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Vegetation reduces cooling demand in low-income neighborhoods on hot days in Chicago

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Abstract

Cooling energy demand is sensitive to urban form and socioeconomic characteristics of cities. Climate change will impact how these characteristics influence cooling demand. We use random forest machine learning methods to analyze the sensitivity of cooling demand in Chicago, IL, to weather, vegetation, building type, socioeconomic, and control variables by dividing census tracts of the city into four groups: below-Q1 income–hot days; above-Q1 income–hot days; below-Q1 income–regular days; and above-Q1 income–regular days. Below-Q1 census tracts experienced an increase in cooling demand on hot days while above-Q1 census tracts did not see an increase in demand. Weather (i.e. heat index and wind speed) and control variables (i.e. month of year, holidays and weekends) unsurprisingly had the most influence on cooling demand. Among the variables of interest, vegetation was associated with reduced cooling demand for below-Q1 income on hot days and increased cooling demand for below-Q1 income on regular days. In above-Q1 income census tracts building type was the most closely associated non-weather or control variable with cooling demand. The sensitivity of cooling demand for below-Q1 income census tracts to vegetation on hot days suggests vegetation could become more important for keeping cities cool for low-income populations as global temperatures increase. This result further highlights the importance of considering environmental justice in urban design.

1. Introduction

Cooling demand lays at the crux of climate change and human well-being (Khosla *et al* 2021). Rapid rates of urbanization and climate change are expected to increase the global population exposed to extreme heat (Tuholske *et al* 2021). Urban areas can be up to 7 °C warmer than surrounding rural areas, a phenomenon referred to as the urban heat island (UHI) effect (Oke 1982, Peng *et al* 2012, Streutker 2002). The interaction of the UHI effect with accelerated urbanization and climate change—which is increasing the severity and frequency of extreme heat events (Fischer *et al* 2021, Meehl and Tebaldi 2004, Russo *et al* 2014)—means that while heatwaves are regional events, urban centers may become the foci of the most frequent and severe heat events. Over 55% of the global population lives in urban areas, a proportion expected to increase to 68% by 2050 (United Nations 2019), which translates to an additional 2.5 billion people frequently experiencing extreme urban heat. Current projections suggest a 1.5 °C target for global warming is no longer feasible, which will result in hundreds of more cooling degree days (degree-days above 65 °F or 18 °C) in many parts of the world (Miranda *et al* 2023). The most severe impacts will fall on members of communities least able to escape them (Lehnert *et al* 2020).

Events such as the heatwave in Chicago in 1995 (Semenza *et al* 1996) and those across Europe in 2003 (Beniston 2004) and 2019 (Xu *et al* 2020) show the adverse impacts of extreme temperatures on human health, economic systems, and environmental systems (Huang *et al* 2023). Robine *et al* (2008) estimated the heatwaves across Europe in 2003 prompted widespread adverse economic impacts and caused 70,000 excess deaths—a figure nearly matched in 2022 and that could become the new normal for Europe by 2030 (Ballester *et al* 2023). In 2021 the heatwave and associated drought in the Pacific Northwest US caused an estimated \$8.9 billion in damages (NCEI 2022).

To mitigate the increasing frequency and severity of climate disasters, the concept of resilience has become a dominant paradigm in several disciplines, including engineering (Bruneau *et al* 2003), ecology (Holling 1973), and the social sciences (Adger 2000). A resilient system has the capacity to learn from previous disturbances, persist through disturbances, adapt during disturbances, and transform to more ideal state during and after a disturbances (Elmqvist *et al* 2019, Zanotti *et al* 2020). Building resilient cities requires an examination of both external and internal drivers of disturbance and understanding community, city, and regional scale resources for increasing resilience.

Extreme heat events are disturbances, and an increasing number of studies on the interactions of urban heat and energy have been conducted. Temperature drives cooling demand more than any other weather variable (Gallo Cassarino *et al* 2018), and the UHI effect increases building energy consumption (Li *et al* 2019). In urban areas temperature is shaped by the interaction of human energy use behaviors (Meggers *et al* 2016), the built environment (Yin *et al* 2018), and the amount and spatial arrangement of vegetation in the city (Yan *et al* 2019). Most of the trapped heat in a city comes from radiation from the Sun. Human activities, such as air conditioning and transportation, also contribute significantly to urban heating (Salamanca *et al* 2014). The built environment, such as roads and buildings, traps and absorbs heat, which slows the transfer of heat out of the system. Conversely, urban vegetation—specifically urban tree canopy—not only disrupts the absorptive capacity of the built environment through the provision of shade, but also speeds the transfer of heat out of the system through evapotranspiration (Rahman *et al* 2020). Planting urban trees has been suggested as a promising strategy for climate and pollution adaptation (Pataki *et al* 2021).

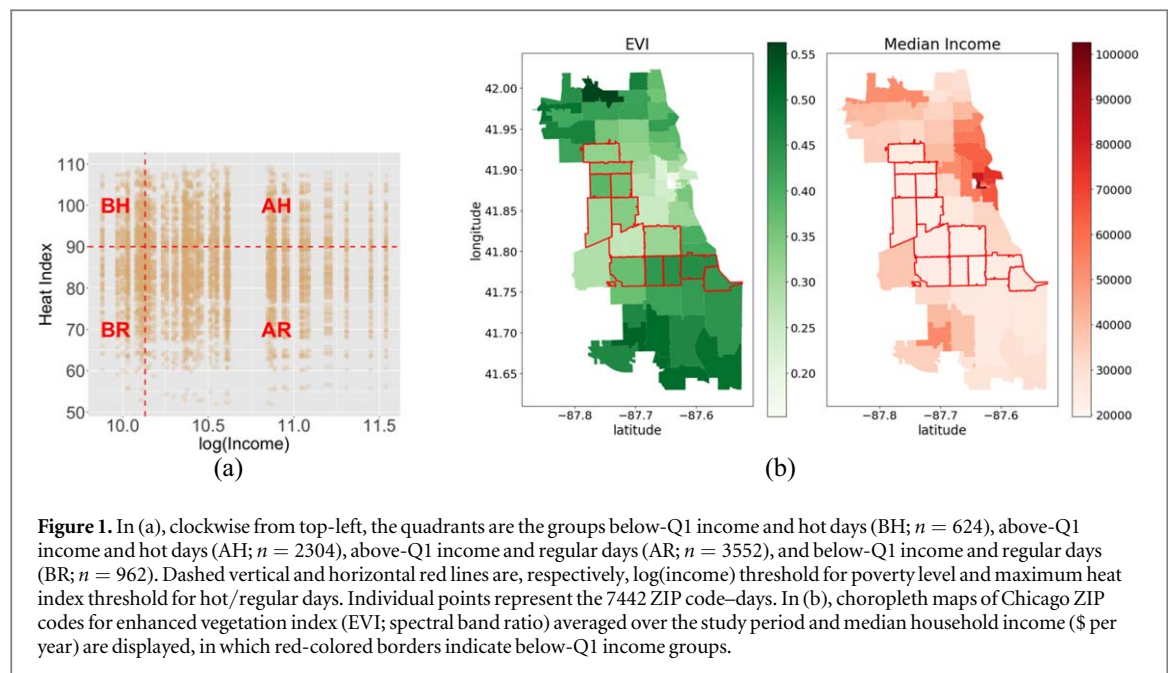
Urban vegetation can cool the temperature of cities (Carlson *et al* 1981, Gallo *et al* 1993, Rahman *et al* 2020, Ziter *et al* 2019), but few studies observe the direct impact of urban vegetation on cooling energy demand in the city. Recent studies connect vegetation and cooling demand using simulation (Erell and Zhou 2022, Ko 2018). Moss *et al* (2019) performed a meta-analysis on evapotranspiration rates for a variety of tree species to simulate the cooling impact of urban trees. Using a theoretical model of the built environment, they estimated that the cooling provided by trees reduced energy demand costs in inner London by over 2.1 million annually. While valuable, theoretical models fail to capture the nuance of heterogeneous urban landscapes, where the heterogeneity extends from vegetation patch types to the uneven distribution of tree canopy. Managing cooling demand requires a better real-world understanding of not only the elements introducing and influencing heat, but also the capacity of residents to respond to the increased temperatures the heat creates.

The inequity of socioeconomic resources impacts both overall cooling demand and the ability of individuals to respond to extreme heat events. Socioeconomic and behavioral factors influence how, when, or if a household uses cooling (Steemers and Yun 2009, Pfenninger *et al* 2014). Heatwaves in the past two decades have revealed the vulnerability of disadvantaged populations to extreme heat events (Thomson *et al* 2019). The distribution of heat in urban areas disproportionately impacts marginalized populations and communities of color. In the Midwest US city of Cleveland, higher land surface temperatures correlated with minoritized neighborhoods (Declet-Barreto *et al* 2016). This trend has been seen in cities across the US, including in the metropolitan areas of Pinellas County, FL (Mitchell and Chakraborty 2014), and cities across the Southwest US (Dialesandro *et al* 2021). Often, this discrepancy in urban heat is paired with a discrepancy in tree canopy cover.

Many studies have reported positive correlations between urban canopy and wealth (Landry *et al* 2020, Gerrish and Watkins 2018, Schwarz *et al* 2015). Pham *et al* (2012) demonstrated minoritized communities often have less canopy area and that this discrepancy is more pronounced on public land than private land, meaning there are fewer street trees and parks in these communities. Not only are poorer neighborhoods more vulnerable to extreme events due to less canopy cover, but the urban canopy within those neighborhoods is more vulnerable to those events, as well (Landry *et al* 2020).

The impact of cooling from vegetation goes beyond mitigating the UHI effect that can exacerbate extreme heat events. It also addresses the significant sustainability challenge of reducing energy demand (Khosla *et al* 2021). Many studies have explored the cooling effect of vegetation in cities, but few have linked this effect with potential impacts on electricity demand. Furthermore, studies that have focused on cooling demand neglect the influence of cooling demand drivers will change under extreme temperatures. Managing the increase in cooling demand is critical to sustainable and resilient development (Khosla *et al* 2021).

In this study we examined the sensitivity of cooling demand of communities to vegetative extent and income under warming temperatures. We used a random forest (RF) analysis approach to understand the role of



vegetation in mitigating energy use compared to other meteorological, physical, and social characteristics. We distinguished the importance of drivers of energy demand on average, or ‘regular,’ days and ‘hot’ days (heat index above 90 °F) and between economic classes. We used Chicago, IL, US as a representative large city situated in a temperate climate with a diverse population and land use distribution.

2. Data and methods

2.1. Site description

Chicago is the third largest city in the US (figure 1(b)). It extends over 227.63 square miles and has a population of over 2.7 million from diverse ethnic backgrounds (29.2% Black or African American, 28.6% Hispanic or Latino, and 33.3% White). Over 17% of Chicago residents are below the poverty line, which is higher than the national average of 11% (US Census Bureau 2020). Most of the land in Chicago is dedicated to residential areas and utility and transportation corridors. Natural areas, institutional areas, and commercial areas all take up small but similar areas (Brandt *et al* 2017). Like many urban areas around the world, the number of extreme heat days in Chicago is increasing. From 1961 to 1990, Chicago experienced 347 days when the temperature failed to drop below 70°F. This count increased to 507 days from 1991 to 2020 (NCEI 2022).

2.2. Data sources

The data used in this study consisted of residential electricity demand data, heat index and wind speed data, socioeconomic data, and vegetation index data across 61 ZIP code areas of Chicago. The electricity demand data were anonymized residential data collected every 30-min at the ZIP code-scale from Commonwealth Edison (ComEd). The month and day of the year were taken into account as control variables (i.e. weekends and holidays have different electricity patterns). The heat index and wind speed (collectively called weather data) are constituted at a temporal resolution of 3 h and a spatial resolution of 4 km from the National Centers for Environmental Prediction (NCEP) of the National Oceanic and Atmospheric Administration (NOAA). Socioeconomic data included median household income, the proportion of the nonwhite population, as well as the proportion of Hispanic population, the proportion of the population with at least a bachelor’s degree, and unemployment rate, as well as residential building type and year of construction, from the 2017 5-Year ACS. Socioeconomic data was downloaded at the ZIP code-scale from the US Census Bureau’s American Community Survey (ACS). For the vegetation index data, the enhanced vegetation index (EVI) was downloaded from the National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS). Raw EVI data has a temporal resolution of 16 days and a spatial resolution of 250 m. The time of year variables (henceforth called control variables) were embedded in the electricity demand data (see appendix A for more detail about the data used in this study).

Data were selected for the summer months June through September 2017 to capture the overlap between the hottest temperatures of the year and fullest canopy cover. We aggregated all data to the same spatial and

Table 1. RMSE of each fitted model. The best RMSE for each group is in bold.

Group	RF		GBM		BART		MARS		GLM		GAM		SVM	
	train	test	train	test	train	test	train	test	train	test	train	test	train	test
BH	0.12	0.11	0.14	0.15	0.12	0.12	0.15	0.15	0.23	0.21	0.20	0.21	0.21	0.21
BR	0.064	0.057	0.085	0.081	0.070	0.065	0.096	0.097	0.14	0.14	0.13	0.14	0.14	0.14
AH	0.094	0.098	0.12	0.12	0.10	0.11	0.15	0.15	0.20	0.19	0.20	0.19	0.20	0.19
AR	0.058	0.054	0.082	0.082	0.070	0.17	0.10	0.11	0.14	0.14	0.13	0.14	0.14	0.15
Avg.	0.083	0.080	0.11	0.11	0.091	0.091	0.12	0.12	0.18	0.17	0.17	0.17	0.17	0.17

temporal resolution for the analysis. Electricity demand data had the coarsest spatial resolution at the ZIP code-scale, so we aggregated all data to the ZIP code-scale. Based on convention in the literature, we used the daily-level (i.e. daily sum of electricity demand) for the temporal resolution (Lyon and Barnston 2017, Anderson and Bell 2011).

2.3. Data processing

We pre-processed the electricity consumption data to better represent the demand characteristics of each ZIP code. Instead of dividing cooling demand by population in each ZIP code, we introduced the relative demand, which can better represent the sensitivity of demands in response to extreme climatic events (see appendix A.6).

We then reduced the dimensions of the demographics dataset by consolidating categorical variables into larger categorical variables. We combined two building type variables—single-detached and single-attached—into one variable named *single-family type*. We combined buildings with more than 2 units and less than 20 units into a variable named *multi-family type*. We called buildings with more than 20 units *large-apartment type*. We also separated years of construction into two groups—pre- and post-2010—using the natural break closest to the median of building construction years, and we aggregated education level into *bachelors and above* and *other*. Lastly, we normalized variance in population among different ZIP code areas by converting all demographic variable values to percent.

There were in total 7442 data points in total, and we split the dataset into 75% training set and 25% test set. We used the training set for fitting parameters and hyper-parameters of each predictive model with the 5-fold cross validation method, and test set for the model comparison.

2.4. Data analysis

We built several predictive models of the relative electricity demand from weather, socioeconomic, and environmental variables. Then, we analyzed sensitivity of electricity demand against extreme heat events (i.e. heatwaves) in relation to socioeconomic and environmental variables, using model inferencing techniques. We created four groups based on the median household income and the daily maximum heat index to compare how different income levels reacted to higher temperatures. To form the groups, we first split the median household income into two categories: income level below \$25,100 (below-Q1 income), which is the 2018 federal poverty threshold for four-person families (HHS 2020), and income level above \$25,100 (above-Q1 income). Approximately 20% of regions were below-Q1 income. We then divided the daily maximum heat index into two groups: heat index above 90 °F (hot days) and below 90 °F (regular days). A heat index value 90 °F is the 'Extreme Caution' threshold from the National Weather Service of NOAA (NWS 2020). Approximately 40% of the summer days in 2017 were classified as hot days. The resulting four groups were below-Q1 income and hot days (BH; $n = 624$), below-Q1 income and regular days (BR; $n = 962$), above-Q1 income and hot days (AH; $n = 2304$), and above-Q1 income and regular days (AR; $n = 3552$; figure 1).

For each group, we trained multiple supervised machine learning models to compare out-of-sample predictive accuracy: 1) generalized linear models (GLM), 2) generalized additive models (GAM), 3) multivariate adaptive regression splines (MARS), 4) random forest (RF), 5) gradient boosted tree machine (GBM), and 6) Bayesian additive regression trees (BART) (see appendix B for more information on machine learning methods). Then, we selected the best model for predicting cooling demand based on out-of-sample root mean square error (RMSE), which was RF for all groups (table 1). All the experiments were conducted using models in the *caret* package v6.0.86 in R v3.6.2 (Kuhn M 2008).

RF is a tree-based method, which typically have low bias and high interpretability. RF loses some of its interpretability to lower variance and improve its predictive accuracy. We used two model inferencing techniques to interpret the final RF model: variable importance and partial dependence. Both of these are effective tools to post-analyze non-parametric models. To prevent misinterpreting spurious relationships, we

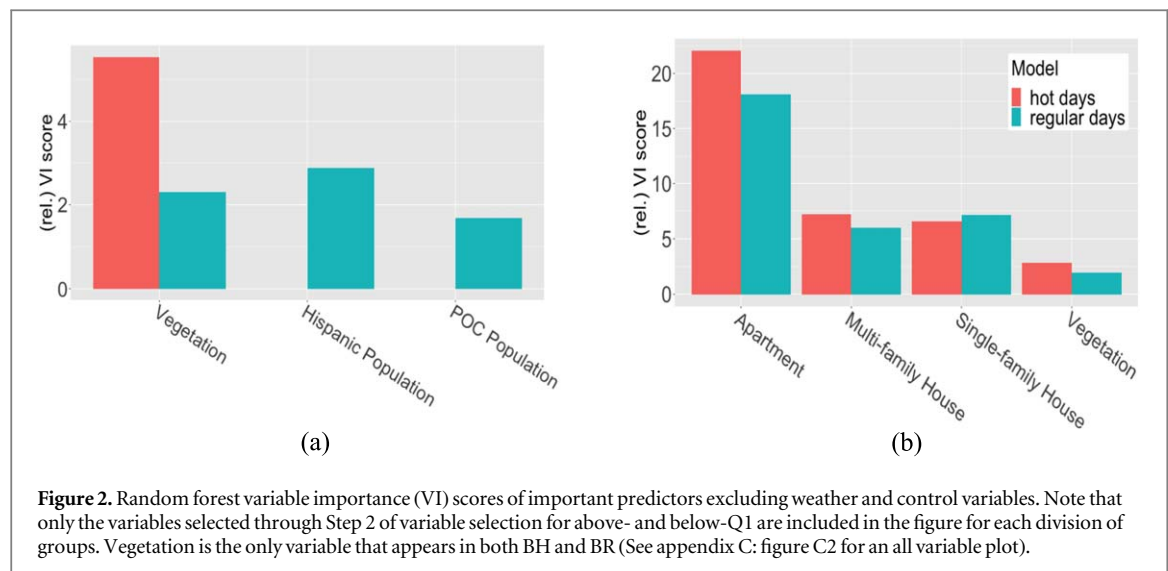


Table 2. VSURF results; variables are ordered from the highest importance to the lowest importance. Vegetation, socioeconomic, and building type variables are in boldface.

Group	Step 1: elimination	Step 2: for-interpretation
BH	Wind Speed, Heat Index, Non-working Day, July, June, August, Vegetation	up-to July
BR	Heat Index, July, August, Wind Speed, June, Non-working Day, Vegetation, Hispanic Population, POC Population, Apartment, Multi-family House, random, Single-family House	up-to POC Population
AH	Heat Index, Wind Speed, June, Non-working Day, August, July, Apartment, Multi-family House, Single-family House, Education, Vegetation, Income, Building Age 10+yr, Unemployment Rate, POC Population	up-to Single-family House
AR	Heat Index, July, Wind Speed, August, June, Non-working Day, Apartment, Multi-family House, Single-family House, Education, Vegetation, Income, Building Age 10+yr, POC Population, Unemployment Rate, Hispanic Population	up-to Single-family House

used data-driven variable selection first to eliminate the least important variables then to select the most influential variables.

3. Results

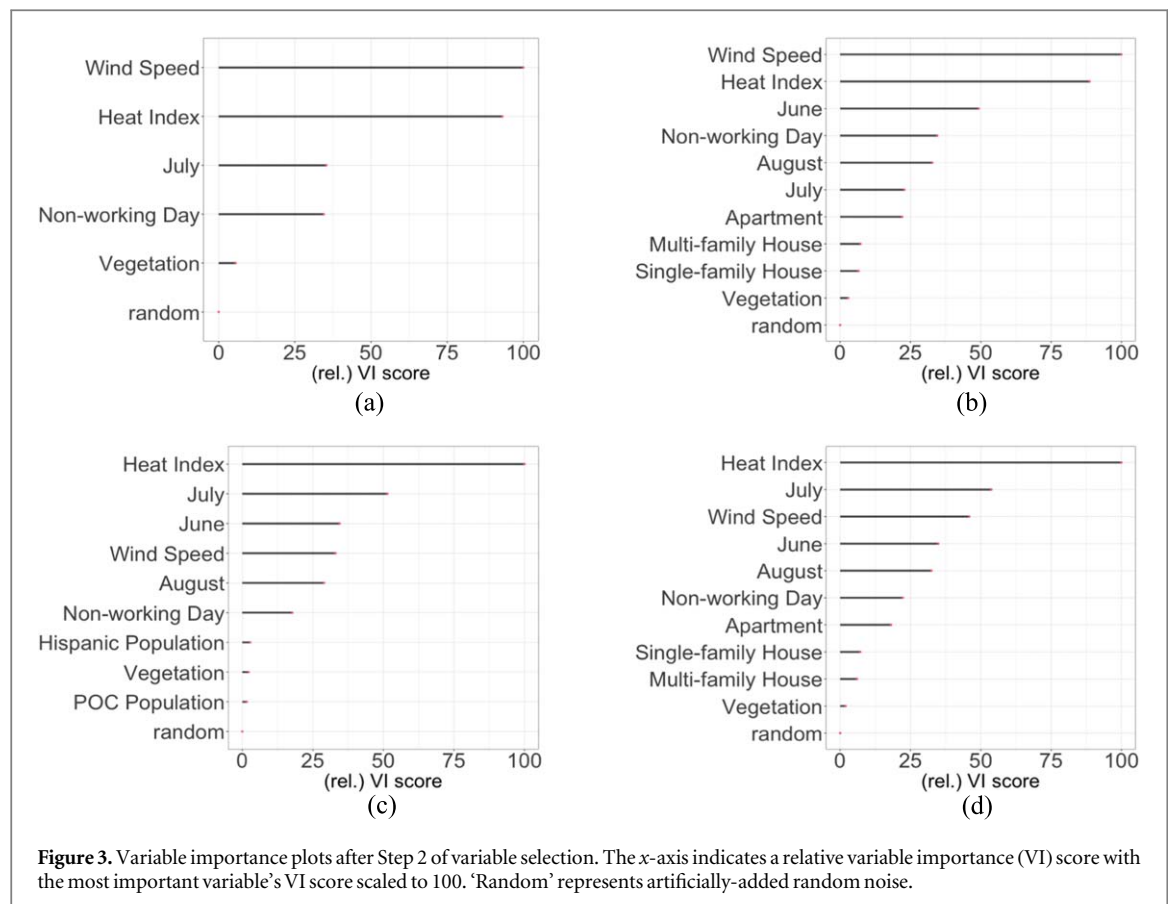
EVI (henceforth called vegetation) appears as the key predictor for cooling demand during hot days for the below-Q1 income group and is more important during hot days than during regular days for both income groups (figure 2). This was also true when the dataset was run on the full-variable models (i.e. without variable selection).

3.1. Variable selection

Vegetation was the only non-weather or non-control variable kept during the first elimination step of variable selection for all groups (table 2; See appendix B.4.2 for variable selection methods). However, the second step of for-interpretation variable selection rarely selected vegetation or any socioeconomic variables. Although vegetation was not selected in BH, AH, and AR in the second step of variable selection, we included vegetation in the RF model training to ensure we could describe what relationship does exist between vegetation and cooling demand for each group per the objectives of the study.

3.2. Associations of variables

Variable selection selects weather and control variables as the best predictors of cooling demand for each group (table 2). In all groups, weather variables are the most important predictors of cooling demand; specifically maximum heat index is the most important predictor of demand during regular days and maximum wind speed is the most important predictor during hot days. For above-Q1 groups, building type follows the weather and control variables in importance, and the association of vegetation with cooling demand is stronger than randomness (figures 3(b) and (d)). In below-Q1 groups, vegetation and race follow the weather and control



variables in importance (figures 3(a) and (c)). The importance of socioeconomic variables remains similar or slightly lower on hot days (see appendix C).

3.3. Directions of associations

The maximum heat index and maximum wind speed are positively associated with cooling demand (figure 4(a) and (b)). Above-Q1 groups living in apartments have lower cooling demand than those living in single-family residences (figure 4(c)). Off-day, a control variable, is an important predictor for all four groups (figure 4(d)). On hot days, people use more energy during weekdays (i.e. Non-working day equal to 1), while, on regular days, people use more energy during weekends. Vegetation is positively associated with cooling demand for below-Q1 income on regular days but is negatively associated with cooling demand for above-Q1 income on hot days (figure 4(e)).

In the above-Q1 income groups, building type was more important in the above-Q1 income and hot days group (AH). Apartment buildings are much less sensitive to heat stress than other types of buildings, observing that the relative demand is close to 1.0 when the proportion of apartment type building is high (figure 4(c)). The regions with more apartment buildings have comparatively steady cooling demand with higher relative demand on regular days and lower relative demand on hot days compared to other regions.

Vegetation increased in importance on hot days in both income groups (figure 2). The association with vegetation is higher in below-Q1 income groups, and higher vegetation tends to decrease with cooling demand sensitivity (figures 2 and 4(e)). For BH (4(e), top-left), vegetation is negatively associated with the relative demand, while for BR (4(e), bottom-left), vegetation is positively associated on regular days.

However, the association with vegetation becomes weaker in above-Q1, which is evidenced by the slope becoming moderate and the confidence intervals narrowing (figure 4(e)). We also observe that this association between vegetation and cooling demand is robust to the heat index threshold for hot days; that is, when we increase the heat index threshold, the observed trend remains the same. Note that, in these partial dependence plots, we took only the marginal association of vegetation into account excluding the effects of weather variables (thus, excluding the cooling effect of urban vegetation), and vegetation still has an influence on human behavior with respect to energy consumption.

Vegetation demonstrates a stronger association with cooling demand during hot days than during regular days for both income groups (figure 2). This was also true when the model was run on the full-variable models (i.e. without VSURF).

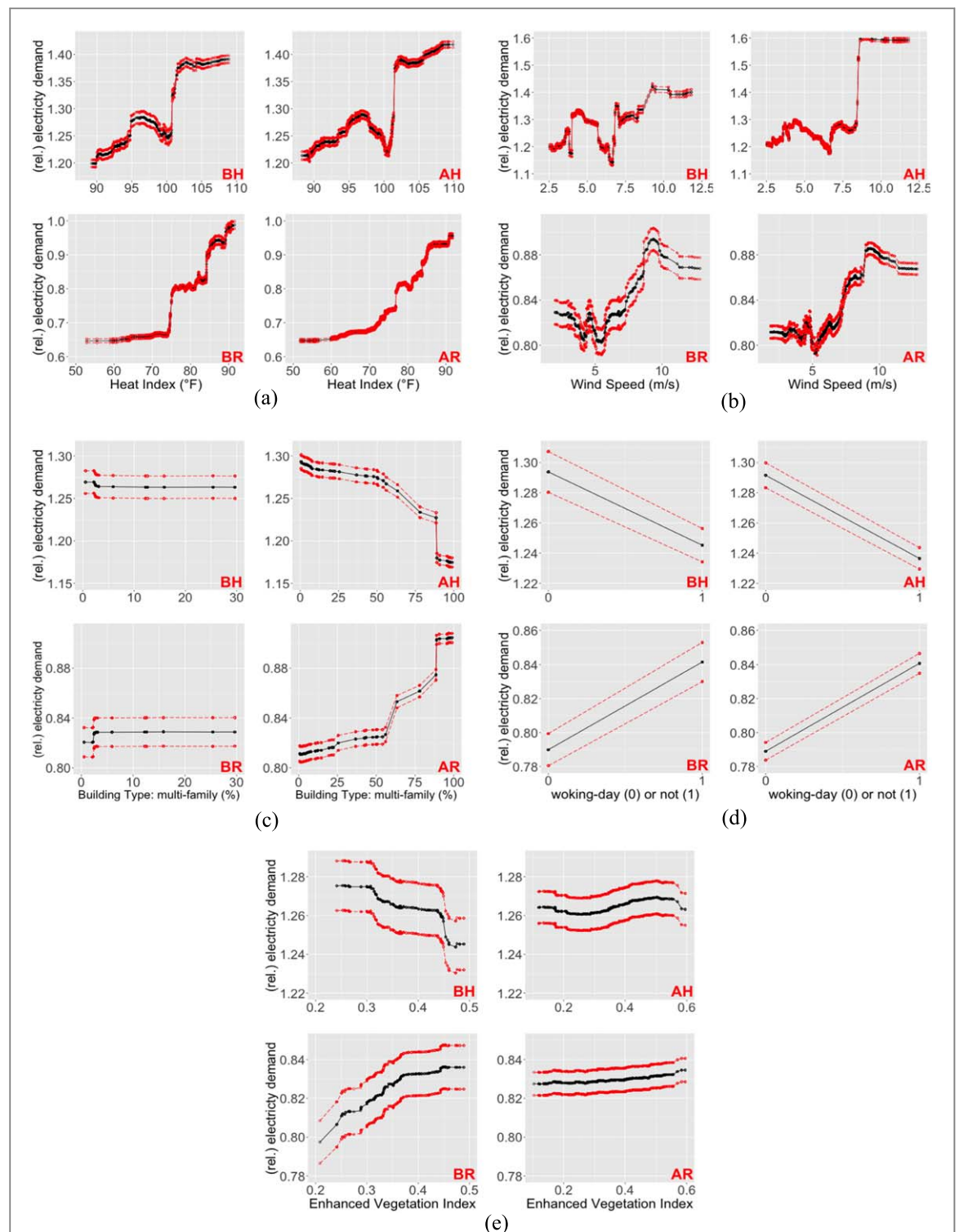


Figure 4. Partial dependence plots of cooling demand. In each quartet of plots, clockwise starting top-left, the plots are below-Q1 income and hot days (BH), above-Q1 income and hot days (AH), above-Q1 income and regular days (AR), and below-Q1 income and regular days (BR). Note the varying y-axes.

4. Discussion

This Chicago-based study analyzed the sensitivity of cooling demand to environmental and socioeconomic resources of communities under warming temperatures. In particular, the impact of vegetation was studied. A random forest model identified the predictive value of urban characteristics on cooling demand for four groups of ZIP codes delineated by wealth and temperature. The results showed vegetation is an important driver of cooling demand in low-income neighborhoods, reducing cooling demand on hot days and increasing cooling demand on regular days. Furthermore, the results indicate that low-income, low-vegetation communities react

to heat stress more drastically by increasing electricity demands than low-income, high-vegetation communities. For above-Q1 income groups, building type (*e.g.*, *single family* versus *multi-family* residence) superseded vegetation in importance. However, the importance of vegetation increased for both below- and above-Q1 income groups for hot days.

Weather and control parameters were the most influential drivers of cooling demand, but these parameters are not easily adjusted. Other urban characteristics, such as vegetation, building type, or distribution of wealth can be influenced by policy. Vegetation area was the most influential driver of cooling demand in below-Q1 ZIP codes on hot days. Vegetated area has long been shown to impact urban temperatures (Erell and Zhou 2022, Ko 2018, Skelhorn *et al* 2016). Urban vegetation can serve as a refuge from heat stress (Yan *et al* 2019), and lower income groups may be more likely to use this shelter effect during extreme heat events, which may explain the higher sensitivity displayed in low-income, low-vegetated ZIP codes. Vegetated area exhibited a positive relationship with cooling demand for below-Q1 income groups on regular days. This result was surprising given the cooling effect of trees (Rahman *et al* 2020), but tree canopy can trap heat. Additionally, some patterns may be lost at the spatial, temporal, or economic resolutions used in this study. The mechanisms underlying this result bear further study.

Low-income neighborhoods often have less vegetation than their wealthier counterparts (Declat-Barreto *et al* 2016, Pham *et al* 2012) and are more exposed to extreme heat (Chakraborty *et al* 2019, Yin *et al* 2023). Public parks and cooling centers help residents combat extreme heat events, but cooling centers require air conditioning, which requires more energy to run, and access can be uneven (Fraser *et al* 2017). Low-income populations also have fewer resources to respond to the effects of extreme heat (Rosenthal *et al* 2014). Lower cooling demand means residents are spending less on cooling, resulting in less strain on the electrical grid (Khosla *et al* 2021). As more days meet the hot day threshold, reducing the costs under-resourced communities face can increase their resilience.

While below-Q1 ZIP codes consistently experienced an increase in demand on hot days, above-Q1 ZIP codes did not exhibit this trend. Furthermore, in the wealthier ZIP codes, no relationship between hot days and cooling demand existed in the model. Perhaps wealthier ZIP codes have more household items drawing power so whatever increase in power usage is offset by a reduction in other electricity use, or the residents of these ZIP codes have more capacity to travel to cooler places in anticipation of hot days. In addition to the magnitude of cooling demand not changing between regular and hot days in above-Q1 ZIP codes, the non-control variables for above-Q1 ZIP codes show little change in importance (figure 3). Building type remains more important to cooling demand in above-Q1 ZIP codes than vegetation. Indeed, the effects of vegetation in above-Q1 groups may be due to other factors, such as the effect of Chicago's downtown. The results suggest large apartment buildings experience less cooling demand on hot days, which aligns with existing empirical studies that high-rise residential buildings tend to have less cooling demand than single-family or low-rise apartment buildings, especially in extreme consumption cases (Kaza 2010). Despite building type driving cooling demand more than vegetation in above-Q1 groups, the importance of vegetation still increases on hot days (figure 2).

Urban vegetation both affects and is affected by the urban climate. How this relationship changes with the warming global climate will impact what mechanisms are available to cool cities (Winbourne *et al* 2020). This study suggests the importance of vegetation on cooling demand increases on hot days; however, the vulnerability of vegetation also increases on hot days. Cooling from vegetation is dependent on the health of the vegetation: Water-stressed vegetation undergoes reduced evapotranspiration, and weakened canopy provides less shade. Furthermore, vegetation can die if heat or water stress from heatwaves or drought is too severe or persists too long Marchin *et al* 2022.

Though extreme heat events can disrupt ecosystems, there are ways to improve the resilience of urban vegetation. Diversity and quantity of vegetation can mitigate some vegetation sensitivity to extreme heat events. Planting vegetation climate-consciously in locations within cities the vegetation can survive may both improve the resilience of the vegetation and the resilience of the city.

Studies modeling cooling demand typically use daily mean temperature (Colelli and De Cian 2020). By using daily maximum heat index, we incorporate the impact of urban characteristics at more extreme temperatures, which could soon be the norm (Hayhoe *et al* 2010). Separating hot days from regular days allows us to describe the sensitivity of the factors influencing urban temperatures, similar to (Zhao *et al* 2023). With climate change scenarios suggesting more days will fit the criteria of hot days, understanding the influence of urban characteristics at hotter temperatures can help build better cooling demand models and guide urban design. The results of this study suggest vegetation is the strongest non-weather and non-control driver of cooling demand in below-Q1 ZIP code. This result emphasizes the importance of environmental justice in urban forests since low-income neighborhoods tend to have less vegetation (Nesbitt *et al* 2019).

Corroborating the impact of vegetation on cooling demand with data on access to urban forests and cooling centers further could inform where cooling interventions are most needed. Regardless, correlations between vegetation extent and reduced cooling demand do exist at the ZIP code level. Since ZIP codes can vary in extent,

however, the homogeneity of more densely populated ZIP codes compared to less densely populated ZIP codes could be a valuable future point of analysis. Ultimately, understanding how vegetation and building type interact with temperatures to increase or decrease energy demand for cooling can lead to more resilient cities.

5. Conclusion

This work shows that higher levels of vegetation are associated with lower levels of cooling demand, especially in low-income neighborhoods on hot days. With a plenitude of literature espousing the dearth of maintained vegetation in low-income areas, these results offer another reason to plant climate-appropriate trees in survivable areas.

Since temperatures are anticipated to rise, we include a variable describing 'hot' days to study how the characteristics of cities may influence cooling demand as temperatures increase. For low-income ZIP codes, vegetation significantly increases in importance. For high-income ZIP codes, both large-apartment building type and vegetation experience subtle increases in importance for predicting cooling demand.

To counteract the ill-effects of increasing frequency and severity of extreme heat events, we must understand what factors influence how individuals react to extreme heat events. We need also consider how the complexity and heterogeneity of responses to extreme heat events in urban areas will reflect the urban systems themselves. Understanding how the characteristics of cities influence cooling demand in a warming climate helps us build more resilient cities. Future work could explore the interactions of urban characteristics and warm temperatures for more cities than just Chicago. Exploring the effects on groups with other vulnerabilities, such as old age, could also help characterize the current gaps in extreme heat mitigation.

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Data availability statement

The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

Conflict of interest

The authors declare no conflicts of interest exist relevant to this study.

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