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The Impact of Street Trees on Temperature Reduction in a Nature-Based Climate Adaptation Program in George Town, Malaysia

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Abstract: Nature-based solutions have been promoted as an effective strategy to address climate impacts, including urban temperature reduction. In this paper, we analyze the impacts of the introduction of street trees on temperature (Universal Thermal Climate Index, UTCI) for three different dates, 2000, 2023, and 2050. A 3D model was developed in Rhinoceros software for a part of George Town, on Penang Island. Four different sections of streets were simulated after integration of the model with the Grasshopper plug-in, where a parametric system was built for temperature measurements based on simulations in the Ladybug and Honeybee plug-ins. The tree species used were selected from a pool of tree species commonly planted in urban settings in Malaysia that have low and medium sensitivity to climate impacts. The results show a maximum reduction of 7 °C between 2000 and 2050, achieved on a street with an NW–SE orientation that was planted with three rows of trees. The minimum UTCI reduction achieved was 3 °C, between 2023 and 2050, in a street with NW–SE orientation that was planted with one tree row. The two streets with a SW–NE orientation showed a 5 °C temperature reduction between 2023 and 2050. Both streets have only one row of trees but different species and sizes, with the bigger trees reducing the temperature in a slightly larger area. The results show the importance of introducing and safeguarding street trees to reduce urban temperatures in the country, potentially keeping temperatures below life-threatening levels, thereby safeguarding urban health, while also reducing costs of energy consumption. Solar orientation, the number of tree rows, and their distribution impact the outcomes. The findings provide useful guidance for climate-conscious urban planning practices in Malaysia.

Keywords: urban adaptation; nature-based solutions; street trees; Grasshopper; Ladybug; microclimate simulation; UTCI

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1. Introduction

In the coming decades, urban areas in Malaysia are expected to face increased exposure to extreme heat due to climate change and the urban heat island (UHI) effect [1–3]. Extreme heat is among the most dangerous natural hazards globally [4]. Urban areas are particularly exposed, with heatwave days rising at a rate twice as fast in cities compared to rural or natural environments [5]. The combined impact of climate change and the UHI is projected to have significant repercussions on public health [1,6–8], leading to reduced work capacity and productivity among vulnerable populations [9]. Outdoor activities may also be severely compromised. In addition to temperature, humidity plays a critical role in limiting the human body's ability to regulate its temperature [9]. Research indicates that humid heat poses an even greater threat to human life than previously understood [10]. The frequency of extreme humid heat events has more than doubled since 1979 [11]. This threat is often measured by wet-bulb temperature (WBT), the equilibrium temperature of a wetted thermometer in high winds, commonly used to predict human heat stress [12], resulting from the combination of high relative humidity and temperature. When the air temperature exceeds a certain threshold, the body can only reduce metabolic heat through sweat-based latent cooling, which relies on sweat evaporation [13]. However, at WBT levels above approximately 35 °C—considered the threshold for human survivability in climate science [12]—this cooling mechanism becomes ineffective [10]. Reaching this threshold is a serious concern for Malaysia, as the country has very high relative humidity, between 75% and 95%, and average temperatures range from 23.7 °C to 31.3 °C [14]. Urban temperatures in the country often exceed comfortable levels for humans, and more than half of household energy consumption is dedicated to maintaining thermal comfort through air conditioning and refrigeration [15]. Another way of measuring temperature is the UTCI, defined as the air temperature under reference conditions that would produce the same physiological response as the actual environmental conditions. The difference between UTCI and air temperature is influenced by the actual values of air temperature, mean radiant temperature, wind speed, and humidity, which are expressed as either water vapor pressure or relative humidity [16]. UTCI values are categorized as follows: above +46 indicates extreme heat stress; +38 to +46 indicates very strong heat stress; +32 to +38 indicates strong heat stress; and +26 to +32 indicates moderate heat stress [17]. Previous studies focused on UTCI have shown Peninsular Malaysia to be exposed to extreme heat stress levels [18].

To address this challenge, the goal is to reduce urban temperatures, since relative humidity is not easily altered. Nature-based solutions (NbS) are highlighted as a potential central solution for climate change and are recommended for global implementation [19]. The benefits of NbS extend beyond addressing climate change, offering multifunctional advantages across social, public health, biodiversity, and financial domains, and have demonstrated favorable cost-benefit ratios [20]. In urban settings, NbS can be pivotal in transitioning towards more livable and sustainable high-density models [21]. Introducing green spaces has been identified as the most effective strategy for controlling rising temperatures [22]. Vegetation can significantly reduce urban climate impacts, helping to restore conditions closer to those before climate change [23], and can regulate the microclimate to mitigate the impact of heat waves [24].

Strategic planting involves selecting the most advantageous types of spaces, plants, and species, both generally and for specific locations. For instance, in the case of street trees, the arrangement of leaves and the shape of the canopy are crucial, with sparse crowns and large leaves providing better cooling effects [25]. Malaysia's equatorial climate appears to offer a natural advantage for implementing NbS, as the vegetation growth rate is significantly higher compared to other climates. It is important, however, to plant climate-resilient tree species. Among various NbS urban typologies for microclimate regulation, street trees have been identified as being the most effective [22,26]. They occupy minimal ground space, making them ideal for urban settings, and offer extensive protection from radiation for people, animals, structures, and materials, thus mitigating the urban heat island (UHI) effect [27]. Even a small number of trees can considerably reduce excessive heat [24]. The multiple benefits of urban green spaces are well-documented in research, particularly regarding public health. Green spaces provide cooling effects that help alleviate stress from overheating, which can lead to health impairments and increased mortality rates [24]. Moreover, they are associated with lower rates of obesity, cardiovascular diseases, high blood pressure, respiratory conditions, and diabetes [28]. Additional advantages include enhanced social cohesion, economic benefits, and aesthetic value [29].

Research has been conducted focusing on the impact of street trees in reducing urban temperatures, such as a study from 2024 showing an effective impact in reducing urban temperatures in Tacoma, Washington, USA [30]. A different study from 2021 used high-resolution satellite data from 293 European cities to assess the potential of urban trees to reduce land surface temperatures (LSTs) and showed that urban trees cool urban areas, especially in summer and during heat extremes (by 0–4 K on average in Southern Europe and by 8–12 K in Central Europe) [31]. Protecting existing urban trees and expanding urban tree planting are important measures to ensure climate resilience in urban areas [30]. A more detailed understanding of the cooling effects of green infrastructure is essential to inform and guide effective management and planning decisions [30]; urban trees' heat-mitigation effectiveness across climates spaces remains underexplored [31]. The novelty of this study is the examination of the impacts of street tree planting in the context of Malaysia, with its particular climate and architecture. This is timely research, as the question of urban trees is being discussed in the public arena due to deaths caused by trees falling [32,33]. Articles in mainstream media have emphasized the importance of technical concerns around the planting of trees in the country and their benefits in combatting climate change and enhancing the quality of life by reducing the urban heat island [34]. Trees are central to Malaysia's history and identity, often naming local places [34], and multiple urban greening campaigns have been developed, before and after independence, mostly focused on the ornamental component of urban greening [35]. The Greening Malaysia Program—a 5-year (2021–2025) initiative by the Ministry of Natural Resources, Environment, and Climate Change—includes the National 100 Million Tree Planting Campaign and aims to raise public awareness about the importance of green spaces and forests for well-being, quality of life, and enhancing the country's ecosystem and biodiversity [36]. A study has been developed focusing on the climate-resilience of urban trees in Malaysia to identify tree species that can withstand the climate of the future [2], and this study shows the impact of planting these species in terms of temperature reduction.

In this study, a model is developed to simulate the impact of introducing street trees on temperature reduction in Penang Island, located in Peninsular Malaysia at 5.3673° N, 100.2486° E. The street sections modeled are part of the nature-based climate adaptation program for the urban areas of Penang Island (PNBCAP) and will be tree-lined in the short-term. Promising results show a reduction in temperature between 3 °C and 7 °C, achieved with matured trees.

2. The Penang Program

2.1. Background

The design of the Nature-Based Climate Adaptation Program for the urban areas of Penang Island (PNBCAP) began in 2019, spearheaded by Think City, a Malaysian social impact organization. As the first program of its kind in Malaysia, the PNBCAP faced unique challenges due to the absence of a national adaptation plan (NAP), leaving no existing framework to follow. While waiting for the federal government to develop an NAP was an option, immediate action was necessary to protect the population from ongoing climate impacts. Penang, similar to much of coastal Malaysia, is at significant risk. Southeast Asia has been identified as one of the three global regions most vulnerable to climate change [37]. The decision was made to proceed, despite the lack of a pre-existing framework. To effectively reduce and manage climate impacts, the program's design was guided by a science-driven approach. This approach must account for various uncertainties related to the degree of impacts and representative concentration pathway (RCP) scenarios, which differ based on global collective action. However, certain impacts are expected across all scenarios for Malaysia, including rising temperatures, more frequent and severe extreme weather events, and sea level rise [38].

The governance structure of the PNBCAP involves collaboration among six primary stakeholders: the three executing entities, Think City (TC), the City Council of Penang Island (MBPP), the Department of Drainage and Irrigation (JPS); the Ministry of Natural Resources, Environment, and Climate Change (NRECC); UN-Habitat (UNH); and the Adaptation Fund (AF). Think City initiated and designed the program, bringing MBPP and JPS on board as executing partners, while UN-Habitat serves as the multilateral implementing entity (MIE) for the AF. TC also engaged with the National Designated Authority (NDA) for the AF to secure feedback, support, and endorsement. Since the program's inception in 2019, the NDA in Malaysia has transitioned from the Ministry of Energy, Science, Technology, Environment, and Climate Change (MESTECC) to the Ministry of Environment and Water (KASA) in 2020, and currently to NRECC [39].

The five-year program officially commenced in September 2022 with an inception workshop, having received USD 10 million in funding from the AF. The PNBCAP focuses on implementing nature-based solutions to mitigate the urban heat island (UHI) effect and reduce overall temperatures, as well as to improve stormwater management and decrease flooding. Additionally, the program includes components to strengthen social resilience and institutional capacity. The two pilot project areas in Penang Island are the George Town and Bayan Lepas mukims (sub-districts) (Figure 1).

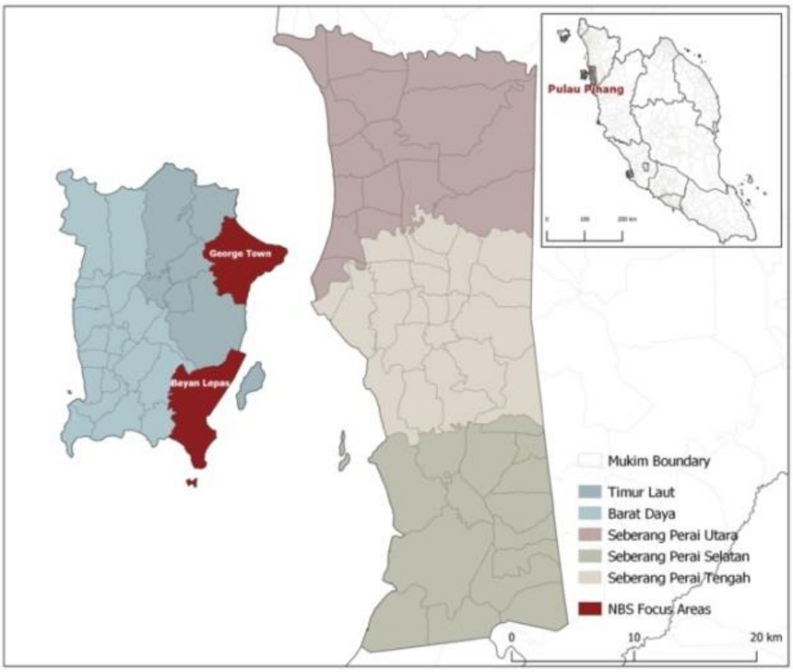

Figure 1. Map of Penang, George Town and Bayan Lepas mukims. Copyright by Think City. Source: Adaptation Fund, 2021 [40].

The two areas were chosen due to their diverse urban structure and substantial challenges in terms of climate impacts: George Town is a heritage area particularly vulnerable to both heat and flooding, and Bayan Lepas is a new urban area with wide streets and blocks and a strong presence of industry, which carries additional sources of heat. George Town, where the UNESCO core site is located (Figure 2), is densely built and has high levels of UHI effect, previously identified in remote sensing (Figure 3).

Figure 2. View over George Town, Penang Island. Copyright by Think City. Source: Castelo et al., 2023 [39].

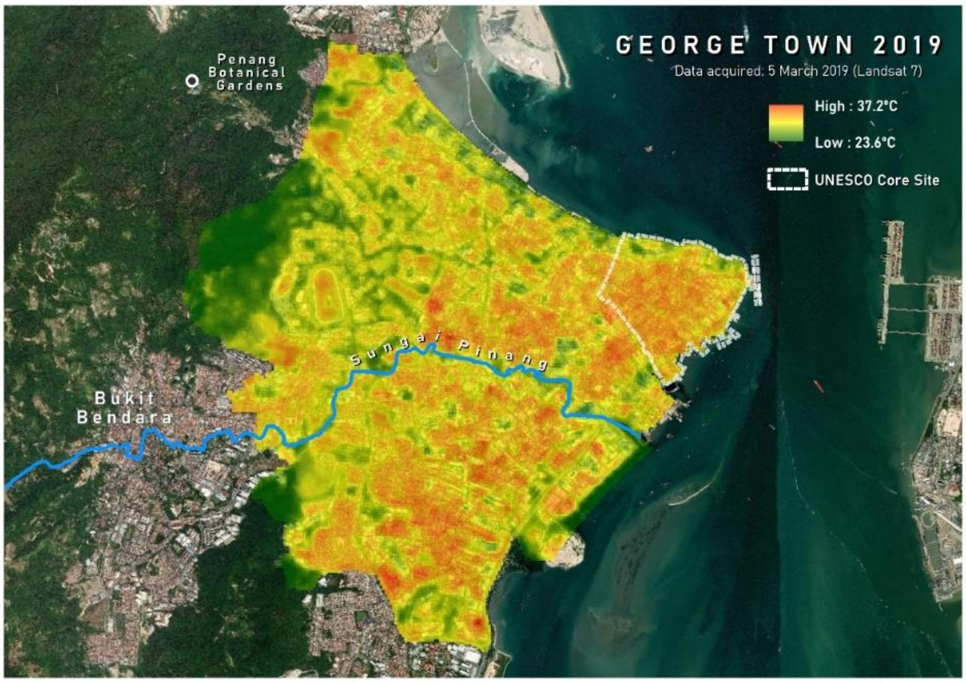

Figure 3. Land surface temperature of George Town, 2019. Source: Castelo et al., 2024 [41].

2.2. Urban Greening Component

The PNBCAP includes an urban greening component, which comprises the following initiatives: (a) planting street trees, (b) greening parking areas, (c) urban agriculture, (d) developing pocket parks in vacant spaces, and (e) greening built structures, rooftops, and facades.

Strategic analysis and planning are crucial, as green spaces need to be established in optimal locations to maximize the benefits in terms of reducing the UHI effect, considering factors such as solar orientation and air circulation. Street trees have been identified as being the most effective at accomplishing this goal, as mentioned previously. When selecting tree species to reduce urban temperatures, it is crucial to account for the impacts of climate change on candidate species. Tree species are vulnerable to climate impacts, and as they take a substantial time to mature and deliver benefits, there is a risk that, under climate change, trees planted today will reach maturity in a climate for which they are no longer suited. Studies from different parts of the world and employing different methodologies have highlighted the importance of understanding the climate resilience of urban tree species. A study conducted in California evaluated 73 species based on habitat suitability, physiology, and biological interactions, planting and assessing 144 specimens in experimental plots [42]. In Shanghai, another study focused on 65 urban tree species and developed an assessment framework to evaluate their adaptability to climate change impacts [43]. A third study [44] subjected 20 Australasian tree and shrub species to heat and drought stresses, revealing that water loss at high temperatures can push species toward mortality thresholds faster than anticipated. Each study's adopted methodology is tailored to specific goals, reflecting their respective locations' unique regional and climatic considerations.

Urban trees in Malaysian cities are anticipated to face heightened vulnerability to climate change, particularly due to projected declines in suitable habitats in warmer regions [45]. Regions located at lower latitudes are expected to encounter greater risks associated with climate change impacts [46]. Considering the issue's importance, a study was conducted on the climate resilience of urban tree species in Peninsular Malaysia to assist in the choice of tree species to be planted under the urban greening component of PNBCAP [2].

2.3. Climate-Resilient Urban Tree Species Study and ACResT Database

The study focused on assessing the resilience of tree species to climate-related stresses within Malaysian urban environments [2]. Its objective was to identify species that are more likely to withstand future changes in Malaysia's urban climate, thereby contributing valuable insights for future-oriented and climate-aware urban forestry management. The protocol used to evaluate species resilience to climate change draws heavily from the approach introduced by Lee et al. (2019) [47], which was inspired by the framework initially developed by Foden et al. (2013) [48]. Foden and colleagues established a framework that examines three key dimensions of vulnerability to climate change: (1) 'exposure' (the anticipated extent and nature of climatic changes affecting a species); (2) 'sensitivity' (the species' capacity to persist in its current habitat despite climate change); and (3) 'adaptive capacity' (the species' ability to endure through dispersal or microevolutionary changes). Each dimension includes specific criteria and associated assessment protocols that are systematically applied to assess the vulnerability of each species to climate change. Although Peninsular Malaysia has approximately 2830 tree species [49], urban spaces feature a limited selection. According to the species occurrence matrix in the Global Urban Tree Inventory, Kuala Lumpur and Putrajaya, Malaysia, host 60 and 71 tree species, respectively [50]. The study covers only 220 species (approximately 8%) of the total tree flora in Peninsular Malaysia. A more comprehensive representation of Malaysian tree taxa is essential, considering the country's rich biodiversity and its significant global contribution to tree diversity. A total of eight criteria were used to assess sensitivity or resilience in the study. The findings indicate that climate change is already affecting urban tree species in Malaysia, with different species displaying varying vulnerabilities to these impacts [2]. Assessing the resilience of tree species to various climate effects is vital for selecting species that can thrive in Malaysia's future climate. Similar conclusions have been drawn from the studies developed for California [42], Shanghai [43], and Australasia [44,45].

During the study's development, it became evident that as climate impacts continue to evolve, ongoing documentation of climate resilience is essential. This effort will also facilitate the analysis of a wider range of tree species. To support this, the Atlas for Climate Resilient Tree Species (ACResT) was created, compiling planting suitability data for tree species found in Malaysia [51]. This database serves as a practical and comprehensive tool for selecting tree species, featuring links to nurseries where these species are available. ACResT also serves as a platform for documenting species characteristics, including attributes related to climate change resilience, reflecting the diverse species found in Malaysia and anticipating shifts in weather patterns in the digital age. The assessments conducted on the 220 species in the study are accessible on the database, allowing for broader review by practitioners to ensure consistent application of criteria. This process aims to gather additional insights into the aspects categorized as 'Unknown' in assessments. The database includes information on urban suitability and biodiversity, as well as cultural and economic values associated with each species.

The tree species selected to be planted in the PNBCAP were selected from the pool of low- or intermediate-sensitivity species identified in the study and accessible in the ACResT platform.

2.4. Street Tree Planting Schemes

Street tree planting schemes were developed for the PNBCAP. This study focuses on four street sections in George Town (Figure 4): one that was renovated before the initiation of the PNBCAP and three that will be tree-lined as part of the program. Gat Lebuh China, the street renovated in 2017, had tree-lined sections introduced at that time.

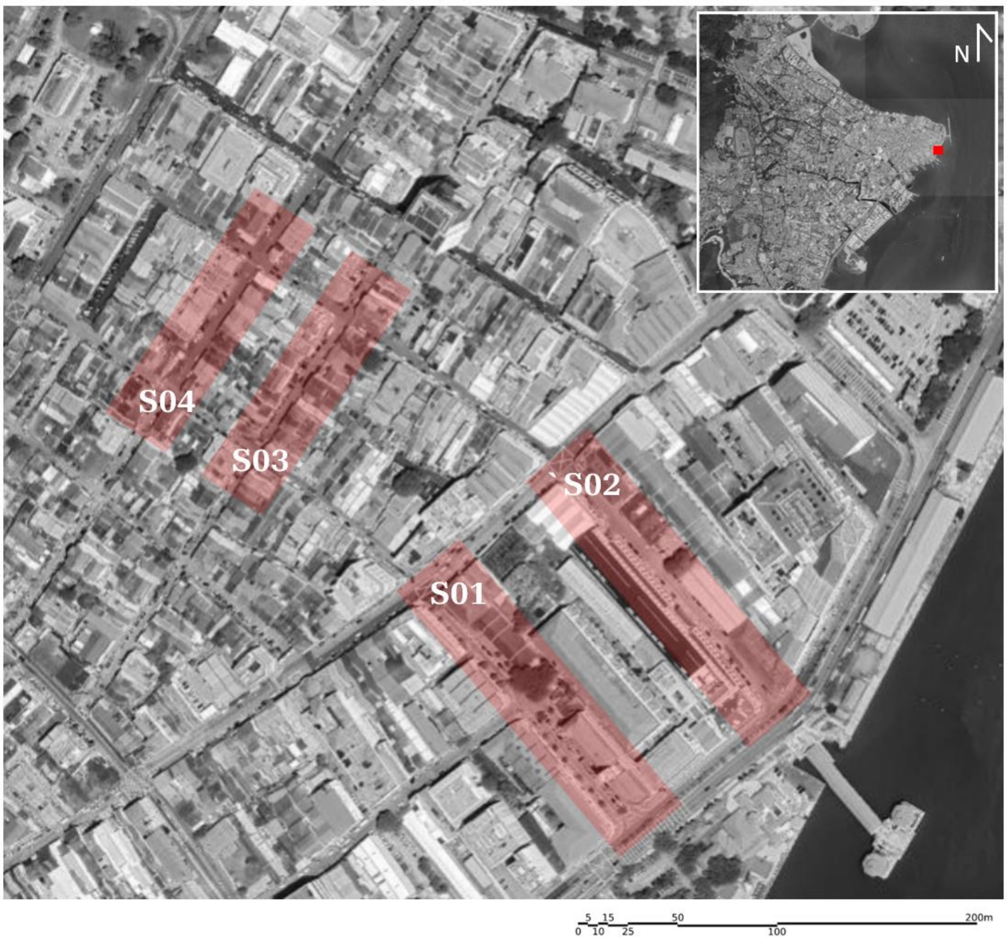

Figure 4. Location of street sections modeled, S01–S04.

The other streets are Gat Lebuh Gereja (S01), parallel and adjacent to Gat Lebuh China (S02); Lebuh Penang (S03); and Lebuh King (S04), parallel and adjacent to Lebuh Penang. None of these streets currently have street trees planted, but all three are scheduled to have them introduced under PNBCAP within the next three years.

Gat Lebuh China (Figures 5 and 6) currently has three rows of trees: two on the sidewalks and one in the center, in between the directions of travel. On the sidewalks, the species *Talipariti tiliaceum*, having the common name of sea hibiscus in Malaysia, was planted. This medium-sized, round-shaped tree species has low sensitivity to climate impacts, as evaluated in the research [2] and documented on the ACresT website [51]. In the center, two tree species are planted, *Conocarpus erectus*, commonly known in Malaysia as buttonwood, and *Pterocarpus indicus*, commonly known as angsana tree. The first is a medium-sized, round-shaped tree, planted in most of the street section. This species' climate resilience is unknown. The second species is a large, dome-shaped tree, located only in the intersections with other trees, where a wider planter was introduced. *Pterocarpus indicus* has intermediate sensitivity to climate impacts, as evaluated in the research and documented on the ACresT website. Two mature *Pterocarpus indicus* are pre-existing in the middle section of the street.

Figure 5. S01, Gat Lebuh China, 2023. Copyright: Melissa Sivaraj, Think City.

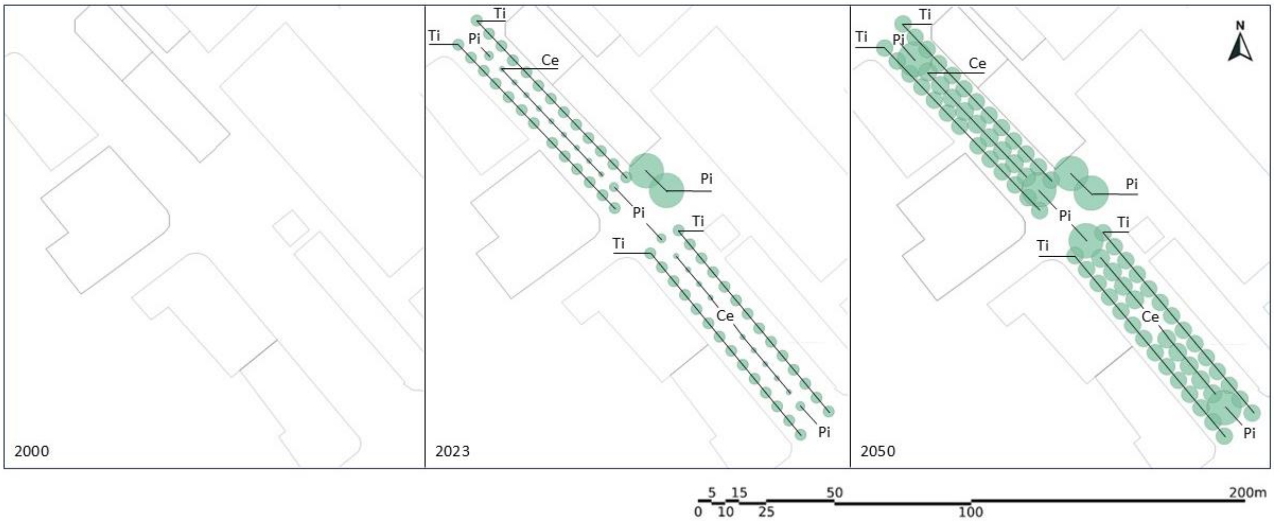

Figure 6. Tree-lined trees in Gat Lebuh China, George Town, Penang, 2000, 2023, and 2050. Ce: *Conocarpus erectus*; Pi: *Pterocarpus indicus*; Ti: *Talipariti tiliaceum*.

In Gat Lebuh Gereja (Figure 7), the species selected to be planted was *Lagerstroemia speciosa*, commonly known in Malaysia as pride of India. This medium-sized, round-shaped tree has intermediate sensitivity to climate impacts, as evaluated in the research and documented on the ACresT website.

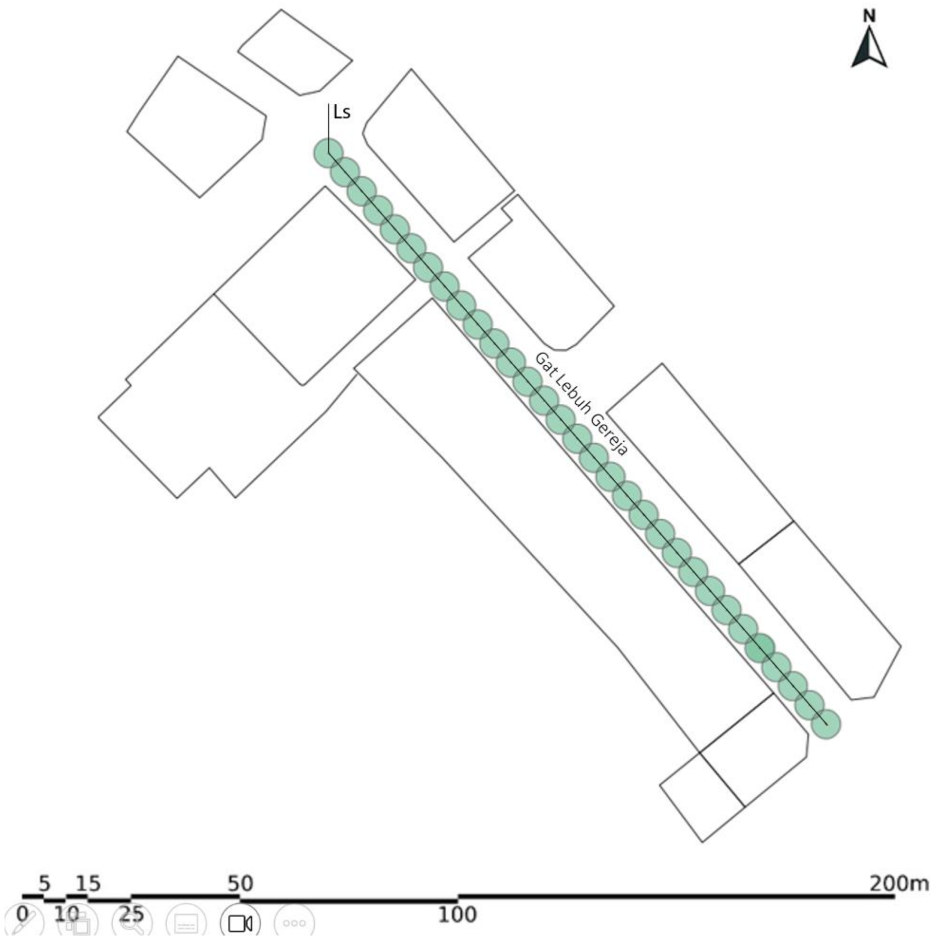

Figure 7. Street tree plan for S02 (Gat Lebuh Gereja). Ls: *Lagerstroemia speciosa*.

The tree species used in sections S02–S04 and two of the three species in S01 are presented in Table 1.

Table 1. S01–S04 tree species characteristics. Source: Chen et al. (2015) [52].

	Tree Species	Height (m)	Diameter of Canopy (m)
1	*Conocarpus erectus*	13 m	7 m
2	*Lagerstroemia speciosa*	12 m	8 m
3	*Pteleocarpa lamponga*	24 m	13 m
4	*Talipariti tiliaceum*	10 m	6 m
5	*Pterocarpus indicus*	25 m	18 m

In Lebuh Penang (Figure 8), the species selected to be planted was *Pteleocarpa lamponga*, commonly known as tembusu tikus in Malaysia. This large, oval-shaped tree has intermediate sensitivity to climate impacts, as evaluated in the research and documented on the ACresT website.

Figure 8. Street tree plans for S03 and S04 (Lebuh Penang and Lebuh King). Pl: *Pteleocarpa lamponga*; Tt: *Talipariti tiliaceum*.

In Lebuh King (Figure 8), the species selected to be planted was *Talipariti tiliaceum*, commonly known as sea hibiscus in Malaysia. This medium-sized, round-shaped tree, also planted in Gat Lebuh China, has low sensitivity to climate impacts, as evaluated in the research and documented on the ACresT website.

3. Methodology

3.1. Methodological Procedures

To carry out the experiment, a methodology consisting of four stages was applied, where the first two stages are related to the definitions of the area of study, and the last two are related to the simulation itself.

The first step consisted of the model definition, when the object definition for the simulations was carried out and its sections that can be used as case studies were defined. Once this definition was made, the tree growth stages, whose shading impacts can be evaluated, were selected.

The second step consisted of the definition of the climate file to be used in the simulations and the selection of the analysis periods that were intended to measure the effectiveness of the trees.

Then, for the third stage, the software used for the digital modeling of the built volume and the vegetation was chosen to sequentially define and use the environmental analysis and engine plug-ins for running the simulation.

Finally, the fourth stage was the definition of the desired metric to export the simulation results according to what is aimed to be evaluated. After these stages, conclusions were made.

3.2. Case Study

This research is based on the impact of the introduction of trees in urban streets, as planned in the PNBCAP. Therefore, the case study has its object defined as a part of the urban area of George Town, on Penang Island, digitally modeled as shown in Figure 9, where a set of building blocks of different dimensions and streets with different geographic orientations are contained.

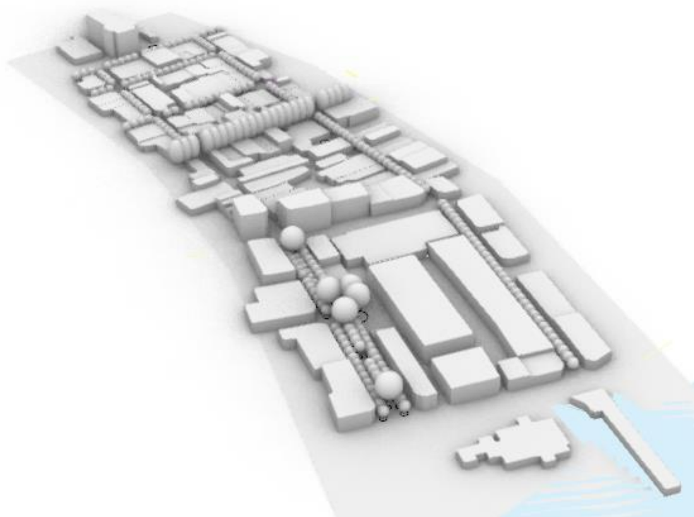

Figure 9. Digital model developed for part of George Town, Penang, in Rhinoceros 3D 7 software. The year 2050, with all trees illustrated as being mature—including Gat Lebuh China (S01), Gat Lebuh Gereja (S02), Lebuh Penang (S03), and Lebuh King (S04).

Four different street sections were selected, identified in Section 2.4., and the simulations were carried out for different time frames based on the growth stage of the trees. For Section 01 (S01), simulations were carried out in three different scenarios, considering a past scenario of the absence of planted trees (2000); the current growth stage of the trees (2023); and a future scenario, where trees will reach maturity (2050). For Section 02 (S02), Section 03 (S03), and Section 04 (S04), simulations were carried out for two scenarios on these streets: the current stage without trees (2023) and in the future, with the trees having grown to their mature size (2050). All the tree species were chosen from a pool of low- to medium-sensitivity to climate impacts, and the model was developed considering each species' growth rate, mature size, height, width, and canopy shape.

A current existing climate file in EPW format was applied to Penang (a historical average of temperatures starting in 1973), obtained from measurements carried out at the local airport. Additionally, the period chosen to carry out the analyses was the month of May, as it is the hottest month in Peninsular Malaysia, in a time frame from 11 am to 2 pm, the hottest time of the day.

Rhinoceros 3D software, integrated into the Grasshopper plug-in, was used, in which a parametric system was built that allowed temperature measurements based on simulations in the Ladybug 1.8.0 and Honeybee plug-ins. The Grasshopper plug-in is a visual programming language, where it is possible to install the Ladybug and Honeybee environmental analysis plug-ins.

Ladybug allows climate data analyses to be carried out by generating diagrams, considering aspects such as shading, geometry, and radiation. Ladybug 1.8.0 is a collection of computational applications integrated with validated energy and environmental simulation engines, such as Radiance 6.0a and EnergyPlus 24.1.0.

Honeybee uses the same simulation mechanisms to create and allow visualizations of energy models, working in a complementary way to Ladybug. In this way, the modeled system considered existing buildings, with their morphological characteristics; existing and planned trees; and the paving material. Honeybee is the plug-in where zones are created for the use of validated simulation engines, such as EnergyPlus.

Because of this, the process of modeling an urban area in Rhinoceros 3D, followed by the insertion of the model in Grasshopper, with the assembly of a system for environmental analysis in Ladybug + Honeybee constitutes a valid methodology for understanding the environmental behavior of different scenarios, both indoors and outdoors. Furthermore, the possibility of parameterization that the software allows for the constructed digital model is capable of allowing changes to the project quickly and punctually, if the simulations do not meet expectations. Additionally, the simulation processing time proved to be satisfactory, being faster than other software tested, whose simulations became unfeasible for large stretches of streets with the processing capacity of the computers available for this research.

Once the system was built, it employed simulations based on the Universal Thermal Climate Index metrics (UTCI) to generate temperature maps from a grid of points modeled every two meters, one meter above the ground level.

The general workflow of the experiment is shown in Figure 10.

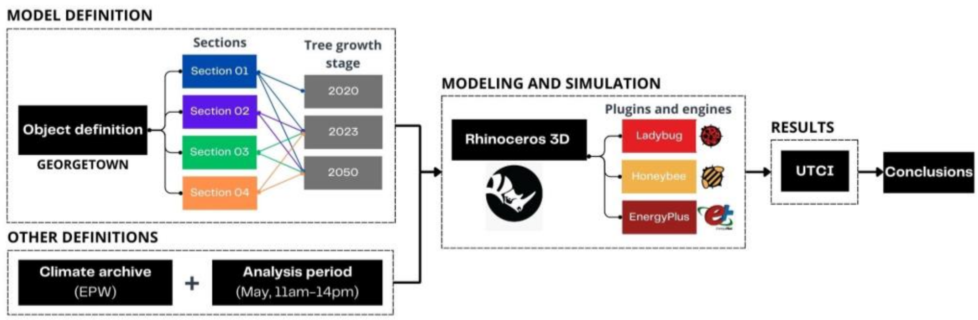

Figure 10. General workflow of the experiment.

4. Results

The results of the simulations of temperature reduction provided by the insertion of trees in the three different time frames—2000, 2023, and 2050—were exported in the form of a UTCI spatial map from the grid assembled with temperatures in °C, as can be seen in Figure 11, Figure 12, Figure 13, and Figure 14, which represent S01, S02, S03, and S04, respectively.

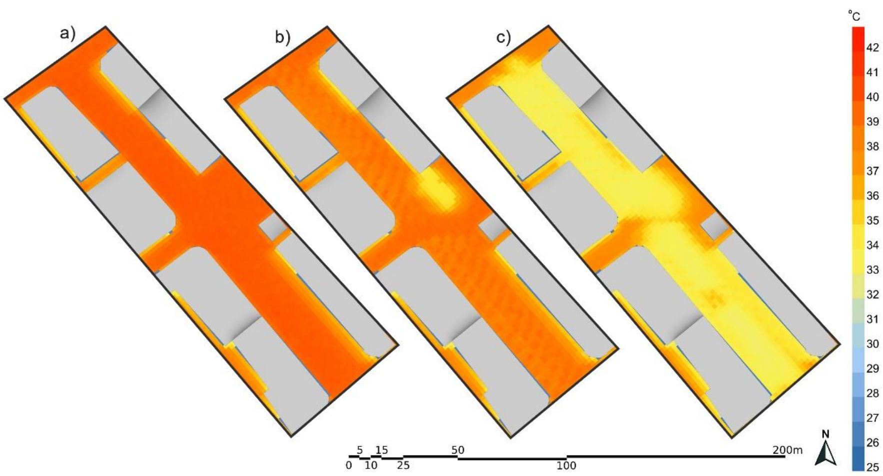

Figure 11. Simulated UTCI for S01, 2000 (**a**), 2023 (**b**), and 2050 (**c**).

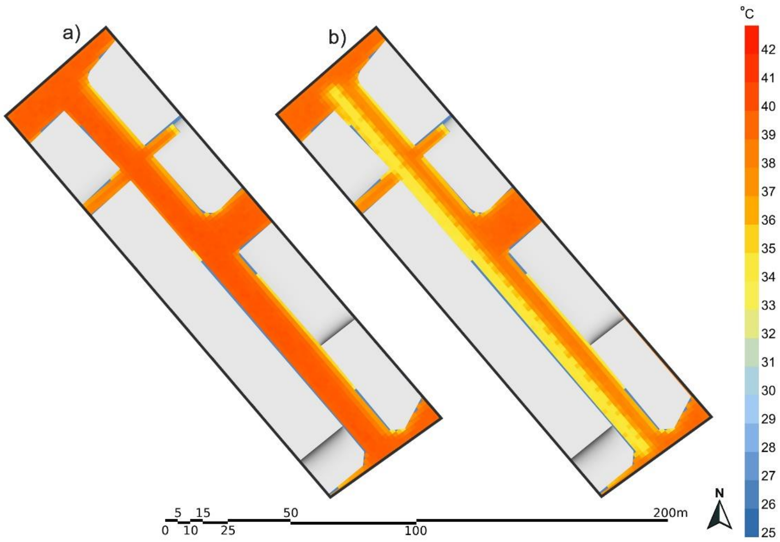

Figure 12. Simulated UTCI for S02, 2023 (**a**) and 2050 (**b**).

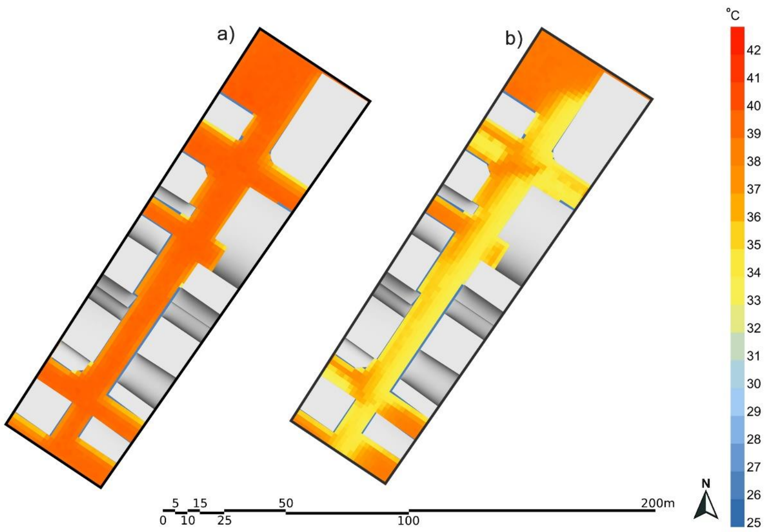

Figure 13. Simulated UTCI for S03, 2023 (**a**) and 2050 (**b**).

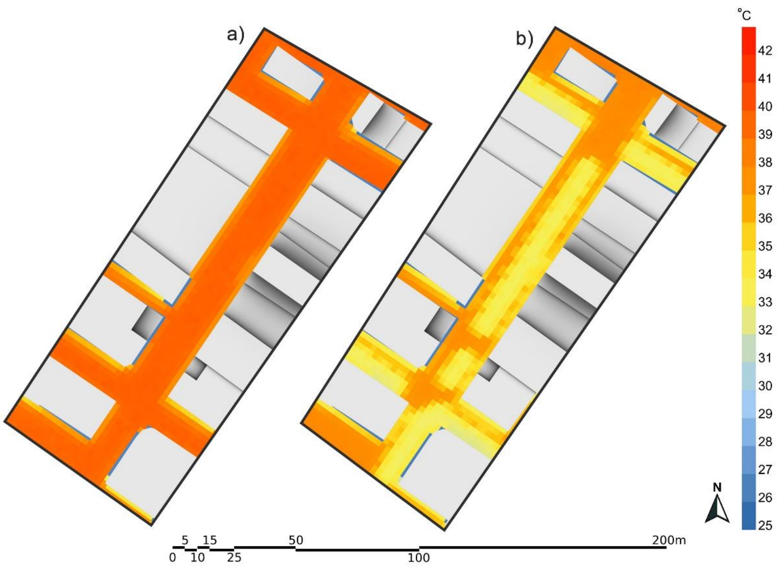

Figure 14. Simulated UTCI for S04, 2023 (**a**) and 2050 (**b**).

Additionally, the analysis of the data obtained from the spatial maps was summarized in Table 2, containing numerical comparisons of temperature reduction between the different time intervals, identifying the percentages of the area that had each temperature reduction for each one of the four scenarios simulated.

Table 2. Simulated UTCI for sections 01 (2000, 2023, 2050), and 02, 03, and 04 (2023, 2050).

Sections	**UTCI (°C) 2000**	**UTCI (°C) 2023**	**UTCI (°C) 2050**	**UTCI Reduction (°C) 2000–2023 * 2023–2050 ** 2000–2050 ***
Section 01	40 °C	38 °C (with a cooler spot of 34 °C beneath two mature trees)	33 °C	2 °C *; 5 °C **; 7 °C ***
Section 02	-	40 °C	37 °C (40% of the street); 34 °C beneath the trees (40% of the street). Approx. 20% in between temperatures.	3 °C **; 6 °C **
Section 03	-	39 °C	34 °C (with spots of 35 °C).	5 °C **
Section 04	-	39 °C	34 °C (with spots of 33 °C, 35 °C, and 36 °C).	5 °C **

* UTCI difference over the time interval between 2023 and 2000. ** UTCI difference over the time interval between 2023 and 2050. *** UTCI difference over the time interval between 2050 and 2020.

5. Discussion

The results reveal a maximum temperature reduction of 7 °C in section 01 between 2000 and 2050, on the NW–SE-oriented street with three rows of trees. The UHI effect appears to have been eliminated in this section. Between 2000 and 2023, there was a 2 °C temperature reduction, just 6 years after the trees were planted. This suggests that temperature reduction can be relevant even if the trees have not fully matured.

The minimum reduction, 3 °C, occurred on a NW–SE-oriented street with only one row of trees. The two streets with a SW–NE orientation were cooler by 1 °C before tree planting, achieving a 5 °C temperature reduction in 2050. These streets each have a single row of trees, but different species and sizes, with the bigger trees cooling a larger area but not substantially. The difference in size does not appear to have been reflected proportionally in terms of temperature reduction. Solar orientation proved to be of consequence: one single row of trees was more impactful in terms of temperature reduction in the cases of SW–NE orientation than in the NW–SE orientation. Solar orientation, the number of tree rows, and their distribution all influence the effectiveness of temperature reduction.

However, one of the two main limitations of this study is the limited size of the model, which consists of four separate street sections with a maximum length of 200 m. This reduces the potential of representation of interrelated impacts of all new tree-lined streets in reducing the UHI effect. An overall model for the entirety of George Town can allow for exploring the temperature reduction as a result of the implementation of all the urban greening components, beyond tree-lined streets. The models can also be developed not only for the horizon of 2050, when trees are expected to reach maturity, but also in previous states of development, to understand the impact of different stages of tree growth.

Another main limitation of this study is in using only one climate parameter for 2000, 2023, and 2050. The temperature reduction obtained in the simulations does not, therefore, account for the temperature increase that will take place by 2050. It is important, however, to establish a baseline scenario of temperature reduction resulting from the introduction of street trees with no temperature changes, which can be compared with further models developed in the future for different SSPs. This research is the first of several planned studies, ideally culminating with the entire George Town district modeled under

SSP2-4.5, SSP3-7.0, and SSP5-8.5, and including the full scope of the PNBCAP's urban greening components.

6. Conclusions

This study demonstrates that introducing street trees can effectively reduce urban temperatures in Malaysia, reducing the UTCI between 3 °C and 7 °C when they reach maturity. The methodology allows the anticipation of the contribution of the urban greening components to climate impacts in terms of temperature reduction. The outcomes of this study offer valuable data and insights to inform the ongoing national debate on the risks and benefits of urban trees.

The findings indicate that street trees can effectively lower urban temperatures in Malaysia, potentially saving lives by keeping temperatures below life-threatening scenarios, while reducing energy costs. The findings also show variations of impact that may provide useful guidance for urban planting. Such is the case of solar orientation: one single tree row is more impactful for temperature reduction in a SW–NE orientation than for NW–SE orientations at this urban scale. NW–SE streets seem to benefit from having a minimum of two rows of trees.

The studies being planned will offer more detailed information on the impact of urban greening strategies. Further research into the integration of street trees with green facades, roof gardens, and other types of green spaces could provide valuable insights into the most effective combinations of urban greening across various scales and typologies. Additionally, exploring these interactions in different urban settings may yield more granular data on how these combinations affect temperature regulation and other environmental factors. Such findings will enhance the understanding of how NbS can be optimized for urban heat adaptation and overall climate resilience, offering significant guidance for climate-conscious urban planning practices in Malaysia.

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