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How do heat and flood risk drive residential green infrastructure implementation in Phoenix, Arizona?

Sara Meerow[1] · Alysha M. Helmrich[2] · Riley Andrade[3] · Kelli L. Larson[4]

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Abstract

Green infrastructure is an increasingly popular strategy to simultaneously address challenges associated with urbanization and global environmental change, including increased flooding and rising temperatures. While many cities aim to expand green infrastructure to deliver ecosystem services, their impacts will be limited without significant uptake on private property. Most studies and programs to date focus on public land, so little is known about what would motivate private residents to implement green infrastructure. This study addresses this gap, combining household survey and spatial data from the Phoenix metropolitan region in Arizona by examining what factors predict green infrastructure implementation, with a particular focus on flooding and heat risks. The results suggest that residents are generally aware of their relative exposure to these hazards, but their risk perceptions do not translate into increased implementation of green infrastructure. Prior experience of flood damage is a predictor of stormwater infrastructure implementation, but experience with heat did not impact planting vegetation to mitigate the effects of extreme temperatures. Instead, the decision to implement green infrastructure is likely constrained by limited capacity based on income and homeownership, which can impede people's ability to make management decisions on private residential property. More research is needed to unpack the seemingly complex factors that shape residents' decisions to implement green infrastructure on their property.

Keywords Green infrastructure · Heat · Flooding · Ecosystem services · Climate change · Risk perceptions

Introduction

Cities worldwide are looking for strategies to enhance their sustainability and resilience in the face of unprecedented environmental change (Ahern 2011). Urban green infrastructure – including different configurations of vegetation and landscape features to capture stormwater and mitigate heat – are one strategy increasingly promoted by researchers and policymakers (Demuzere et al. 2014; Fletcher et al. 2015). A growing number of cities have ambitious plans to expand green infrastructure, justified by claims that these investments will address a number of urban challenges by providing ecosystem services, including improved flood management and mitigation of the urban heat island and rising temperatures (Tzoulas et al. 2007; Meerow and Newell 2017; Finewood et al. 2019). Our study addresses green infrastructure used to mitigate flooding and extreme heat, and how people's experiences with these environmental conditions may influence green infrastructure implementation in private residences.

We focus on private property in residential yards and neighborhoods since a large percentage of most urban areas consists of privately-owned residential land. For example, in the Phoenix metropolitan region more than 45% of the land area is residential (Keys et al. 2007), and Loram et al. (2008) note that as much as a quarter of all urban areas in U.K. cities consist of private gardens. In order for green infrastructure to have a major impact on heat and flooding problems, it needs to be widely implemented throughout a city (Matthews et al. 2015). This includes residential properties where it is difficult for local governments to enforce the implementation of green infrastructure. Indeed, most of the leading green infrastructure

✉ Sara Meerow
Sara.Meerow@asu.edu

1 School of Geographical Sciences and Urban Planning, Arizona State University, 975 S Myrtle Ave, Tempe, AZ 85281, USA

2 School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ, USA

3 Department of Natural Resources & Environmental Sciences, University of Illinois at Urbana – Champaign, Champaign, IL, USA

4 School of Geographical Sciences and Urban Planning & School of Sustainability, Arizona State University, Tempe, AZ, USA

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programs in U.S. cities focus on public lands including parks and rights–of-way, such as New York City's multimillion dollar program (PLANYC 2010; Meerow 2020). This is a logical first step, but scaling up green infrastructure at a regional scale will require widespread adoption by private landowners (Montalto et al. 2013). For example, Philadelphia's billion dollar *Green City, Clean Waters* green infrastructure program – one of the earliest and most ambitious plans in the U.S. – depends on implementation on private residences (Fitzgerald and Laufer 2016; Heckert and Rosan 2016). Uptake on private land was initially low, and Philadelphia had to try a number of programs and incentives before settling on residential grants to achieve participation targets (Fitzgerald and Laufer 2016). Another study by Turner et al. (2015) identified low rates of residential participation in city green infrastructure programs near Cleveland, Ohio. The authors connect these low rates to residents' perceptions and attitudes, including skepticism about green infrastructure's effectiveness in attenuating runoff and viewing stormwater management as a low priority as well as primarily the local government's responsibility.

Given the importance of residential participation in green infrastructure programs, it is surprising that, to date, much of the research on opportunities and challenges for green infrastructure implementation focuses on local government initiatives and publicly-owned land. Meanwhile, what motivates private residents to adopt green infrastructure "remains unclear" (Turner et al. 2015). As Baptiste et al. (2015, p. 1) observe, "there is a need to understand the view of the public regarding the use of green infrastructure in their neighborhoods, specifically the factors that influence the public's willingness to implement green infrastructure on private properties." Additionally, just because someone indicates the desire for, or importance of green infrastructure, does not mean they will implement it in their yard (Turner et al. 2015). This is because external factors—such as social norms, available time and money, or parcel size—all act as potential constraints on decisions people make about managing their property (Cook et al. 2012).

Flooding is a problem in cities regardless of local climates because urban development increases the amount of impervious surfaces, which increase the total volume and peak flows of runoff when it rains (Liu et al. 2014). This is further exacerbated by climate change, which in many places is changing precipitation patterns and leading to more intense storms (Baker et al. 2019). Existing stormwater infrastructure, which is often undersized or aging, is not able to handle the added runoff, which leads to flooding and potential water quality problems (e.g., untreated wastewater entering local water bodies due to combined sewer overflows). Decentralized green infrastructure can help address these concerns by managing water at its source, thereby reducing the burden on existing stormwater and wastewater systems and decreasing the likelihood of flooding and water quality problems (Zellner et al. 2016).

Impervious surfaces in urban areas are also a major contributor to the urban heat island (UHI), which makes urban areas significantly hotter than surrounding areas (Stone and Rodgers 2001). In our study area of Phoenix, Arizona, for example, nighttime temperatures have increased by up to six degrees Celsius during the hot summer season in recent decades (Brazel et al. 2007). The UHI, in combination with rising global temperatures associated with climate change, is increasing extreme heat risks, which are already the deadliest weather-related hazard in the U.S. (Hondula et al. 2015). Expanding green infrastructure can help to cool the local environment by reducing impervious surfaces and by increasing shading and evapotranspiration with vegetation (Norton et al. 2015; Zölch et al. 2016).

Green infrastructure may provide communities with stormwater and heat mitigation ecosystem services, but it can also produce disservices like pests and allergens, and there are other tradeoffs to consider (Pataki et al. 2011). Particularly in arid cities, there is an important tradeoff between the cooling benefits of vegetation and the use of scarce water resources for irrigation (Gober et al. 2009). Installing green infrastructure requires an initial capital investment and resources for maintenance to function properly (Matsler 2019). There is even growing concern that the development of attractive green infrastructure in some neighborhoods may spur green gentrification, thus residents fearing displacement may oppose implementation (Anguelovski et al. 2018).

Moreover, while the flood and heat mitigation benefits of green infrastructure are widely recognized in the literature and city plans, the broader public may not make this connection (Barnhill and Smardon 2012). Of the few studies that we identified on residential adoption of green infrastructure (Keeley et al. 2013; Baptiste et al. 2015; Turner et al. 2015), only one included perceptions of flooding risks (Turner et al. 2015). Furthermore, at least when it comes to heat, prior studies indicate that metro Phoenix residents' perceptions of whether their neighborhood is relatively hotter than others are related to conditions on the ground (Ruddell et al. 2010; Jenerette et al. 2016). However, to our knowledge, no research has specifically examined how both perceptions and actual heat and flooding risks motivate individuals to make changes to their property and implement green infrastructure.

Our study seeks to address this gap by identifying the drivers of green infrastructure implementation in private residences in the metropolitan area of Phoenix, Arizona in the U.S. Combining data from a household survey conducted in a cross-section of neighborhoods and other spatial datasets, we examine what factors motivate households to implement green infrastructure. In particular, we test whether flooding or heat risks are significant motivators of action, since stormwater management and cooling are two benefits that cities commonly seek to gain through green infrastructure (Derkzen et al. 2017). Specifically, this study seeks to address the following research question:

How do perceptions and experiences of environmental hazards (heat and flooding) influence residential implementation of green infrastructure?

To begin answering this question, we examine the percentage of residents in our sample who have recently implemented green infrastructure and explore the influence of risk perceptions and experiences on implementation of green infrastructure, controlling for demographic characteristics that may be associated with this decision. First, we focus on the relationship between flooding risk and green infrastructure implementation. We look at whether residents that perceive flooding to be a great risk, have experienced flood damage to their homes, or live closer to official flood hazard zones, are more likely to implement green stormwater infrastructure or add vegetation on their property. We take a similar approach to examine the relationship between heat risk and green infrastructure implementation. We explore whether residents who perceive heat to be a greater risk to their household or neighborhood, who have experienced heat illness, or who live in hotter neighborhoods are more likely to add vegetation or use plants for cooling on their property.

Methods

Study site: Phoenix metropolitan region, Arizona

Our study draws on data from the Phoenix metropolitan region (Phoenix metro) in central Arizona (Fig. 1). Located in the Sonoran Desert, the City of Phoenix and its surrounding suburban and exurban communities are home to over 4.5 million residents. People are drawn to the region partly due to its ample sunshine and mild winters. With a semi-arid climate, the area receives an average of 20.4 cm (8 in.) of precipitation annually. Most of the precipitation events occur during the winter rainy season and summer monsoon season, when flash floods can harm people and property. Meanwhile, in the summer months of June to September, triple-digit temperatures (in Fahrenheit, or 37 degrees Celsius) are common (Gober 2006). With the UHI, even nighttime temperatures remain high in the summer and heat stress is a serious threat throughout the region (NPR 2018).

While the Phoenix metro may not be regarded as a national leader in green infrastructure implementation, local governments in the region are looking to change that. Moreover, the region is widely recognized for its advanced heat resilience planning and policies (Hondula et al. 2019). The City of Phoenix, for example, has a Tree and Shade Master Plan that seeks to increase tree canopy from 10 to 25%, largely for cooling benefits (Middel et al. 2015). As early as 2013, the U.S. Environmental Protection Agency (EPA) conducted a study of opportunities and barriers for green infrastructure in Phoenix (EPA 2013). More recently, local governments and organizations collaborated on a Greater Phoenix Green Infrastructure and Low Impact Development Handbook that provides design guidance, although focused primarily on hydrologic functions (Dibble Engineering and Logan Simpson 2018).

Survey design

Our primary data source is a household survey conducted in twelve neighborhoods throughout the Phoenix metro from June through August 2017 (Larson et al. 2020). Survey neighborhoods were delineated by Census Block Groups and stratified to represent factors such as socioeconomic status and location within the city (i.e., core versus fringe). A total of 1400 households were included in the sample. These households were sent a mailing of the full survey with the option to receive a Spanish version, as well as paid-for postage for the respondent to mail the survey back. If they did not respond, they were sent two additional postcard reminders and another full version of the survey. Pre- and post-incentives were used to increase the response rate. Each initial mailing contained a $5 incentive, with a randomly assigned post-incentive varying from $5–$40 to the participant or a charity organization (for details on this experimental design, see Smith et al. 2020).

With a response rate of 39.4%, the final sample size was 496 respondents. The sample demographics were similar to the population of the surveyed neighborhoods in terms of gender, income, and age. The average household income ranged from $80,000 to $100,000, and considering only adults could participate, the average age of respondents was 51. The sample was more highly educated than the population with over half (56%) of the respondents achieving a bachelor's degree or higher level of education. One-fifth of respondents identified as Mexican or Latinx, which is less than the population of the study neighborhoods. Given the sample demographics and targeted survey design, caution must be exercised in generalizing the results to the entire Phoenix metro. Because this study focuses on green infrastructure implementation, which would not be possible in an apartment or condo that lacked a private yard, we limited the analysis to the 381 respondents residing in single-family homes. We did not eliminate renters, although we recognize they might have some restrictions on the changes they can make to the property. Instead, we control for home ownership.

Variables, data sources, and analyses

To evaluate how flooding and heat risk influences residential green infrastructure implementation for single-family residences, we examined five dependent variables derived from three survey questions. The first one focused on green stormwater infrastructure and asked residents, "Have you ever made each of the following changes to retain rainwater on your property at your current home or yard?" The response options included rain garden, rain barrel, altered the slope of the yard, added gutters, and other. The second question asked residents about implementation of added vegetation – or vegetative infrastructure – more generally: "In the last five years, have you made each of the following changes to the yard of the home that you live in now?" The options included planting trees, planting grass, and adding desert plants. Both questions were converted into both a binary scale (made any one of the changes or did not) as well as an additive scale (adding up how many of the green infrastructure types the resident selected as implemented in their yard). Additionally, a final question asked whether or not a household used plants for cooling. These five variables represent households' implementation of green infrastructure: green stormwater infrastructure binary, green stormwater infrastructure scale, vegetative infrastructure binary, vegetative infrastructure scale, and plants used for cooling (see Table 1 for details).

We examined the relationship between these five dependent variables and seven central independent variables (see Table 2 for details) that represent residents' perceptions and experiences with flood and heat events. Five of these variables came from the survey. These include questions about perceived risk of flooding and heat for a respondent's household, perception of their neighborhood's heat exposure, experience with home damage from flooding, and experience with heat illness in the household. To evaluate perceptions and experience in the context of flooding and heat risks, we included physical data on residents' relative flooding and heat exposure. National Flood Hazard Layer (NFHL) data from the Federal Emergency Management Agency (FEMA) were used to calculate each household's exposure to flooding (20,140,408, Version 1.1.1.0; Federal Emergency Management Agency 2014). NFHL data incorporate all flood insurance rate maps and map revisions that have been issued against those databases. We used NFHL data to identify the distance from the respondent's property to the nearest Special Flood Hazard Areas (SFHAs). SFHAs are defined as areas having a 1% annual flood chance (100-year flood area), and are widely used in the U.S. for insurance and policy. We used the gDistance function in the R package "rgdal" to calculate the distance in meters from the respondent's parcel to the nearest SFHA (Bivand et al. 2018). Limitations of the FEMA data include the fact that it is primarily focused on fluvial flooding, rather than pluvial flooding and small-scale hydrological factors that could lead to site-level flooding (Pralle 2019; Wing et al. 2017), which are the primary focus of small-scale green stormwater infrastructure features. That being said, it is the only flooding dataset that was publicly available for the entire study area, and thus, the best available way to spatially assess relative flood risks.

Local exposure to heat was assesed using maximum land surface temperature (LST), calculated from data provided by the online global Land Surface Temperature Esimation tool (Parastatidis et al. 2017). LST rasters were overlaid for every month in 2017, and the maximum LST value of every cell was extracted to create a single raster. This raster was then used to extract the maximum LST within a 50 m buffer of each respondent's parcel. Maximum LST was caculated using the R packages "rgeos" (Bivand and Rundel 2020) and "raster" (Hijmans 2018). For the sample, the maximim land surface temperature was 56.78 C (134 Fareneheit). While land surface temperature is not the same as the air temperature people experience, the two are generally correlated (Good 2016). Prior research also suggests that surface temperatures are correlated

Table 1 Dependent variables: Explanation and descriptive statistics

Variable Name	Description	Mean	Median	Standard Deviation	No response (%)
Green Stormwater Infrastructure Binary	A yes (1)/no (0) evaluation of whether a resident had implemented any of the following on their property: rain gardens, rain barrels, altered yard slope, and added gutters.	0.267	0.000	0.443	11.5
Green Stormwater Infrastructure Scale	An additive evaluation (1–4) of how many of the following residents had implemented: rain gardens, rain barrels, altered yard slope, or added gutters. (Rescaled 0–1)	0.121	0.000	0.218	11.5
Vegetative Infrastructure Binary	A yes (1) /no (0) evaluation of whether a resident had made any of the following changes to their property: planting trees, grass, and/or desert plants.	0.678	1.000	0.468	11.3
Vegetative Infrastructure Scale	An additive evaluation (1–3) of how many of the following residents had implemented: planting trees, grass, and desert plants. (Rescaled 0–1)	0.390	0.333	0.333	11.3
Plants Used for Cooling (Binary)	In the previous summer, the resident used trees and plants to cool their home using yes (1) /no (0).	0.688	1.000	0.464	15.0

Table 2 Independent variables: Explanation and descriptive statistics

Variable Name	Description	Mean	Median	Standard Deviation	No response (%)
House Damage from Flooding	Resident has experienced damage to their house due to flooding rated on a scale from 1 (strongly disagree) to 5 (strongly agree) and normalized from 0 and 1.	0.176	0.000	0.306	1.3
Flood Risk Perception	How serious are the risks posed by [floods] for your household and your way of life? Responses were ranked between 1 (not at all serious) to 5 (extremely serious) and normalized between 0 and 1.	0.354	0.250	0.289	1.8
Distance from Flood Zone*[1]	Distance of residence (in meters) to a flood zone.	0.235	0.109	0.292	NA
Heat Risk Perception (Individual)	How serious are the risks posed by [extreme heat] for your household and your way of life? Responses were ranked between 1 (not at all serious) to 5 (extremely serious) and normalized between 0 and 1.	0.675	0.750	0.266	1.0
Heat Risk Perception (Community)	Thinking about this last summer of 2016, to what extant do you think your neighborhood was cooler or hotter than most other neighborhoods in the Valley or do you think it was about the same temperature as other neighborhoods? Responses were ranked between 1 (a lot cooler) to 5 (a lot hotter) and normalized between 0 and 1.	0.495	0.500	0.199	13.9
Experienced Heat Illness	During last summer, did you or anyone else in your household have symptoms related to heat or high temperatures such as leg cramps, dry mouth, dizziness, fatigue, fainting, rapid heartbeat or hallucinations? Binary (0: no and 1: yes).	0.258	0.000	0.438	1.3
Maximum Land Surface Temperature (LST)*[2]	Maximum land surface temperature (in Celsius) near the residence. Continuous.	0.528	0.509	0.179	NA

**Not part of survey*

[1] *Flood zone data from* FEMA

[2] *LST data comes from* Parastatidis et al. 2017

with heat deaths in the Phoenix metro (Harlan et al. 2013). Like the flood maps, LST maps represent a publically accessible dataset that covers the entire study area, and which gives a reasonable indication of relative exposure.

We also controlled for a number of demographic variables in our analyses that have been shown in previous studies to relate to residential landscaping behavior and could constrain a household's ability to implement green infrastructure (Jenerette et al. 2011; Cook et al. 2012): age, income, education, homeownership, time (in years) spent at current residence, gender, and ethnicity. Details about these variables and descriptive statistics are provided in Table A1 of the supplementary material. All variables were normalized between 0 and 1 by subtracting the minimum value from the value of interest and dividing by the range.

Models for the continuous dependent variables (i.e., the scales) were estimated using ordinary least squares regression and models for the binary dependent variables were estimated using logistic regression. As many of the key independent variables overlap theoretically, we ran separate models predicting each dependent variable separately for each independent variable. Note that each of these models included controls for the demographic variables listed above. The results of bivariate models without these controls are provided in the supplementary material (Tables A3-A9), along with the results of a multivariate model that includes all demographic variables (Table A10). We also ran Pearson's correlations between all independent and demographic control variables. All statistical analyses were computed using the R statistical software (R version 4.0.0).

Results

First, it is worth noting that a minority of surveyed residents implemented green stormwater infrastructure of any kind (Table 1). Only 27% of residents said they made at least one of the listed changes to their yards (green stormwater infrastructure, binary variable), whereas 73% said they did not make any changes. The most common change was altering the slope of the yard (16%), followed by adding gutters (16%), rain barrels (4%), other (4%), and rain gardens (3%) to retain water on their property. Of the 100 residents (27%) who made a change, only one third implemented more than one type of green stormwater infrastructure, and only three residents said they made three or more different changes.

In contrast, the majority of the residents (69%) said they had planted something in the last five years (vegetative infrastructure). When we compare the binary variables for vegetative and stormwater infrastructure, it appears that only 76 residents (20%) implemented some type of green stormwater infrastructure and vegetative infrastructure.

Overall, we find few statistically significant relationships between flooding and heat risk experiences with green infrastructure implementation (see Table 3 for results). Experience with house damage from flooding was a significant predictor

($p < 0.01$) of green stormwater infrastructure for both the binary and scale variables, even when controlling for demographic variables (age, gender, ethnicity, education, income, home ownership, and time (in years) spent at current residence). Counter to what we expected, we found no significant relationship between experiences with heat illness, perceptions of heat risks, and maximim LST independent variables and the vegetative infrastructure and plants used for cooling dependent variables. Maximum LST was significantly related ($p < 0.01$) to the green stormwater infrastructure variables.

Physical versus perceived flood and heat risk

Examining correlations between physical indicators of heat and flood exposure with perceptions of risk generally suggests that residents are aware of their risks (Fig. 1 and 2). Residents who lived closer to a flood zone perceived flood risks to their household as significantly higher than those who lived farther away (coefficient = −0.185, significant at $p < 0.01$). Residents who reported higher individual heat risks were also significantly more likely to live in areas with a higher maximum land surface temperature compared to others (coefficient = 0.186, significant at $p < 0.05$). Additionally, residents who perceived their neighborhood as hotter than surrounding neighborhoods were significantly more likely to live in an area with a higher maximum LST (coefficient = 0.285, significant at $p < 0.01$).

Flood and heat risk and green infrastructure implementation

Residents who have experienced a flood event that damaged their homes (13% of respondents) were significantly more likely to implement green stormwater infrastructure ($p < 0.01$) (Table 3). This is true even when controlling for demographic factors. However, this strong relationship was not observed between flood experience and the implementation of vegetative infrastructure. This suggests that residents are not planting more vegetation to combat flooding, but utilizing alternative decentralized stormwater protection such as rain barrels, additional gutters, and/or altered yard slopes. While we did not find a statistically significant relationship between perceived flood risk and green stormwater infrastructure implementation when controlling for demographic variables, the bivariate relationship is marginally significant for both the green stormwater infrastructure binary and scale variables ($p < 0.1$) (Supplementary Material, Table A4). No significant relationships were found between green infrastructure implementation and distance from the flood zone. These results suggest that experience with flood hazards may be an important driver of green stormwater infrastructure, but not implementation of vegetation broadly.

Heat risk (as measured by maximum LST), perceptions of heat risk, and experience with heat illness do not appear to greatly influence the implementation of vegetative infrastructure or the use of plants for cooling. Surprisingly, we do see a significant relationship ($p < 0.01$) between maximum LST and the green stormwater infrastructure implementation variables (Table 3).

In addition to controlling for demographic variables, we also looked at whether these variables were significantly related to green infrastructure implementation (Supplementary Material, Table A10). Homeownership emerged as a significant predictor of green infrastructure implementation. Specifically, homeowners were significantly more likely to implement vegetative infrastructure (binary and scale variables; $p < 0.05$) and green stormwater infrastructure (binary variable, $p < 0.1$). Income was also a predictor of vegetative infrastructure (binary $p < 0.1$; scale $p < 0.01$). Finally, the longer a respondent had owned their home, the more vegetative infrastructure they had installed ($p < 0.05$).

Discussion

One of our key findings is that Phoenix metro residents who have experienced flood damages at their current residence are significantly more likely to implement green stormwater infrastructure but not necessarily more likely to add vegetation to their homes. Thus, it would seem that there are other factors driving planting decisions, such aesthetic preferences and social factors (Conway 2016; Avolio et al. 2018). Contrary to what we would expect, perceived heat risk at an individual and community level, exposure to heat, and experience with heat-related illness are not significant predictors of implementing vegetative infrastructure or even using plants for cooling. However, similar to other studies in the region (Ruddell et al. 2010; Jenerette et al. 2016), we find that people reliably assess their relative exposure to extreme heat and flooding. Our respondents' accurate assessments of risk are important because they highlight that people recognize increased environmental risks; however, they are not necessarily using green infrastructure to mitigate these ill-effects.

Green infrastructure implementation on private property

If cities are going to meet their ambitious green infrastructure implementation targets and achieve desired ecosystem services, they will need high levels of participation by private landowners, including residents (Montalto et al. 2013). This has proven challenging, even in high profile green infrastructure programs like Philadelphia's (Fitzgerald and Laufer 2016). Likewise, we find that only a small portion of Phoenix metro residents are implementing green infrastructure (Table 1). Considerable monetary incentives might be necessary to facilitate adoption, as was the case in Philadelphia (Mayer et al. 2012; Bos and Brown 2015). Currently those do not exist in the Phoenix metro.

Table 3 The relationship between flooding and heat risk and green infrastructure implementation: Coefficients and standard errors from individual regression models controlling for demographic variables

Variable	Green Stormwater Infrastructure Binary	Green Stormwater Infrastructure Scale	Vegetative Infrastructure Binary	Vegetative Infrastructure Scale	Plants Used for Cooling
Flooding Risk					
House Damage from Flooding	1.587*** (0.472)	0.171*** (0.048)	0.438 (0.518)	0.044 (0.068)	0.559 (0.540)
Flood Risk Perception	0.837 (0.514)	0.081 (0.051)	−0.441 (0.503)	−0.065 (0.070)	0.313 (0.514)
Distance from Flood Zone	−0.391 (0.472)	−0.071 (0.048)	−0.037 (0.489)	−0.051 (0.065)	1.422** (0.588)
Heat Risk					
Experienced Heat Illness	0.248 (0.330)	0.016 (0.033)	−0.373 (0.319)	−0.020 (0.045)	0.219 (0.327)
Heat Risk Perception (Individual)	0.532 (0.555)	0.069 (0.055)	−0.443 (0.567)	−0.022 (0.078)	−0.201 (0.558)
Heat Risk Perception (Community)	0.105 (0.742)	0.015 (0.077)	−1.036 (0.777)	−0.012 (0.106)	−0.689 (0.807)
Maximum LST	3.665*** (1.109)	0.305*** (0.095)	0.056 (0.935)	0.053 (0.133)	−0.085 (0.959)

Note: Each entry is a coefficient and standard error (in parentheses) from a multivariate regression model between each independent and dependent variable controlling for age, income, education, home ownership, time spent at current residence, gender, and ethnicity. For full model outputs see supplementary material, Tables A3–A9; *Significance levels: *p < 0.1; **p < 0.05; ***p < 0.01*

Designing effective policies to incentivize green infrastructure adoption requires an understanding of what motivates residents to implement it in their own homes, yet relatively few studies have focused on this (Baptiste et al. 2015; Turner et al. 2015). Mitigation of flooding and heat are two of the most common benefits—or ecosystem services—associated with green infrastructure (Tzoulas et al. 2007). But no other studies could be identified that specifically looked at whether residents' awareness of environmental risks motivated them to implement green infrastructure around their homes, thus our research begins to address an important gap in the literature.

One of our findings that confirms the results of previous studies (Bos and Brown 2015; Turner et al. 2015) is that uptake of green infrastructure, especially green stormwater infrastructure, is fairly low. Furthermore, the fact that only 20% of the respondents that reported having implemented some kind of green stormwater infrastructure also reported having planted something suggests that green stormwater infrastructure in the Phoenix metro may not always coincide with added vegetation, which could limit the scope of co-benefits the green stormwater infrastructure can be assumed to provide (Mcphillips and Matsler 2019). For example, air quality benefits often attributed to green stormwater infrastructure generally assume that it includes vegetation.

Flood risk and green infrastructure implementation

We find that residents are generally aware of their flood risks, since we see a significant inverse relationship between distance from FEMA flood zones and perceived flood risk. This stands in contrast to much of the literature about the public's understanding of flood hazards, but it is more in line with recent survey work by Harlan et al. (2019) suggesting that people are in fact aware of their potential exposure. However, our survey results show that residents living within a flood zone were not more likely to have implemented green stormwater infrastructure than those outside (Supplementary Material, Table A2). It is possible that this is influenced by the fact that the Phoenix metro is semi-arid, and overall risks of chronic flooding may be lower than in cities that receive more precipitation. Indeed, we see that residents perceive their flood risk to be relatively low (on average, less than a somewhat serious risk). It is also possible that the few residents with major flooding issues added green stormwater infrastructure to their home at some point, but not in the last five years, which is the range the survey asked. It is also possible that households are adding green stormwater infrastructure in response to more localized nuisance or flash flooding, which is not captured in potentially problematic FEMA flood maps (for a detailed account of issues with FEMA flood mapping see Pralle (2019)). If nuisance flooding is more of the driver, this could explain why we see a significant relationship between green stormwater infrastructure and flood damage, but not proximity to flood hazard zones. Similarly, Turner et al. (2015) showed that residents in Cleveland, Ohio with green infrastructure were more likely to agree that stormwater runoff led to flooding problems for their neighborhood.

Heat risk and green infrastructure implementation

Since Phoenix is the hottest city in the United States (Zheng et al. 2014) and receives limited precipitation given its desert environment, it is perhaps more surprising that we do not find heat risk to be a significant predictor for adding vegetation or making changes to retain rainwater on site (which could be used to irrigate vegetation). This comes despite research showing that vegetation can significantly cool the local environment in arid cities (Middel et al. 2015; Wang et al. 2016) and the observation that 68% of the respondents claimed to use plants for cooling. Consistent with other studies (Jenerette et al. 2016), our findings do suggest that residents accurately perceive their relative heat risk, since our physical measure of heat exposure is related to heat risk perceptions. Overall perceptions of heat risk are quite high (88% saw it as at least a somewhat serious risk to their household). Nevertheless, this does not make households more likely to implement green infrastructure. One possible explanation for this surprising finding could be that compared with other heat adaptation strategies, most notably air conditioning, vegetation is seen as less of a priority. This is supported by data from the survey showing that 97% of those who responded reported using a central air conditioner (AC) to cool their home and nearly 95% used a fan. Additionally, if residents are unaware of additional cooling benefits of vegetation beyond shading (e.g., evapotranspiration), they might not consider all types of planting as a heat mitigation strategy. There may also be a temperature threshold above which residents simply retreat indoors. However, strategies based on mitigation in the indoor environment may further exacerbate inequalities for heat risk, since not everyone who has central AC can consistently cool their homes (Wright et al. 2020). In our study, 36% percent of respondents reported being too hot in their home during the past year.

Alternative drivers and constraints for green infrastructure implementation

Although we find a clear link between perceptions and risks, these did not necessarily translate to people making changes to their property in order to address these risks. As a result, higher levels of risk may not be sufficient to induce changes in household-level behavior. It is possible that overall levels of perceived risk are just not high enough to strongly motivate action. For example, overall levels of flood risk are quite low. Alternatively, residents may not believe that green infrastructure is the most effective way to mitigate their risk. When it comes to coping with heat, the survey evidence suggests that vegetation is not the main strategy. In particular, while 68% of respondents said they used plants for cooling, 97% said they used a central AC.

Alternatively, financial or other constraints could be preventing households from making changes. For example, money is a prominent constraint on urban plant abundance and biodiversity because it takes human resources to plant and maintain vegetation in cities (Avolio et al. 2020). Indeed, our regression models reveal income and homeownership as statistically significant predictors of vegetative infrastructure implementation (Tables A3-A10

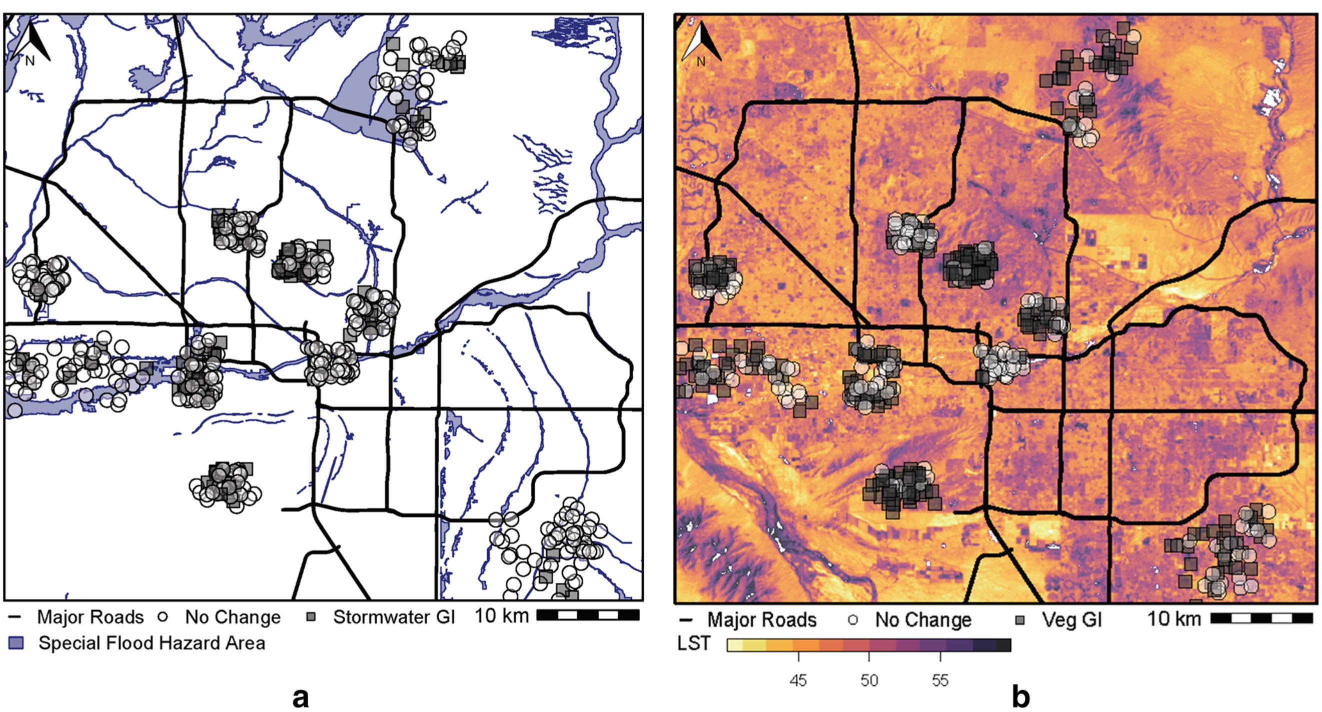

Fig. 1 Flooding and heat risk and green infrastructure implementation in the Phoenix metro: **a** (left) shows locations of surveyed households represented by the green stormwater infrastructure binary variable and flood hazard areas; **b** (right) shows households represented by the vegetative infrastructure implementation binary variable and land surface temperatures (LST)

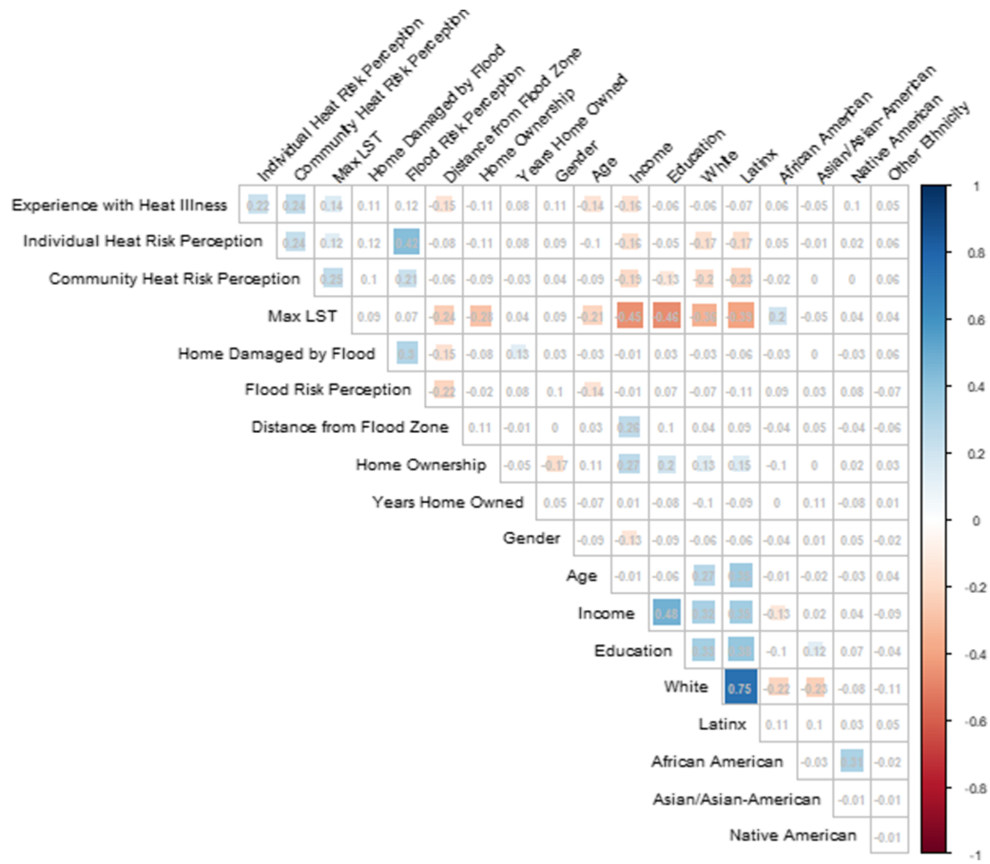

Fig. 2 Bivariate Pearson's correlation matrix for independent variables and demographic characteristics

in Supplementary Material). However, when we run the regression models with just the subset of the sample ($N =$ 154) that indicated that they were homeowners and had a household income above the sample median (> $80,000), heat and flood risk perceptions are still not significant predictors of green infrastructure implementation. Many studies have shown environmental risks to be inequitably distributed throughout cities (Ringquist 2005), and the Phoenix metro follows this trend (Fig. 1). The people who experience more environmental hazards are also commonly vulnerable populations without the capacity or resources to effectively respond to these risks.

Indeed, social factors, such as income and race and ethnicity, tend to be associated with both vulnerability and environmental risk (Harlan et al. 2006) and also act as structural constraints on yard management decisions (Cook et al. 2012). Our results suggest that this holds true in Phoenix. Meanwhile, education and income are negatively correlated with maximum land surface temperature (Fig. 2), meaning that when it comes to heat, the people most at risk may not have the knowledge or means to respond by making changes to their yards. Interestingly, there does not seem to be the same relationship between demographics and flood risk in the Phoenix metro. Green infrastructure policies aimed at providing ecosystem services such as heat or flood mitigation to the communities that need them most must address these constraints to household implementation.

Study limitations and future research needs

While we believe this study begins to fill an important gap in our understanding of urban green infrastructure implementation, and ultimately planning, it is important to acknowledge its limitations and the need for more research on this topic. First, this represents a single survey conducted in just one metropolitan region, and a desert city at that. Future studies should examine these questions in other cities with different climates and climatic risk profiles. Second, this survey was not primarily designed for the analyses we focus on in this paper. A future study could specifically ask survey respondents whether they implemented green infrastructure, why or why not, and what services or disservices they think it would provide. For example, it would be useful to understand whether, how, and in what contexts people think that different types of green infrastructure or vegetation meaningfully mitigate flooding and heat risks. While we have examined a number of correlations between environmental risks and green infrastructure implementation, more in-depth research (e.g., interviews) would also be helpful in truly determining causation.

Conclusion

Cities are increasingly focused on expanding green infrastructure, whether defined more narrowly in terms of decentralized stormwater management technologies or broadly as vegetation, to address urban environmental challenges. Flooding and heat mitigation are two of the most commonly cited ecosystem services provided by green infrastructure. Yet, if cities are going to realize these benefits and make green infrastructure a centerpiece of resilience-building efforts, it will need to be scaled up and implemented widely on private property. Most green infrastructure programs and studies to date focus on implementation on public property or right-of-ways. However, we know relatively little about what would motivate residents to implement green infrastructure on their private property, which makes up a significant proportion of urban land.

This study addressed this gap by combining a household survey with other spatial datasets to examine whether heat and flood risks and risk perceptions were predictors of green infrastructure implementation in Phoenix, Arizona. Our findings suggest a complex picture. We found that a minority of surveyed residents had implemented green stormwater infrastructure, but the majority added vegetation to their property. Residents showed awareness of their relative flooding and heat risks with risk perceptions matching physical measures, but this did not substantially influence adoption of mitigating green infrastructure. Residents who experienced damage to their home from flooding were more likely to implement green stormwater infrastructure. However, it does not appear that mitigating extreme heat or flooding (regulating ecosystem services) was a prominent factor influencing vegetative infrastructure implementation. While flood and heat risk perceptions were not significant predictors of adding vegetation, income and homeownership were. Therefore, it is possible that financial constraints limit residents' ability to implement green infrastructure. Future research should examine whether these patterns are consistent over time and in other regions and unpack in more depth residents' motivations and constraints for green infrastructure on private property. This will help cities to design effective green infrastructure policies and programs that can meet ambitious ecosystem service goals.

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Data availability Data available from https://sustainability.asu.edu/caplter/research/long-term-monitoring/phoenix-area-social-survey/

Compliance with ethical standards

Conflicts of interest/competing interests None.

Code availability Available upon request

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