect of climate gentrification, the extent of two variables (*Housing value* and *Green infrastructure*) within the 5 year-long effect decreased more than the 10 year-long effect. Housing vacancy status as a displacement implication (*Housing vacancy* variable) revealed a decreasing trend in the 5 year-long effect.

Comparing the entire study area, our selected four counties revealed the higher levels of heat exposure except for Cuyahoga county embracing Cleveland metropolitan city illustrated in Appendix 1. By and large, most socioeconomic vulnerability attributes also showed the higher degree than the entire study areas. As hypothesized, four counties reflecting urban attributes (categorized as 'metro' according to the urban and rural continuum by USDA Economic Research Service) revealed lower levels of green infrastructure than the entire areas. There remain differences in the degree of housing vacancy and housing value among the selected four counties and the entire study areas. Such a gap of gentrification outcomes implies that it is necessary to take into consideration heterogenous effects of climate risks and socioeconomic constructs. In terms of institutional aspects in response to climate risks, most counties had climate action plans and have been implementing climate action in attempting to enhance adaptation and minimize maladaptation to climate risks.

Drawing on the temporal dynamics of gentrification effects in the context of climate risks, our work paid more attention to the heat exposure as a driving force for climate gentrification effect by comparing the entire study area with the selected four counties. As illustrated in Fig. 3, we selected three variables (i.e., *Housing value, Housing vacancy*, and *Green infrastructure*) associated with the potential of climate gentrification effect. Overall, in the context of temporal effects and the entire study area, housing value increased, while housing vacancy status and the extent of green infrastructure decreased. As with the selected four counties as potential heat vulnerable regions, similar results were exhibited in light of housing value and green infrastructure compared to the entire study area outlined above. However, the results were opposite considering housing vacancy status. This implies that residents who live in the heat vulnerable regions (and heat exposure) are much more likely to out-migrate.

As with the climate adaptation policy intervention, heat vulnerable regions that have experienced heat exposure made lower green infrastructure effort than the entire study area. Often adopted as climate adaptation or maladaptation policy tools, green infrastructure status (effort) failed to represent positive roles in mitigating the heat risks. Given that green infrastructure effort in general conceived as a primary driver in reducing heat risks, our findings need to be re-examined under the causal relationships with more specific time order rather than the wide study period applied in our work.

Accounting for the role of green infrastructure effort, we focused more on the potential heat vulnerable regions within our study area. Correlation analysis on the relationships between housing value, housing vacancy, and green infrastructure variables was conducted in accordance with the temporal effects (i.e., 5 year-long and 10 year-long effects). Except for Cook county (see Fig. 4 (b)–(c)), the association between housing value and green infrastructure variables exhibited the positive direction, but the correlation between housing vacancy status and green infrastructure was negative. Such associations were stronger under the 5- year long effect and more heat exposure effect if we pay more attention to the coefficients. Cook county encompassing Chicago metropolitan city also revealed a similar association in terms of housing vacancy status.

4.2. *Climate gentrification and green infrastructure in the context of heat risks*

Taking into consideration the first research phase, we examine the potential role of green infrastructure effort as heat adaptation policy intervention in response to the two hypotheses outlined above. For the

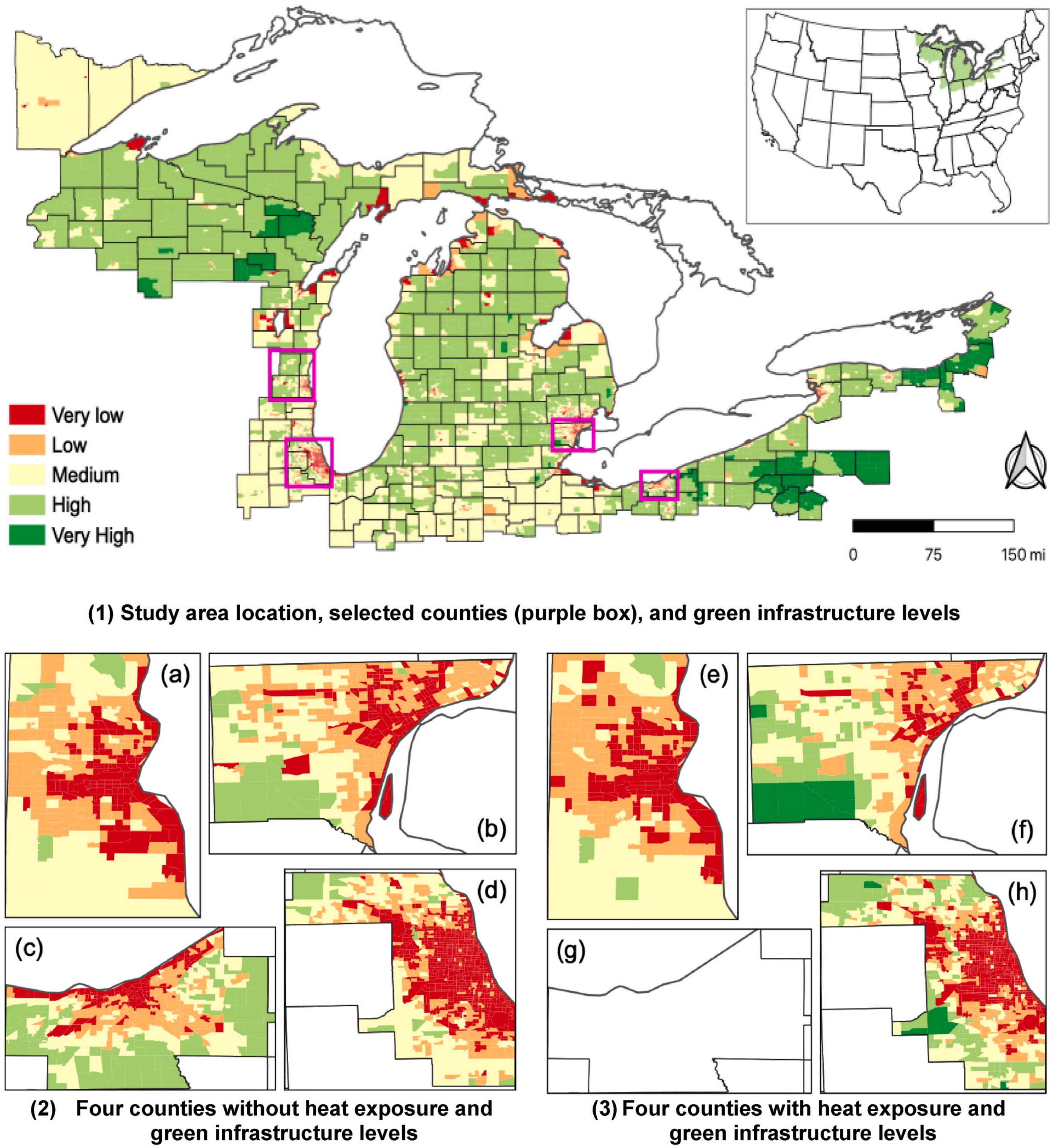


Fig. 2. Study area and green infrastructure levels
Note: (a) and (e) indicate Milwaukee county (Wisconsin), (b) and (f) are Wayne county (Michigan), (c) and (g) are Cuyahoga county (Ohio), (d) and (h) indicate Cook county (Illinois). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

research phase, we focused on climate gentrification within the entire study area and selected four counties encompassing metropolitan cities of the study area aligned with the temporal effects (i.e., 5 year-long effect, 10 year-long effect). Empirical findings of the climate gentrification effect by the two hypotheses are summarized in Table 2. Given that the role of green infrastructure effort in housing value (logged *Housing value* $_t$) as gentrification outcomes over the past 5 years (2010–2015, as a 5 year-long effect), most variables concerned with housing value, green infrastructure, and socio-economic vulnerability variables were positively related to housing value (see Model (1) to (4)). Within the casual relationships, our work placed an emphasis on 'time lag effect' particularly considering housing value and green infrastructure. By adding 'one year before (t-1)' effect to the housing value and green infrastructure, we attempted to reflect the time lag effect of policy response and the close interrelationships between independent variables and outcome variable, with a form of '*Housing value* $_{t-1}$' and '*Green*

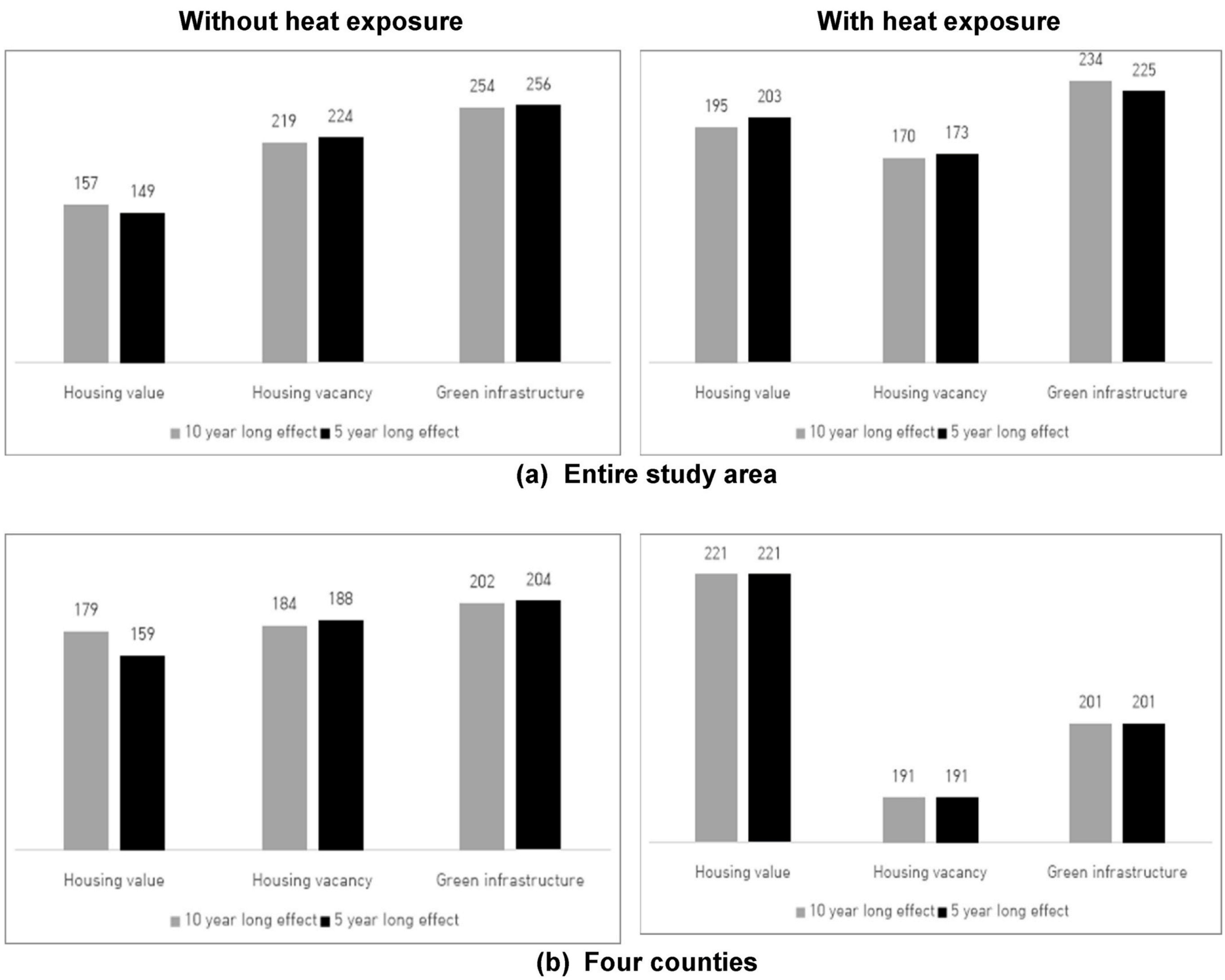


Fig. 3. Temporal dynamics of housing value, housing vacancy, and green infrastructure according to the heat exposure status within the entire study area and four counties.

infrastructure $_{t-1}$.'

Green infrastructure effort as a climate adaptation policy intervention exhibited positive influence on housing value with or without the consideration of heat exposure. However, such influence becomes negative in case we rethink the moderate role of green infrastructure as a form of interaction effects between housing value and green infrastructure The results showed heterogenous effects aligned with green infrastructure effort and heat exposure. From the findings, it should be assumed that we need to consider the dynamics of gentrification outcomes and green infrastructure effort to identify the dynamics of climate gentrification.

In a similar way, empirical findings on green infrastructure effort were illustrated in the context of 10 year-long effect and high heat exposure (see Model (5) to (8)). With greater attention on the temporal effects of the last ten years (2010–2019) and heat exposure, such green infrastructure efforts exhibited positive roles in housing value (see Models (5) and (7)). The results relied on controlling for socio-economic vulnerability status. Higher levels of socio-economic status (*Housing value*, *Income*, *White*, *Education* variables) resulted in higher levels of housing value without the consideration of heat exposure. However, such relationships were reversed in cases of higher levels of Renter and lower levels of GINI (as socioeconomic vulnerabilities). Compared to the impacts of heat exposure (see Models (2) and (4)), the coefficient values were smaller while heat exposure was minimal. This finding implies that the role of socioeconomic vulnerability should be considered by reflecting heterogenous effects of climate risks, societal constructs, and time lag effects of policy implementation.

Focusing on the second hypothesis, Models (9) to (16) reflect the effects of green infrastructure effort and housing value on the housing vacancy status that represents the potential of residential displacement. Such empirical results address the mechanism of climate gentrification with primary outcomes of gentrification (i.e., housing value and displacement). Considering the positive associations of greater socio-economic status and greater housing vacancy, housing value and green infrastructure effort revealed rather ambiguous findings. Under both 5 year-long and 10 year-long effects and without the consideration of heat exposure, housing value (as a gentrification effect) exhibited a positive relationship with residential displacement. This result implies that housing value is effective in explaining residential displacement given some heat exposure remained. Overall, greater socioeconomic conditions (or lower socioeconomic vulnerabilities) led to the likelihood of higher housing vacancy without the consideration of heat exposure.

Focusing on the role of green infrastructure effort in gentrification outcomes particularly in the context of heat risks (heat exposure), we generated four graphs that describe the probability of climate gentrification in Fig. 5. Derived from Models (8) and (16) of Tables 2 and 10-

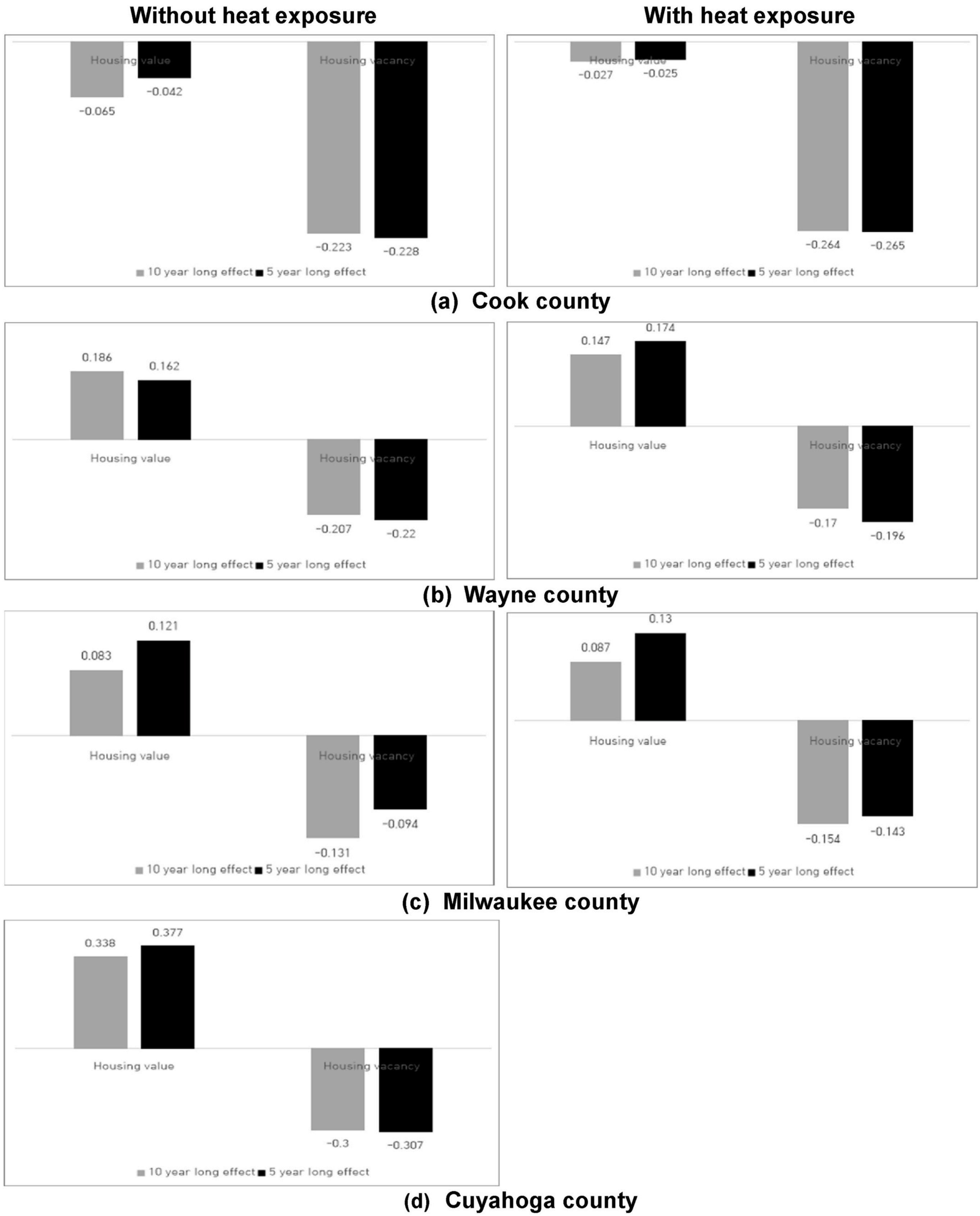
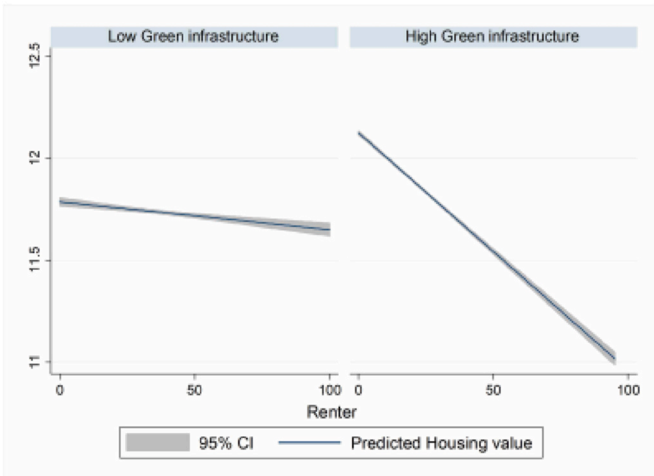
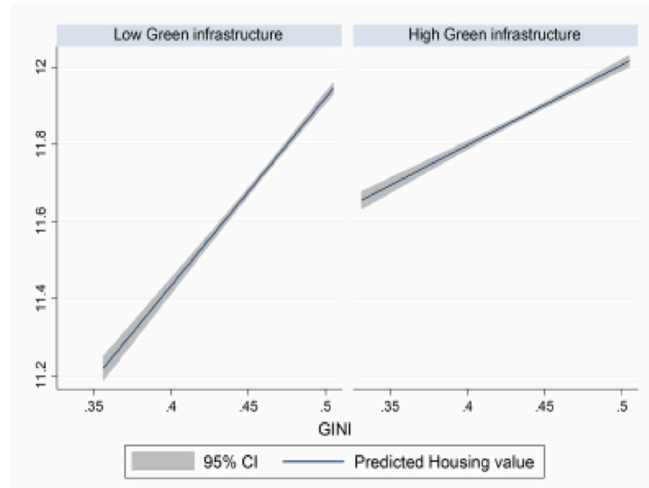


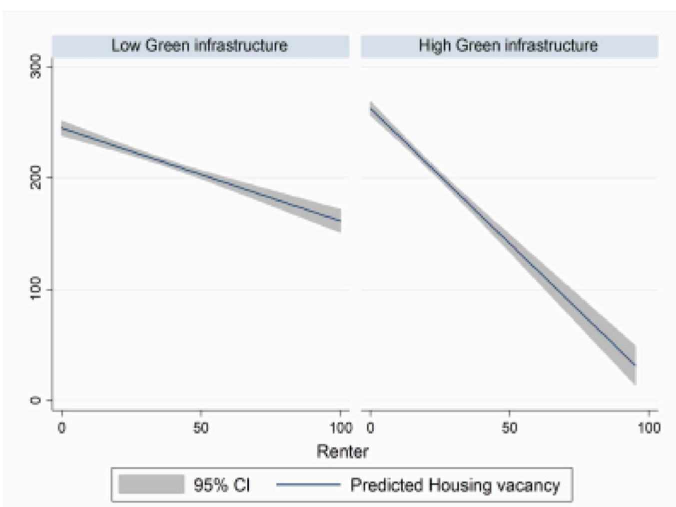
Fig. 4. Correlation between green infrastructure efforts and gentrification effects in the context of heat exposure within four counties.



(a) Predicted housing value by renter and green infrastructure



(b) Predicted housing value by gini and green infrastructure



(c) Predicted housing vacancy by renter and green infrastructure

(d) Predicted housing vacancy by gini and green infrastructure

Fig. 5. Green infrastructure efforts, gentrification effects (Housing value and Housing vacancy), and socio-economic vulnerability within the impact of heat exposure. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

year long effect, each graph denotes the predicted housing value or housing vacancy by levels of green infrastructure effort and *Renter* and *GINI* variables as socio-economic vulnerability. Lower and higher levels of the green infrastructure effort were measured by the middle point of the entire value of green infrastructure variable. Two graphs of Fig. 5 (a)–(b) describe the association between probability of housing value and the levels of *Renter* (a) and *GINI* (b) in case of more heat exposure according to the degrees of green infrastructure effort. The higher renter levels (or greater socio-economic vulnerability) are related to the lower housing value. However, within the relationships, the degree of housing value decreased more in the case of higher green infrastructure effort. By and large, higher income inequalities (i.e., higher levels of *GINI* variable) are associated with the higher housing value. The slope of the links became small when the green infrastructure effort was higher. Such a decline of *Renter* and *GINI* as socioeconomic vulnerabilities to climate risks reflects that green infrastructure effort as a heat adaptation or maladaptation policy intervention can play a vital role in reducing housing value.

With more attention to the links between socioeconomic vulnerability and housing vacancy status under the heat exposure, specific graphs were illustrated in Fig. 5(c) and (d). The lower levels of economic conditions and higher socioeconomic vulnerabilities (i.e., higher level of *Renter* variable) led to the lower likelihood of housing vacancy, but the decline exhibited more severe when we consider the higher effort of green infrastructure (see Fig. 5 (c)). The result highlights that we need to fully re-examine the complex relations between residential displacement supposed by climate risks, green infrastructure as climate policy measures, and other socio-economic status. As depicted in Fig. 5 (d), the negative relationships between *GINI* and the likelihood of housing vacancy were exhibited under the condition of higher green infrastructure effort. This finding implies that the role of green infrastructure effort should be considered by reflecting heterogenous effects of climate risks, societal constructs, and time lag effects of policy implementation.

Table 2
Climate gentrification effects by two hypotheses and temporal effects.

	5 year- long effect				10 year- long effect			
	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)	Model (7)	Model (8)
Hypothesis I (Housing value-gentrification: log *Housing value* $_t$**)**								
Intercept	−0.086*** (0.019)	0.306*** (0.049)	−0.734*** (0.043)	−0.378*** (0.090)	−0.092*** (0.012)	−0.204*** (0.032)	−0.144*** (0.037)	−0.447*** (0.073)
Housing value $_{t-1}$ *(logged)*	1.003*** (0.001)	0.939*** (0.003)	1.053*** (0.003)	0.993*** (0.006)	1.007*** (0.001)	0.953*** (0.002)	1.005*** (0.003)	0.948*** (0.006)
Green infrastructure $_{t-1}$	0.090*** (0.008)	0.403** (0.165)	0.168*** (0.023)	0.890** (0.322)	0.037*** (0.006)	0.054 (0.117)	0.118*** (0.021)	−0.469 (0.289)
Housing value $_{t-1}$ × *Green infrastructure* $_{t-1}$	−6.40e-08* (3.65e-08)	−0.036** (0.013)	−3.02e-07*** (7.20e-08)	−0.076** (0.026)	−6.47e-08** (2.44e-08)	−0.004 (0.009)	1.08e-07 (6.76e-08)	−0.040* (0.023)
Renter $_t$		−0.0004*** (0.00004)		−0.0007*** (0.00009)		−0.0007*** (0.00003)		−0.001*** (0.00007)
Income $_t$ *(logged)*		0.035*** (0.002)		0.039*** (0.005)		0.060*** (0.002)		0.082*** (0.004)
White $_t$		0.0005*** (0.00002)		0.0001*** (0.00004)		0.0003*** (0.00002)		0.0003*** (0.00004)
Education $_t$		0.0009*** (0.00005)		0.0003*** (0.00008)		0.00002*** (8.28e-07)		0.00006*** (2.46e-06)
GINI $_t$		0.197*** (0.020)		0.180*** (0.041)		0.089*** (0.015)		0.138*** (0.035)
Number of observations	32,762	24,434	8983	8983	62,875	38,582	12,068	11,410
Heat exposure	No	No	Yes	Yes	No	No	Yes	Yes

	Model (9)	Model (10)	Model (11)	Model (12)	Model (13)	Model (14)	Model (15)	Model (16)
Hypothesis II (Housing vacancy-gentrification: *Housing vacancy* $_t$**)**								
Intercept	−1.957* (1.059)	71.025*** (14.757)	1.330* (1.971)	121.939*** (21.338)	−1.004 (0.711)	86.534*** (8.291)	2.105 (1.689)	115.113*** (13.470)
Housing vacancy $_{t-1}$	0.990*** (0.002)	0.989*** (0.002)	0.990*** (0.006)	0.989*** (0.006)	0.986*** (0.001)	0.984*** (0.002)	0.986*** (0.005)	0.987*** (0.006)
Green infrastructure $_{t-1}$	9.847** (3.930)	20.710*** (5.284)	11.729 (7.897)	−6.139 (9.477)	3.482 (2.629)	24.082*** (3.941)	5.476 (6.599)	8.157 (8.315)
Housing vacancy $_{t-1}$ × *Green infrastructure* $_{t-1}$	0.051*** (0.008)	0.045*** (0.010)	−0.042 (0.030)	−0.099** (0.031)	0.053*** (0.005)	0.049*** (0.007)	−0.033 (0.023)	−0.096** (0.027)
Housing value $_{t-1}$ *(logged)*		8.566*** (0.886)		0.926 (1.184)		6.875*** (0.625)		3.567*** (0.888)
Renter $_t$		−0.419*** (0.024)		−0.434*** (0.036)		−0.347*** (0.018)		−7.538*** (0.996)
Income $_t$ *(logged)*		−13.264*** (1.496)		−10.812*** (2.199)		−13.021*** (1.049)		−12.090*** (1.622)
White $_t$		−0.024* (0.012)		−0.116*** (0.018)		0.003 (0.010)		−0.110*** (0.016)
Education $_t$		−0.091*** (0.026)		−0.005 (0.033)		−0.00007 (0.0004)		0.001 (0.0009)
GINI $_t$		−14.210 (10.154)		−27.554* (16.075)		−21.861** (7.520)		−0.637 (13.274)
Number of observations	33,247	24,450	9109	8991	63,964	38,640	12,276	11,426
Heat exposure	No	No	Yes	Yes	No	No	Yes	Yes

Note: *: $p < 0.1$, **:$p < 0.05$, ***: $p < 0.001$, Standard errors in parentheses, × : interaction term.

5. Conclusions and discussion

5.1. Summary

Our work builds on the relationships between climate gentrification effect and green infrastructure effort in the context of heat exposure and adaptation or maladaptation policy across the U.S. Great Lakes region and within the selected four counties. Following two hypothesis-based effects that entail housing value and housing vacancy as gentrification effects and the extent of climate risks, we attempted to address temporal dynamics (5 year-long effect and 10 year-long effect) of gentrification effects and green infrastructure effort over a recent 10-year period. Our findings demonstrate that green infrastructure efforts such as climate adaptation or maladaptation measures has much to do with climate gentrification effects even though our work was preliminary in dealing with the complex relations (as heterogenous effects) between climate stress, social response, and policy measures. Our work shed lights on the need to rethink green infrastructure efforts as climate policy intervention to the specific regions with climate and social vulnerability by considering gentrification effects.

5.2. Caveats, future research needs, and policy implications

Despite insights based on empirical hypotheses and temporal and spatial dynamics of climate gentrification, our approach is preliminary with several limitations. In this work, we account for the dynamics of climate gentrification by two hypotheses derived from gentrification effects (i.e., housing value, housing vacancy). However, rather than rethinking the gentrification process as dynamic, our approach only relied on secondary data with causal relationships or liner association. Future research needs to reflect climate gentrification dynamics by including more substantive hypotheses or mixed methods and perceived data sources. In addition, more individuals are moving toward high climate risk-prone areas (flooding, wildfires, drought, extreme heat) since the COVID-19 pandemic started within the United States. The study estimated that the pandemic allowed people to move to major metropolitan cities within the Sun Belt due to the combination of remote work, low mortgage rates, and housing prices due to the warm weather and low taxes. Although such finding needs to be further examined, our work should reexamine the climate migration pattern together with the extension of study period.

Considering studies on the nexus of climate and society, our work was limited to reflect the complex of climate risks and integrating social and policy variables within our study area and spatial levels. We relied on county-level climate risk variables derived from extreme heat status within the open data resource. Socio-economic vulnerability variables used in our work were based on census track or county level. Such spatial mismatch can generate some bias in obtaining more robust results. Future research needs to obtain more accurate and historical shifts and qualitative measures in green infrastructure attributes (e.g., NDVI, NDBI, NDBal), climate action plan or hazard mitigation plan efficacy (e.g., Connolly, 2025), urban heat mitigation strategies (e.g., urban heat island effect), socio-economic projections and adaptation planning process (e.g., Prall et al., 2023), land surface temperature and its connection to land use land cover change, and others (e.g., stewardship of green infrastructure).

In addition, this study was limited in reflecting complicated climate risks. Our work only focused on heat risks. However, our study areas have been exposed to other climate risks (e.g., sea level rise, flooding) as a form of compound hazards. Given that there remain diverse climate change-relevant risks, more work is necessary to examine climate risk dynamics (e.g., perceived or observed climate change on seasonal temperature change, addressed in the work of Pfeifer and Otto (2023)), and integrate socio-economic and climate policies. In light of climate adaptation policy measures, our work is only focused on green infrastructure. We attempted to advance the role of green infrastructure based on two research hypotheses. However, such measurable policies as tangible policy instrument is constrained to fully reflect policy efforts to enhance adaptation and minimize maladaptation to climate risks.

Furthermore, future research should account for collaborative governance and adaptation policy networks (for instance, among intergovernmental or interorganizational agencies) as intangible policy instruments by using qualitative and quantitative methods. Regarding social vulnerability used in our work, we failed to deal with the importance of vulnerability within the climate gentrification dynamics or the 'interrelationships between climate trajectories and projected social vulnerability in the context of climate governance.' Social vulnerability attributes that represent the degree of social and economic status can be closely connected with the gentrification outcomes. For future research, we need further work connecting social vulnerability and climate gentrification and further reconsidering 'virtuous cycle of governance quality, effective climate change mitigation, and just outcomes support.' In this study, we attempted to complement prior work by evidencing theoretical based hypotheses on climate gentrification that incorporate heat exposure and green infrastructure as climate adaptation or maladaptation policy intervention. Even if our work reveals several limitations, it has the potential to extend and develop relevant work relying primarily on theoretical underpinnings. Our work can provide some insights into the tensions between green infrastructure and gentrification and a better understanding of climate adaptation policies.

CRediT authorship contribution statement

Hyun Kim: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Hyewon Kim:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Donghoon Lee:** Writing – review & editing, Investigation, Data curation. **Gyu Seomun:** Writing – review & editing, Investigation, Data curation. **Kyle Maurice Woosnam:** Writing-review & editing, Investigation.

Declaration of competing interest

The authors declare that there is no financial or other interests or personal relationships that could be perceived as influencing the work reported in this manuscript.

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Appendix 1. Comparison of empirical variable levels and institutional aspects within four counties

Empirical variables and institutional aspects	Cook county		Wayne county		Milwaukee county		Cuyahoga county	
	5 year-long effect	10 year- long effect	5 year-long effect	10 year- long effect	5 year- long effect	10 year- long effect	5 year- long effect	10 year- long effect
Heat days	2.0 (1.41)	1.20 (1.46)	0.83 (0.89)	0.70 (0.90)	1.00 (1.82)	1.00 (1.54)	0	0
Heat exposure	0.66 (0.47)	0.40 (0.48)	0.50 (0.50)	0.40 (0.48)	0.33 (0.47)	0.40 (0.48)	0	0
Renter	37.49 (19.65)	38.26 (19.69)	28.57 (16.02)	29.58 (16.37)	44.76 (17.95)	45.70 (17.90)	33.85 (19.44)	34.78 (19.43)
Income	56,486 (28,351)	59,186 (30,627)	42,452 (24,474)	43,716 (25,810)	44,535 (22,600)	46,067 (23,255)	45,686 (26,327)	47,300 (27,719)
White	52.70 (32.59)	52.80 (32.19)	45.86 (38.94)	45.85 (38.51)	58.62 (34.24)	57.62 (33.93)	56.86 (35.36)	56.05 (35.05)
Education	32.75 (23.57)	32.44 (69.76)	18.60 (15.60)	14.08 (34.62)	25.81 (19.80)	20.47 (42.69)	25.66 (19.35)	19.96 (43.39)
GINI	0.49 (0.005)	0.49 (0.007)	0.47 (0.008)	0.48 (0.01)	0.45 (0.008)	0.46 (0.01)	0.48 (0.007)	0.49 (0.009)
Housing vacancy	18.21 (15.49)	17.48 (15.25)	23.84 (18.47)	23.47 (18.88)	12.43 (84.84)	12.28 (8.44)	19.02 (14.18)	18.65 (13.93)
Housing value	260,872 (137,106)	260,172 (145,729)	96,737 (69,357)	97,952 (77,062)	152,950 (75,698)	149,867 (79,853)	126,562 (73,220)	125,173 (76,141)
Green infrastructure	0.18 (0.07)	0.18 (0.07)	0.22 (0.04)	0.23 (0.05)	0.20 (0.06)	0.20 (0.05)	0.23 (0.06)	0.23 (0.06)
Urban and rural continuum	Metro		Metro		Metro		Metro	
Climate action plan	Yes		Yes		Yes		Yes	

Note: standard deviation in parentheses.

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