Exploring Solutions to Urban Heat Islands: Case Studies from Canadian Metropolises

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Objective

Marked by high internal city temperatures, the Urban Heat Island effect (UHI) continues to increase in severity worldwide. Current mitigation techniques are largely based on applying the physics from cooler, undeveloped land to modern construction techniques and technologies. Using major Canadian cities as a base to prove the existence and influence of UHI, we intend to explore alternative mitigation techniques inspired by historically underrepresented cultures.

Present in numerous civilizations due to its natural abundance, bamboo is a strong candidate as a sustainable building material. Owing to its high-water content and unique structural composition, bamboo acts as an effective heat buffer and dissipater in place of brick and concrete. Furthermore, inspired by conductive pavements, we discuss the cooling potential of rammed earth roads as an alternative for rarely used, or low-load roads such as by lanes and linked roads.

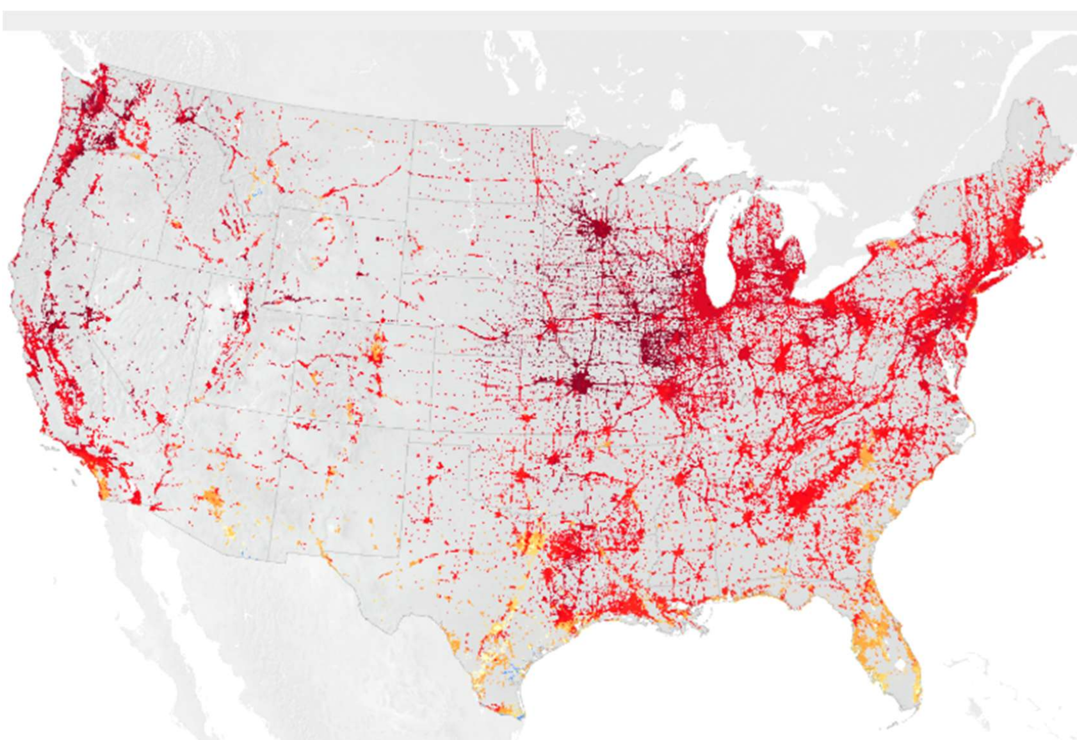

Figure 1: A visualization of heat islands in the US. (Autore, Rizzi, & Taylor, n.d.)

Introduction

What is UHI?

As concerns over climate change increase worldwide, one characteristic phenomenon that has steadily grown in significance is the observation of “heat islands”. Within large, industrialized cities, there is a substantial temperature increase relative to the surrounding rural areas (Fig 1). This is what has become known as the urban heat island effect (UHI). More specifically, UHI describes the creation of “heat islands” in cities, where temperatures will far exceed that of green areas such as large parks, rural land, or even bodies of water. (Autore, Rizzi, & Taylor, n.d.) (Hayes, et al., 2022) (Mirzaei & Haghighat, 2010)

The most telling symptom of an urban heat island is vastly increased nighttime temperatures. Due to the more effective heat emission present in natural, undeveloped land, at night, without a source of heat, rural temperatures will drop rapidly relative to their city centre counterparts. City blocks will retain the heat they have built up during the daytime, before slowly releasing it at night, typically through conduction. The resulting latent heating means that cities will be unable to cool down before the coming morning, exacerbating the effect day after day. (Autore, Rizzi, & Taylor, n.d.) (Mirzaei & Haghighat, 2010) (Mohajerani, Bakaric, & Jeffrey-Bailey, 2017)

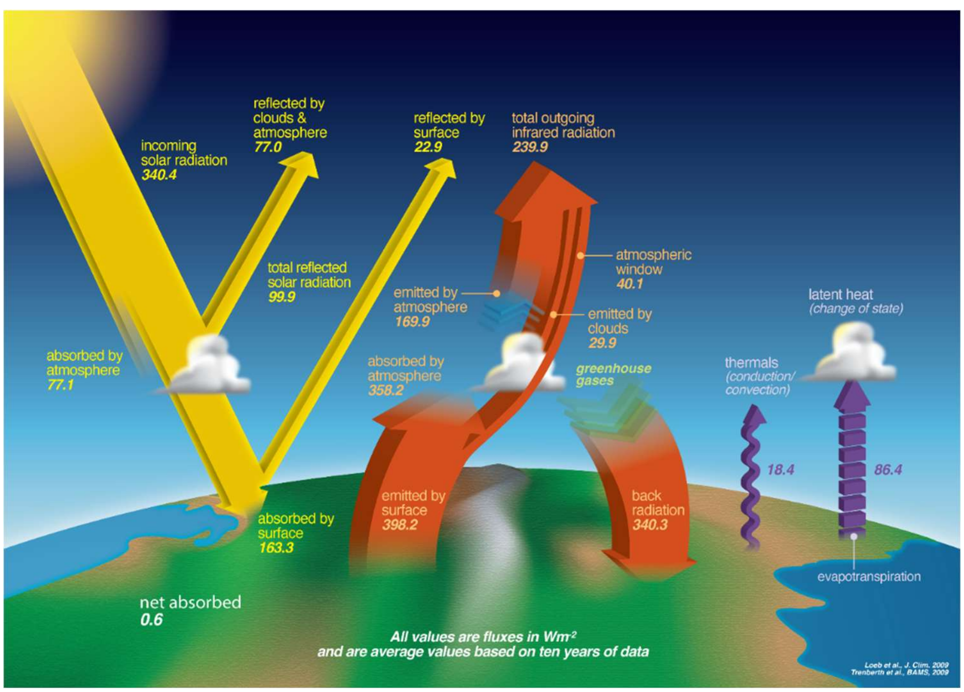

Figure 2. The balance between the energy received by Earth through sunlight, and the energy released by Earth into space. (Autore, Rizzi, & Taylor, n.d.)

Notably, the marked increase in temperatures carries with it a major risk of heat stroke, and exacerbated energy usage within the city. Residential units, food, and technology, for example, all require air conditioning, or cooling for a plethora of reasons. UHI bolsters the energy consumption for cooling units, inadvertently accelerating climate change, and sometimes causing potential power outages in cities as it grows increasingly challenging to meet energy demands. In addition, observations suggest that UHI reduces outdoor air quality through higher pollutant concentrations. (Mirzaei & Haghighat, 2010) (O'Malley, Piroozfar, Farr, & Pomponi, 2015)

Important Factors in UHI

On Earth, large portions of sunlight are reflected by clouds, or have their heat absorbed into the atmosphere. Eventually, those atmospheric particles release that heat back into space. On the surface, something very similar happens. Sunlight can be reflected by the surface or absorbed before having its heat emitted back into the atmosphere. These three main factors are the crux of UHI. How much heat from sunlight is reflected, absorbed, and emitted by the surface inside and outside cities. (Fig 2) (Autore, Rizzi, & Taylor, n.d.)

So, what is the property possessed by cloud cover that makes it so efficient at reflecting sunlight? The colouration and reflectivity of cloud cover is indicative of a material with high albedo. Albedo, on a scale from 0-1, is a measure of how effective a material is at absorbing heat, 0 being the most effective, 1 being the most reflective. Clouds and bodies of water possess high albedo, and so heat up quite slowly. Owing to their high altitude, clouds additionally prevent heat from passing into the lower layers of the atmosphere. (Hayes, et al., 2022) (O'Malley, Piroozfar, Farr, & Pomponi, 2015)

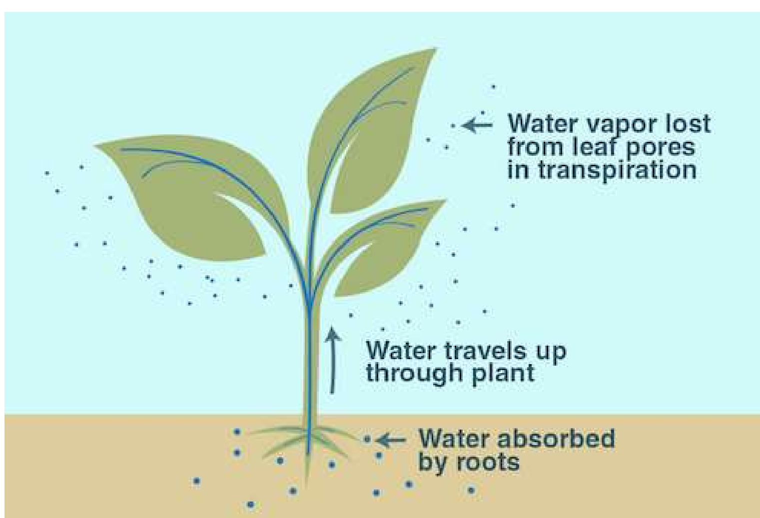

Figure 3: The process of plant transpiration. (NASA JPL/Caltech)

Another major contributor to UHI is the presence of plant life and water. Water has a very high specific heat capacity, and, since it can evaporate, quickly dissipates heat back into the atmosphere. So, not only does it heat up slowly, but it also actively removes heat from the surface. Its heat moderation effects are well-known in climate science and can be easily observed in countless seaside and lake-side cities worldwide. Plants, because they typically absorb water, possess similar cooling properties. Through transpiration, plants both intake ground water and expel it back into the air as water vapor. (Fig 3) (Hayes, et al., 2022) (O'Malley, Piroozfar, Farr, & Pomponi, 2015)

With reference to the above discussion: why is it that cities are so much hotter? The answer is industrialized materials. Asphalt and concrete (A-C), two major building blocks of cities, suffer from low albedo, and a high volumetric heat capacity. Therefore, without effective methods of heat dissipation, asphalt and concrete heats up to high temperatures under sunlight. Unlike plants and water, it cannot transpire or evaporate. A-C will gradually build up heat and maintain warmth inside cities through conduction. (Mohajerani, Bakaric, & Jeffrey-Bailey, 2017)

One such familiar example of the above might be Toronto city. Among the largest in Canada, Toronto is a prosperous cityscape which no doubt exemplifies a potential heat island. In stark contrast, King, a nearby rural town, dominated by plant life, strays away from the widespread coverage of A-C, thus possessing a marginally weaker UHI effect. We intend to investigate this in more detail.

Modern Mitigation Techniques

Just as clouds interrupt and reflect sunlight, we can accomplish something similar with light or reflective paint. Simply by painting over existing materials, we can decrease the albedo, thus causing it to heat up slower than it would have previously. (Hayes, et al., 2022) (O'Malley, Piroozfar, Farr, & Pomponi, 2015)

Another direct mitigation technique is the practice of building “green” or “living surfaces”, where plants are grown on infrastructure. This may include diverse gardens with plants as large as trees on rooftops, or vines sparsely planted on the side of a wall (Fig 4). By moving one of the main sources of cooling inside cities, we can leverage plants’ transpiration capabilities in place of A-C. (Hayes, et al., 2022) (Mohajerani, Bakaric, & Jeffrey-Bailey, 2017)

Combining the above two strategies with human ingenuity, cooling pavements apply a myriad of mitigation techniques to oppose UHI. In addition to being designed with high albedo, cooling pavements may be porous and water absorbent, thermally conductive, or possess high heat inertia.

Porous pavements, inspired by plant transpiration, remove excess heat quickly, but suffer from fragility. Conductive pavements are intended to transfer heat into the subgrade, and high inertia surfaces possess improved specific heat capacity. Both conductive and high inertia surfaces have been observed to decrease daytime temperatures but increase nighttime temperatures. (Pan, et al., 2022) (Qin & Hiller, 2014) (Santamouris, 2013)

Figure 4: Three different "levels" of vegetated surface reviewed by Canada's NRC (Hayes, et al., 2022)

Methodology

To analyze Urban Heat Island Effect, temperature data for two Canadian cities was obtained from publicly available data from Environment Canada. (Canada, 2024) The first city analyzed was Toronto and the hourly temperature data was compared against the suburb of King City. The data for Toronto city was collected at the co-ordinates 43°40'00.0"N, 79°24'00.0"W. The site is densely populated with little to no greenery or open spaces around it. On the other hand, the data for King city was collected at 43°57'48.7"N, 79°34'26.8"W. The site for King city data is surrounded by farmland and trees with very little urbanization around it. The site for King city is about a 35-minute drive north from the site of Toronto. The topography of both sites is shown in the images below.

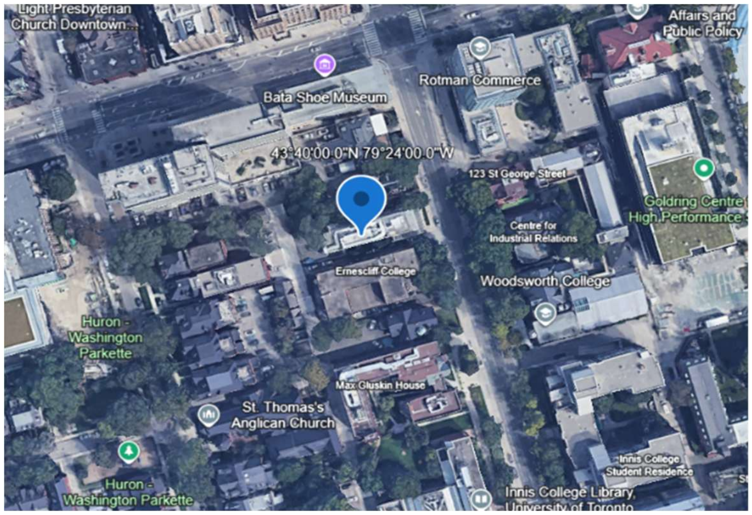

Figure 5: Temperature data site for Toronto [Google Earth]

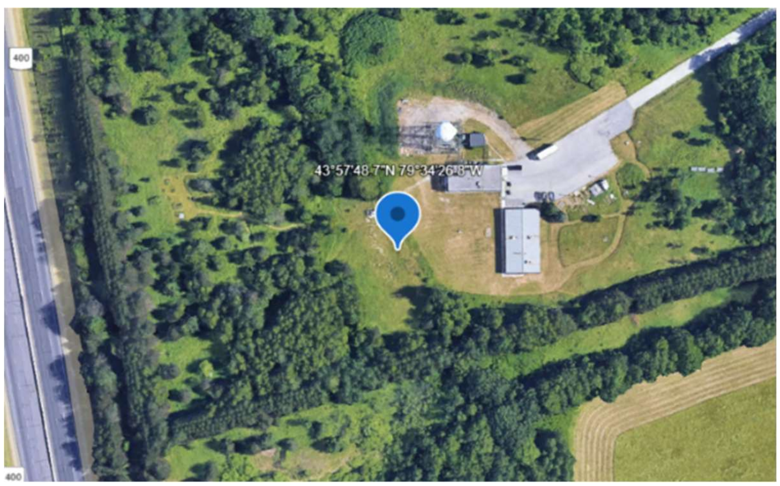

Figure 6 Temperature data site for King City. [Google Earth]

To contrast UHI effect in Toronto with a city that does not have as many skyscrapers, Edmonton was chosen as a second case study. The temperature data from the city was contrasted with the temperature data from the Oliver ADGM site located around 12 km away just outside the city. The data collection site for Edmonton city is located at 53°29'24.050" N, 113°32'16.000" W and the data collection site for Oliver ADGM is located at 53°39'00.000" N, 113°21'00.000" W. The site in Edmonton is not as densely urbanized as Toronto, with there being wider open spaces and almost no skyscrapers around it. The area mostly consists of houses and roads. The Olver ADGM site consists mostly of farmland around it with no urbanization around it. The topography of both sites is shown below.

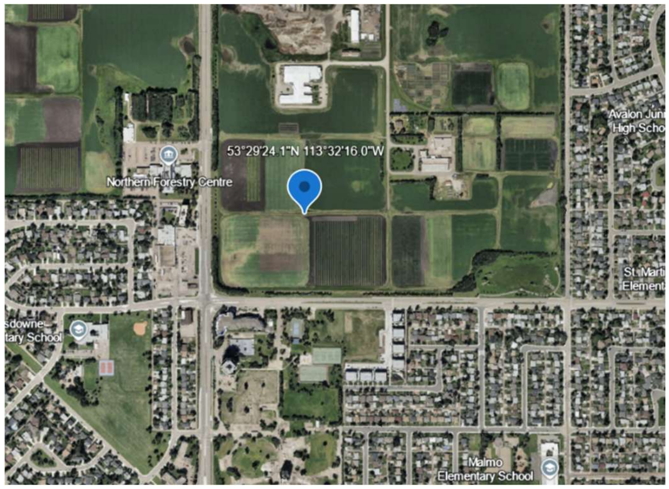

Figure 7 Temperature data site for Edmonton. [Google Earth]

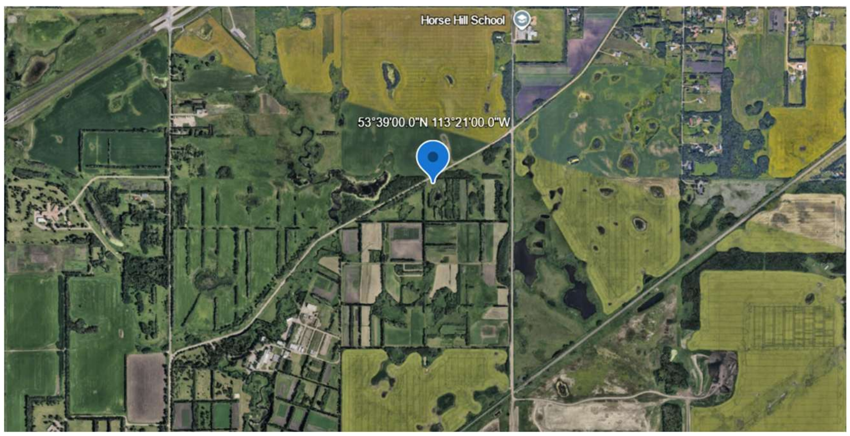

Figure 8 Temperature Data site for Oliver ADGM [Google Earth]

The temperature data was obtained as CSV files and fed into a python program to create line graphs for 21st and 22nd July. The line graphs compare the hourly temperature data between the selected sites.

Results and Analysis

Toronto Vs King City

The two graphs below show the hourly temperature data for Toronto and King city for 21 and 22 July 2024. In both graphs the blue line represents the temperatures for Toronto and the red line represents the temperatures for King city.

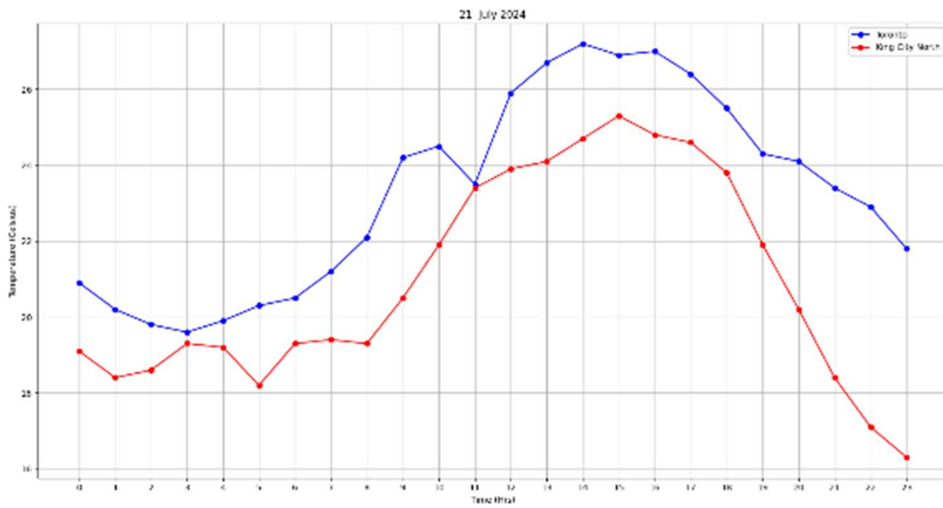

Figure 9 Temperature data comparison between Toronto and King City for 21 July 2024

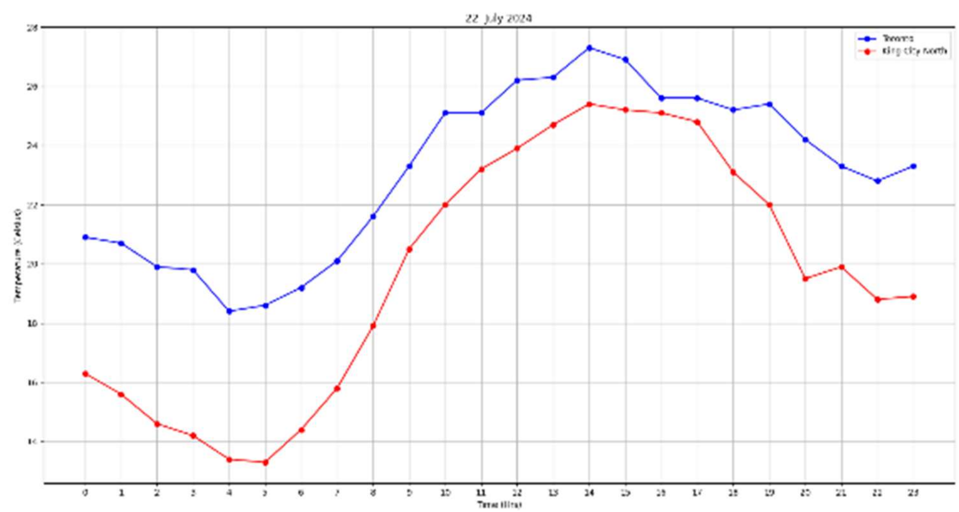

Figure 10 Temperature data comparison between Toronto and King City for 22 July 2024

Looking at the temperature graph for 21 July it can be seen that Toronto has consistently higher temperature than king city over the twenty-four-hour period. The daytime peak of Toronto occurs at 1400 hrs. in the afternoon with the temperature of ~27 °C. At the same time the temperature at King city is ~24 °C with the temperature difference between the two sites being around 3 °C. The temperature for king city sees sharp drop in starting around ~24 °C at 1800 hrs. and goes all the way down to ~16 °C at 2300 hrs. The temperature at Toronto at 2300 hrs. was recorded at ~22 °C with the difference in temperature now being ~6 °C. The same trend can be seen in the graph for 22 July. The temperature difference between the two sites starts at ~5 °C at midnight and then drops to just ~0.5 °C around 1600 hrs. But then the temperature difference between the two sites rises again to ~4.5 °C at 2300 hrs.

Even with its close proximity to Lake Ontario, the data clearly suggests that the city of Toronto experiences a significant amount of UHI effect. The city of Toronto has deployed a few mitigation techniques in the past, an example of which is the Green Roof bylaw. In 2009, Toronto became the first city in North America to mandate green roofs on new developments exceeding 2,000 square meters. The Green Roof Bylaw requires 20–60% of the available roof space to be greened, depending on the building's size. Developers can opt for a cash-in-lieu payment, which funds the Eco-Roof Incentive Program. (Toronto, 2009) The techniques used by the city in the past have been multi-faceted and comprehensive striving to achieve a more sustainable urban development. The bylaws implemented by the city mostly apply to new buildings and older infrastructure remains mostly unchanged. Based on this summer's data it can be clearly seen that the city needs to take a more direct approach to counter the UHI effect.

Edmonton Vs Oliver ADGM

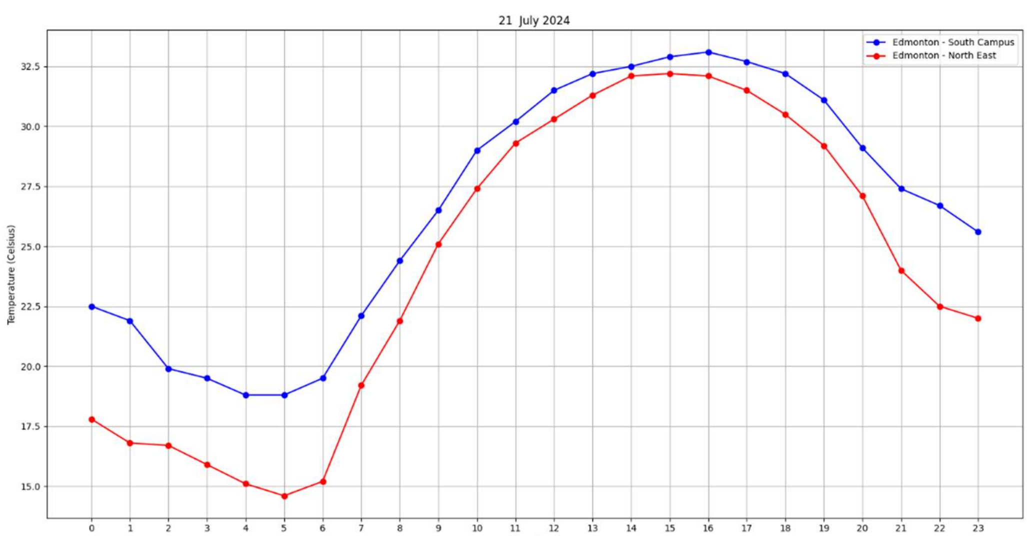

Figure 11 Temperature Data comparison between Edmonton and Oliver ADGM for 21 July 2024

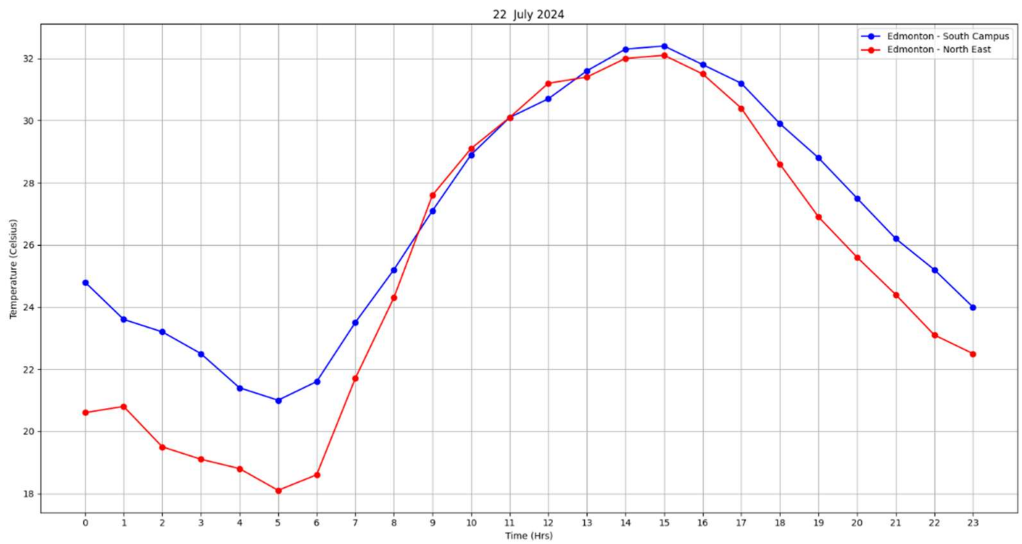

Figure 12 Temperature Data comparison between Edmonton and Oliver ADGM for 22 July 2024

The graphs above contrast the hourly temperature data from the city of Edmonton (South Campus) with the temperature data from the Oliver ADGM site (Northeast). In both graphs the blue line represents the city of Edmonton, and the red line represents Oliver ADGM. The same trend that was observed in the Toronto case study can be seen in the two graphs above. Starting midnight on 21st July 2024 the temperature at the South campus site is almost 5° C higher than the Oliver ADGM site. The difference in temperatures shrinks down to less than 0.5° C in the afternoon. Then in the evening the temperature at both sites starts to drop. The temperature difference between both sites at midnight on the 22nd July 2024 rises to around 4° C and flows the same trend as the day before.

Unlike Toronto, the site of Edmonton (South campus) has almost no skyscrapers around it and has a lot of open space. The amount of soil coverage is the only topographical difference between the South Campus site and Oliver ADGM site, with more area around the south campus site being covered by concrete and asphalt. This clearly shows just how much concrete and asphalt exacerbate the UHI effect.

Discussion

The use of Bamboo as a building material and replacing low traffic asphalt and concrete roads with Rammed Earth Roads can be used as effective techniques to mitigate the UHI effect. The inspiration for both techniques come from indigenous building techniques and practices from around the world.

Bamboo

The concept of incorporating bamboo within exterior concrete walls involves creating a three-layered wall system designed to enhance thermal performance and combat Urban Heat Island effects. The wall assembly consists of an exterior concrete layer that maintains structural integrity and weather resistance, a middle layer composed of processed bamboo material providing thermal insulation, and an interior concrete layer completing the structural envelope. This configuration requires the bamboo material to be properly treated and processed to ensure durability and fire resistance while maintaining its thermal insulation properties.

Bamboo has been an integral part of construction in many indigenous cultures across the globe, particularly in Asia and South America. For centuries, communities have utilized bamboo for various structural purposes due to its strength, flexibility, and rapid growth rate. A notable example is in the Philippines, where bamboo is traditionally used not just for constructing dwellings but also for various community structures (Fig 11) (Constancia, 2012). This indigenous application underscores a deep understanding of natural material properties and sustainability, which is essential in the context of modern environmental challenges.

Figure 11: Bahay Kubo, an indigenous house used in the Philippines which is made by bamboo (Constancia, 2012)

Bamboo exhibits remarkable thermal insulation properties that make it an excellent candidate for building material applications aimed at UHI mitigation. Scientific studies have demonstrated that processed bamboo possesses a significantly lower thermal conductivity (0.136-0.154 W/mK) compared to traditional concrete (0.348-0.467 W/mK) (Wang, Demartino, Xiao, & Li, 2018), indicating superior heat transfer resistance. This exceptional thermal performance is attributed to bamboo's unique structural composition, characterized by a hierarchical arrangement of air-filled cavities. These natural air pockets, which comprise 44-70% of the material's cross-sectional area (Huang, Wenshao, Ansell, John, & Andy, 2016), remain stable even after processing and contribute substantially to bamboo's insulating capabilities. The combination of low thermal conductivity and preserved cellular structure makes bamboo particularly effective at regulating heat transfer through building elements.

The integration of bamboo as a middle layer within concrete exterior building walls presents a promising strategy for UHI mitigation through its effective management of daytime heat absorption. The bamboo layer's low thermal conductivity and natural air cavity structure create a significant thermal barrier that impedes heat transfer through the wall assembly. When solar radiation contacts the exterior concrete surface during peak daylight hours, the bamboo layer's insulating properties substantially reduce the amount of heat penetrating to the interior concrete layer. This reduction in heat transfer through the building envelope leads to decreased thermal loading on the structure, subsequently lowering the cooling energy demands of buildings. The reduced cooling requirement results in diminished heat rejection from air conditioning systems, thereby decreasing the anthropogenic heat contribution to the urban environment. This cascade of thermal benefits directly addresses one of the primary mechanisms of UHI formation - the excessive heat absorption and storage in building materials.

The second significant contribution of bamboo-integrated concrete walls to UHI mitigation manifests during nighttime hours, when urban areas typically experience the most pronounced heat island effects. Traditional concrete walls absorb and store substantial amounts of heat during the day, releasing this accumulated thermal energy during the night and contributing to elevated urban temperatures. However, the bamboo middle layer's thermal properties significantly reduce the total heat storage capacity of the wall assembly. The decreased heat storage, combined with the bamboo layer's insulating properties, results in a more gradual and reduced heat release pattern during nighttime hours. This moderated heat emission pattern helps lower the intensity of nocturnal UHI effects, as less stored heat is available to be released back into the urban environment. The cumulative effect of reduced nighttime heat release across multiple buildings equipped with bamboo-integrated walls could substantially contribute to decreasing the temperature differential between urban and rural areas during nighttime hours, directly addressing one of the fundamental characteristics of the urban heat island phenomenon.

The implementation of bamboo-integrated concrete walls faces several notable limitations and challenges that require careful consideration. The durability and longevity of the bamboo layer within the concrete sandwich system remain a concern, as exposure to moisture or inadequate treatment could lead to material degradation over time, potentially compromising the wall's thermal performance and structural integrity. Fire safety presents another significant challenge, necessitating proper treatment of the bamboo material and compliance with building fire codes, which may increase construction costs and complexity. The construction process itself requires precise engineering and installation techniques to ensure proper integration of the three layers while maintaining structural stability, potentially demanding specialized expertise and increasing labor costs. Furthermore, the long-term performance and maintenance requirements of these composite walls in various climatic conditions remain relatively unknown, as extensive real-world performance data is limited. There are also structural considerations regarding the interface between bamboo and concrete layers, including potential issues with thermal expansion and contraction, which could affect the wall system's long-term stability. These limitations highlight the need for further research, testing, and development of standardized construction methods before widespread implementation can be achieved.

Rammed Earth Road

Another potential UHI mitigation technique is constructing rammed earth roads to replace low traffic roads that been constructed by concrete and asphalt such as driveways and residential streets, *Figure 12* shows a part of driveway road in Toronto which made by concrete, the idea is to replace these roads with rammed earth roads. This solution addresses both temperature regulation and UHI mitigation, offering multiple environmental benefits for urban spaces.

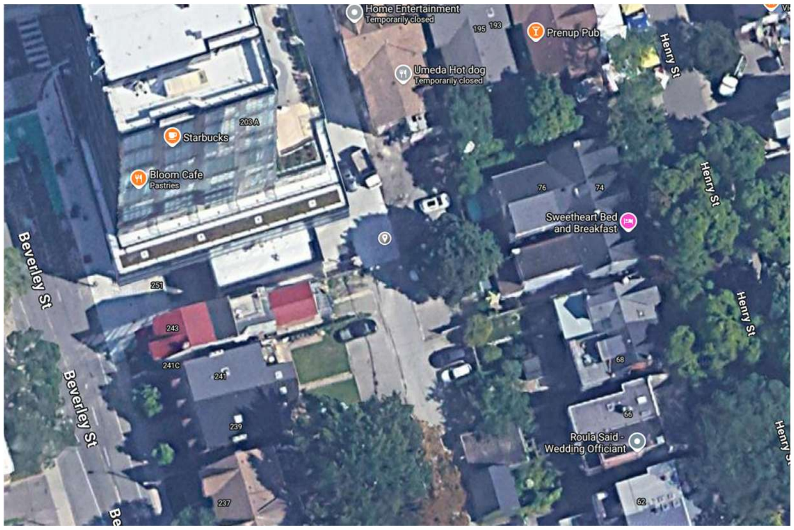

Figure 12: The concrete driveway in Toronto [Google Earth]

The temperature data from Toronto and King City shows significant temperature differences, particularly during nighttime hours, with variations of up to 6°C. This difference stems largely from the extensive use of asphalt and concrete surfaces in Toronto's urban environment and increased soil coverage in King City's landscape.

This idea of using rammed earth roads draws inspiration from indigenous communities worldwide, where unpaved dirt pathways have served as primary transportation routes for thousands of years. Native American settlements and ancient Asian communities all utilized natural dirt surfaces for local transportation needs. (Hendrickson, 2017) These historical precedents demonstrate not only the practicality of unpaved surfaces but also their sustainability in various climatic conditions. Before the widespread adoption of concrete and asphalt in the early 20th century, rammed earth roads were the norm in most human settlements, proving their viability for areas with moderate traffic.

The effectiveness of rammed earth roads in combating Urban Heat Island effects stems from several fundamental properties. Dirt's natural composition makes it an excellent medium for heat dissipation through multiple mechanisms., Dirt's porosity and water retention capabilities enable significant cooling through evaporation (Abu-Hamdeh, 2003). When moisture within the dirt structure evaporates, it carries heat away from the surface, creating a natural cooling effect that mimics the temperature regulation processes found in natural environments.

Furthermore, dirt facilitates heat conduction into deeper ground layers (Wang, Li, & Xu, 2021). This vertical heat transfer prevents surface heat accumulation, contrasting sharply with conventional pavements that tend to trap and retain heat. Unlike asphalt and concrete, which create a thermal barrier, dirt allows heat to move into the subgrade, utilizing the earth's natural thermal mass for heat dissipation.

Although there are significant advantages to using this method, there are also several limitations. In the context of Canadian urban environments, the extreme climate made the challenges for this technique. The freeze-thaw cycles characteristic of Canadian winters represents a primary concern. These cycles can severely compromise the structural integrity of rammed earth roads, leading to surface deterioration and potential road failure during spring thaw periods. The natural water retention property of dirt, while beneficial for cooling effects, becomes problematic during heavy rainfall events, spring snowmelt, and extended wet periods. These conditions can transform rammed earth roads into muddy, potentially impassable surfaces. The maintenance requirements for rammed earth roads in an urban context would be substantially more demanding than conventional pavements. Regular dust suppression and seasonal adaptations would necessitate specialized equipment and increased labor resources. The maintenance would need to vary significantly across seasons, creating operational complexities and potentially higher long-term costs compared to traditional paving solutions.

Conclusion

Temperature data clearly shows differences of up to 6°C between Toronto and King City, and up to 5° C between the Edmonton and Oliver ADGM, with particularly pronounced disparities during nighttime hours. Traditional mitigation techniques such as green roofs, while important, may need to be supplemented with more innovative solutions. The research presents two promising approaches: the integration of bamboo within concrete wall systems and the implementation of rammed earth roads in low-traffic areas. Bamboo provides sustainable benefits through its natural characteristics, while rammed earth roads present natural cooling mechanisms through evaporation and heat dissipation. These solutions, inspired by indigenous construction practices and modern engineering, represent a balanced approach to addressing UHI effects. However, successful implementation requires careful consideration of limitations and proper maintenance. As cities continue to grow and climate challenges intensify, the integration of these sustainable solutions, combined with existing mitigation strategies, will be crucial for creating more resilient urban environments.