Artificial intelligence in urban forestry

Strategic tree placement for improved climate adaptation

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Abstract

This study explores the integration of Artificial Intelligence (AI) into urban forestry practice—i.e., AI-driven urban tree-planting practices to optimise tree placement to enhance urban microclimates. Utilising the Ant Colony Optimisation (ACO) algorithm, this research strategically positioned trees within an urban park to improve thermal comfort and overall climatic conditions. Detailed simulations conducted during the hottest week of the year assessed the impact of these optimised tree placements. The results demonstrate significant improvements in urban microclimate conditions, including reduced temperatures and increased shading, thereby highlighting the potential of AI-driven approaches in urban planning. This paper provides invaluable insights for policymakers and urban planners advocating the incorporation of AI technologies to develop sustainable and resilient urban environments and new insights for urban forestry. These findings underscore AI's pivotal role in climate change mitigation and adaptation and offer innovative solutions to enhance urban living conditions.

Introduction

Background

In the age of climate change, Artificial Intelligence (AI) has so much to offer to urban forestry with its innovative approaches to managing and enhancing green spaces within cities (De Lima Araujo et al. 2021). As the impact of climate change has become increasingly apparent, the role of natural solutions in mitigating and adapting to these changes has gained significant attention (Donatti et al. 2022; Debele et al. 2023). Among these solutions, trees stand out as one of the most effective and versatile tools for addressing climate-related challenges (Bäckstrand & Lövbrand 2006; Degirmenci et al. 2021). Trees contribute to climate regulation through a variety of mechanisms, making them indispensable for creating sustainable and resilient urban and rural environments (Figure 1).

One of the primary ways trees combat climate change is through carbon sequestration. Trees take in carbon dioxide (CO_2) from the atmosphere and use photosynthesis to turn it into biomass (Baral & Guha 2004). This process not only reduces the concentration of greenhouse gases in the atmosphere but also stores carbon in the form of trunks, branches, leaves, and roots (Johnson & Gerhold 2003). This carbon can remain sequestered for decades or even centuries, providing a long-term solution to offset anthropogenic emissions. Research has indicated that forests and urban trees are crucial for global carbon storage, highlighting the importance of maintaining and expanding tree cover (Velasco et al. 2016).

Beyond their role in carbon sequestration, trees play a vital role in regulating temperature, especially in urban areas (Teskey et al. 2015). Urbanisation often leads to the creation of urban heat islands, where temperatures are significantly higher than those in the surrounding rural areas due to human activities and infrastructure (Kamruzzaman et al. 2018). Trees help mitigate this effect by providing shade and through transpiration, where they release water vapour and cool the air (Coutts et al. 2016). Studies have shown that the presence of trees can reduce local temperatures by several degrees, thereby creating more comfortable and stable microclimates (Aminipouri et al. 2019; Armson et al. 2012; Bäckstrand & Lövbrand 2006).

In addition to their cooling effects, trees contribute to energy conservation. By strategically planting trees around buildings, energy consumption for heating and cooling can be significantly reduced (Sawka et al. 2013). In summer time, trees provide shade that lowers the demand for air conditioning, whereas in winter, they can act as windbreaks, reducing heating costs. This reduction in energy use not only lowers greenhouse gas emissions from power generation but also translates into economic savings for residents and businesses (Carver et al. 2004; Hwang et al. 2017).

Additionally, by absorbing ozone (O_3), ammonia (NH_3), and nitrogen oxides (NO_x), trees help improve air quality. They trap particulate matter in their leaves and bark, which can lead to a significant reduction in respiratory health issues, particularly in urban areas (Nowak et al. 2018; Nowak et al. 2006). The ability to filter air pollutants underscores the critical role of urban forestry initiatives in promoting public health and environmental quality (Steinparzer et al. 2023).

Water management is another area where trees provide substantial benefits. They intercept rainfall, reduce runoff, and minimise the risk of flooding (Marapara et al. 2021). Their root systems enhance soil infiltration and groundwater recharge while also preventing soil erosion. These functions are essential for maintaining healthy hydrological cycles and protecting

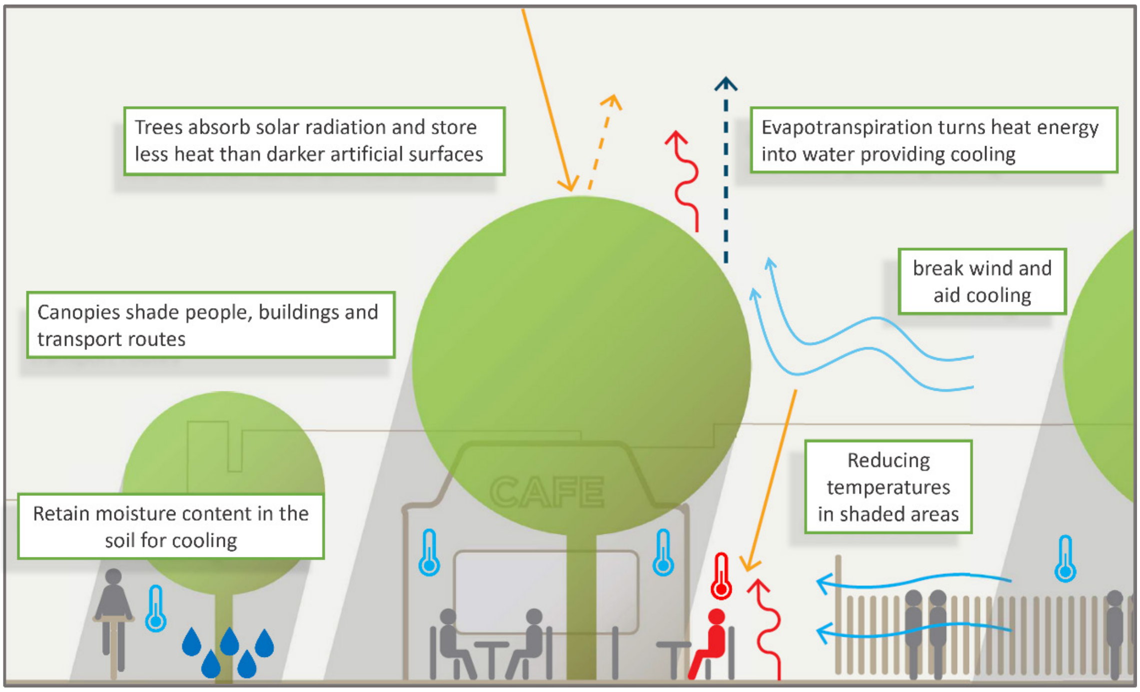

Figure 1: Impact of trees on the surround areas (Shaamala et al. 2024b).

water resources, particularly in urban environments, where impervious surfaces are prevalent (Berland et al. 2017; Russo et al. 2020). Moreover, trees support biodiversity by providing habitat and food sources for a wide range of wildlife species (Barrios et al. 2018). In particular, urban forests, which are vital for plant reproduction and food security, are crucial for pollinators such as bees and birds. Biodiversity underpins ecosystem services crucial for human well-being and resilience, highlighting the interconnectedness between natural and human systems (King et al. 2021).

The social and economic benefits of these trees were equally significant. Green spaces with trees offer recreational opportunities, reduce stress, and enhance mental health (Pasanen et al. 2023). Mature trees often have a higher market value, contributing to economic stability and growth in communities (King et al. 2021). Furthermore, trees enhance the resilience of both natural and human systems to climatic variability (Simonson et al. 2021). They provide shade and reduce heat stress in urban areas, which is particularly important as global temperatures increase. Trees can also serve as natural barriers against extreme weather events such as storms and floods (Van Hespen et al. 2023), thus protecting infrastructure and human lives.

Recent advancements in tree-location optimisation have further highlighted the importance of strategic tree placement in urban planning (Zhao et al. 2018; Shaamala et al. 2024b). Using computational models, urban planners can optimise tree locations to maximise their environmental benefits (Stojakovic et al. 2020). Optimised tree placement can enhance cooling effects, improve air quality, and increase carbon sequestration efficiency. These models consider various factors, such as local climate, existing vegetation, urban infrastructure, and socioeconomic considerations, to identify the most effective locations for planting trees (Shaamala et al. 2024a).

AI has emerged as a powerful tool for enhancing the effectiveness of tree-planting and management strategies. AI algorithms can analyse vast amounts of data to predict optimal planting locations, forecast the growth and health of urban forests, and model the environmental impact of tree-planting initiatives (Bajsanski et al. 2016; Wallenberg et al. 2022). The ability of AI to process and analyse complex datasets enables it to identify the best locations for tree planting, considering various environmental and infrastructural constraints (Chen et al. 2008; Hao et al. 2023). Additionally, AI models can simulate the potential impact of different tree configurations on urban microclimates, helping to optimise tree placement for maximum cooling and air quality improvement (Shaamala et al. 2024b).

In summary, the integration of AI into urban forestry practices enhances the precision and effectiveness of tree-planting strategies. By leveraging AI capabilities, urban planners can create greener, healthier, and more resilient cities, ultimately contributing to improved environmental quality and human well-being.

Tree optimisation objectives

The tree optimisation objectives were categorised into six critical climate change mitigation goals (Shaamala et al. 2024a) (Figure 2): (a) enhancing air quality by absorbing pollutants and filtering particulate matter; (b) supporting biodiversity and ecosystem security by providing habitats and connecting ecological corridors; (c) increasing energy efficiency through

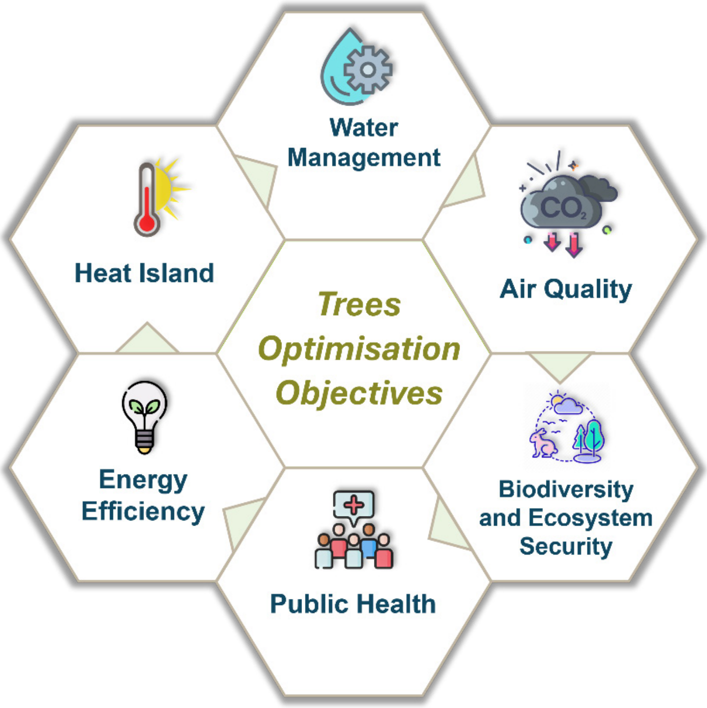

Figure 2. Tree optimisation objectives (Shaamala et al. 2024a).

natural cooling and shading to reduce reliance on air conditioning; (d) promoting public health by creating green spaces that encourage physical activity and improve mental well-being; (e) mitigating urban heat islands by reducing surface and air temperatures; and (f) optimising water management by improving stormwater infiltration and reducing runoff. Collectively, these objectives contribute toward creating a more resilient and sustainable urban environment.

Case study: optimising tree locations for enhancing urban thermal heat

In this study, we employed a multistep optimisation approach to enhance urban heat mitigation through strategic tree placement. The methodology involves the integration of an optimisation algorithm to identify optimal tree locations within an urban park setting, considering multiple constraints and environmental factors (Figure 3). The primary objective is to minimise the Universal Thermal Climate Index (UTCI), thereby improving thermal comfort in urban areas.

Study area

The methodology selected a hypothetical study area and established the initial conditions. A 50×50m plot was chosen, which is an appropriate size for an urban park suitable for conducting tree-optimization experiments. The terrain was assumed to be generally flat with limited existing vegetation cover, making it ideal for analysing the impact of newly planted trees. The soil type in the area was assumed to be loamy, providing favourable conditions for tree growth owing to its good drainage and nutrient-holding capacity. This soil type supports deep root growth without requiring significant soil modification (Figure 4).

Simulation period selection

The simulations to evaluate the cooling effect of tree placement during extreme heat were conducted in Brisbane, Queensland's capital, during the hottest week of February 2023—i.e., 17th-23rd. During this period, temperatures ranged from 23°C to 37°C, which is typical of Brisbane's summer and its pronounced urban heat island effect. The subtropical climate of Brisbane, characterised by high relative humidity, intensifies the perceived heat beyond the actual air temperature. This combination of high temperature and humidity significantly affects human comfort, energy consumption, and urban liveability. By focusing on this particular week, this study aimed to examine tree allocation optimisation under challenging and increasingly common climatic conditions, providing insights into effective strategies for enhancing urban thermal comfort.

Optimisation trajectory and UTCI reduction

The Ant Colony Optimisation (ACO) algorithm is a nature-inspired optimisation technique based on the foraging behaviour of ants (Dorigo & Di Caro 1999). In this algorithm, artificial ants build solutions to optimisation problems by simulating the way real ants find the shortest paths to food sources. The algorithm iteratively improves solutions by reinforcing paths that lead to better outcomes, making it a powerful tool for solving complex problems. The results demonstrated that the ACO algorithm effectively optimised tree locations to enhance the

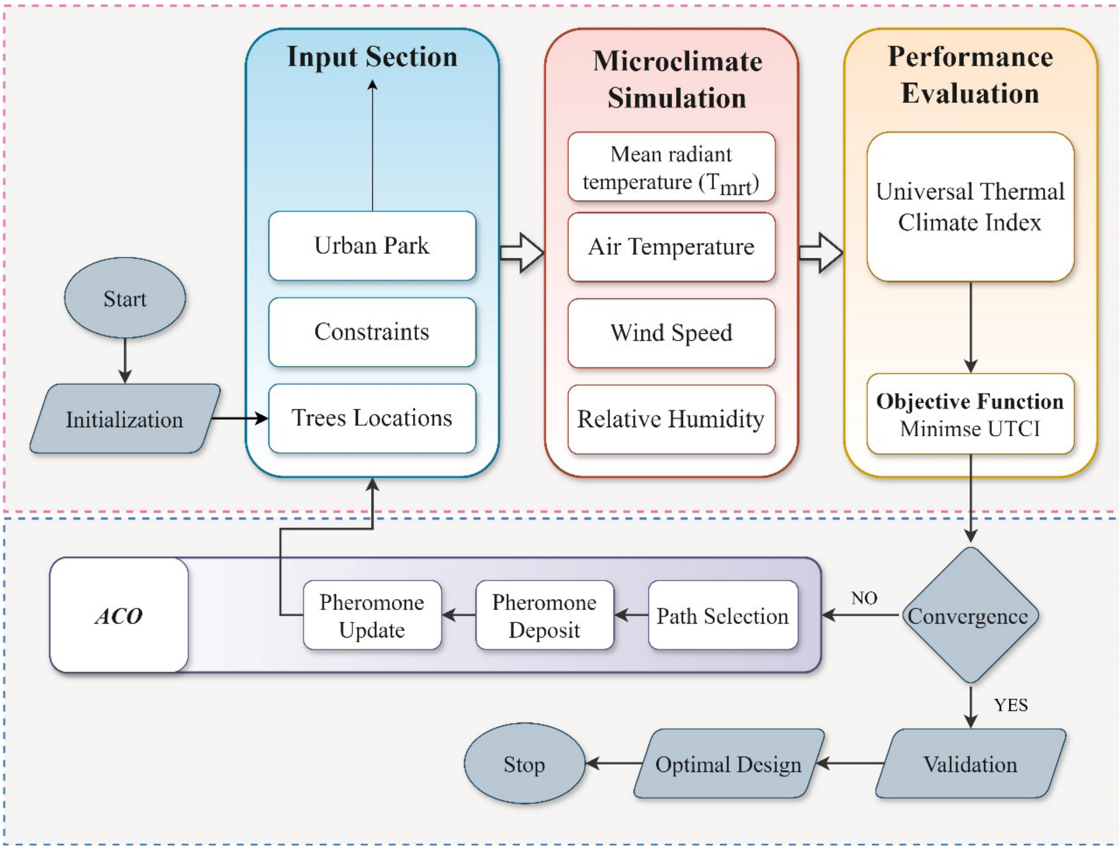

Figure 3. Research methodology (Shaamala et al. 2024b).

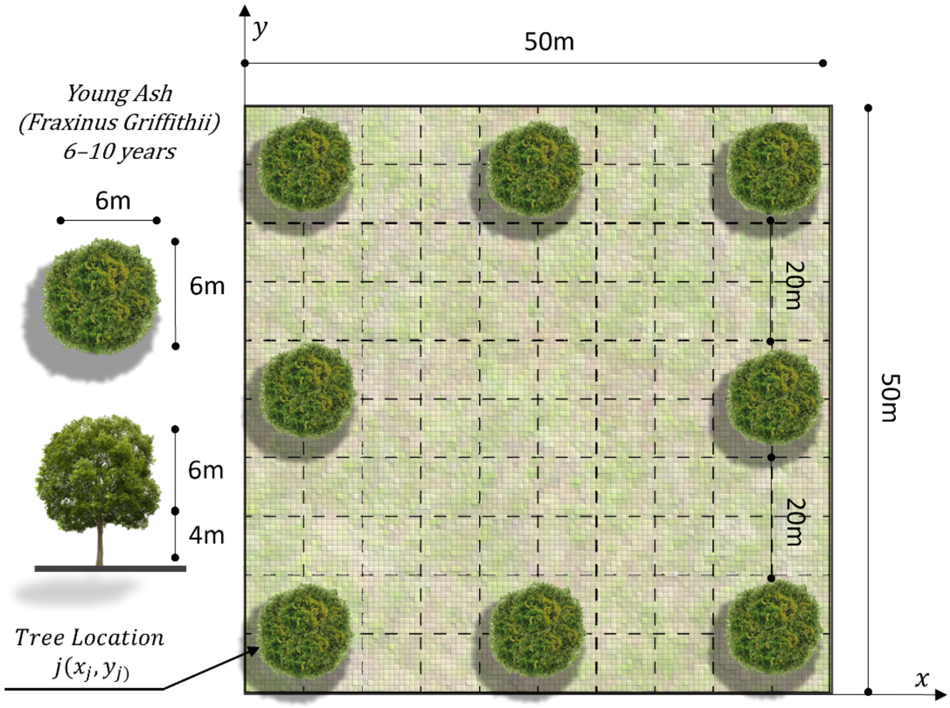

Figure 4. Study area.

urban microclimate (Figure 5). The performance of ACO was typified by a systematic and careful decrease in UTCI values. Although this methodical optimisation process takes longer to converge than some other algorithms, it demonstrates how meticulous and comprehensive the ACO's methodology is in determining the best locations for trees. The ACO strategy involved a step-by-step reduction in UTCI, reflecting its methodological search and placement adjustments. This careful optimisation ensures a comprehensive exploration of the search space, leading to well-considered tree configurations that maximise urban thermal comfort. The consistent decrease in UTCI values using ACO indicated a steady improvement in the urban microclimate, demonstrating the capability of the algorithm to enhance thermal comfort through strategic tree placement.

Overall, the ACO's systematic approach and gradual optimisation process make it a reliable method for urban planners to achieve significant and sustained improvements in urban microclimate conditions.

Spatial configurations from the optimisation algorithm

This study evaluated the tree spatial arrangements suggested by ACO. Figure 6 provides a visual representation of this configuration. The tree configuration pattern generated by ACO follows a clustering approach. Trees were placed in clusters to create concentrated areas of shade, effectively forming microclimatic havens within the urban park. This targeted placement helps significantly reduce the temperatures in the identified hotspots.

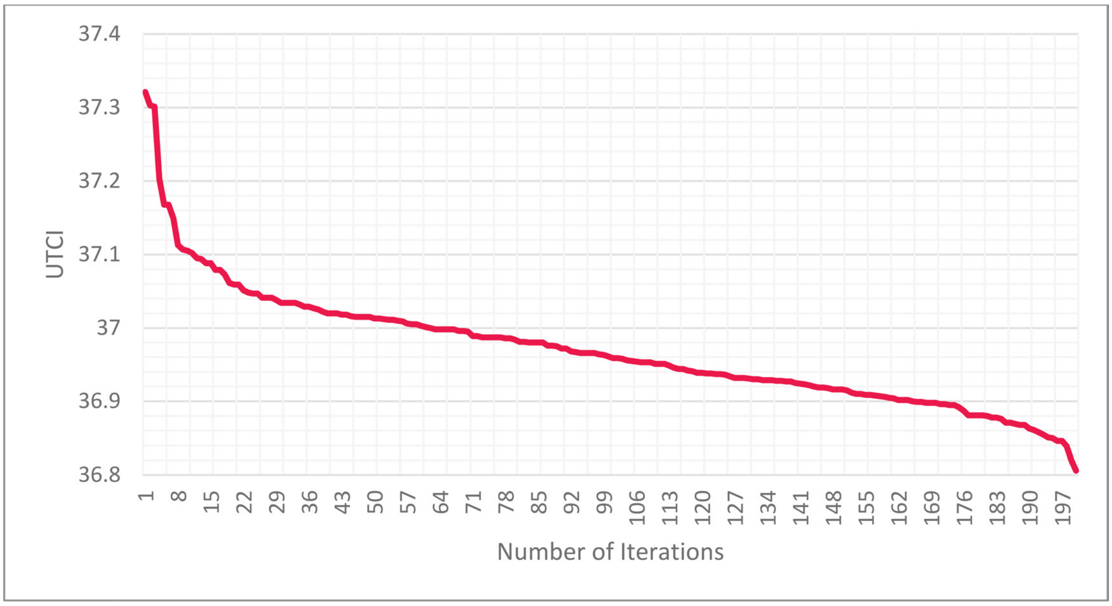

Figure 5. Performance of the optimisation algorithm.

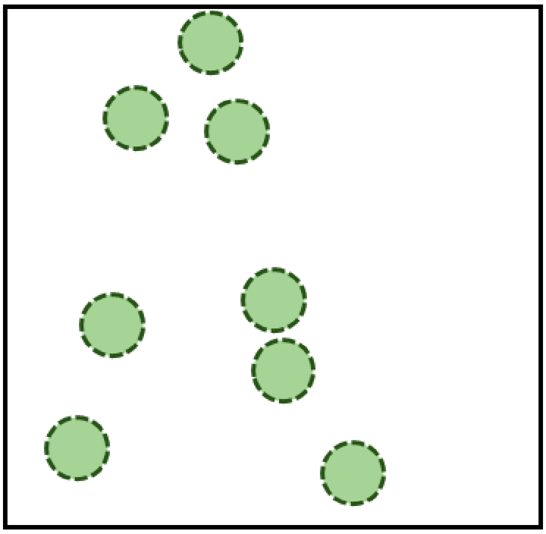

Figure 6. Optimal configurations created by ACO algorithm.

Microclimate simulation for optimal scenarios

To assess the efficacy of the proposed approach, we performed several in-depth microclimate simulations to evaluate the effectiveness of the proposed method for tree placement optimisation. These simulations were created to assess how important urban microclimate variables that impact UTCI are affected by the ideal tree configuration created by ACO. As illustrated in Figure 7, the ideal arrangement produced the best results for a variety of microclimatic parameters.

Figure 8 illustrates the simulation results, showing how tree distribution affects urban microclimates using thermal maps. These maps show significant differences in air temperature according to tree location. Each thermal map generated by the optimisation algorithm highlights the significant impact of the spatial configuration of trees on potential air temperatures in urban areas. Temperatures ranged from below 27°C to above 34°C, with cooler temperatures found under tree canopies.

The most significant cooling effect occurred in scenarios in which trees were strategically placed in the identified hotspots. In the ACO-optimised scenario, the central areas showed significantly lower temperatures, demonstrating that optimal tree placement enhanced shading and reduced heat. This emphasises the importance of intentional tree positioning in reducing urban heat and improving thermal comfort. The ability of the ACO method

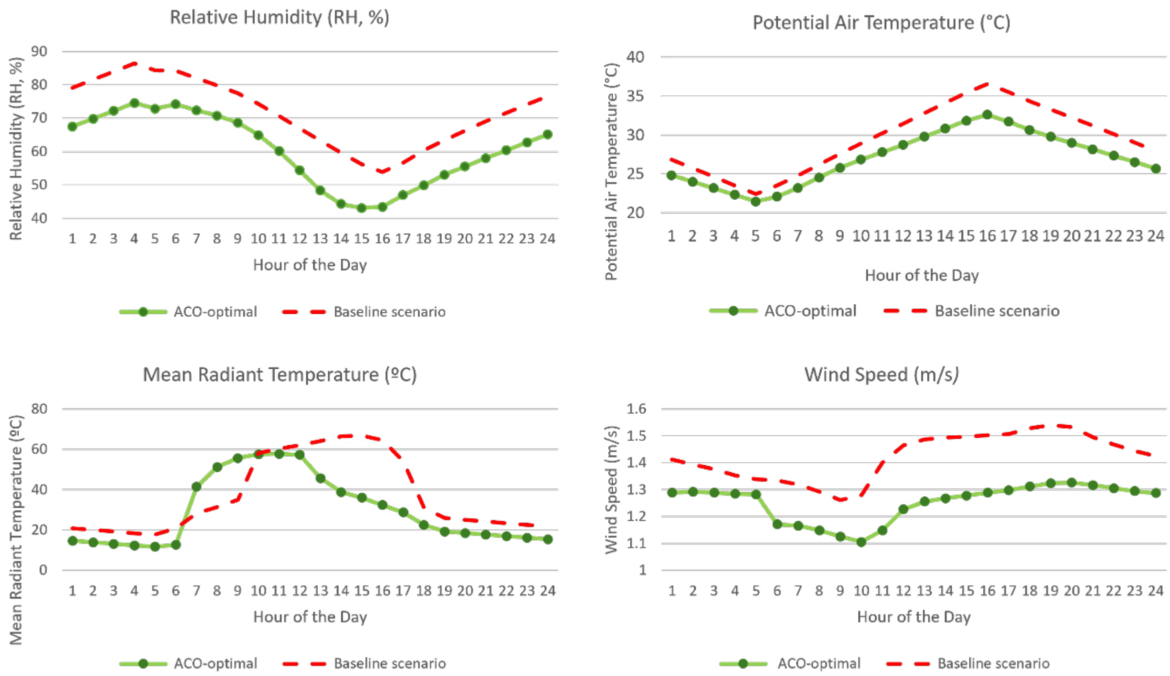

Figure 7. Tree location impacts on relative humidity, air temperature, mean radiant temperature, and wind speed: optimal versus baseline configurations.

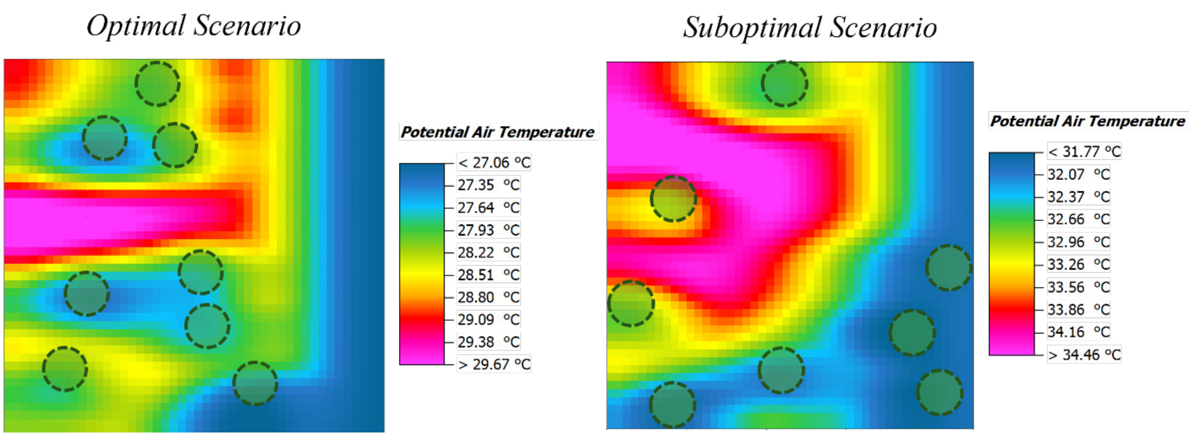

Figure 8. Variation in air temperature for different configuration scenarios.

to systematically lower temperatures in specific areas validates its effectiveness in enhancing urban microclimates through optimised tree placement.

Findings and discussion

This study presents an innovative approach to urban forestry and planning utilising AI, specifically ACO, to optimise trees' location and enhance urban microclimates. This study highlights the significant potential of integrating AI into urban forestry practices for climate adaptation and mitigation. By strategically positioning trees, this study demonstrated notable improvements in thermal comfort and reduced temperatures. The simulations revealed that the ACO algorithm effectively identified optimal tree locations, leading to significant reductions in the UTCI. This index, which combines air temperature, humidity, wind speed, and mean radiant temperature, serves as a crucial measure of thermal comfort.

The strategic clustering of trees, as determined by ACO, created concentrated areas of shade, forming microclimatic havens that significantly lowered local temperatures. The systematic placement of trees underscores the robustness and precision of the ACO approach for enhancing urban thermal comfort. Integrating AI technologies into urban planning represents a forward-thinking approach that prioritises both environmental sustainability and human wellbeing. AI's ability to process and analyse complex datasets enables urban planners to identify the most effective locations for tree planting, considering various environmental and infrastructural constraints.

Moreover, the findings underscore the importance of not only increasing tree cover but also optimising tree locations to maximise environmental and climatic benefits. By leveraging AI, cities can develop more effective climate adaptation strategies to address the challenges caused by rising global temperatures and urban heat islands. This research provides evidence that the AI-driven optimisation of tree placement can lead to more efficient cooling of urban areas, thereby enhancing the quality of life for urban residents.

From a policy perspective, this study highlights the importance of optimising tree locations and groupings instead of simply increasing the overall number of trees. These findings suggest that strategically placed trees offer significantly greater cooling effects than random distributions. This insight could shape policy guidelines that prioritise specific tree placement strategies to maximise urban cooling benefits. Policies incorporating AI-driven tree placement optimisation could lead to more resilient and sustainable urban environments, providing long-term benefits in climate adaptation and urban liveability.

The findings advocate a holistic approach to urban forestry, where AI algorithms can continuously adapt to changing environmental conditions and urban growth patterns, ensuring that tree placement strategies remain effective over time. This dynamic approach to urban forestry can help cities become more adaptable to future climate scenarios, providing a proactive solution to the ongoing challenges of urban heat islands and climate change.

In conclusion, this study demonstrates the transformative potential of integrating AI technologies such as the ACO algorithm into urban forestry and planning. By optimising tree placement, AI can significantly improve thermal comfort, reduce temperature, and contribute to the overall sustainability of urban environments. These insights are crucial for policymakers and urban planners who aim to create more resilient and liveable cities in the face of climate change. The continued development and implementation of AI-driven strategies in urban forestry will be essential for fostering healthier, greener, and more sustainable urban spaces for future generations.

Concluding remarks

AI offers significant potential for climate change mitigation and adaptation for cities (D'Amico et al. 2020; Repette et al. 2021; Son et al. 2023). As presented in this paper by leveraging advanced data analytics and machine learning algorithms, AI can optimise urban forestry by identifying the best tree locations that help adapting to the changing climate. This study illustrated the substantial benefits of integrating AI algorithms, specifically ACO, into urban forestry practices to enhance urban microclimates. By optimising tree locations, the ACO algorithm effectively reduces UTCI, thereby improving thermal comfort in urban areas. These findings highlight the importance of not only increasing tree cover but also optimising tree locations to maximise environmental benefits. This study also highlighted the broader implications of AI in urban planning. By incorporating AI technologies, cities can develop more effective climate adaptation strategies to address the challenges posed by rising global temperatures and urban heat islands. The use of AI to optimise tree placement exemplifies a forward-thinking approach to urban design that prioritises both environmental sustainability and human well-being. Future research should focus on refining optimisation algorithms and expanding their scope to incorporate more complex urban environments and diverse climatic conditions.

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