

URBAN HEAT ISLAND MITIGATION DUE TO ENHANCED EVAPOTRANSPIRATION IN AN URBAN GARDEN IN SAINT PAUL, MINNESOTA, USA

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ABSTRACT

As a result of extensive urban development coupled with warming temperatures, urban heat islands (UHI) have become an important factor affecting energy consumption and human health in cities. Prior research has shown that evapotranspiration (ET) from urban vegetation can have a significant cooling effect, but there are relatively few direct measurements from urban vegetable gardens. We compared hourly temperature measurements during two summers (2017 and 2018) in a 750 m² research garden at the University of St. Thomas (Saint Paul, Minnesota, USA) to hourly temperatures at the nearby Minneapolis-Saint Paul (MSP) International Airport, located 6 km to the south. We also quantified seasonal ET (June–October) in 132 garden plots and five reference turfgrass plots during the summers of 2017 and 2018. For both years, an increase in temperature of 1.00°C at the MSP airport resulted in an average increase of 0.55°C in the research garden. At temperatures greater than 22°C, the garden was cooler on average compared to MSP airport. ET in the garden plots was significantly higher than in the grass reference plots both years, with means of 46 cm for garden plots compared to 19 cm for grass plots in 2017, and 51 cm for garden plots compared to 33 cm for grass plots in 2018. These results are consistent with other research showing potentially large benefits of cooling through ET from urban gardens that are primarily aimed at crop production.

Keywords: urban agriculture, vegetation, temperature.

1 INTRODUCTION

As a result of extensive urban development coupled with warming temperatures, urban heat islands (UHI) have become an important factor affecting energy consumption and quality of life in cities. Reduced vegetation cover in urban areas relative to the surrounding region results in decreased evapotranspiration (ET), causing a reduction in latent heat consumption and thereby leaving more energy available as sensible heat, resulting in higher land surface temperatures [1]. There is a strong relationship between impervious surface cover and land surface temperature in cities [2], with streets being especially susceptible [3]. Likewise, vegetated areas in cities are known to reduce maximum temperature, for example [4], [5], and urban designers are increasingly calling for more greenspace to mitigate UHI effects [6].

Previous research has shown that evapotranspiration (ET) from urban vegetation can have a significant cooling effect in cities. For example, a large greenspace in London caused temperature reductions of 1.1°C on summer months, and a maximum of 4°C observed on some nights, with cooling effects extending from 20–440 m from the edge of the greenspace [5]. Trees and shrubs reduced soil temperature by 5.7°C in a mid-sized city in the UK, which was 0.6°C warmer than nearby rural areas [7]. In Beirut, areas of the city with larger garden fractions have up to 6°C cooler temperatures compared to surrounding areas [8]. In addition to natural vegetation within cities, green roofs have been a focus of research on UHI mitigation [1], [9]. Green roofs cool individual buildings through a combination of ET, physical shading, and insulation, and also contribute to urban cooling [9], [10]. For

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example, a model simulating 50% green roof coverage in a city predicted temperature reductions of 2°C [9].

In addition to natural vegetation in cities and highly engineered green roofs, urban vegetable gardens represent another land use that has received somewhat less attention for UHI mitigation potential. Urban gardens may be similar or more extensive in area compared to green roofs; urban vegetable gardens have been estimated to account for 0.04% of land area in Chicago [11], 0.1% of land area in Saint Paul, Minnesota [12], and 3.6% of land area in Montreal [13]. For comparison, Chicago, a leading city in green roof technology, has approximately 0.5 km² of vegetated square roofs in the 606 km² metropolitan area [14], or 0.08% land coverage. Additionally, unlike other forms of urban greenspace, many urban vegetable gardens receive supplemental irrigation during dry periods, increasing potential evapotranspiration and associated cooling. The potential impact of urban gardens on UHI mitigation has been considered in some previous analyses [1], [15], but empirical data on ET and cooling from urban gardens are limited.

We analyzed data from summer months over two years from a large urban garden in Saint Paul, Minnesota, USA, to evaluate the extent of UHI mitigation. We hypothesize that elevated ET rates from the irrigated garden will result in cooling rates that exceed documented rates for natural urban vegetation and green roofs.

2 METHODS

2.1 Garden description

The research garden at the University of Saint Thomas (Saint Paul, Minnesota, USA) is located at 44°56'17"N, 93°11'46"W. The garden, established in 2011, consists of 32 replicated 4 m² research plots growing peppers, carrots, bush beans, and collard greens. Research plots receive annual inputs of compost (either manure compost or municipal compost, targeted either to crop nitrogen or phosphorus demand), synthetic fertilizer, or no inputs. Garden soil, on average, has 9.4% organic matter, compared to surrounding soil below turfgrass which has 5.1% organic matter. Additional plots are dedicated to crop production and pollinator habitat, with a total area of approximately 1000 m². The garden is situated on a 1.8 ha park-like area with approximately 50% tree cover. The research garden is located 20 m from an adjacent classroom building, and 250 m from the Mississippi River.

2.2 Temperature measurements

Hourly temperature readings for the garden were collected using Decagon instruments/datalogger, installed at a height of 1.0 m near the center of the garden. To quantify potential UHI mitigation by the garden, we compared temperature data collected at the Minneapolis-Saint Paul International Airport (MSP), located 6.6 km SSW of the garden. MSP data were taken from the Iowa State climate data repository (<http://mesonet.agron.iastate.edu>). Temperature measurements at MSP are made in an open, grassy area located 35 m from an airplane taxiway, 250 m from the nearest building, 3.2 km from the Minnesota River, 3.5 km from the Mississippi River, and 2.1 km from Lake Nokomis.

Paired hourly temperature observations from the research garden and MSP airport were compiled from 1 June–30 August for 2017 and 2018, and any hours with missing observations were not used. 2,144 paired observations (out of a possible 2,184) were used for 2017, and 2,180 paired observations were used for 2018.



Regression analysis (using JMP Pro 15) was used to determine the slope of the relationship between airport temperature observations and garden temperature observations.

2.3 Evapotranspiration measurements

Evapotranspiration was calculated for the 2017 and 2018 growing seasons (30 May 2017–18 October 2017; 24 May 2018–20 October 2018), as difference between water inputs (rainfall and supplemental watering) and water loss through leachate. Rainfall was measured using an ECRN-50 rain gauge with 1 mm resolution, connected to a EM50 data logger (Decagon Devices). Supplemental watering of garden was quantified by applying water for a set amount of time (typically 30 or 45 seconds) to each 4 m² plot, and measuring the amount of time required to fill a 10 L bucket on each watering date. Water was distributed evenly across study plots. Turfgrass was not watered and received only ambient rainfall.

Leachate was quantified by weekly measurements of water volume collected in 128 lysimeters installed below each 1 m² garden subplot, and five additional lysimeters installed below turfgrass around perimeter of research garden. Each lysimeter consisted of a funnel with diameter 11.8 cm (surface area 109.3 cm²) attached to a 1 L plastic bottle. The top of the funnel was buried to a depth of 10 cm (below the rooting zone). Flexible polymer tubing ran from the collection bottle to the soil surface, and stone wool was used to plug the hole in the funnel to prevent soil from entering the collection bottle. Water was removed from each lysimeter using a syringe weekly during the growing season (June–October), and the volume was measured using graduated cylinder. Lysimeters were replaced each growing season. Soil moisture was measured in all garden study plots and control turfgrass plots approximately three times per week during the growing season in 2017, using a General DSMM500 soil moisture meter.

3 RESULTS

3.1 Temperature measurements

The mean air temperature observed at the research garden during June–August 2017 was 22.6°C, compared to 23.3°C for MSP airport. Airport temperature exceeded garden temperature in 1,286 paired observations in 2017, whereas garden temperature was greater in 855 observations. For summer 2018, mean air temperature in the research garden was 21.4°C, compared to 22.1°C at the MSP airport. Airport temperature exceeded garden temperature in 1301 paired observations in 2018, whereas garden temperature was greater in 876 observations.

Regression analysis shows that an increase of 1.00°C at the MSP airport resulted in an average increase of $0.56 \pm 0.02^\circ\text{C}$ (mean \pm SE) in the research garden in 2017 (Fig. 1), and $0.55 \pm 0.02^\circ\text{C}$ in 2018 (Fig. 2). Garden temperatures tended to be cooler than airport temperatures when airport temperatures exceeded 21°C, and warmer than airport temperatures at temperatures below 21°C during the summer months.

3.2 Evapotranspiration measurements

During the 2017 growing season, the UST research garden received 48.1 cm ambient rainfall, and 15.2 cm supplemental watering. During the 2018 growing season, the garden received 62.1 cm ambient rainfall, and 12.6 cm supplemental watering. Despite receiving 20–30%



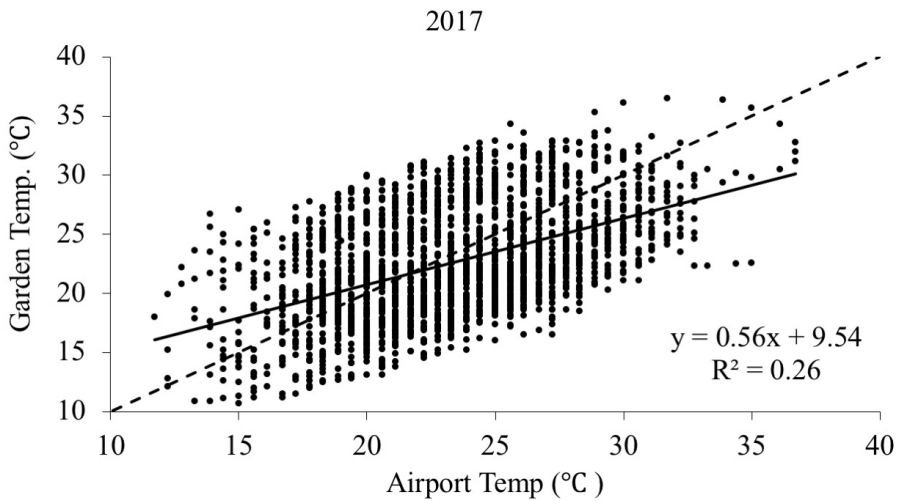


Figure 1: Relationship between measured hourly air temperature at the UST research garden and MSP airport during summer 2017. The solid line is a regression line; the dashed line is a 1:1 line.

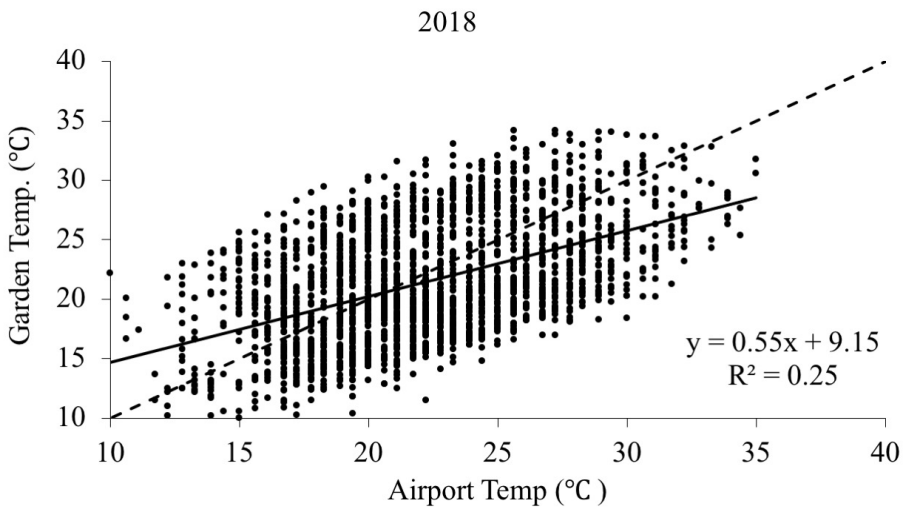


Figure 2: Relationship between measured hourly air temperature at the UST research garden and MSP airport during summer 2018. The solid line is a regression line; the dashed line is a 1:1 line.

higher water inputs due to supplemental watering, garden plots had leachate fluxes 20–40% lower compared to grass plots (Table 1). Estimated ET flux in garden plots was 140% greater than in grass plots in 2017, and 55% greater in 2018 (Table 1). Soil moisture observations had a mean of 16.6% (± 0.1) in garden plots in 2017, compared to 13.4% (± 1.4) in grass plots.

Table 1: Water budgets for garden plots and grass plots from 2017 (30 May–18 October) and 2018 (24 May–20 October) growing seasons.

| | Garden plots n = 128 mean | SE | Grass plots n = 5 mean | SE |
|----------------------------|------------------------------|-----|---------------------------|-----|
| 2017 | | | | |
| Total rainfall (cm) | 48.1 | | 48.1 | |
| Supplemental watering (cm) | 15.2 | | 0.0 | |
| Total water input (cm) | 63.3 | | 48.1 | |
| Leachate (cm) | 16.8 | 1.0 | 28.6 | 4.8 |
| Evapotranspiration (cm) | 46.5 | 1.0 | 19.5 | 4.8 |
| 2018 | | | | |
| Total rainfall (cm) | 62.1 | | 62.1 | |
| Supplemental watering (cm) | 12.6 | | 0.0 | |
| Total water input (cm) | 74.0 | | 62.1 | |
| Leachate (cm) | 23.7 | 0.9 | 29.2 | 6.3 |
| Evapotranspiration (cm) | 51.0 | 0.9 | 32.9 | 6.3 |

4 DISCUSSION

Our results support the hypothesis that elevated ET in an urban vegetable garden can contribute significantly to UHI mitigation, similar to cooling effects documented from green roofs and natural urban vegetation. Temperatures in the garden were moderated relative to airport temperatures, with a greater magnitude of cooling observed at higher temperatures. At temperatures above 21.7°C (in 2017) or 20.3°C (in 2018), garden temperatures tended to be cooler than temperatures at the MSP airport. For the warmest temperatures observed at MSP airport (approximately 35°C), garden temperatures were, on average, nearly 6°C cooler.

Our results are consistent with the few other available empirical data on cooling effects of urban gardens. A study in Rosario, Argentina, found that the cooling effects of urban agriculture gardens of only 0.2 ha were similar to the effects of gardens and parks that were 2–3 ha [16]. Likewise, the empirical data from our study is in agreement with results from a modeling study indicating that urban gardens can reduce surface temperatures by 5–10°C [15].

Evapotranspiration in garden plots was approximately double the rates observed in nearby turfgrass plots, potentially accounting for much of the observed cooling. While supplemental watering in the garden allowed for additional ET in garden plots, it is notable that cumulative leachate in garden plots was lower compared to turfgrass plots during both seasons, despite the additional water added. As a result, the total fraction of water inputs that are removed through ET is much higher in garden plots (73.4% in 2017 and 68.9% in 2018) relative to turfgrass control plots (40.5% in 2017 and 53.0% in 2018). The higher soil moisture observed in garden plots attests to the capacity of compost-amended garden soil to store water until it is used by plants. Many garden vegetable crops also have deeper root systems compared to turfgrass, allowing water to be extracted from deeper in the soil. Most leachate follows heavy

rain events, when the capacity of the soil to retain water has been saturated. Because supplemental watering only occurs during relatively dry periods, the contribution to leaching is minimal; thus, ET is the fate of nearly all of this additional water. This finding is in agreement with the conclusions of Mariani et al. [17] which found that soil water reservoirs are important in UHI mitigation in urban parks. A synthesis of UHI data from 35 cities worldwide found that the effects of vegetative cooling increase sharply when ET exceeds 61.7 mm/month [18]; ET in our garden plots exceeded 90 mm/month, compared to rates of 40–60 mm/month for the turfgrass plots.

We cannot be sure that all cooling from the garden site was attributed to elevated ET in the garden itself; other factors, such as nearby tree cover or proximity to the Mississippi River may have also contributed to cooling. One study found cooling effects extending up to 300m from a large river [19], but other studies have found more limited [20] or no [21] cooling effects of rivers. While our study has only two spatial data points, a spatially-intensive study in the Minneapolis-Saint Paul Metropolitan Area using 170 sensors shows that both the UST research garden and the MSP airport are well within the UHI zone [22], experiencing summer daytime mean temperatures approximately 1.0°C higher than surrounding rural areas. That study showed no discernable cooling effect of proximity to the Mississippi or Minnesota Rivers [22].

Our study provides some of the first empirical evidence showing that high ET from urban gardens dedicated to vegetable production may result in local UHI mitigation. Because green roofs and other urban green space generally do not receive supplemental irrigation, ET from vegetable gardens is likely to be greater, potentially magnifying the local cooling effect. Moreover, since urban vegetable gardens are more widespread and less costly than green roofs, their cumulative effect on UHI mitigation may be substantial, and deserves more attention. Importantly, there are many other ecosystem services documented from outdoor urban crop production [23], [24], so UHI mitigation is an added benefit which may contribute to more livable, sustainable cities.

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