Spring 5-21-2022

Assessing urban heat island mitigation capacities of green infrastructure to address heat vulnerability inequities in San Francisco, California

Kelly L. Hyde
klhyde@usfca.edu

This Master's Project

Assessing Urban Heat Island Mitigation Capacities of Green Infrastructure to Address Heat Vulnerability Inequities in San Francisco, CA

By

Kelly Hyde

is submitted in partial fulfillment of the
requirements for the degree of

Master of Science

in

Environmental Management

at the

University of San Francisco

Submitted		Received	
………………………………………		………………………………………	
Kelly Hyde	Date	John Callaway, Ph.D	Date

Table of Contents

List of Figures

List of Tables

Abstract

With extreme heat events projected to become more frequent and longer lasting, heat vulnerable communities affected by urban heat islands face disproportionate heat impacts. While cities have adopted heat adaptation efforts, there needs to be a focus on vulnerable communities to ensure an equitable distribution of adaptation efforts. Green infrastructure has been a long standing heat adaptation method with benefits including reduced temperatures, reduced energy consumption, and reduced air pollution. This research analyzed the heat mitigation capacity of four green infrastructure types and identified heat vulnerable communities to address whether current green infrastructure in San Francisco is equitably distributed. Dense tree cover and increased tree abundance had positive impacts on the mitigation ability of each green infrastructure type. San Francisco census tracts with 4.1% poverty had the highest amount of tree abundance and were situated in the coolest parts of the city, while census tracts with 71% poverty were lacking green infrastructure and experienced hotter temperatures. In order for San Francisco to ensure green infrastructure is equitably distributed, I recommend that the scoring process for heat vulnerabilities to be modified to consider smaller communities, green infrastructure heat mitigation goals be set for individual districts, resources for community led street tree implementation be directed toward vulnerable communities, and green roof retrofitting subsidies or grants offered to existing building. Extreme heat events will continue to affect vulnerable communities if cities are not well prepared, and a just distribution of the resources already being implemented needs to be a priority.

Introduction

Urban heat island impacts

Rapid urbanization in cities around the world have caused an increase in anthropogenic greenhouse gas emissions, increasing the effects of climate change. As greenhouse gas emissions increase, the average global temperature is rising. The International Panel on Climate Change has reported that global temperatures have increased 1.5ºC per century, and the next 1.5ºC increase could have irreversible consequences (IPCC 2014). Extreme heat is amplified in urban areas in comparison to suburban and rural environments due to lack of air flow in the urban landscape and increased solar radiation from an excess of dark materials such as pavements and buildings. This phenomenon is known as an urban heat island (UHI). Effects of UHIs are expected to worsen with global warming increasing the severity and length of extreme heat events, requiring immediate action from city leaders to mitigate public health impacts.

Impacts from UHIs include increased land surface temperatures, increased energy consumption, and worsening air pollution. Urban environments usually consist of dark colored, impermeable surfaces such as concrete and asphalt, which are highly effective at retaining heat. Dark colored materials used for pavement and building structures absorb solar radiation, creating a low-albedo surface which stores excess heat in buildings and increases temperatures in urban areas (Baniassadi et al., 2018). With cities becoming densely populated and more developed, dark surfaces decrease the albedo of city-cores far more than rural surrounding areas (Taha, 1997). Nath et al. (2021) take this idea further by comparing land surface temperatures to the different albedo producing urban morphology types (UMTs) of New York City (i.e. land uses). They find that the built environment has the biggest impact on UHIs, showing that industrialized urban areas with a higher density of dark surfaces increase land surface temperature the most. With the increase in surface and ambient temperatures, buildings absorb excess heat and require more energy consumption for indoor cooling. With every 1ºC increase in outdoor temperature, studies have shown that electricity demand can increase by 2-4% (Rosenfeld et al., 1998). This increase in energy production exacerbates air pollution through emissions accumulating in the urban environment.

The effects of UHIs can be exacerbated by lack of access to suitable infrastructure, such as housing types and cooling methods. Different housing types have the ability to be more or less vulnerable to heat. For example, in the United Kingdom, flats and townhouses were found to have a 1ºC hotter temperature than standalone houses (Macintyre et al., 2018), while in China there was a higher risk of incurring a heat-related illness when living on the top floor of an apartment building (Semenza et al., 1996). Flats or apartments are more often occupied by low-income residents, where seeking more adequately thermal resistant housing would not be an option.

Many studies have found that access to efficient cooling methods in the event of excessive heat is unequal. Cooling methods can be a life-saving alternative when daytime temperatures are high and persist into the night (Macintyre et al., 2018). Many heat vulnerability index's list no or little access to air-conditioning as a leading vulnerability (Reid et al., 2009). Having access to a working air-conditioner led to an 80% reduction of risk of death during the 1995 Chicago heat wave (Semenza et al., 1996). This, coupled with lack of equally distributed cooling centers, extremely limits access to heat reducing infrastructure. Bradford et al. found that the distribution of cooling centers, such as libraries and senior centers, to be unequal in urban areas. With the rise of urban heat in cities which are not adapted to these temperatures, the existing distribution of this infrastructure is unequitable given the heat vulnerability index. Although these conditions have been coined "thermal comfort", the lack of comfort can have dangerous health risks for humans.

During extreme heat events, humans have a limitation of exposure before experiencing heat related illnesses. Adverse health impacts include but are not limited to dizziness, fatigue, heat stroke, heat exhaustion, coma, and death (Macintyre et al., 2018). Susceptibility to heat related mortality is widespread during heat waves, as shown by the estimated 700 deaths during the 1997 heatwave in Chicago, IL. and 35,000 deaths during the 2003 heatwave in Europe (Harlan et al., 2006). These illnesses can occur with greater strength and severity when exposure is higher or underlying health conditions are present. Vulnerable groups such as the elderly, children, people with disabilities, homeless people, low-income, and people who work outdoors are therefore communities that need to be focused on when adapting mitigation efforts.

Adaptive strategies in a changing climate

To combat the effects caused by UHI, many different mitigation strategies have been adopted over recent decades. Studies dating back to the 1970s found that the biggest cause of rising temperatures in cities is due to low-albedo materials that have a high thermal capacity and heat conductivity, leading to the discovery that light surfaces are able to reduce the amount of heat retained by buildings (Akbari et al., 2001). This "cool roofs" discovery began a movement of studies that tested the extent of temperature reduction roofs could achieve if albedo was raised (Pisello, 2017; Rosenfeld et al., 1998; Santamouris, 2014; Zinzi & Agnoli, 2012). Varying from white paints of different materials and eventually to green roofs made of increasing levels of vegetation loads, green infrastructure became emerging topic in the climate change adaptation field.

The most successful and inexpensive counter to temperature altering conditions is the implementation of green infrastructure. Green infrastructure is thought of as a multifunctional urban green space, having the capacity to provide ecosystem services as well as provide a civil investment in infrastructure and human health and well-being (Tzoulas et al., 2007). An upgraded urban green space into connected system of urban forests, parks and open spaces, street trees, and green roofs can therefore increase ecosystem function and biodiversity in urban areas while promoting public health. Using climate models to predict future temperatures in Manchester, Gill et al. (2007) found that tree cover and green roofs kept temperatures from increasing more than 3ºC in city centers through 2080, while reducing just 10% of green infrastructure would increase temperatures by 7ºC to 8.2ºC. With climate change likely to amplify the effects of UHIs, there needs to be wide spread access to green infrastructure across affected cities.

Purpose of research

Global warming is an issue for city planners because extreme heat has dire consequences for the well-being of citizens and the fight against climate change. Adaptive measures need to be initiated with physical urban landscapes in mind and the intention of preserving the unique social structures of individual cities. The objective of this paper is to assess the urban heat island mitigation capacity of different adaptation strategies, focusing on the equity of emerging green infrastructure types. In order to understand how green infrastructure can play a role in mitigating harmful UHI impacts for the most vulnerable populations, this paper will address four research questions:

How can urban green infrastructure be best utilized to ensure urban heat island effects on vulnerable communities are mitigated?

- *How does green infrastructure mitigate UHI effects?*
- *Which communities are most vulnerable due to increased heat sensitivity, heat exposure, and decreased access to health care?*
- *What are possible areas for implementing equitable green infrastructure in San Francisco to ensure the urban heat island is not disproportionately affecting vulnerable communities?*

Methodology

Comparative analysis

In order to outline what type of green infrastructure will benefit vulnerable communities the most and where, green infrastructure mitigation capacity and vulnerabilities to heat will be reviewed through a comparative analysis. Four green infrastructure types, urban forests, parks and open spaces, street trees, and building-integrated infrastructure will be compared on their capacity to mitigate rising temperatures, rising energy consumption, and worsening air pollution. These results will be used to outline the positive, negative, and neutral effects each type of green infrastructures have on mitigating the effects of UHIs. Next, a vulnerability analysis will be used to outline where the climate gap is present in communities vulnerable to heat. These points will be used in discussion and recommendations of where green infrastructure should be located in respect to need and vulnerabilities.

San Francisco GI case study

A case study of San Francisco will outline the equitable distribution of green infrastructure and current status of green infrastructure initiatives which contribute to UHI mitigation. Several datasets will consistently be used to assess urban tree canopy distribution, urban street tree distribution, and green roof ordinance status (Table 1). Land surface temperature (LST) data will be acquired from the NASA ECOSTRESS satellite mission, which was acquired during the late evening on September 27th, 2020. This data will be delivered as raw swaths, requiring conversion to grid raster format using a python script in Anoconda. Once input into ArcGIS Pro, the Zonal Statistic tool will be used on this raster dataset to find mean LST of each census tract in the urban tree canopy assessment and each park in the park cooling extent assessment.

Table 1. Sources of geospatial and demographic data acquired for this study.

Data Title	Source	Format	Raster resolution	Date Acquired/Published
Land surface temperatures	NASA ECOSTRESS	Raster	90m	27-Sep-20
Land cover classifications	NOAA Landsat 8	Raster	30m	17-Aug-17
CalEnviroScreen census tract scores	Office of Environmental Health Hazards Assessment	Vector - polygon	N/A	1-Oct-21
Demographic data	Office of Environmental Health Hazards Assessment	Table	N/A	1-Oct-21
San Francisco parks, census tract boundaries	San Francisco Recreation and Parks	Vector - Polygon	N/A	Last Updated: 2022
San Francisco street trees	San Francisco Public Works	Vector – Point	N/A	Last Updated: 2021
San Francisco green roofs	City and County of San Francisco	Vector - Point	N/A	Last Updated: 2019

In order to assess the urban tree canopy of San Francisco, land classification data was acquired from NOAA's Landsat 8 satellite. The raw data was comprised of 25 land classifications, 5 of which had zero pixels in the study area and the remaining 20 will be reclassified into 7 classifications to better represent the study area: impervious cover (high, medium, low developed), forest (evergreen, deciduous, and mixed), open space, grassland/scrub (grassland, scrub, cultivated), wetland (estuarine scrub and estuarine emergent), bareland/beach, and water (open water, aquatic bed). After reclassifying, the raster will be converted to polygon and an intersection between land classifications and census tracts will be tabulated in order to acquire percent land cover per census tract. The census tracts chosen for this analysis will be decided by finding the top and bottom five CalEnviroScreen scoring census tracts. Using Excel, the resulting table will be joined with LST Zonal Statistics of census tracts to associate mean LST to each census tract.

Street tree distribution will be analyzed using data acquired from the City and County of San Francisco. The city regularly updates the database containing location data of every street tree planted and maintained by the San Francisco Department of Public Works. The last date that this dataset was updated was May 27th, 2021. These data points will be compared with 2010 census tracts in order to have an accurate relationship with census tract delineations present during the years of other data sets used. Street tree points will be summarized within census tracts using ArcGIS Online to count amount of street trees per census tract. This data will be used to compare the same census tract samples from the previous analysis stage. Street tree orientation and distribution among the individual census tracts will be assessed quantitively in street trees per square mile and per population size, as well as qualitatively in distribution of street trees across the census tracts and across individual streets.

Lastly, green roof point data will be acquired from the City and County of San Francisco. This dataset is updated periodically, the last date being in 2019. No day or month was indicated on the dataset. Green roofs inputted into this dataset are green roofs that are in compliance with the "Better Roofs" ordinance which states that any new construction under a certain height should have 25% adaptive roofing, including living roofs. This point data will be inputted into ArcGIS Online and overlayed with the San Francisco Heat Vulnerability Index in order to outline where newly built green roofs are being implemented and where this adaptive infrastructure is lacking.

Analysis of UHI Mitigation Capacity of Green Infrastructure Types

Due to rising global temperatures, the need for nature-based adaptation strategies in urban areas is increasing. Urban areas that experience UHIs benefit from nature-based adaptation strategies, or green infrastructure, by utilizing the ecosystem services and climate adaptation benefits which trees and vegetation provide (Ordóñez Barona, 2015). The effectiveness of different green infrastructure types to provide relief from UHI impacts, hereby called mitigation capacity, differs by each type. In an urban setting, green infrastructure can be implemented at multiple scales (Figure 1): the neighborhood scale (urban forests), block scale (urban parks), street scale (street trees), and building scale (building-integrated infrastructure) (Livesley et al., 2016). These individual scales make up the urban tree canopy, a term which will be used in this paper to describe all tree cover in a given urban area. Urban tree canopy is defined as the collection of trees from parks, streets, and both public and private vegetated land in an urban area (US Forest Service, 2015), and have distinct UHI mitigation capacities. In order to understand how green infrastructure mitigates the effects of UHIs, I will analyze the heat mitigation capacity of four green infrastructure types: urban forests, parks and open space, street trees, and building-integrated infrastructure.

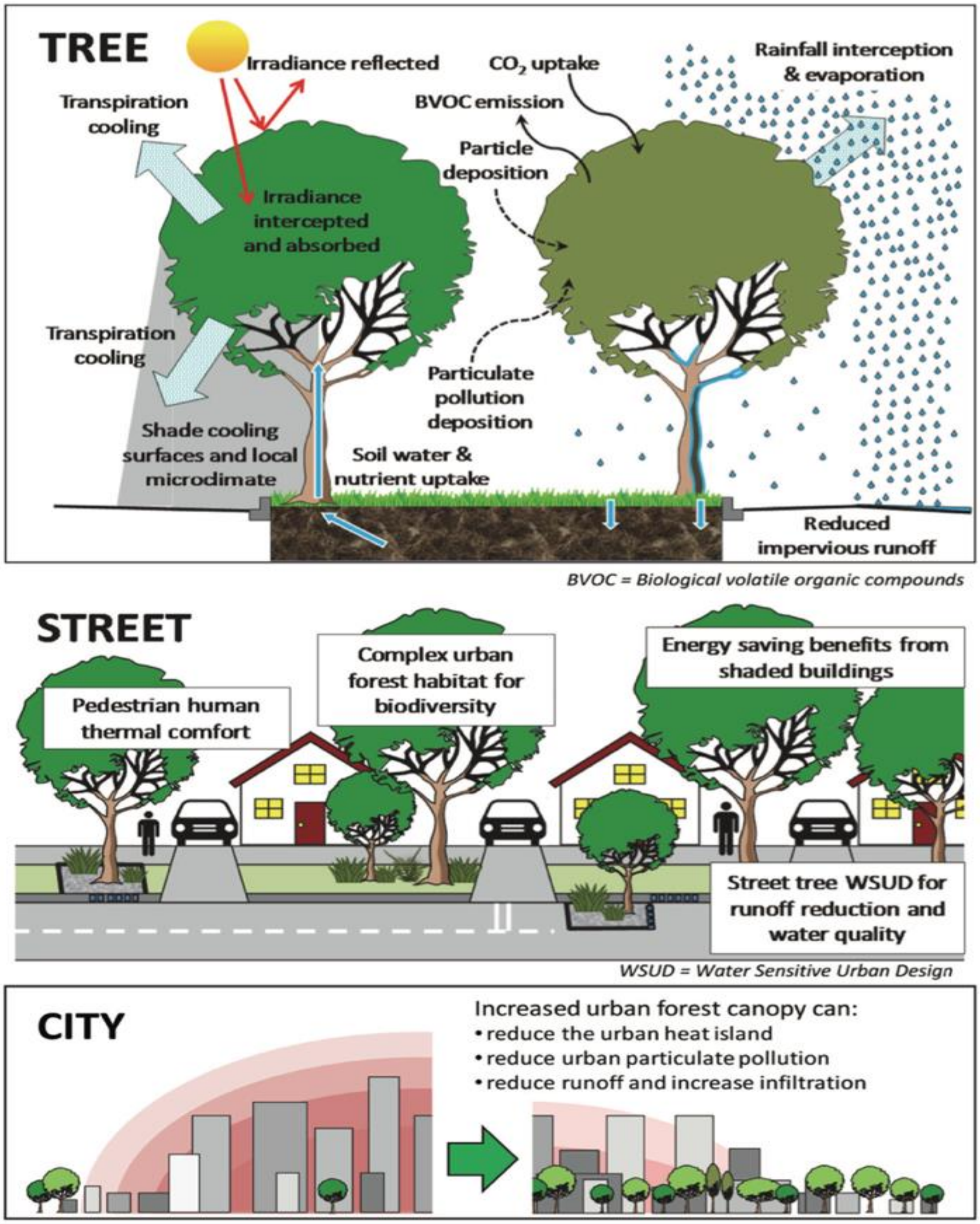

Figure 1. Urban tree canopy ecosystem services at the tree, street, and city scale (Livesley et al., 2016)

Urban forests

At the neighborhood scale of the urban tree canopy, urban forests are described as natural areas with dense tree cover and vegetation (US Forest Service, 2015). While “urban tree canopy” and “urban forest” are often used interchangeably in literature, the classification of “park and open space” and “urban forest” is usually determined by the size of the park and tree density (Pregitzer et al., 2019). These larger parks are often preserves for critical natural resources that smaller parks are not typically suited for. For example, San Francisco has several large parks that are managed by the Park Forestry and Natural Areas programs within the San Francisco Recreation and Parks Department (SFRPD). Golden Gate Park in San Francisco is a manmade urban forest that was built on 1,017 acres of sand dunes and now features dense trees, groves, and lakes that is maintained by SFRPD. One of the many natural areas within this park contains a native oak woodland that serves as a preserve for native and migratory birds while protecting the park from invasive species. The large area of Golden Gate Park provides many unique ecosystem services and influences climate at the neighborhood scale, and therefore would meet the designation of an urban forest.

The most important quality of urban forests in mitigating UHI effects is the ability to provide shade and reduce land surface temperatures (LST) to improve urban thermal comfort over a relatively large area. This cooling effect is due to the transformation of sensible heat to latent heat through evapotranspiration from trees (Moss et al., 2019). The latent heat reduces temperatures compared to LST measurements in areas where urban forests provide shade and evapotranspiration cooling (Livesley et al., 2016). In addition, cooler air is transported from urban forests by winds that influence the temperatures of surrounding neighborhoods, creating a gradient with coolest temperatures closest to the forest and rising with distance (Sugawara et al., 2016). This is known as the cooling extent of the forest. Golden Gate Park in San Francisco reduces ambient temperatures around the direct perimeter of the 250 acre urban forest by as much as 4ºC within a 250 meter cooling extent. (Figure 2, Huang 1987). Downtown temperatures on the eastern side of the city differ by as much as 9ºC (17ºF) compared to the inner sections of the urban forest. The distribution of downwind reduction in temperatures is heavily dependent on climate zones and factors such as humidity, rainfall, and urban density (Table 2). For example, urban forests within humid climates have a range of cooling extents but lower temperature reductions than areas that are not as humid. While climatic factors that contribute to heat reduction may vary from city to city, the spatial distribution of cooling extent (CE) provided by urban forests shows urban forests can provide cooler temperatures up to 800 m in radius (Sugawara et al., 2016). Urban heat islands affects all climates in different ways, and with temperatures on the rise these urban forests are crucial to reducing the impacts.

Table 2. Spatial distribution of cooling extent (CE) from parks varies in urban forests dependent on climate zone and cooling factors.

Urban forest location	**CE range (m)**	**Temperature reduction (ºC)**	**Climate**	**Key cooling factors**	**Source**
Nanjing City, China	267-883	0.3-2.3	Sub-tropical	Precipitation, humidity	Yin, S. et al. 2022
Seoul, Korea	240	4.7	Temperate	Precipitation, nighttime cooling	Lee, S. H. et al. 2009
Göteborg, Sweden	800	5.9	Mediterranean	Precipitation, building envelopes	Upmanis, H. et al. 1998
San Francisco, California	250	4	Mediterranean	Marine layer, humidity	Huang et al. 1987

Sources: Upmanis, H. et al., Lee, S. H., et al., and Yin. S., et al. (2009; 1998; 2022)

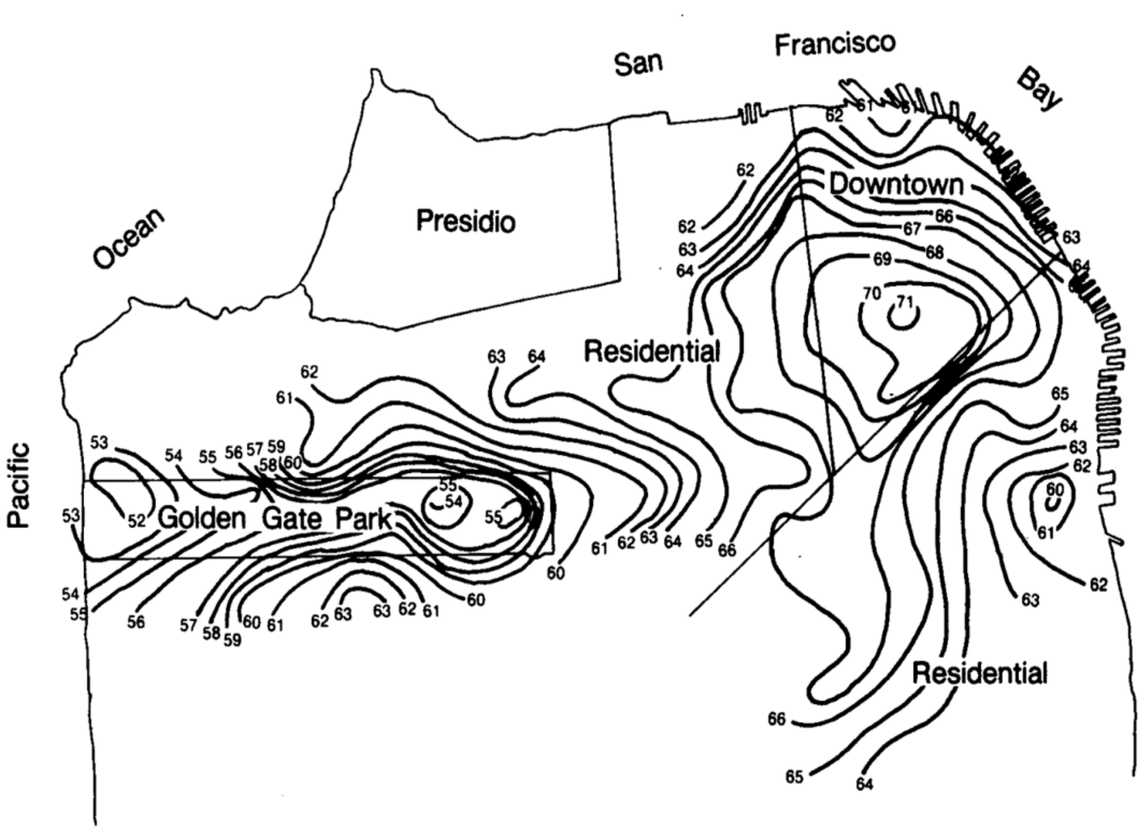

Figure 2. City temperatures in San Francisco in 1952, showing as much as 9.3ºC (17ºF) difference between the urban forest (Golden Gate Park) and the surrounding neighborhoods *(Huang et al., 1987)*

Increased urban heat also results in higher demands for energy by increasing ambient temperatures and requiring an increased use of cooling appliances. It is estimated that with every 1ºC increase in temperature, electricity demand in cities increases by 2-4% (Akbari et al., 2001). Urban forests help to alleviate higher energy demands through both direct and indirect processes such as reducing temperature, humidity, windspeed and solar gain (Huang 1987). Given that these factors are dependent on local climates, the energy reduction capacity is variable between urban areas. With an increase in overall urban tree canopy of 25%, even dry, arid climates such as Sacramento and Phoenix could see 25% and 46% savings in energy, respectfully (Akbari, 2002). In hot climates, nighttime cooling is essential, although the effects of UHI reduce the relief from high temperatures and increases energy consumption as a result (Doick et al., 2014). This goes hand in hand with mitigating rising temperatures as cities increasingly rely on emission producing air-conditioners as buildings get hotter during the day and retain heat at night.

Lastly, poor air quality as a result of UHIs can be mitigated successfully with large scale urban forests to improve environmental quality and human health. Trees are able to uptake air pollutants through the leaf stomata, where the gas then diffuses into the tissues (Smith, 2012). The efficiency of this process is dependent on a variety of physical and meteorological variables. Some tree species have longer seasons of retaining foliage (in-leaf season) or do not lose their leaves at all, increasing the amount of air pollutant removal (Nowak et al., 2006). Precipitation rate also impacts the ability of trees to effectively store pollutants, leading to decreased pollutant storing with increased precipitation (Nowak et al., 2006). This is due to the increased ability of pollutants to be deposited onto leaves when dry, also known as dry deposition (García de Jalón et al., 2019). A Los Angeles urban forest consists of long in-leaf seasons and low precipitation rate due to the city's location, which led to the highest annual pollution removal amount per unit of tree cover compared to 55 other cities (Nowak et al., 2006). All of these factors combined with the amount of tree cover and concentration of pollutants ultimately decides how much leaf surface is available to uptake pollutants, making large urban forests a highly effective air pollutant sink.

Parks and open spaces

Parks and open spaces are defined as recreational green spaces with access to lawns, trees, and occasionally natural areas such as trails and exploration areas. These differ from urban forests in that they are landscaped spaces which can include built structures that provide shade or water features that alleviate heat stress, contributing to human mental health and comfort (Lin et al., 2015). Parks are effective at reducing temperatures at the block scale due to the horizontal transport of cool air and evapotranspiration of trees, creating a gradient of cool air that extends the bounds of the park area, creating a cool island effect from the park (Chang & Li, 2014). Park features and any pavement present can negate the cooling ability of trees and in some instances turn parks into heat islands, given that pavement makes up more than 50% of some parks (Chang & Li, 2014). This range of thermal performance is due to the configuration of the landscape elements in the park and whether they influence a cooling effect or a heating effect. Considering the various factors of park size, vegetation features, and built features, parks and open spaces cooling efficiency is largely dependent on how the green space is built.

Parks and open spaces are known as “cool islands” because of their ability to reduce LST of surrounding blocks and therefore limit the intensity of UHI impacts (Dousset & Gourmelon, 2003). Similar to urban forests, parks and open spaces reduction of surrounding temperatures correlates to the park size as well as vegetation density (Chang & Li, 2014). Temperature reductions can be similar despite park size, but CE can be increased with larger park sizes. For example, Monteiro et al. found that while average temperature reductions between four small parks and two medium parks in London only differ by 0.2ºC, CE of medium parks is 1.5 to 2.8 times greater than small parks (2016). This finding suggests that there is a linear relationship between CE and park size and non-linear relationship between cooling intensity and park size. This can likely be attributed to the variety of amenities that parks offer, some of which contribute low-albedo surfaces rather than heat mitigating green spaces. This can be in the form of asphalt or concrete sport courts, paved plazas, or buildings. Due to this, parks and open spaces are not a consistent resource to use for reducing temperatures, but rather used to provide a variety of other amenities to park visitors.

Parks and open spaces can reduce excess energy consumption brought on by increased use of cooling units through the same process as urban forests by reducing nearby temperatures. While urban forests are not typically in the city center, parks and open spaces are ideal in urban settings because less acreage is required. Dense urban areas with multi-story residential and commercial buildings can benefit from shading of nearby parks and help reduce energy consumption, but is greatly reduced in efficiency with the increase in building heights (Chang & Li, 2014). Potentially energy saving shade from trees will only reduce the need for air-conditioning for floors which lie below tree canopy, or the highest point under the tree before shade is available (Akbari et al., 1997). Reducing below tree canopy temperatures can have beneficial impacts on below and above tree canopy air quality.

Through the same processes as urban forests, parks and open spaces are able to reduce air pollution through leaf surfaces. Given that urban areas tend to be densely populated and create more air pollution, the frequency of vegetated parks can greatly reduce pollutants the closer they are to the pollutant source (Bolund & Hunhammar, 1999). One study in Auckland, New Zealand found that urban tree canopy on a city street can store pollutants, reduce upward transport of NO_2 emitted from vehicles, and reduce downward transport of fresh air into below canopy spaces (Salmond et al., 2013). Salmond et al. found that air samples near buildings contained significantly more NO_2 emitted from vehicles in samples taken below the tree canopy near the ground floor compared to above canopy at the first floor of the building (Figure 3). Due to reduced air flow in dense canopy covers, the difference in NO_2 concentration is almost two fold during on-leaf seasons, although the concentrations are approximately equivalent during off-leaf seasons. These results show that denser urban tree canopies on streets with high vehicular activity can greatly reduce NO_2 concentrations above tree canopy during in-leaf seasons while NO_2 concentrations under tree canopy remain the same. The reduction of air pollutants that parks can provide is a great benefit for cities that are able to have evenly disbursed parks and open spaces, although distribution tends to be dependent on available land to turn into parks. In an effort to create an evenly distributed urban tree canopy in a city, street trees can be used as supplemental urban heat island mitigation tools to fill in gaps.

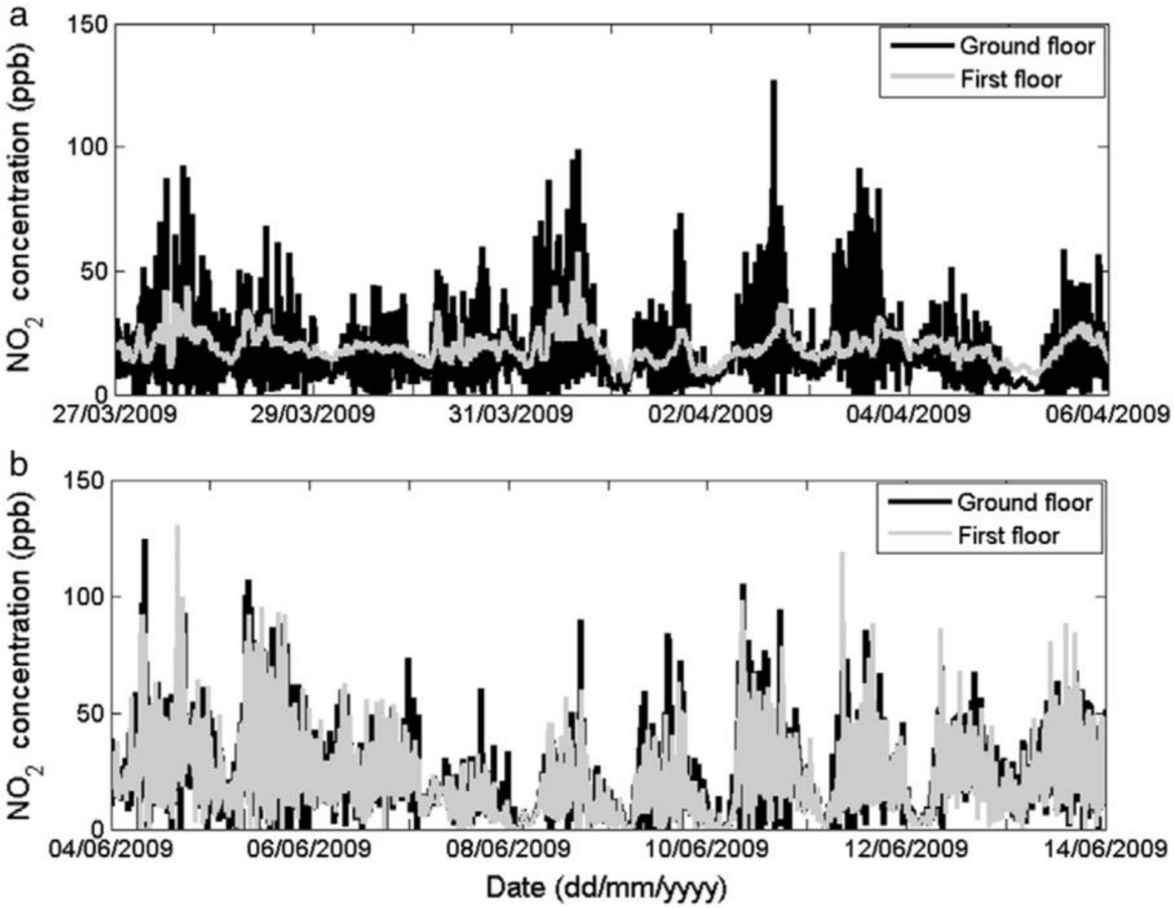

Figure 3. NO_2 concentrations at ground floor (below canopy) and first floor (above canopy) during on-leaf (a.) and off-leaf (b.) seasons (Salmond et al., 2013)

Street trees

The urban tree canopy is made of up of large urban forests at the canopy scale, parks and open spaces at the neighborhood scale, and street trees at the street scale. While the large areas of urban forests and parks and open spaces have the capacity to house many trees, street trees are able to be conveniently planted in small plots directly outside buildings and along roads. When used in tandem with larger green infrastructure, street trees can be an effective method in distributing tree cover evenly within urban areas. Planting street trees is a rapidly increasing climate change mitigation initiative because of their capacity to reduce effects of UHIs (Gillner et al., 2015). This ‘greening’ at the street level provides similar reductions in temperatures, energy consumption, and poor air-quality at a more dispersed rate than what urban forests and parks and open spaces are able to provide.

The most important quality of urban street trees is the reduction of ambient temperatures under the tree canopy. This below-canopy reduction in temperatures is most prevalent on hot summer days in the afternoon, when UHI effects are most severe (Rahman et al., 2018). The capacity for street trees to reduce temperatures is dependent on percent tree cover and tree species seasonal conditions (Sanusia et al., 2015). The amount of trees on a street, the size of the tree crown, the amount of foliage present on each tree all contribute to percent of tree cover (Sanusia et al., 2015). Streets with a high percentage of tree cover and species of trees with large leaf structures will therefore be more beneficial in influencing ambient street temperatures.

While tree species and crown area can influence the amount of shade provided and rate of evapotranspiration, location and orientation of street trees contributes to below canopy temperature reductions. Trees that are positioned in close proximity to other trees can provide better shade coverage, which is standardly quantified as the sky view factor (SVF). The SVF is the percentage of sky that can be viewed from the street, with a value of 0 being an entirely enclosed space and providing the most temperature reduction benefits (Wang, Y. & Akbari, 2016). When tree species, structure, and orientation are modeled to determine best street level temperature reductions, trees that have a larger crown, lower SVF, and spaced closer together are able to reduce under canopy air temperatures by 5.2ºC (Table 4). A similar study conducted in 2 US cities with Mediterranean climates and 2 Chinese cities with the same climates found that CE from street trees increases with tree cover and LST, with thresholds for CE being dependent on city climate (Wang, J. et al., 2022). Hot and dry climates influence evapotranspiration rates more than hot and humid climates (Brümmer et al., 2012), suggesting that cities should focus street tree initiatives in areas where tree cover does not meet the threshold required to lower temperatures for that climate (Table 4). These thresholds can be helpful to consider which species and what orientations are suitable for streets with differing needs and resources.

Table 3. Results from simulations produced by Wang and Akbari 2016 show that tree species with larger tree crowns, such as Linden, oriented without spaces between trees, can reduce temperatures by approximately 3ºC.

Tree Species	Average Crown (m)	Orientation	SVF	Air Temperature Reduction (ºC)
Elm	9	With Space	0.39	-2
		Without Space	0.29	-3.1
Maple	12	With Space	0.26	-4
		Without Space	0.11	-4.2
Linden	12	With Space	0.33	-5
		Without Space	0.1	-5.2

Table 4. Adapted from Wang, J. et al. 2022, hot/dry climates have a high rate of evapotranspiration, requiring more tree planting initiatives in neighborhoods with less UTC coverage than hot/humid climates.

Neighborhood Summer Climate	Neighborhood UTC Cover
Hot/dry	~7%
Hot/humid	~25%

Building-integrated infrastructure

While trees throughout a city help to maintain effects from urban heat islands, urban thermal balance is largely influenced by the materials used on structures and buildings. These materials are the first point of contact with solar and infrared radiation, therefore determining whether radiation will be absorbed into the building or reflected away (Santamouris et al., 2011). Building-integrated infrastructure such as cool roofs, green roofs, and green walls are made with materials designed to reflect or absorb solar radiation, thus regulating ambient heat before it enters the building (Santamouris et al., 2011). This can be an effective method of regulating effects of UHIs, especially in areas that have low tree cover from urban forests, parks and open spaces, and street trees. These three building-integrated infrastructure types are effective strategies to mitigating UHI impacts by providing thermal comfort, reduced air pollution, and reduced energy consumption as a result of less solar radiation absorbed.

A major challenge of UHIs is increased energy demand caused by excess solar radiation on the exterior of buildings, or the space between urban buildings that contains streets, sidewalks, and other urban features also known as the urban canyon (Alexandri & Jones, 2008). While indoor thermal comfort can be mitigated by the use of air-conditioners, the use of these appliances further exacerbates the impacts of UHIs by contributing more heat energy into the urban canyon (Santamouris, 2014). Energy consumption and excess heat emissions from appliances can therefore be reduced by limiting solar radiation infiltration via vegetated or reflective surfaces (Baniassadi et al., 2018). The amount of energy reduced is dependent on the type of roof used, the insulation features of the building, and the performance of the building, with low-performance buildings referring to buildings unequipped with air-conditioning units (Zinzi & Agnoli, 2012). The temperature reducing potential of cool materials on buildings is dependent on how high the coating solar reflectance and emissivity is, making the surface of a building cooler and reducing energy demand and cooling load. The available literature suggests that cool roofing can reduce low-performance buildings energy usage by as much as 41% in urban Mediterranean climates (Santamouris, 2014). This reduction in energy demand makes cool roofs an effective strategy against energy consumption increases caused by UHI impacts in urban areas while reducing excess emissions from energy consumption.

Cool roofs are a long standing, advanced approach for reflecting solar radiation off roofs, resulting in less absorbed heat into buildings (Rosenfeld et al., 1998). Cool roofs are characterized by high solar reflectance and high infrared emittance of the light-colored coatings they are comprised of (Santamouris et al., 2011). By applying cool materials, solar reflectance and infrared emittance is increased, effectively reducing surface temperatures of the building that would otherwise penetrate surfaces and transfer to ambient air (Figure 4). In one study involving 16 different coatings, white colored coating reduced surface temperatures of concrete they were applied to by 7.5ºC compared to the low solar reflectance and low infrared emittance of dark colored surfaces that increased surface temperatures 15ºC (Synnefa et al., 2006). These characteristics result in a reduction of heat penetrating into buildings that are coated with cool materials (Figure 5). This method of surface temperature cooling has the potential to greatly reduce energy consumption in a cost effective manner.

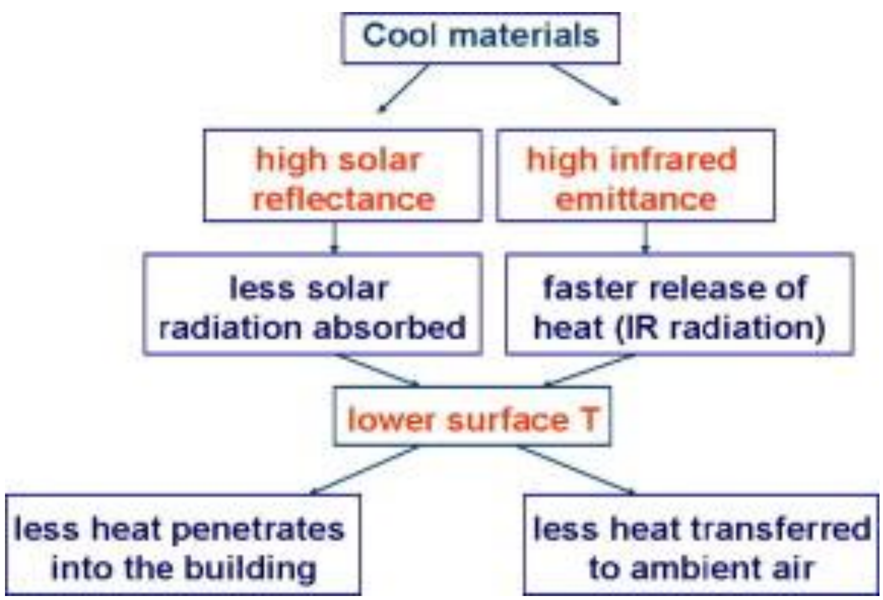

Figure 4. Solar radiation alteration properties of cool materials.

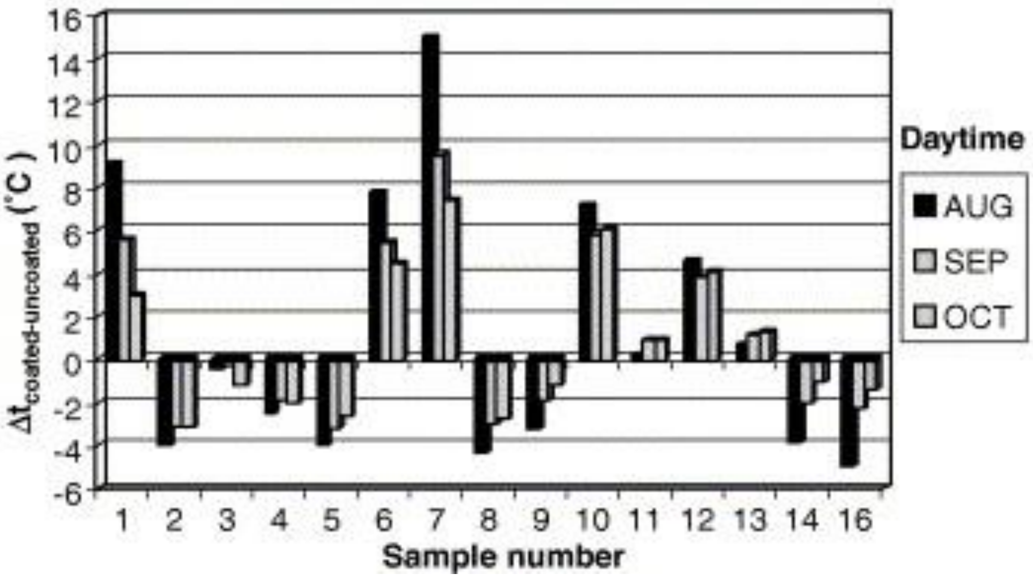

Figure 5. Change in mean daily surface temperatures of concrete blocks were applied with 16 different coatings, showing the darkest coatings (samples 1 and 7) significantly increasing surface temperatures compared to the lightest colored coatings (samples 8 and 16)

While cool roofs are solely designed to reflect solar radiation, green roofs have the added benefit of insulating surfaces through soil and evapotranspiration of vegetation (Zinzi & Agnoli, 2012). One study found that green roofs consistently decreased building surface temperatures as much as 20ºC in nine observed cities (Figure 6) by providing a high-albedo surface and reducing the amount of solar radiation absorbed into the building (Baniassadi et al., 2018). Surface temperatures are typically much higher than air temperatures, though these extreme temperatures on low-albedo surfaces radiate into buildings and make an insulating layer of vegetation valuable to indoor temperatures. There are two types of green roofs: extensive roofs which are covered in a light layer of vegetation with minimal roots and maintenance needs, and intensive roofs which are covered in heavier vegetation such as trees and shrubs (Baniassadi et al., 2018). While the dense vegetation and deep soil structure of intensive roofs has the ability to reduce temperatures more effectively than extensive roofs, retrofitting buildings with greens roofs can be costly and the type of green roof installed is dependent on the existing design of buildings (Berardi et al., 2014).

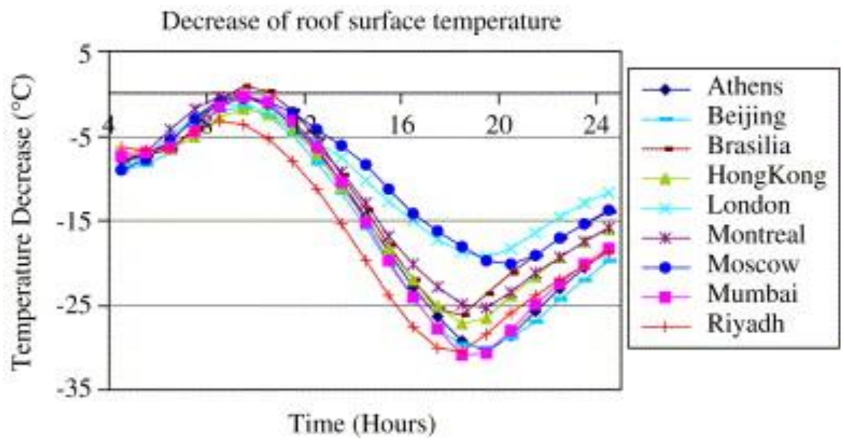

Figure 6. Vegetated "green roofs" significantly decrease building surface temperatures in 9 cities, with a maximum decrease of -27ºC. (Alexandri & Jones, 2008)

Green walls have the same cooling effect as green roofs with the additional benefit of increasing albedo of surfaces all around the building (Santamouris, 2014). A major benefit of green walls is the flexibility in where they can be placed on buildings. The low-albedo materials on the sides of buildings contribute heat to urban canyons by increasing solar radiation absorption and transferring the heated latent heat to ambient air (Loughner et al., 2012). Green walls are able to lower the amount of heat that is transferred from buildings into the ambient air and reduce temperatures. Buildings that have green walls alone are able to reduce temperatures by 2.6ºC to 5.1ºC (Figure 7), while a combination of green roofs and walls are able to reduce air temperatures by 3.6ºC to 11.3ºC (Alexandri & Jones, 2008). These cooling effects have the possibility to improve human comfort within residential buildings, especially when present in urban areas with other green infrastructure types.

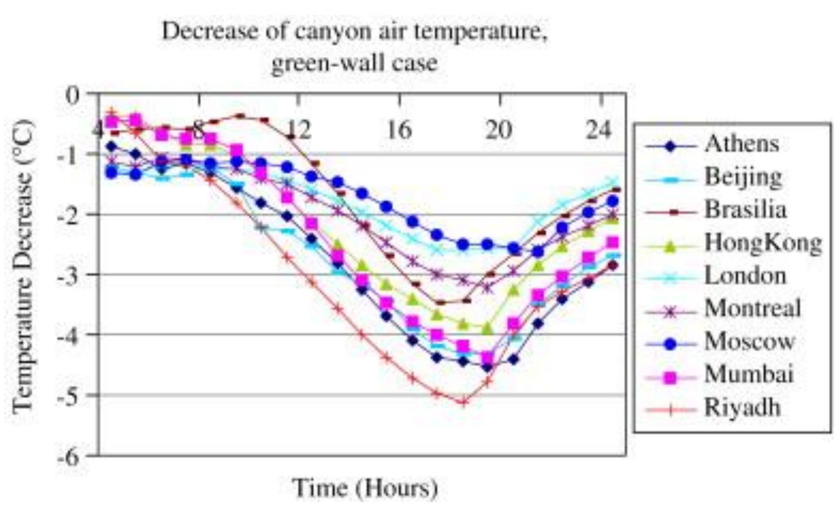

Figure 7. Vegetated "green walls" moderately decrease air temperatures in 9 cities, with a maximum of 5.1ºC. (Alexandri & Jones, 2008)

Building-integrated green infrastructure also has the benefit of being retrofitted to existing structures in an urban environment, providing more surface area of vegetation that can directly and indirectly reduce air pollutants. An increase in energy demand can lead to increased emissions from air-conditioning units used to cool buildings affected by UHIs (Baniassadi et al., 2018). Green roofs and cool roofs can indirectly mitigate appliance emissions by lowering energy consumption as a result of reducing solar radiation absorbed into the building (Takebayashi & Moriyama, 2007). Green roofs are able to directly reduce air pollution by uptake of contaminants through the surface area on vegetation (Yang et al., 2008). Similar to previously outlined green infrastructure types, the removal is dependent on pollution concentrations, weather conditions, and growth of vegetation (Yang et al., 2008). In Chicago, where winters are cold (-8.7ºC to -1.7ºC) and summers are hot and humid, green roofs are most effective at removing pollutants from May to July, during peak on-leaf season (Figure 8). The effective direct and indirect pollution abatement capacity of green and cool roofs helps to mitigate the effects of UHIs by reducing pollutants caused by excess heat.

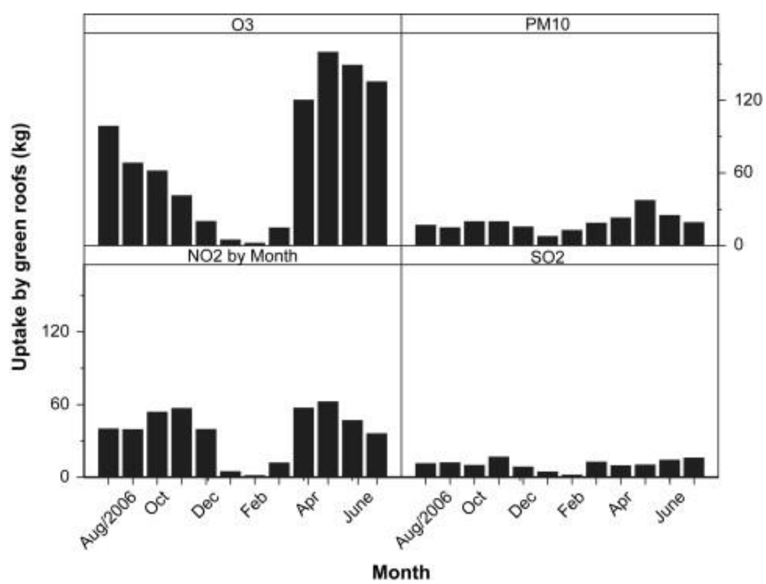

Figure 8. Pollution abatement capacity of green roofs in Chicago (Yang et al., 2008).

The capacity for these four green infrastructure types in mitigating the main impacts from UHIs is overall highly beneficial. Urban forests are beneficial to all impacts of UHIs, although these are uncommon in urban areas and difficult to implement due to existing development. While parks and open spaces are frequently developed in urban areas, they have the most variability in capacity to mitigate effects from UHIs due to inconsistent park designs, frequency within urban landscape, and climate. Street trees can be used to increase the overall urban tree canopy and provide small benefits to each impact in areas that are not benefitting from urban forests or parks and open spaces. Building-integrated infrastructure has highly successful mitigation capacity, although is expensive to implement and maintain.

Each type has a varying capacity to mitigate UHI effects (Table 5), making it important to incorporate all green infrastructure types in urban design with good distribution across urban districts. Where urban forests are best at reducing temperatures in nearby blocks, street trees and building-integrated infrastructure can supplement the blocks that are not within the urban forest cooling extent. Parks and open spaces have a lot of variability in features depending on community needs, meaning that while a neighborhood might have many parks, a park does not automatically mean vegetation that can reduce UHI impacts. While this list of UHI impacts and mitigation capacity factors is non-exhaustive, UHI impacts can be mitigated successfully by a variety of green infrastructure if used in effective orientations. By utilizing all types of green infrastructure, a good distribution of urban heat island benefits can be achieved in cities.

Table 5. Summary of UHI impacts mitigated by green infrastructure types

UHI impact category	Urban green infrastructure type			
	Urban forests	Parks & open spaces	Street trees	Building-integrated
Temperature	**Best**	**Little effect**	**Good**	**Better**
Energy consumption	**Good**	**Little effect**	**Better**	**Best**
Air-quality/greenhouse gases	**Good**	**Good**	**Better**	**Best**

Human Vulnerabilities to UHI Effects

Heat-related illnesses are an increasing concern in urban areas due to the urban heat island effect and rising temperatures. The International Panel on Climate Change (IPCC) reports that it is virtually certain that temperatures will continue to rise, having already seen a 1.31-1.51ºC increase in land surface air temperature between 1880-2018 and cities will see a faster rate of increase in global temperature compared to previous decades (IPCC, 2019). Current concerns relating to UHI effects in cities, how they affect people, and who is disproportionately affected will continue to worsen due to this temperature rise. Based on IPCC climate change projections, over the next 40 years, cities will see a faster rate of increase in global temperature compared to previous decades (IPCC, 2019). Increasing temperatures mean that communities that are typically not used to high temperatures will endure more dangerous heat waves and have a harder time adjusting. The IPCC reports that anthropogenic warming will create new, hot weather climates in tropical areas and areas of high elevation (2019). This threat has already been observed in a recent study by Blunden and Boyer (2021), who found that 3 countries in the Caribbean reported new high annual mean temperatures and 17 countries in Europe as well as Japan, Mexico, and Seychelles reported record breaking annual mean temperatures. With global means increasing annually, the demands for heat-mitigating resources will also increase.

The effects of UHIs are most felt during the day, although with heat waves lasting longer and sustaining more intense temperatures (IPCC, 2019), people are unable to find respite in lower nighttime temperatures. When exposed to these high temperatures for a long period of time, physiological effects can range from dizziness, weakness, fatigue, cramps, fainting, organ failure, coma, and death (O'Neill & Ebi, 2009). Heat-related illnesses can be dangerous during prolonged heatwaves, especially when extra stress is put on the healthcare system and energy grid. A 1995 heatwave in Chicago resulted in rolling blackouts which left thousands of residents with no air-conditioning, prolonging illnesses and leaving many without access to lifesaving treatment (Semenza et al., 1996). Since then, heatwaves have increased along with the likelihood of heat-related illnesses. These symptoms are possible for anyone to experience under extreme conditions, although certain populations can be affected more severely.

Vulnerable populations are already experiencing climate change impacts due to a variety of factors out of their control. The disparity between minority populations and their increased degree of suffering due to climate change is known as the climate gap (Shonkoff et al., 2009). The climate gap includes any effect from climate in which some communities are experiencing worse effects over other communities. In regard to heat, vulnerable populations which are more at risk include people who have increased heat sensitivities, experience increased heat exposure, and lack access to treatment (Martinez et al., 2021). Heat sensitive populations experience illnesses due to heat at a faster rate due to underlying health factors. Heat exposed populations are more at risk to heat-related illness given their inability to find or unequal access to protection from high temperatures. Each of the populations can experience a lack of access to treatment due to many factors, although unequal distribution of resources can also lead to lack of access to healthcare in general (Martinez et al., 2021). In order to understand how the climate gap is perpetuated through the effects of UHIs and to address the disproportionate impacts, local governments must identify their most vulnerable populations and allocate resources appropriately.

Heat sensitives

Heat-related illnesses are most common and most deadly in heat sensitive populations, including the elderly and people with underlying health conditions. While illnesses during heatwaves can occur in any individual, heat sensitive individuals are burdened with physiological differences that make recovering from high temperatures a much harder endeavor. For elderly people, the thermoregulation system changes as an individual ages, increasing the risk of hyperthermia with hyperthermia with age (Kovats & Hajat, 2008)**.** Age-related physiological health risks to heat can also be exacerbated by various types of medication commonly ingested by the elderly, as well as age-related diseases or disorders (Flynn et al., 2005). Heat stroke is a common illness in elderly populations because of the easily altered thermoregulation at old age (Kovats & Hajat, 2008). These symptoms happen quickly, especially in the event of a heat wave in an area affected by UHI which lacks nighttime cooling. During a sustained heat wave in 1995, Chicago lost 680 individuals over the age of 76 years old to heat-related illness (Semenza et al., 1996). With heatwaves expected to last longer and become more severe with climate change, heat sensitive populations such as the elderly are an especially increasing concern.

Similarly, having a disability or a previous health concern is likely to increase heat risk and sensitivity (Basagaña et al., 2011). Making up approximately 15 percent of the population, people with disabilities can be affected directly or indirectly by extreme heat and is highly dependent on the type of disability (e.g. mental, intellectual, physical, sensory) (Kosanic et al., 2022). For example, a person with a sensory disorder may not be directly impacted with accessing cooling centers or green spaces as a person with a physical disability, although may be indirectly impacted with difficulties adjusting to new places for long periods of time in the event of a heat wave (Kosanic et al., 2022). The range of possible impacts is wide considering the vast amount of disabilities, thus requiring an inclusive approach when analyzing the needs of disabled persons within individual communities.

Heat exposure

By reducing the interaction between humans and increased heat, exposure can be limited and heat-related illnesses can be avoided. Access to cooling centers and green space is important to reduce exposure for communities that do not have access to cooling appliances indoors. Green space, specifically, is often distributed disproportionally and leads to less access for disadvantaged people of a certain race, ethnicity, or economic class (Wolch et al., 2014). Nesbitt et al. (2019) analyzed green space access in 10 U.S. cities, finding that there is disproportionate access to green space, with green space being favored in areas with higher education and median incomes. This study did not find a notable association between park area and higher education and median incomes, which indicates that while neighborhoods of a lower socioeconomic status may have access to parks, the neighborhoods do not meet the threshold of tree cover to provide any thermal regulating benefits.

Measuring access to green space can be challenging given the variety of park characteristics such as facilities, tree cover, size, and park hours, placing emphasis on the requirement for needs assessments to be conducted at a hyper-localized, neighborhood level (Wolch et al., 2014). Some neighborhoods might benefit more from recreational features in parks if tree canopy cover is high, while some areas may require more street trees is tree canopy cover is low. With more tree cover in low-income areas, energy demands for air-conditioning would significantly decline, heat-related illness would be less common, and particulate air pollution could be reduced (Landry & Chakraborty, 2009). While air-conditioning is common, energy can be costly and leaves low-income communities residing in low-performance buildings having to bear the brunt of heat waves in housing types not suitable for extreme heat. In the 1995 Chicago heatwave, many of the deaths could have been avoided if a rolling blackout had not put over 30,000 residents without access to air-conditioning (Semenza et al., 1996). This essential heat-mitigating resource is not available to many low-income individuals, especially in cities that have not historically experienced hot weather and therefore do not have air-conditioning as a basic amenity in homes. In homes and buildings that need to be retrofitted with air-conditioning and central cooling, this will further put a strain on the energy grid and increase emissions (Auffhammer et al., 2017).

Workers who endure the heat outdoors are also a vulnerable population. Li et al. found that during the hottest times of the day, productivity on two construction sites in China went down 0.57%, while on the other hand the risk of heat-stress injuries is greatly increased during this 1 C increase in temperature (2016). Kjellstrom et al. (2009) found that this productivity loss will increase with climate change, with a decrease of productivity upwards of 17% by 2080. The affected industries are all essential to society, such as agricultural, communication, and construction workers. Decreased productivity and overall well-being of these workers would affect more than just individual industries, cities could see a shift in the day to day operations.

Access to treatment

Many factors could contribute to whether an individual has access to healthcare. This could include available income to cover healthcare cost or availability of transportation to a healthcare facility. In the event of a heat-related illness, having access to treatment could be the difference between life and death. Homeless individuals are considered at an immediate risk during extreme heat due to direct exposure, lack of resources, and access to treatment. Being exposed to extreme temperatures can increase their odds of experiencing a heat-related illness without the equal access to medical services (Lowe, 2016). Without equal access to medical services, illnesses sustained from the heat such as sunburns, lethargy, heat stroke, and dehydration have the likelihood of going untreated and getting worse (Cusack et al., 2013). While some of these symptoms might not be life threatening enough to warrant an expensive trip to the hospital, heatwaves that are more severe and frequent could prolong illnesses and create long-term complications (Lowe, 2016). Resources toward access to health care can help limit the risk of this vulnerable population and is becoming more important with future climate change concerns.

San Francisco Parks UHI Mitigation Analysis:

The reviewed literature has given examples of how each green infrastructure type mitigates UHI impacts and which communities are affected most by heat. These results will be applied to San Francisco, California, a county with a robust parks system and emerging green city ordinances. The following spatial analysis will aim to evaluate whether green infrastructure is being utilized in the areas of greatest need with consideration to age, poverty levels, and housing security. The resulting analysis will be used to recommend alternative green infrastructure for future development. The following issues will be explored:

1.) Urban tree canopy distribution: land cover comparison between high and low ranking CalEnviroScreen census tracts
2.) Street tree distribution: comparison of street tree amounts, orientation, and distribution among census tracts with high and low heat vulnerability
3.) Better roofs: Status of current new construction green roofs ordinance

Study area

The San Francisco Bay Area is characterized as a Mediterranean climate, having wet winters and dry, hot summers, and consists of unique microclimates as a result of topography, ocean winds, and fog exposure (Ackerly et al., 2018). The study area for this spatial analysis, San Francisco, California, was chosen because of the high number of parks and open spaces present in the dense, urban area of 46.9 square miles. The city is comprised of 16 percent persons over 65, 38.2 percent non-white, 5.7 percent person under 55 living with a disability, and 10 percent living in poverty (Census.gov). The Heat Vulnerability Index distribution across the city shows a clear difference between the west and the east regions of the city (Figure 9). This index was created using 21 demographic and social factors that indicate heat vulnerability, including elderly, disabled, low-income, marginalized races and ethnicities, and homeless persons. The higher the heat index score of each census track, the more sensitive and/or exposed the community is, therefore making it imperative that public green spaces in these areas are mitigating heat and not contributing heat.

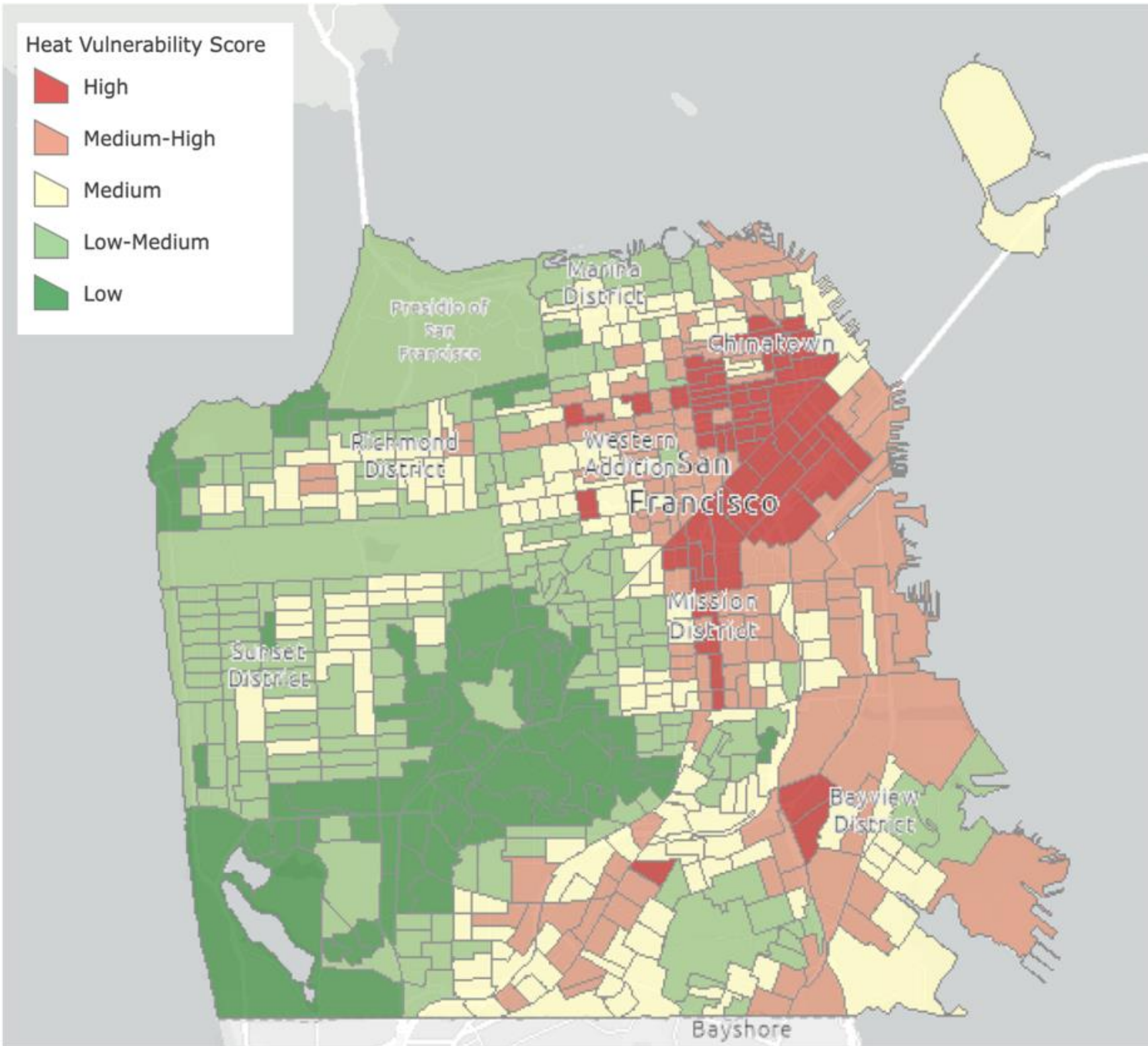

Figure 9. Heat vulnerability scores by census tract in San Francisco tend to be higher in the downtown area and

Background on policies

San Francisco has an extensive parks system that includes more than 200 parks of varying size and features. In recent years, focus has been given to acquisitions in areas of higher needs as defined by San Francisco's Planning Department in the Recreation and Open Space Element (ROSE) of the San Francisco General Plan (2014). The policy states that the city aims to "prioritize acquisition of open space in high needs areas" which are defined as areas with low access to open space and high density of children, youth, seniors, and low-income households (Figure 10). The San Francisco Recreation and Parks department has simplified the hyper-localized parcel data areas into "equity zones" (EZ) which outlines the highest density of high needs blocks.

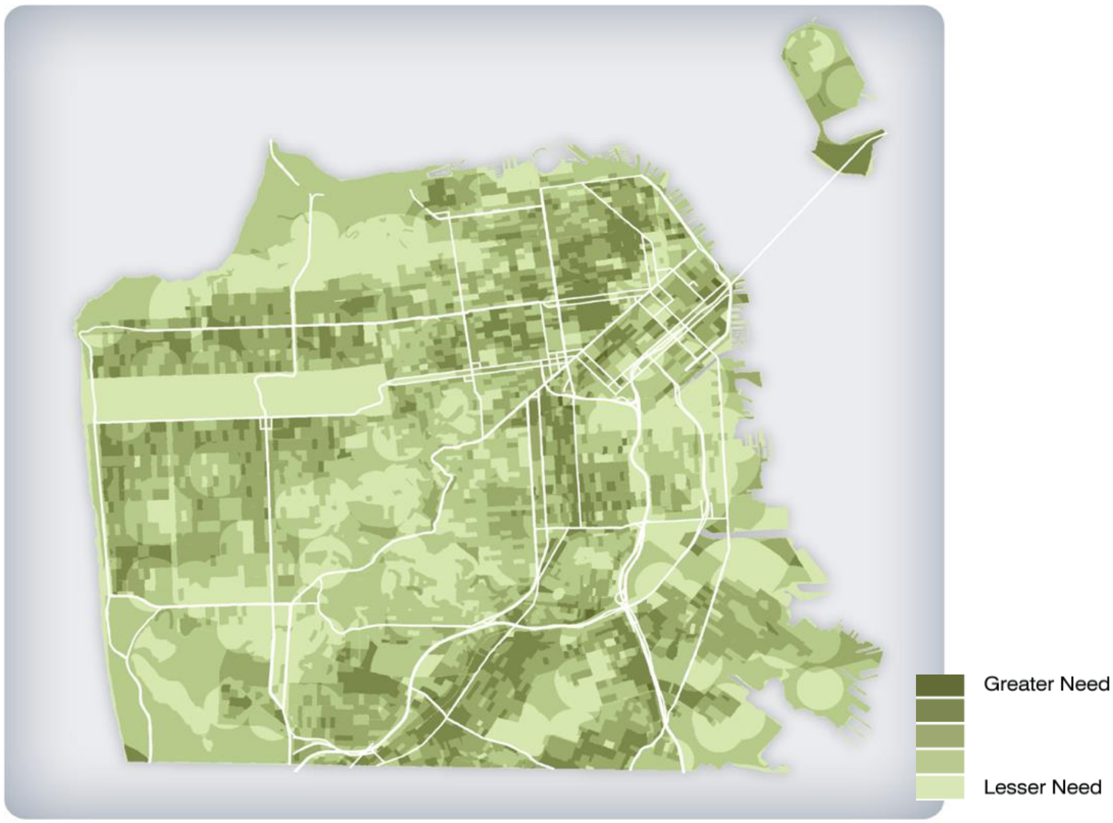

Figure 10. High needs areas in San Francisco where priority is given for new park and recreation acquisitions (SFPD, 2014).

Similar to other counties in California, funds are directed to vulnerable communities in San Francisco with guidance from risk indicators created in the California Communities Environmental Health Screening (CalEnviroScreen). The assessment, created by the Office of Environmental Health Hazards Assessments (OEHHA), uses 21 demographic and environmental risk variables to assign a score to each census tract in California (Figure 11). These scores assist policy makers across the state to direct funds to at risk census tracts, promote environmental laws, and identify opportunities for economic development in an effort to alleviate environmental burdens (OEHHA, 2021). These burdened communities will need to have funding sources correctly allocated to successfully reduce greenhouse gas emissions and mitigate urban heat island impacts.

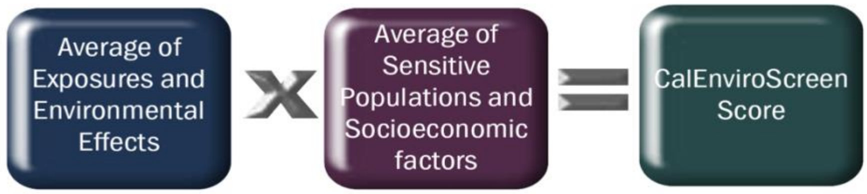

Figure 11. CalEnviroScreen scoring formula: calculated by weighting several exposures, environmental effects, and population characteristics (OEHHA, 2021)

Lastly, San Francisco's "Better Roofs" ordinance was enacted in 2017, marking the first city in the United States to mandate solar or green roofing on new office and residential constructions. European cities have enacted similar legislation since the 1980s with great success. Switzerland and Germany encouraged participants with financial incentives and engaged residents with wide promotion of the programs, leading to a long standing local acceptance. While many cities in the United States have mandated either solar or green roofs, San Francisco is the first to mandate both. This mandate comes as a part of the citywide Climate Action Plan in an effort to achieve city goals of reaching 100 percent renewable energy by 2030 and to reduce greenhouse gases by 80 percent by 2050.

Urban tree canopy distribution

One concern for urban areas with climate change making heatwaves more extreme and longer lasting is whether heat mitigating green space is equitably distributed. Cities and counties that experience urban heat islands are aware of the benefits of green space, though adaptation initiatives come with long timelines and can sometimes spend years in the planning phase (Haaland & van den Bosch, C. K., 2015). As analyzed in earlier sections, green space such as urban forests, parks and open spaces, and street trees are types of green infrastructure that effectively reduce land surface and ambient temperatures at the city, neighborhood, and street scale. On the other hand, impervious surfaces such as asphalt and pavement are the main cause of heat being retained in urban environments. Dense building layouts and priority to sidewalks and roads in downtown areas increase temperatures, leaving residents in high density housing with little to green spaces. Therefore, it is important to understand the current status of green space distribution to ensure grants and policies are directed to localized areas affected by excessive heat. In the following analysis, CalEnviroScreen scores and nighttime land surface temperatures (LST) during a 2020 heatwave will be used to compare land cover and poverty levels between high scoring census tracts to low scoring census tracts within San Francisco. The resulting comparisons will show that districts with highest exposure to heat during heatwaves also lack heat mitigating tree cover and have a high percentage of residents living below the poverty line.

Extreme temperatures often meet ill-prepared San Franciscans in buildings which are typically not equipped to perform well in the event of extreme heat. During a heatwave between September 26th and 30th 2020, day time temperatures rose as high as 35ºC and persisted into the night with highs of 28ºC (United States - National Weather Service, 2020). The average September highs in San Francisco are 21ºC during the day and 11ºC during the night, with day and night averages during the remainder of the year being even lower (United States - National Weather Service, 2020). Figure 12 displays thermal infrared derived LST readings taken aboard NASA's ECOSTRESS satellite, showing the distribution of LST during the second evening of the heatwave. The highest temperatures (yellow being the hottest) were most common on the eastern, bay side of the city and in downtown areas, where tree cover is not very abundant due to dense housing or office buildings and roads or freeways. The boundaries aligned on the map show the 10 sample site that were selected for this distribution analysis, with black outlines being the lowest CalEnviroScreen scored census tracts and white outlines being the highest CalEnviroScreen scored tracts. This map shows clearly that many of the low scored census tracts are situated in the hottest areas, either in downtown or the eastern edge of the city. One census tract, the Treasure Island district located in the San Francisco bay just to the northeast, was included in the lowest five scored census tracts although was omitted from further analysis given its unique, island climate.

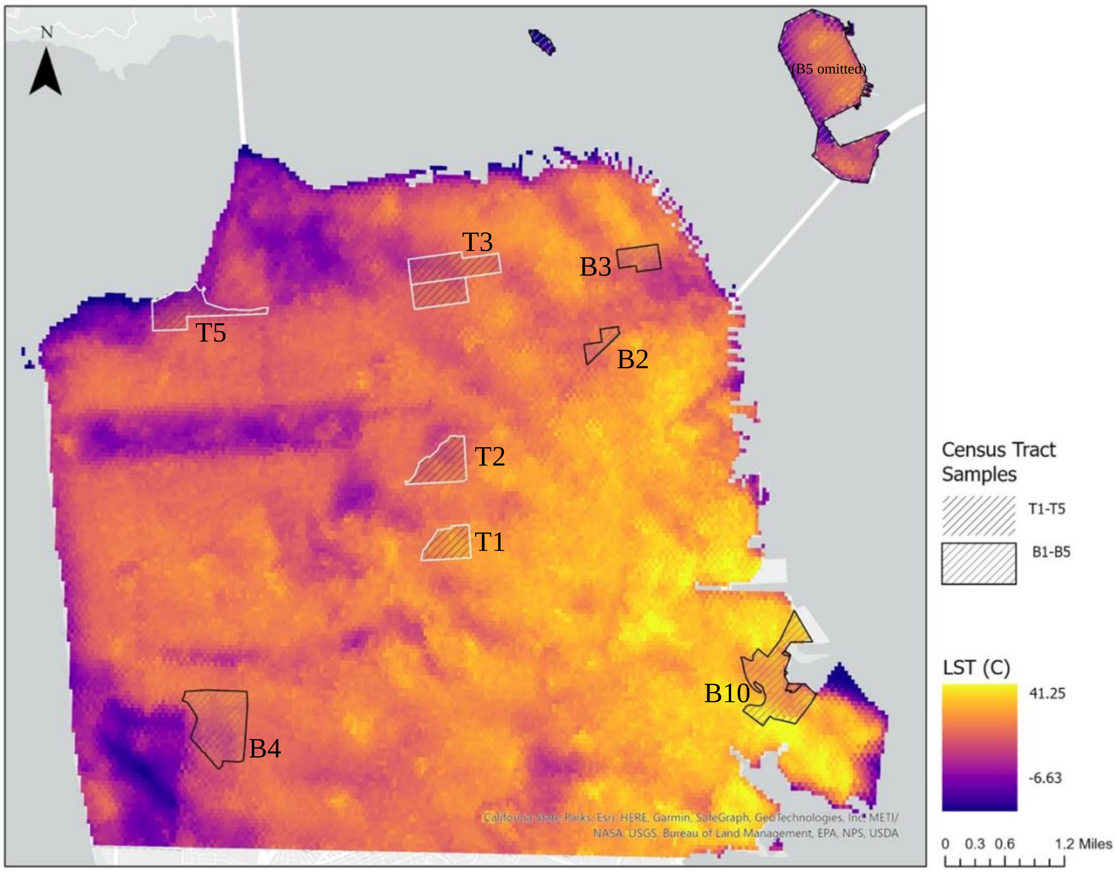

Figure 12. Land surface temperatures (ºC) in San Francisco during a heatwave in 2020, with top CalEnviroScreen census tracks (T1-5) and bottom scoring census tracks (B1-B5).

As this paper has outlined, urban tree canopy is important in reducing land surface temperatures and overall ambient temperatures within cities, neighborhoods, and streetscapes. Temperatures at any of these scales can influence human comfort and areas with less tree cover can influence how much heat residents are exposed to. Table 8 shows the distribution of land cover in the five top CalEnviroScreen scored census tracts (T1-5) and the four bottom scored census tracts (B1-4). The green row outlines a top scoring census tract (T4) with the lowest mean land surface (28.2ºC) temperature had the highest percentage of tree cover and one of the lowest percent impervious cover (88.03%). Contrastingly, the green row shows the census tract with the highest mean land surface (35.8ºC) temperature (B1) had one of the lowest tree cover percentages (1.43%). These census tracts also drastically differ in percentage of population living under the poverty line by 66.9%.

Table 6. Land cover distribution and mean heatwave land surface temperatures (LST) of the top CalEnviroScreen scoring (T1-T5) and the bottom scoring (B1-B4) census tracts. The census track with the lowest mean LST had the highest percent tree cover and second lowest percent impervious surface, while the census track with the highest mean LST had 9.77% more impervious cover and 9.86% less tree cover.

Census Tract Sample	% Poverty	Mean LST (ºC)	% Impervious	% Grassland	% Bareland	% Water	% Tree Cover
T1	3.3	34.4	100	0	0	0	0
T2	5.4	32.1	89.68	1.82	0.38	0	8.10
T3	5.2	31.42	98.15	0.86	0	0	0.99
T4	4.8	28.2	88.03	0.67	0	0	11.29
T5	5.4	28.6	84.44	4.07	4.70	2.65	4.13
B4	67.5	31.6	90.00	0.093	0.88	0	9.01
B3	68.1	32.6	90.55	0	5.59	0	3.87
B2	60.4	32.87	98.01	0	1.98	0	0
B1	71.7	35.8	97.80	0.06	0.123	0.58	1.43

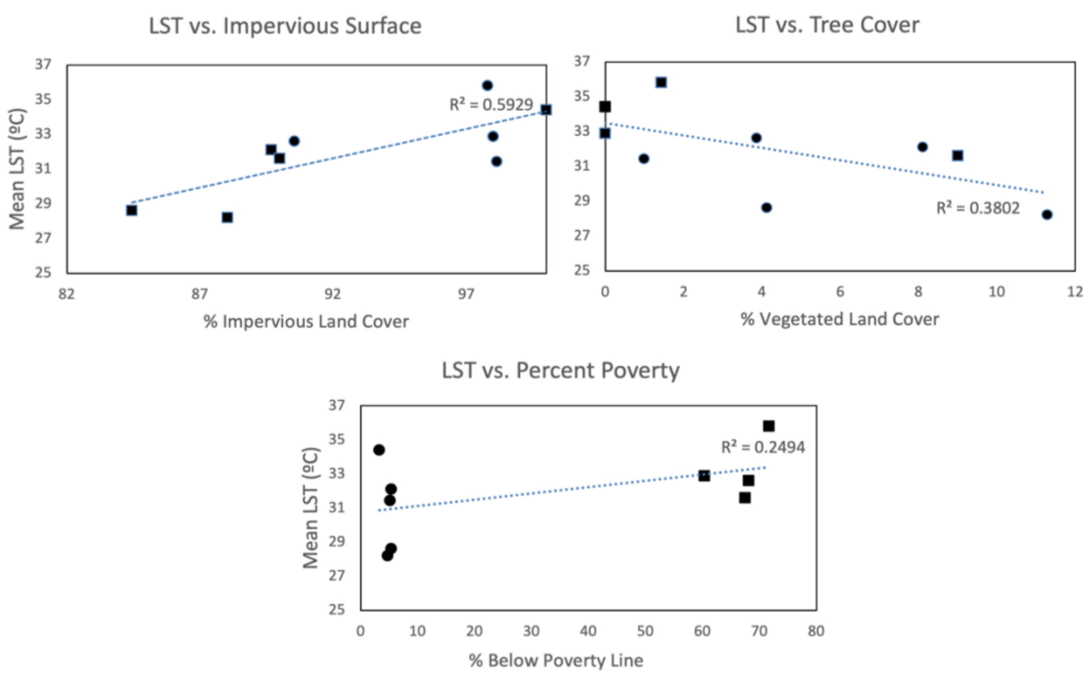

Figure 13. Mean land surface temperatures of census tract samples compared to percent impervious cover (a), percent tree cover (b), and percent poverty (c). Census tracts with high mean LST had a moderate positive correlation with high percentage of impervious land cover and a moderate negative correlation with high percentage of vegetated land cover. The four census tracts that ranked the lowest (squares) on CalEnviroScreen scoring had poverty levels above 60%, with the highest poverty level having the highest mean LST.

While the CalEnviroScreen scoring method takes into account socioeconomic factors and therefore explains the vast differences in poverty levels, the scoring system does not directly factor in exposure to heat. Figure 13 shows the relationship between mean LST and percent impervious cover, percent tree cover, and percent of population below the poverty line. These relationships, without factoring in the score of each census tract, show a moderate relationship between land cover factors. Census tracts that experienced the hottest land surface temperatures also have the most impervious land cover and the lowest percent tree cover. While a weak relationship exists between LST and percent of population below the poverty line, the census tract with the highest LST of 35.8ºC also had 71.7% poverty. These results show that tree cover could be unequally distributed in San Francisco and causing poverty burdened areas to be facing excess heat exposure. In areas of high heat vulnerabilities, the type and distribution of green infrastructure present can help determine whether heat-related illnesses from the effects of urban heat islands is able to be mitigated.

Street tree distribution

In dense urban areas, large sized urban forests and parks and open spaces are not as common when land is already being used for buildings. While city recreation and parks departments acquire land periodically to develop into green spaces, current residents do not see the benefits until after every phase of the acquisition process which can take decades in some cases. Street trees are a great alternative because they can be planted quickly and in small spaces. San Francisco has a vast network of 124,000 street trees that is managed by the San Francisco Public Works department, with a goal to plant 50,000 more trees by 2050. Along with this goal, the StreetTreesSF program was initiated in order to routinely maintain street trees in the city following a history of trees being planted and not taken care of. Residents are able to adopt trees, plant their own, and prune trees on their block, and while this program helps to alleviate that burden on residents, less affluent neighborhoods are still trailing behind in regard to percent tree cover and health of existing trees. Planting and maintaining these street trees needs to be approached in a way that prioritizes areas with less resources available in an effort to balance this uneven distribution and health of trees.

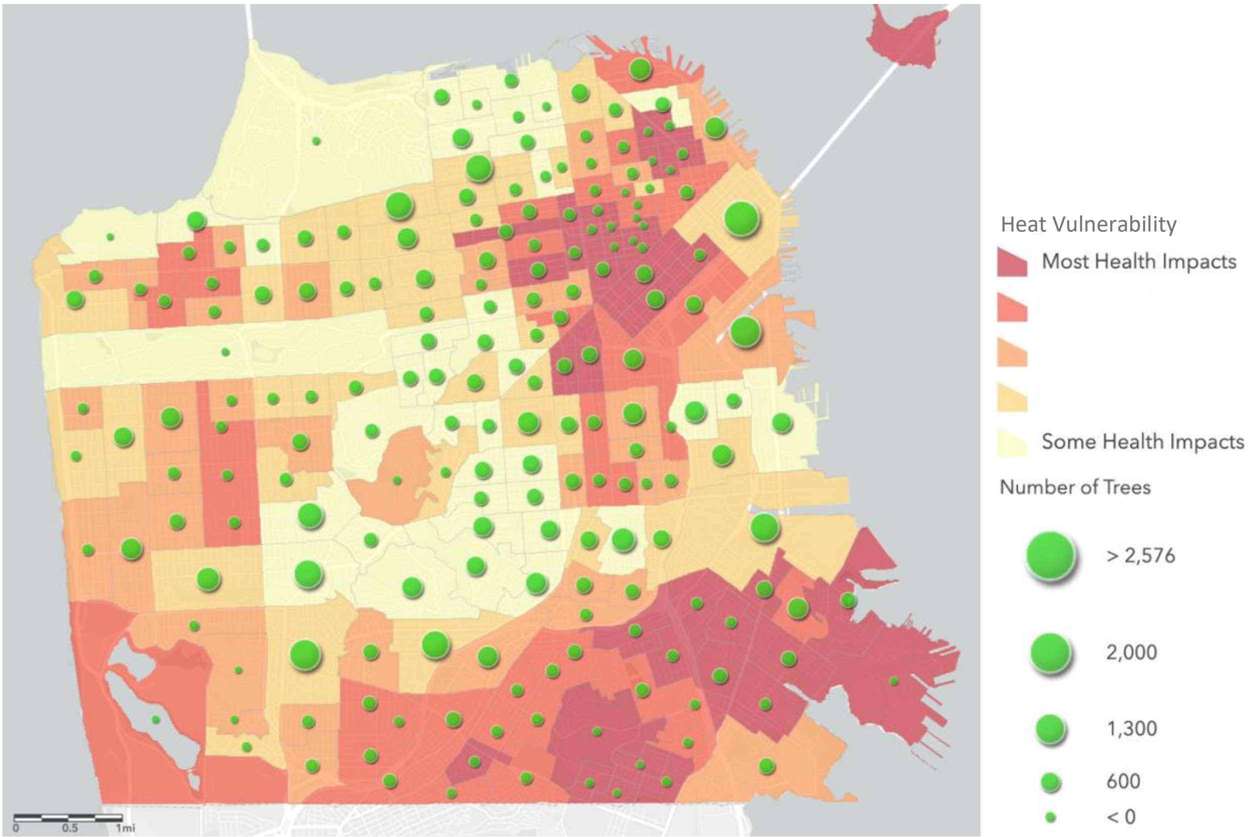

Figure 14. Street tree density and heat vulnerabilities of each census tract in San Francisco

The health of trees and the health of residents alike should be a priority in San Francisco street tree initiatives. Figure 15 shows the proportion of street trees and heat vulnerabilities of census blocks in San Francisco. The northeastern and southeastern quadrants of the city have the lowest number of trees compared to the central, southwest, and northwest areas of the city. These hotter quadrants contain a variety of land uses from residential to office and industrial, though housing is still present. Similarly, the census tracts along the eastern border have much larger numbers of trees than census tracts directly inland from them. This clear difference can also be seen among the distribution of heat vulnerable census tracts from the previous analysis of green infrastructure distribution displayed in Figure 12. The previous analysis explored nine census tracts that were on opposite ends of the CalEnviroScreen ranking list and showed that percent tree cover lacks in census tracts that experienced hottest LST during heatwaves. Those results showed the repercussions of low tree cover, while analyzing the distribution of individual streets trees within each census tract can show a finer scale of how street trees might influence LST.

Street tree distribution across the city is an important contribution to the urban tree canopy as a whole, but finer analysis of tree alignment and orientation within the block and neighborhood scale is essential to understand the benefits at the local levels. The following maps in Figure 16 will analyze the distribution of trees in similarly sized census tracts with differing heat vulnerabilities and mean heatwave LST that was determined previously. First, census tracts within Noe Valley and Chinatown are compared. The heat vulnerability index of these census tracts are on extreme ends of one another, Chinatown being one of the most vulnerable communities considering the high percentages of elderly, non-English speakers, poverty, and dense housing (Census.gov). Despite the high density of housing in Chinatown, there is only 116 street trees across the 0.23 km^2 census tract, with little to no street trees in the western blocks. The top most CalEnviroScreen ranking census tract, T1 in Noe Valley, has the lowest heat vulnerability of the samples and an abundance of evenly spaced street trees. This census tract in Chinatown has a population of 4,477 while the Noe Valley census tract has a population of 3,105 showing that the distribution rate of street trees in Noe Valley is higher per person. This difference in street tree distribution does little to reduce heat effectively in dense neighborhoods.

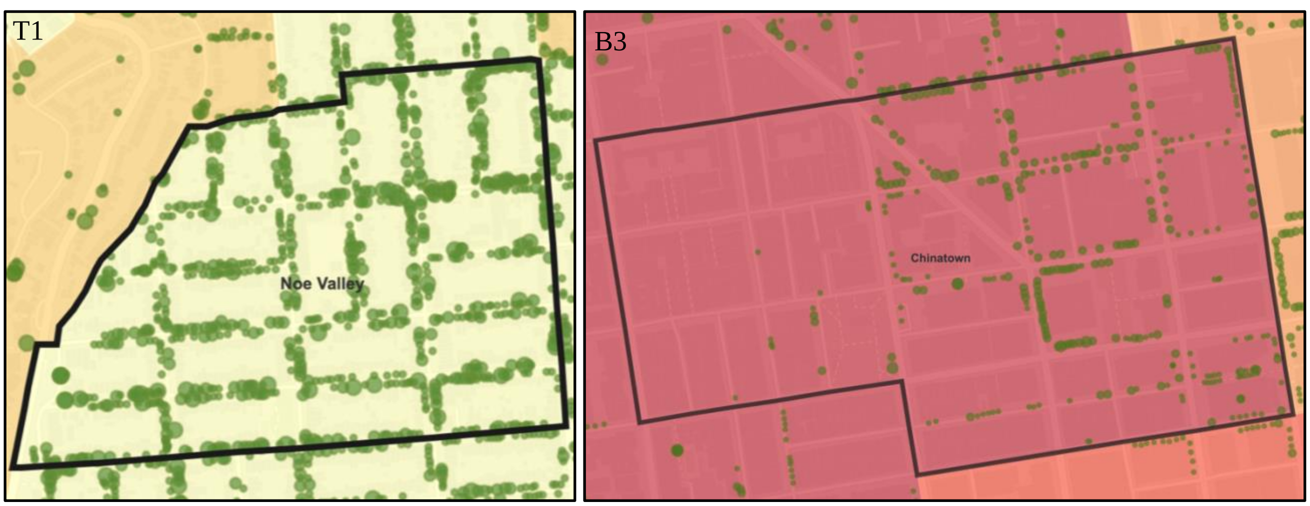

Figure 15. Census tract sample T1 contains evenly distributed 907 street trees across 0.37 km2 and while B3 contains uneven distribution of 116 street trees across 0.23 km2

The next comparison is between census tracts within the Castro/Upper Market and the Tenderloin districts. The Tenderloin district (sample B2) is situated in the downtown area of the city, has a dense buildings housing a population of 71.1% low-income individuals, and is on the highest end of the heat vulnerability index. The Castro/Upper Market district (sample T2) is an upper-class district with only an 5.4% poverty level, situated on the western most edge of the city center. These census tracts were chosen for comparison to show the differences between the inner-most and outer-most city center census tracts. The difference in street trees is clearly displayed in Figure 17, where 832 street trees in T2 that span across an 0.54 km^2 area are evenly distributed between blocks and 194 street trees sparsely cover the outer boundaries of the 0.54 km^2 area of B2. The populations of these census tracts is similar, with Castro/Upper Market having 4,551 residents and Tenderloin having 4,287 residents, though the drastic difference in the number of street trees shows that households could be benefiting from the dense tree cover in a census tract that has little to no vulnerability to heat.

Figure 16. Census tract sample T2 contains evenly distributed 845 street trees across 0.18 km^2 while B3 contains uneven distribution of 194 street trees across 0.08 km^2

While the microclimates and building densities for these census tract samples differ, there is simply a lack of trees being planted in areas of high heat vulnerable communities. When considering areas of similar urban elements such as building density, population size, and climate factors, census tracts should have similar tree cover. This is especially the case in areas with higher percent of people living in poverty who do not have the resources to implement more street trees on their own behalf. The intersections between climate change and human health are many, and with vulnerable communities expected to experience greater climate challenges, the distribution of green infrastructure needs to be planned with priority to these communities.

"Better Roofs" ordinance

In an effort to reduce UHI effects and offset carbon emissions, the "Better Roofs" ordinance in San Francisco has implemented green roofs and solar panels as a requirement in the planning code. While this is a step in the right direction, the policy only applies to newly constructed buildings. San Francisco has some of the highest housing costs in the country, leading to low-income renters being ineligible for most newer housing developments ([] Shalam 2021). New developments often have a small percentage of affordable units, though competition for these units and scarce availability often leads to existing residents being pushed out of their districts.

With current renting trends in mind, the implementation of green roofs appears to benefit higher income renters in new developments. Newer buildings are afforded the luxury of the energy reducing and heat mitigating benefits that green roofs provide, while the low-income buildings in areas with high heat vulnerability are being left behind. Figure 18 shows the distribution of completed and planned green roofs in San Francisco. While many of the completed projects are located in areas with high heat vulnerabilities, such as the downtown area, the census tracts in the southeastern districts have a high number of heat vulnerable census tracts and low number of completed or planned green roofs. These are areas of great concern when considering other vulnerability factors such as access to healthcare and heat exposure, where older buildings not equipped with air-conditioning have little access to green spaces. While this ordinance is aimed to adapt to climate change, newer buildings are already decades ahead of the existing infrastructure that longtime residents will need to retrofit to adapt to climate change impacts.

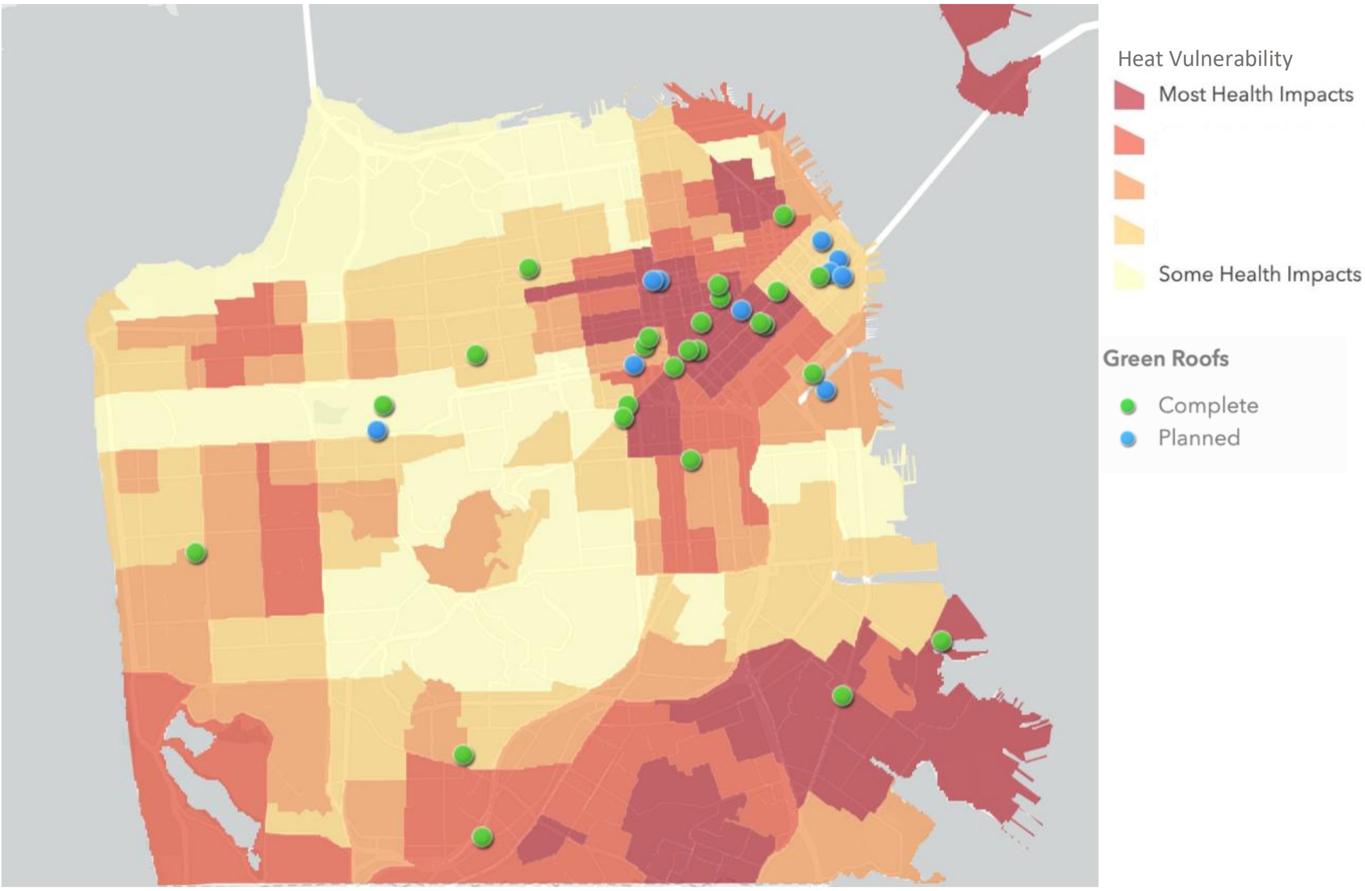

Figure 17. Completed green roofs and planned green roofs in San Francisco are situated predominately in downtown areas, while vulnerable communities in the southeastern quadrant of the city are lacking effective green infrastructure

Conclusion and Recommendations

The objective of my paper was to assess the climate gap between access to green infrastructure and vulnerable communities in urban areas that are affected by urban heat islands. By comparing the heat mitigation capacity of four types of urban green infrastructure and identifying which communities would benefit most from green infrastructure implementation, recommendations can be made regarding community needs. To achieve this objective, two research questions were answered: how does green infrastructure mitigate UHI effects? And which communities are most vulnerable due to increased heat sensitivity, heat exposure, and decreased access to health care? Using these assessments of green infrastructure and vulnerable communities, my paper aimed to analyze the urban area of San Francisco which experiences effects from urban heat islands to understand if current green infrastructure is servicing the needs of vulnerable communities by addressing the final research question: *What are possible areas for implementing equitable green infrastructure in San Francisco to ensure the urban heat island is not disproportionately affecting vulnerable communities?* By recognizing the needs of individual communities in large urban areas facing increasing affects from UHIs, local governments can make better policies for adapting to climate change at a more productive scale.

Recommendation 1: Scoring process for heat vulnerability index should be modified so that smaller communities are not overlooked

With climate change increasing the effects of urban heat islands through more extreme and prolonged heat waves, the health vulnerable communities should not be overlooked. As with the high needs classifications brought on through the Recreation and Open Space Element of the San Francisco General Plan, heat vulnerability indexes should be small in scale and robust in risk factors. The risk factors outlined in this paper, heat exposure, heat sensitivities, and access to health care, can include a number of social and demographic. With San Francisco being a diverse and compact city, these factors need to be analyzed at the block level.

This paper used two heat vulnerability references for analysis: the CalEnviroScreen scores from OEHHA and the Heat Vulnerability Index from the City and County of San Francisco. The CalEnviroScreen scores are a broad system with indicators taking into account averages of air pollution and environmental sensitivities at the census tract level. Averaged sensitivities at the census tract level leave room for misrepresentation of the individual communities by not taking into account population densities. The San Francisco Heat Vulnerability Index is more focused on heat sensitivity factors and is also at the census tract level. Alternatively, vulnerabilities should be analyzed at the block level to include localized factors such as microclimates, access to green infrastructure, and housing density.

Recommendation 2: Green infrastructure threshold goals localized to districts should be set and maintained by conducting annual urban tree canopy assessments

There are many benefits to having a variety of urban green infrastructure types as outlined in this paper: reduction in energy consumption, reduction in ambient air temperatures, and abatement of air pollution. Although, there is a vast difference in the urban envelope between districts within San Francisco. While one district might have high rises and dense housing, others have wide streets and an abundance of tree cover. These differences mean that some districts will need more green infrastructure to provide urban heat island mitigation benefits.

Wang et al. suggests that cities which experience hot and dry summers, such as San Francisco, neighborhoods should compensate heat with 7% tree cover. Several of the most vulnerable census tracts in San Francisco have well below 7% tree cover while high-income areas have as much as 11% tree cover. Individual districts should have tree cover goals with 7% being the minimum and rising depending on heat vulnerabilities, building structure, and distribution of impervious surfaces. With thresholds of tree cover localized to each district, mitigation efforts can be better equipped to serve communities equally to their needs.

Recommendation 3: Resources for community led street tree implementation and maintenance be directed toward neighborhoods with high heat vulnerability

San Francisco has implemented many green infrastructure initiatives in recent years in order to make access to green space more equitable. StreetTreesSF is an ongoing initiative to address unmaintained street trees and to implement 50,000 more by 2050. Through analyzing districts with specific needs to heat vulnerabilities at the block scale, street tree orientation and distribution can be addressed by city led efforts. Although to ensure the longevity and connectedness of this addition to the urban tree canopy is maintained, the city should distribute resources for localized efforts led by communities that otherwise would not have the means. This would mean that vulnerable districts are not forgotten about when street trees are planted, which could lead to tree deaths and districts being led back to square one.

Recommendation 4: Green roof ordinance for newly constructed buildings to add green roof retrofitting subsidies or grants for existing building

Newly constructed buildings have recently been ordered by the city of San Francisco to dedicated 25% of roof space to green roofs and solar panels. This initiative aims to reduce building temperatures and offset carbon emissions, though the benefits are directly only to inhabitants who can afford the luxury of new developments. This effective heat mitigation strategy should be easy to access for all residents, especially residents with high heat vulnerabilities. Heat waves in San Francisco have become more common and many older buildings were constructed in an era where heat mitigation was not a priority given the climate in San Francisco, leading to buildings that retain heat and have no access to air-conditioning. Building-integrated green infrastructure is an effective way of cooling older buildings without adding excess emissions from air-conditioning units. For these reasons, I recommend that the city should expand this ordinance to include benefits to existing buildings that are interested in retrofitting green roofs, cool roofs, or green walls. Grants and subsidies that are offered to building owners would benefit vulnerable neighborhoods by providing essential temperature reduction to buildings and eliminate the need to retrofit air-conditioning into buildings.

Temperatures in San Francisco are rising with global warming, and the current infrastructure reflects a historically cooler climate. The impacts from urban heat islands have not been of high concern for this coastal city, making the need for temperature mitigation unnecessary. Though with increasing summer heatwaves, the city will face more heat-related illnesses in areas that are not equipped with heat mitigating infrastructure. The distribution of green infrastructure has been influenced more by the availability of land acquisitions and less by where the green infrastructure is actually needed. With new innovations in green infrastructure which are efficient in reducing effects of urban heat islands, the time is now to adapt equitably. Decision makers in San Francisco have a chance to analyze with a finer scope at the vulnerabilities of the citizens in this city and prevent heat-related illnesses in the heatwaves to come.

Literature cited

Ackerly, D., Jones, A., Stacey, M., & Riordon, D. (2018). *San Francisco Bay Area summary report*. California's fourth climate change assessment. https://www.energy.ca.gov/sites/default/files/2019-11/Reg_Report-SUM-CCCA4-2018-005_SanFranciscoBayArea_ADA.pdf

Akbari, H. (2002). Shade trees reduce building energy use and CO2 emissions from power plants. *Environmental Pollution*, *116*(SUPPL. 1), S119-S126. 10.1016/S0269-7491(01)00264-0

Akbari, H., Kurn, D. M., Bretz, S. E., & Hanford, J. W. (1997). Peak power and cooling energy savings of shade trees. *Energy and Buildings*, *25*(2), 139-148. 10.1016/s0378-7788(96)01003-1

Akbari, H., Pomerantz, M., & Taha, H. (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy*, *70*(3), 295-310. 10.1016/S0038-092X(00)00089-X

Alexandri, E., & Jones, P. (2008). Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Building and Environment*, *43*(4), 480-493. 10.1016/j.buildenv.2006.10.055

Auffhammer, M., Baylis, P., & Hausman, C. H. (2017). Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United

States. *Proceedings of the National Academy of Sciences of the United States of America, 114*(8), 1886-1891. 10.1073/pnas.1613193114

Baniassadi, A., Sailor, D. J., Crank, P. J., & Ban-Weiss, G. A. (2018). Direct and indirect effects of high-albedo roofs on energy consumption and thermal comfort of residential buildings. *Energy and Buildings, 178*, 71-83. 10.1016/j.enbuild.2018.08.048

Basagaña, X., Sartini, C., Barrera-Gómez, J., Dadvand, P., Cunillera, J., Ostro, B., Sunyer, J., & Medina-Ramón, M. (2011). Heat waves and cause-specific mortality at all ages. *Epidemiology, 22*(6), 765-772. 10.1097/EDE.0b013e31823031c5

Berardi, U., GhaffarianHoseini, A., & GhaffarianHoseini, A. (2014). State-of-the-art analysis of the environmental benefits of green roofs. *Applied Energy, 115*, 411-428. 10.1016/j.apenergy.2013.10.047

Blunden, J., & Boyer, T. (2021). State of the climate in 2020. *Bulletin of the American Meteorological Society, 102*(8), 1-481. 10.1175/2021BAMSStateoftheClimate.1

Bolund, P., & Hunhammar, S. (1999). Ecosystem services in urban areas. *Ecological Economics, 29*(2), 293-301. 10.1016/S0921-8009(99)00013-0

Brümmer, C., Black, T. A., Jassal, R. S., Grant, N. J., Spittlehouse, D. L., Chen, B., Nesic, Z., Amiro, B. D., Arain, M. A., Barr, A. G., Bourque, C. P., Coursolle, C., Dunn, A. L., Flanagan, L. B., Humphreys, E. R., Lafleur, P. M., Margolis, H. A., McCaughey, J. H., & Wofsy, S. C. (2012). How climate and vegetation type influence evapotranspiration and water use efficiency in Canadian forest, peatland and grassland ecosystems. *Agricultural and Forest Meteorology, 153*, 14-30. 10.1016/j.agrformet.2011.04.008

Burillo, D., Chester, M. V., Pincetl, S., & Fournier, E. (2019). Electricity infrastructure vulnerabilities due to long-term growth and extreme heat from climate change in Los Angeles County. *Energy Policy, 128*, 943-953. 10.1016/j.enpol.2018.12.053

Chang, C., & Li, M. (2014). Effects of urban parks on the local urban thermal environment. *Urban Forestry and Urban Greening, 13*(4), 672-681. 10.1016/j.ufug.2014.08.001

Cusack, L., Van Loon, A., Kralik, D., Arbon, P., & Gilbert, S. (2013). Extreme weather-related health needs of people who are homeless. *Australian Journal of Primary Health, 19*(3), 250-255. 10.1071/PY12048

Doick, K. J., Peace, A., & Hutchings, T. R. (2014). The role of one large greenspace in mitigating London's nocturnal urban heat island. *Science of the Total Environment, 493*, 662-671. 10.1016/j.scitotenv.2014.06.048

Dousset, B., & Gourmelon, F. (2003). Satellite multi-sensor data analysis of urban surface temperatures and landcover. *ISPRS Journal of Photogrammetry and Remote Sensing, 58*(1-2), 43-54. 10.1016/S0924-2716(03)00016-9

Flynn, A., McGreevy, C., & Mulkerrin, E. C. (2005). Why do older patients die in a heatwave? *QJM - Monthly Journal of the Association of Physicians, 98*(3), 227-229. 10.1093/qjmed/hci025

García de Jalón, S., Burgess, P. J., Curiel Yuste, J., Moreno, G., Graves, A., Palma, J. H. N., Crous-Duran, J., Kay, S., & Chiabai, A. (2019). Dry deposition of air pollutants on trees at regional scale: A case study in the Basque Country. *Agricultural and Forest Meteorology, 278*, 107648. 10.1016/j.agrformet.2019.107648

Gill, S. E., Handley, J. F., Ennos, A. R., & Pauleit, S. (2007). Adapting cities for climate change: The role of the green infrastructure. *Built Environment, 33*(1), 115-133. 10.2148/benv.33.1.115

Gillner, S., Vogt, J., Tharang, A., Dettmann, S., & Roloff, A. (2015). Role of street trees in mitigating effects of heat and drought at highly sealed urban sites. *Landscape and Urban Planning, 143*, 33-42. 10.1016/j.landurbplan.2015.06.005

Haaland, C., & van den Bosch, C. K. (2015). Challenges and strategies for urban green-space planning in cities undergoing densification: A review. *Urban Forestry and Urban Greening, 14*(4), 760-771. 10.1016/j.ufug.2015.07.009

Harlan, S. L., Brazel, A. J., Prashad, L., Stefanov, W. L., & Larsen, L. (2006). Neighborhood microclimates and vulnerability to heat stress. *Social Science & Medicine (1982), 63*(11), 2847-2863. 10.1016/j.socscimed.2006.07.030

Huang, Y. J., Akbari, H., Taha, H., & Rosenfeld, A. H. (1987). The potential of vegetation in reducing summer cooling loads in residential buildings. *Journal of Climate and Applied Meteorology, 26*(9), 1103-1116. 10.1175/1520-0450(1987)0262.0.CO;2

IPCC. (2019). *Land–climate interactions. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.

Kjellstrom, T., Kovats, R. S., Lloyd, S. J., Holt, T., & Tol, R. S. J. (2009). The direct impact of climate change on regional labor productivity. *Archives of Environmental and Occupational Health, 64*(4), 217-227. 10.1080/19338240903352776

Kosanic, A., Petzold, J., Martín-López, B., & Razanajatovo, M. (2022). An inclusive future: disabled populations in the context of climate and environmental change. *Current Opinion in Environmental Sustainability, 55*10.1016/j.cosust.2022.101159

Kovats, R. S., & Hajat, S. (2008). Heat stress and public health: A critical review. *Annual Review of Public Health, 29,* 41-55. 10.1146/annurev.publhealth.29.020907.090843

Landry, S. M., & Chakraborty, J. (2009). Street trees and equity: Evaluating the spatial distribution of an urban amenity. *Environment and Planning A, 41*(11), 2651-2670. 10.1068/a41236

Lee, S., Lee, K., Jin, W., & Song, H. (2009). Effect of an urban park on air temperature differences in a central business district area. *Landscape and Ecological Engineering, 5*(2), 183-191. 10.1007/s11355-009-0067-6

Li, X., Chow, K. H., Zhu, Y., & Lin, Y. (2016). Evaluating the impacts of high-temperature outdoor working environments on construction labor productivity in China: A case study of rebar workers. *Building and Environment, 95*, 42-52. 10.1016/j.buildenv.2015.09.005

Lin, W., Yu, T., Chang, X., Wu, W., & Zhang, Y. (2015). Calculating cooling extents of green parks using remote sensing: Method and test. *Landscape and Urban Planning, 134*, 66-75. 10.1016/j.landurbplan.2014.10.012

Livesley, S. J., McPherson, G. M., & Calfapietra, C. (2016). The urban forest and ecosystem services: Impacts on urban water, heat, and pollution cycles at the tree, street, and city scale. *Journal of Environmental Quality, 45*(1), 119-124. 10.2134/jeq2015.11.0567

Loughner, C. P., Allen, D. J., Zhang, D., Pickering, K. E., Dickerson, R. R., & Landry, L. (2012). Roles of urban tree canopy and buildings in urban heat island effects: Parameterization and preliminary results. *Journal of Applied Meteorology and Climatology, 51*(10), 1775-1793. 10.1175/JAMC-D-11-0228.1

Lowe, S. A. (2016). An energy and mortality impact assessment of the urban heat island in the US. *Environmental Impact Assessment Review, 56*, 139-144. 10.1016/j.eiar.2015.10.004

Macintyre, H. L., Heaviside, C., Taylor, J., Picetti, R., Symonds, P., Cai, X., & Vardoulakis, S. (2018). Assessing urban population vulnerability and environmental risks across an urban area during heatwaves – Implications for health protection. *Science of the Total Environment, 610-611*, 678-690. 10.1016/j.scitotenv.2017.08.062

Martinez, S., Machard, A., Pellegrino, A., Touili, K., Servant, L., & Bozonnet, E. (2021). A practical approach to the evaluation of local urban overheating– A coastal city case-study. *Energy and Buildings, 253*, 1-13. 10.1016/j.enbuild.2021.111522

Moss, J. L., Doick, K. J., Smith, S., & Shahrestani, M. (2019). Influence of evaporative cooling by urban forests on cooling demand in cities. *Urban Forestry and Urban Greening, 37*, 65-73. 10.1016/j.ufug.2018.07.023

Nath, B., Ni-Meister, W., & Özdoğan, M. (2021). Fine-scale urban heat patterns in New York city measured by ASTER satellite—The role of complex spatial structures. *Remote Sensing, 13*(19), 1-19. 10.3390/rs13193797

Nesbitt, L., Meitner, M. J., Girling, C., Sheppard, S. R. J., & Lu, Y. (2019). Who has access to urban vegetation? A spatial analysis of distributional green equity in 10 US cities. *Landscape and Urban Planning, 181*, 51-79. 10.1016/j.landurbplan.2018.08.007

Nowak, D. J., Crane, D. E., & Stevens, J. C. (2006). Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry and Urban Greening, 4*(3-4), 115-123. 10.1016/j.ufug.2006.01.007

O'Neill, M. S., & Ebi, K. L. (2009). Temperature extremes and health: Impacts of climate variability and change in the United States. *Journal of Occupational and Environmental Medicine, 51*(1), 13-25. 10.1097/JOM.0b013e318173e122

Ordóñez Barona, C. (2015). Adopting public values and climate change adaptation strategies in urban forest management: A review and analysis of the relevant literature. *Journal of Environmental Management, 164*, 215-221. 10.1016/j.jenvman.2015.09.004

Pisello, A. L. (2017). State of the art on the development of cool coatings for buildings and cities. *Solar Energy, 144*, 660-680. 10.1016/j.solener.2017.01.068

Pregitzer, C. C., Ashton, M. S., Charlop-Powers, S., D'Amato, A. W., Frey, B. R., Gunther, B., Hallett, R. A., Pregitzer, K. S., Woodall, C. W., & Bradford, M. A. (2019). Defining and assessing urban forests to inform management and policy. *Environmental Research Letters, 14*(8), 085002. 10.1088/1748-9326/ab2552

Rahman, M. A., Moser, A., Gold, A., Rötzer, T., & Pauleit, S. (2018). Vertical air temperature gradients under the shade of two contrasting urban tree species during different types of summer days. *Science of the Total Environment*, *633*, 100-111. 10.1016/j.scitotenv.2018.03.168

Reid, C. E., O'Neill, M. S., Gronlund, C. J., Brines, S. J., Brown, D. G., Diez-Roux, A. V., & Schwartz, J. (2009). Mapping community determinants of heat vulnerability. *Environmental Health Perspectives, 117*(11), 1730-1736. 10.1289/ehp.0900683

Rosenfeld, A. H., Akbari, H., Romm, J. J., & Pomerantz, M. (1998). Cool communities: Strategies for heat island mitigation and smog reduction. *Energy and Buildings, 28*(1), 51-62. 10.1016/S0378-7788(97)00063-7

Salmond, J. A., Williams, D. E., Laing, G., Kingham, S., Dirks, K., Longley, I., & Henshaw, G. S. (2013). The influence of vegetation on the horizontal and vertical distribution of pollutants in a street canyon. *Science of the Total Environment, 443,* 287-298. 10.1016/j.scitotenv.2012.10.101

Santamouris, M. (2014). Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Solar Energy, 103*, 682-703. 10.1016/j.solener.2012.07.003

Santamouris, M., Synnefa, A., & Karlessi, T. (2011). Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions. *Solar Energy, 85*(12), 3085-3102. 10.1016/j.solener.2010.12.023

Sanusia, R., Johnstone, D., May, P., & Livesley, S. (2015). Street Orientation and Side of the Street Greatly Influence the Microclimatic Benefits Street Trees Can Provide in Summer. *Journal of Environment Quality, 0*10.2134/jeq2015.01.0039

Semenza, J. C., Rubin, C. H., Falter, K. H., Selanikio, J. D., Flanders, W. D., Howe, H. L., & Wilhelm, J. L. (1996). Heat-Related Deaths during the July 1995 Heat Wave in Chicago. *The New England Journal of Medicine, 335*(2), 84-90. 10.1056/NEJM199607113350203

SFPD. (2014). *Recreation and open space element of the San Francisco general plan*

Shonkoff, S. B., Morello-Frosch, R., Pastor, M., & Sadd, J. (2009). Minding the climate gap: Environmental health and equity implications of climate change mitigation policies in California. *Environmental Justice, 2*(4), 173-177. 10.1089/env.2009.0030

Smith, W. H. (2012). *Air Pollution and Forests: Interactions Between Air Contaminants and Forest Ecosystems* (Second ed.). Springer.

Sugawara, H., Shimizu, S., Takahashi, H., Hagiwara, S., Narita, K. -., Mikami, T., & Hirano, T. (2016). Thermal influence of a large green space on a hot urban environment. *Journal of Environmental Quality, 45*(1), 125-133. 10.2134/jeq2015.01.0049

Synnefa, A., Santamouris, M., & Livada, I. (2006). A study of the thermal performance of reflective coatings for the urban environment. *Solar Energy, 80*(8), 968-981. 10.1016/j.solener.2005.08.005

Taha, H. (1997). Urban climates and heat islands: Albedo, evapotranspiration, and anthropogenic heat. *Energy and Buildings, 25*(2), 99-103. 10.1016/s0378-7788(96)00999-1

Takebayashi, H., & Moriyama, M. (2007). Surface heat budget on green roof and high reflection roof for mitigation of urban heat island. *Building and Environment, 42*(8), 2971-2979. 10.1016/j.buildenv.2006.06.017

Tzoulas, K., Korpela, K., Venn, S., Yli-Pelkonen, V., Kaźmierczak, A., Niemela, J., & James, P. (2007). Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review. *Landscape and Urban Planning, 81*(3), 167-178. 10.1016/j.landurbplan.2007.02.001

United States - National Weather Service. (2020). *National Weather Service*.

Upmanis, H., Eliasson, I., & Lindqvist, S. (1998). The influence of green areas on nocturnal temperatures in a high latitude city (Goteborg, Sweden). *International Journal of Climatology, 18*(6), 681-700. 10.1002/(SICI)1097-0088(199805)18:63.0.CO;2-L

US Forest Service. (2015). *Urban Forests.* US Forest Service. http://www.fs.usda.gov/managing-land/urban-forests

Vaz Monteiro, M., Doick, K. J., Handley, P., & Peace, A. (2016). The impact of greenspace size on the extent of local nocturnal air temperature cooling in London. *Urban Forestry & Urban Greening, 16*, 160-169. 10.1016/j.ufug.2016.02.008

Wang, J., Zhou, W., & Jiao, M. (2022). Location matters: planting urban trees in the right places improves cooling. *Frontiers in Ecology and the Environment,* 10.1002/fee.2455

Wang, Y., & Akbari, H. (2016). The effects of street tree planting on Urban Heat Island mitigation in Montreal. *Sustainable Cities and Society, 27*, 122-128. 10.1016/j.scs.2016.04.013

Wolch, J. R., Byrne, J., & Newell, J. P. (2014). Urban green space, public health, and environmental justice: The challenge of making cities 'just green enough'. *Landscape and Urban Planning, 125*, 234-244. 10.1016/j.landurbplan.2014.01.017

Yang, J., Yu, Q., & Gong, P. (2008). Quantifying air pollution removal by green roofs in Chicago. *Atmospheric Environment, 42*(31), 7266-7273. 10.1016/j.atmosenv.2008.07.003

Yin, S., Peng, L. L. H., Feng, N., Wen, H., Ling, Z., Yang, X., & Dong, L. (2022). Spatial-temporal pattern in the cooling effect of a large urban forest and the factors driving it. *Building and Environment, 209*, 108676. 10.1016/j.buildenv.2021.108676

Zinzi, M., & Agnoli, S. (2012). Cool and green roofs. An energy and comfort comparison between passive cooling and mitigation urban heat island techniques for residential buildings in the Mediterranean region. *Energy and Buildings, 55*, 66-76. 10.1016/j.enbuild.2011.09.024