Evaluation of Urban Cooling Interventions

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Heat islands and warming temperatures are a growing global public health concern. Cities worldwide are implementing heat adaptation and mitigation interventions to reduce the urban heat island effect and extreme heat exposures. As listed by the Environmental Protection Agency (USA EPA), these interventions may include: trees/vegetation, green and cool roofs, cool pavements, and broadly improved infrastructure that invests in ‘greener’ practices. Although cities are implementing cooling interventions, little is known about their efficacy. Four interventions often used in urban areas are taken into consideration here: cooling centers, misting stations, cool (or green) roofs, and cool pavements.

Keywords: heat ; climate change ; mitigation ; urban environment ; heat island ; cooling interventions

1. Cool Pavements

Five studies focused on cool pavements in Los Angeles, California, USA [1], Taipei City, Taiwan [2], Acharnes, Greece [3], Ames, Iowa, USA [4], and greater Athens, Greece [5]. Each considered a different type of cool pavement, including solar reflective coating (Guard Top CoolSeal) [1], porous/permeable concrete bricks and porous asphalt [2][3], pervious concrete pavement [4], and light-yellow concrete blocks [5].

1.1. Cool Pavement Evaluation Protocols

Evaluations were designed to quantify the heat differences for cool, compared to control (existing or conventional), pavements by examining surface temperature, ambient air temperature, and heat gain measurements. Two of the five studies estimated human thermal comfort via mean radiant temperature [1] and cooling power comfort index (calculated using observed mean radiant temperature and wind speed) [5]. None included study participants, and one intervention explicitly considered vulnerable populations when trying to find a study location [1].

In Los Angeles, black asphalt pavement was coated with highly reflective Guard Top CoolSeal surfacing in several neighborhoods across 10–12 street blocks each [1]. Data collection took place over the course of one summer day (30 July 2019), from 11:00:00 AM to 9:00:00 PM PDT, in the form of hourly measurements via MaRTy, including: six-directional longwave radiation flux densities, shortwave radiation flux densities (radiation flux densities calculated mean radiant temperature), ambient air temperature, surface temperature, horizonal wind speed, and relative humidity.

In Taipei City, Taiwan, investigators compared 200 m of porous concrete pavement and 200 m of porous asphalt pavement installed in a bicycle lane/pedestrian walkway in front of a high school, with regular concrete and asphalt materials during the wet months of April 2018 and May 2019, as well as the dry month of August 2018 [2]. Surface temperature was collected in 10-min intervals at nine locations between 9:00:00 AM and 9:00:00 PM.

On a sidewalk in front of a school building in Acharnes, Greece, a cool pavement of lime-cement plaster, with a solar reflectivity of 0.69, was installed to replace a conventional pavement with lower solar reflectivity; surface temperature measurements for the cool pavement and an adjacent conventional pavement were collected via hourly thermal images, taken by a FLIR B2 thermal camera device throughout the daytime on 15 June 2015 [3]. In addition to monitoring the change, they used simulation software, Envi-met, to predict temperatures based on the change.

At Iowa State University in Ames, Iowa, a parking lot was used to compare traditional concrete surfacing on top of clay soil, with pervious concrete over a limestone aggregate [4]. Using an array of temperature sensors on the two pavements, daily and cumulative heat gains, as well as ambient air temperature data, were collected throughout the entire summer.

In Athens, Greece, approximately 4500 square-meters of light-yellow concrete blocks were installed in Flisvos park in June and July 2010 [5]. The cool pavement blocks were chosen for their high reflectivity of >0.85 [5]. Surface temperature, ambient temperature, wind speed, and pollutant concentration were collected on two days pre- and post-intervention (for a total of four days) using a mobile station on a vehicle. Additionally, the cooling power comfort index was used to determine thermal comfort, including the mean ambient temperature and wind speed from eight locations ("reference points") in the calculations [5].

1.2. Cool Pavement Intervention Results: Surface Temperature, and Ambient Temperature

In Los Angeles, CoolSeal reduced surface temperatures, compared to unchanged asphalt, throughout the observation period. The greatest differences were recorded at midday, when CoolSeal measured approximately 6 °C lower than untreated asphalt concrete [1]. At night, the reflective pavement was between 1.6 and 1.8 °C cooler than the control. However, there was a gain in the net radiation, such that the mean radiant temperature at midday for the reflective pavement was 4.0 degrees hotter [1]. Given this increase, the authors suggest that people would not want to use hotter sidewalks and state that reflective pavement coatings may not be well-suited to all climates and cities [1].

In Taipei, during storm events, porous asphalt and permeable interlocking concrete bricks showed lower surface temperatures than regular pavements [2]. During dry periods, the surface temperatures of both intervention pavements increased more rapidly as ambient air temperature increased, and they decreased more quickly as ambient air temperature decreased [2]. Observations for 14 September 2018, between 9:00:00 AM and 9:00:00 PM, showed lower temperatures for both intervention materials, compared to the conventional pavement, with a maximum difference of 17 °C for the porous asphalt and 14.3 °C for the permeable interlocking concrete bricks. During storm events, porous asphalt and permeable interlocking concrete bricks showed lower surface temperatures than regular pavements [2].

In Acharnes, Greece, the cool pavement lowered surface temperatures and improved "outdoor conditions" [3]. The mean of the maximum summertime ambient temperatures was 0.3 K cooler for the cool pavement areas, compared to the conventional pavement. The surface temperature was reduced by 10 K [3]. Envi-met simulation predicted similar results.

In Ames, Iowa, during the peaks of five heat waves (wherein a heat wave is more than one day with maximum temperatures above 30 °C), the pervious concrete intervention pavement had lower cumulative heat gains post-heat wave peak [4]. Additionally, sensitivity analyses demonstrated that, on heating days, the intervention pavement had lower cumulative heat gains than the control or traditional concrete. The authors suggest that some of the cooling in the previous system may be attributable to the evaporation of water after rainfall.

The Athens cool pavement intervention, via the cooling power comfort index equation, determined that comfort conditions after installing the pavement dropped from extremely hot to quite/very hot (with the exception being the area monitored near the coast), and the number of visitors to the area increased [5]. While the conventional pavement mean surface temperature was 48.1 °C, the intervention pavement mean surface temperature was 36.8 °C, although comparisons of the cool and conventional pavements near the park yielded negligible differences closer to the sea.

2. Cooling Centers

Four studies evaluated cooling centers, also referred to as "heat refuges" located in Pittsburgh, PA [6], Portland, OR [7], Maricopa County, AZ, and Los Angeles County, CA [8][9]. Cooling centers included libraries, community centers, commercial spaces, and other public buildings with cooling systems available to city residents during extreme heat events. In each article, cooling centers included formal/designated heat refuges and informal/volunteer refuges. Formal heat refuges are buildings that are designated by the city as places for residents to cool off during heat events, whereas volunteer refuges are not formally listed by cities, but open for residents looking for air-conditioned spaces. Informal refuges often include malls, museums, movie theaters, and other commercial places that people go to escape hot weather.

2.1. Cooling Center Evaluation Protocols

All four studies focused on evaluating the population-level proximity, using network analysis software to examine the characteristics and number of residents with access the cooling centers as an adaptive mechanism for coping with extreme heat events [6][7][8][9]. None of the studies measured the temperatures at the cooling centers or human exposure. Access was quantified by the total proportions of the populations in the respective cities within specified travel sheds of cooling centers. A range of demographic characteristics (e.g., race, income, age, language, educational attainment, ethnicity, employment, and health insurance status) for populations with and without these sheds were assessed for equity of access, which was considered critical by authors for evaluating the efficacy of extreme heat exposure interventions.

In three of the four articles evaluating cooling centers, heat vulnerability indexes (HVIs) were developed to analyze the equity of access [6][8][9]. The Pittsburgh study identified six principal factors for their HVI: age, isolation, economic resources, cool spaces, education, language, race, ethnicity, and greenspace [6]. Los Angeles HVI variables included the percent of households: without vehicles, renting, with income below poverty, uninsured, and foreign-born. Maricopa HVI variables included the percent: Hispanic/Latino households, foreign-born, uninsured, income below poverty, construction workers, and single female householders [8]. In Portland, equity of access was characterized by census-block group data on income, race, education, age, and language [7].

2.2. Cooling Center Results: Accessibility and Equity

In Pittsburgh, with the demand for cooling centers per census block group weighted by the HVI, analyses of both present and future access identified the same three highest need neighborhoods, where the authors suggest that maintaining existing cooling centers and opening additional locations should be a priority [6]. In Maricopa, a greater proportion of the official cooling centers served vulnerable populations (25 of 46 official centers), compared to Los Angeles (9 of 94 official centers). However, 46% of the Los Angeles centers were in places with an already high prevalence of publicly accessible air conditioning (AC), compared to 75% in Maricopa. The researchers used the HVI and a location-allocation mapping tool to identify 10 facilities in each county that would maximize accessibility to the greatest number of people in HVI-specific populations [8]. The Portland analysis found that, at an average walking speed, census blocks with higher proportions of Black/African American populations had greater access to cooling centers, while census blocks with higher proportions of elderly or Asian populations had lower access. The range of access, which changes based on walking speed, is 3.4%, 16.9%, and 32.7% for slow, average, and fast walking speeds, respectively [7]. Further analyses of baseline heat exposure factors considered additional vulnerabilities to extreme heat events—central AC prevalence by block group and urban heat island effect—and found that, in Portland, access was limited for slower walkers, as well as Asian and elderly populations [7].

3. Misting Stations

Misting stations were located in Osaka, Japan [10], Ancona and Rome, Italy [11][12][13], Singapore [14], Antofagasta, Chile [15], and Tempe, Arizona [16]. Evaluations were supported by a variety of metrics captured by sensors, indices, meteorological data, and comfort surveys administered to participants, and they measured participants' physiological responses to the misting system.

3.1. Misting Station Design

Two studies evaluated 'dry' misting systems, which are designed to cool users without causing dampness, which is accomplished through the particularly small water droplet sizes achieved in the systems, considered optimal for cooling off in humid climates [14]. In Singapore, the dry misting station was placed under a gazebo two meters from the participant seating and composed of two high pressure air jets, which, when aimed at a water jet, produce fine water droplets [14]. A total of 50 participants, aged 20–30, sat below the misters for a 30-min period and measurements were collected on the globe and ambient air temperature, relative humidity, and solar irradiance immediately to the front of the participants' seating [14]. The second dry mist system consisted of six nozzles, located one meter apart and fed by the fountain in a playground in Rome [11].

The two articles in Ancona and Rome, Italy, tested an overhead system fed by a local fountain. In the second iteration, the system was programmed to regulate misting based on weather conditions [12][13]. In Antofagasta, Chile, a misting station prototype with the capacity for direct and indirect misting was installed in a particularly hot location with mostly dark surfaces and little shade [15]. While the station is not referred to as a 'dry' misting system, authors emphasize that the prototype was designed to emit fine droplets of water to avoid leaving participants feeling damp after using the station [15]. The study in Osaka, Japan, set up a spray station consisting of eight nozzles attached to a fan spraying mist on the participating students in a shaded-tree area [10]. In Tempe, Arizona, USA, researchers focused on the cooling capacity of the misting stations installed in shaded, compared to sunny, areas at five restaurants with outdoor seating, where temperatures often exceed 43 °C in the summer [16].

3.2. Evaluation Protocols

The thermal comfort of people using misting stations was evaluated with qualitative and quantitative data. Five articles used thermal comfort metrics to quantify the cooling capacity of misting stations. These included study participants' skin temperatures, perceived humidity, universal thermal climate index (UTCI), and the physiological equivalent temperature (PET). The UTCI and PET require data collection on ambient air temperature, relative humidity, wind speed, globe temperature, and pressure, as well as inputs for standardized personal human parameters (average height, clothing, etc.) [15][16].

In Arizona, misting stations were installed at five restaurants, and data were sampled in four conditions for 10 min in 10-s intervals each: sun, shade, sun and misting station, and shade and misting station [16]. For the study of a misting prototype conducted in Antofagasta, Chile, participants completed questionnaires on comfort after spending 10 min in the ambient environment (ambient conditions: 30 °C, windy, and cloudy) and after 2–10 min in the mist [15]. The authors used meteorological data to calculate the UTCI, with pre- and post-misting questionnaires administered to study participants [15]. The misting station interventions conducted in Rome and Ancona, Italy, assessed participants' thermal comfort via questionnaires, comparing intervention locations to non-intervention location temperature, humidity, and wind gradients [12]. The Osaka, Japan, study collected participant data via interviews, logging skin temperature, and collecting pre- and post-misting thermal comfort scoring [10].

3.3. Misting Station Results

In all seven evaluations, misting stations were found to successfully cool the spaces where they were installed. Two studies did not include participants, nor were there any analyses of thermal comfort [11][13]. The study in Rome was focused on developing a water spray model, using the misting station to compare simulations with measures [11]. In determining which misting station setup optimized the change in ambient air temperature, the authors reported increased cooling when the station had a greater number of misting nozzles set at lower heights, with the effectiveness decreasing at higher wind speeds [11]. In Ancona, Italy, data collected over a week in August (in 10-s intervals) for temperature and relative humidity demonstrated maximum cooling by 7.4 °C, with relative humidity increases measuring under 13% [13].

The five studies that included study participants found misting stations to have cooling effects. These included decreases in the PET and UTCI metrics in Arizona, USA [15], and Antofagasta, Chile [16]. Study participants at the University of Singapore [14], Rome and Ancona, Italy, and Osaka, Japan, reported feeling cooler after using misting stations, further evidenced by the measured decreases in skin temperature. In Antofagasta, Chile, researchers reported 15 °C cooling in both the UTCI and ambient air temperature [16]. The dry mist system tested at the University of Singapore found that, after using the misting station, 70% of study participants reported feeling cooler on the ASHRAE TSV scale (measuring thermal sensation—how warm it feels), and 50% reported feeling cooler on the Bedford TCV scale (measuring comfort—how comfortable the temperature is) [14]. The study in Rome and Ancona, Italy, found agreement in the qualitative data on perceived coolness and the quantitative measurements; misting areas dropped in temperature by approximately 8 °C [12]. In Osaka, Japan, the skin temperatures of participants dropped (nearly instantaneously) an average of approximately 1 °C, and thermal comfort changed from hot to slightly cool [13]. In Arizona, misting stations placed in the shade significantly lowered the PET (−15.5 °C, $p < 0.05$) and UTCI (−9.7 °C, $p < 0.05$) [16].

4. Cool Roofs

Eight cool roof intervention studies were from Hong Kong, China [17], New York City, USA [18], Ahmedabad, India [19], El Koura, Lebanon [20], Osaka and Kyoto, Japan [21], Rome and Milano, Italy [22], Acharnes, Greece [3], and Beirut, Lebanon [23]. Numerous types of cool roofs were assessed, including intensive and extensive green roofs, high-reflective and white roofs, thermocol insulated roofs, Modroofs, and garden box roofs. Intensive green roofs are roofs with a substrate depth greater than 150-mm and may include herbaceous ground cover, shrubs, and trees, whereas extensive green roofs have shallower depths and, thus, low-growing vegetation [17][18]. Highly reflective roofs and white roofs both are designed to increase the surface reflectivity by painting or installing white or highly reflective roofing materials [19]. Thermocol roofing is an insulation material installed below the current roof inside the home. Modroofs, or modular roofing, consist of waterproof roofing panels made from recycled materials [19]. Finally, garden box roofs, a variety of which were assessed in the articles reviewed here, consist of garden boxes installed on rooftops with plant, soil, and water contents [20][21][23]. All studies included a 'control roof' or comparison roof, in the form of a bare or black roof. Two of the cool roof studies considered human-effects of interventions [17][19] via qualitative data from study participants. Two studies examined the energy savings resulting from cool or green roof installation [3][18]. An overview of the parameters and results of the various cool roofs is provided in **Table 1**.

Table 1. Summary of evaluation metrics and results from cool roof intervention studies.

Type of Roof	Parameters	Results	Article and Location
Intensive green roof	Collected sunny and cloudy day measurements of ambient air temperature, relative humidity, black globe temperature, insolation, wind speed, and surface temperature to calculate the UTCI and PET	Compared to control in sunny weather: surface temperature cooler by 4.9 °C, ambient air temperature by 1.6 °C, UTCI by 5.5 °C, and PET by 10.9 °C	Hong Kong, China [17]
High-reflective roof, extensive green roof	Measured surface, ambient air temperature, and surface albedo at two sampling times (at night and during the day)	The surface temperature for the white and green roofs had a 30 °C lower oscillation than the control roof	New York City, USA [18]
Thermocol, solar reflective paint, airlite ventilation sheeting, modular roofing	Minutely measurements of indoor ambient air temperature and humidity	Indoor ambient air temperature significantly lower for solar reflective white paint (compared to unpainted tin) and thermocol (compared to tin/asbestos)	Ahmedabad, India [19]
Gravel, thin soil vegetated, thick soil vegetated	Minutely measurements for one year of ambient air temperature and surface temperature	Thick soil decreased ambient air temperatures by 35%, compared to a drop by 34% for thin soil	El Koura, Lebanon [20]
Hydroponic greening system for rice	Measured heat flux, surface temperature, and ambient air temperature above systems	Hydroponic ambient air temperature was 1.8 °C cooler than the comparison	Osaka and Kyoto, Japan [21]
Modified bitumen, PVC, polyolefin	Solar reflectance measured every three months for two years	Solar reflectivity diminished by 0.14 and 0.22 at the respective sites	Rome and Milano, Italy [22]
Gray roof tiles	Measured energy saved inside the building and surface temperature of tiles	Energy use was reduced by 17% in the summer months	Acharnes, Greece [3]
Garden boxes (one with mulch substrate, the other cardboard pellets)	Measured temperature under garden boxes and plant growth in the garden boxes	Mulch substrate measured a maximum temperature 2 °C cooler than control box	Beirut, Lebanon [23]

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