Modeling and Evaluation of the Outdoor Comfort of a Residential Area taking into account Climate Change and the Dynamic Growth of Green Infrastructure

Scientific thesis for the degree of
M.Sc. Resource-efficient and Sustainable Building
at the TUM School of Engineering and Design
of the Technical University of Munich

Superwised by	Dr. Michael Vollmer Prof. Dr.-Ing. Werner Lang Institute of Energy Efficient and Sustainable Design and Building
Submitted by	Alexandra Lüttich Biedersteinerstr. 26 80805 München alexandra.luettich@tum.de
Submitted	Munich, January 30, 2024

Vereinbarung

zwischen

der Technischen Universität München, vertreten durch ihren Präsidenten, Arcisstraße 21, 80290 München

hier handelnd der Lehrstuhl für Energieeffizientes und Nachhaltiges Planen und Bauen (Univ.-Prof. Dr.-Ing. W. Lang), Arcisstr. 21, 80333 München

– nachfolgend TUM –

und

Frau Alexandra Lüttich, Biedersteinerstraße 26, 80805 München

– nachfolgend Autorin –

Die Autorin wünscht, dass die von ihr an der TUM erstellte Masterarbeit mit dem Titel

> ”Modelling and Evaluation of the Outdoor Comfort of a Residential Area taking into account Climate Change and the Dynamic Growth of Green Infrastructure”

☒ auf mediaTUM und der Webseite des Lehrstuhls für Energieeffizientes und Nachhaltiges Planen und Bauen mit dem Namen der Verfasserin, dem Titel der Arbeit, den Betreuer:innen und dem Erscheinungsjahr genannt werden darf.

☐ in Bibliotheken der TUM, einschließlich mediaTUM und die Präsenzbibliothek des Lehrstuhls für Energieeffizientes und Nachhaltiges Planen und Bauen, Studierenden und Besucher:innen zugänglich gemacht und veröffentlicht werden darf. Dies schließt auch Inhalte von Abschlusspräsentationen ein.

☐ mit einem Sperrvermerk versehen und nicht an Dritte weitergegeben wird.

Zu diesem Zweck überträgt die Autorin der TUM zeitlich und örtlich unbefristet das nichtausschließliche Nutzungs- und Veröffentlichungsrecht an der Masterarbeit.

Die Autorin versichert, dass sie alleinige Inhaberin aller Rechte an der Masterarbeit ist und der weltweiten Veröffentlichung keine Rechte Dritter entgegenstehen, bspw. an Abbildungen, beschränkende Absprachen mit Verlagen, Arbeitgebern oder Unterstützern der Masterarbeit. Die Autorin stellt die TUM und deren Beschäftigte insofern von Ansprüchen und Forderungen Dritter sowie den damit verbundenen Kosten frei.

Eine elektronische Fassung der Masterarbeit als pdf-Datei hat die Autorin dieser Vereinbarung beigefügt. Die TUM ist berechtigt, ggf. notwendig werdende Konvertierungen der Datei in andere Formate vorzunehmen.

Vergütungen werden nicht gewährt. Eine Verpflichtung der TUM zur Veröffentlichung für eine bestimmte Dauer besteht nicht.

Die Autorin hat jederzeit das Recht, die mit dieser Vereinbarung eingeräumten Rechte schriftlich zu widerrufen. Die TUM wird die Veröffentlichung nach dem Widerruf in einer angemessenen Frist und auf etwaige Kosten der Autorin rückgängig machen, soweit rechtlich und tatsächlich möglich und zumutbar.

Die TUM haftet nur für vorsätzlich oder grob fahrlässig verursachte Schäden. Im Falle grober Fahrlässigkeit ist die Haftung auf den vorhersehbaren Schaden begrenzt; für mittelbare Schäden, Folgeschäden sowie unbefugte nachträgliche Veränderungen der veröffentlichten Masterarbeit ist die Haftung bei grober Fahrlässigkeit ausgeschlossen.

Die vorstehenden Haftungsbeschränkungen gelten nicht für Verletzungen des Lebens, des Körpers oder der Gesundheit.

Meinungsverschiedenheiten im Zusammenhang mit dieser Vereinbarung bemühen sich die TUM und die Autorin einvernehmlich zu klären. Auf diese Vereinbarung findet deutsches Recht unter Ausschluss kollisionsrechtlicher Regelungen Anwendung. Ausschließlicher Gerichtsstand ist München.

München, den 30. Januar 2024 | München, den 30. Januar 2024

.... | ....
(TUM) | (Autorin)

Erklärung

Ich versichere hiermit, dass ich die von mir eingereichte Abschlussarbeit selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

München, den 30. Januar 2024

Ort, Datum, Unterschrift

Contents

Abstract 3

List of abbreviations 4

1 Introduction 5

2 Motivation and Theoretical Background 7
- 2.1 Motivation . . . 7
- 2.2 Literature Review . . . 9
- 2.3 Model descriptions . . . 12
  - 2.3.1 Description of ENVI-met . . . 12
  - 2.3.2 Description of CityTree . . . 14
- 2.4 Climate Projection models . . . 15
- 2.5 Thermal comfort indices . . . 17

3 Methodology: Model Setup and Simulations 18
- 3.1 Model setup and input data ENVI-met . . . 20
- 3.2 Dynamic vegetation model . . . 24
- 3.3 Simulations . . . 26
  - 3.3.1 Example model domain . . . 27
  - 3.3.2 Simulation variations . . . 30

4 Results and Discussion 31
- 4.1 Tree growth results . . . 31
- 4.2 Thermal Comfort results . . . 36
- 4.3 Development of tree growth and thermal comfort over time . . . 43
- 4.4 Challenges and Efficiency . . . 45

5 Conclusion and Outlook 48

List of Figures 51

List of Tables 52

Appendix 55
- A Calculations CityTree . . . 56
  - A.1 Growth graphs for Tilia cordata and Aesculus hippocastanum . . . 60

B Difference comparison maps UTCI with and without trees 61
C Spatial UTCI distribution of all simulation variants 62
C.1 Area for average temporal development 63

Abstract

In view of climate change, adaptation strategies in urban planning are necessary to ensure thermal comfort in outdoor areas in the future. The implementation of green infrastructure is a proven measure to combat heat stress. Trees, in particular, offer great potential through various ecosystem services. How the planned vegetation develops under different climatic conditions and influences thermal comfort in the future is investigated using the CityTree tree model and numerical simulations with ENVI-met for a case study in Bamberg. No significant differences in tree growth were found for the location when modeling with different climate scenarios, with the local climate scenarios showing similar precipitation patterns for the future. The modeling of urban trees still offers much potential for development, especially in long-term dynamization. The results of the ENVI-met simulations show that thermal comfort is not in an acceptable range for any scenario but is improved by the trees on the study site by an average of 2.2 - 2.9 °C UTCI. The location of the trees should be adapted to the orientation of the building, especially on south-facing facades, where there is little reduction of heat stress through vegetation. The results confirm general guidelines regarding GI and thermal comfort but show that site-specific analysis is important and that current measures are not sufficient against the development of climate change.

List of abbreviations

DBH: Diameter at Breast Height

GI: Green Infrastructure

IPCC: Intergovernmental Panel on Climate Change

RCP: Representative Concentration Pathway

UHI: Urban Heat Island

UTCI: Universal Thermal Climate Index

1. Introduction

Climate change is a global phenomenon, and its effects are witnessed in many regions nowadays. In Germany, new heat records are reached every year, posing a significant health risk during the summer months (Bayerisches Landesamt für Umwelt, 2022). The urban heat island effect aggravates this situation, which can be felt by the population living in cities. To mitigate these consequences, a shift towards climate-adapted urban planning is essential, with green infrastructure measures playing a valuable role.

Research has extensively explored how urban greenery, particularly trees, enhances outdoor thermal comfort. Trees not only ease heat stress but also provide a variety of ecosystem services beneficial for thermal comfort and well-being (Gatto et al., 2020; Klemm et al., 2015). Despite the wide-ranging research, there is still a need to model green infrastructure measures. This is because the impact on microclimates varies greatly depending on the specific location and environmental conditions of each region. Therefore, a localized approach to green infrastructure planning is necessary to combat the increasing urban heat stress targeted.

In this master's thesis, the focus is on assessing the long-term effectiveness of current green infrastructure (GI) planning strategies. It emphasizes the importance of a holistic approach in understanding the intricate interactions that shape microclimates, especially under evolving environmental conditions. The central hypothesis of this research is that the strategic incorporation of green infrastructure will significantly enhance outdoor thermal comfort. Additionally, by incorporating tree growth models, adaptation strategies can be adjusted to align with various future climate scenarios.

Guiding this research are two critical questions: Firstly, how should green infrastructure be planned to ensure that thermal comfort in outdoor spaces is also guaranteed in the future? And secondly, how will the planned vegetation develop under various water and climate conditions? These questions are investigated to understand the interplay between GI planning and its effectiveness in adapting urban environments to climatic changes.

The objective of this thesis is to evaluate the impact of planned trees under future conditions, incorporating the growth of the trees into the model. To address the research questions, a case study will be conducted using a simulation-based approach. The ENVI-met software is used to simulate the microclimate of a neighborhood area, focusing on particularly hot future days. Vegetation growth is considered by adjusting the tree model at different time intervals based on the results of the urban tree model

CityTree and data from the literature. The Universal Thermal Climate Index (UTCI) will serve as the metric for evaluating thermal comfort in outdoor spaces. The work aims to develop strategies for resilient and climate-adaptive green infrastructure through these simulations.

A particular research gap is bridged by integrating interdisciplinary fields: this study connects tree growth modeling with microclimate simulations in long-term future scenarios and evaluates outdoor thermal comfort under these conditions. The practical application of this research is demonstrated through a case study of the ECO+ project situated near Bamberg, Germany. This project lends practical significance to the study, while the simulation provides a deeper understanding and enables the derivation of recommended actions. The findings from this thesis are anticipated to assist in the development of sustainable and climate-resilient planning methods, thereby contributing to the urban adaptation strategies necessary for climate change mitigation.

This thesis is structured to simplify a comprehensive understanding of the theory, as well as its findings and implications. It begins with an overview of the theoretical foundations relevant to the master thesis topics, encompassing elements of tree modeling, climate projections, and thermal comfort assessment. The subsequent chapter outlines the methodology, introducing the ENVI-met and CityTree software, which are employed to carry out the simulations. The workflow for their implementation and the creation of the model area is explained. Following this, the Results and Discussion chapter presents the simulation outcomes, interprets them, and addresses the limitations and challenges encountered during the simulation process. This section also examines recommended actions for planning climate-adapted green infrastructure within the scope of this case study. Concluding the thesis, the final chapter synthesizes the findings and offers perspectives on potential future research directions.

2. Motivation and Theoretical Background

This chapter discusses the motivation behind the research and the author's personal background. It elaborates on the specific problem and knowledge gap addressed by the study. Moreover, it provides information about the case study area near Bamberg. In addition, this chapter provides an overview of the current state of the art and research related to the topic of simulating thermal comfort and the modeling of trees. Finally, the chapter introduces the modeling software used in this thesis and its theoretical principles.

2.1 Motivation

This master's thesis is based on an interdisciplinary academic foundation combining environmental engineering, architectural and urban design, and civil engineering. The combination of disciplines is particularly relevant in the context of urban sustainability. Urban environments are complex ecosystems in which different elements like the built environment, energy systems, local conditions, and vegetation interact in interdependent ways. This complexity requires an integrative, holistic approach to urban planning to create sustainable and livable places. Especially considering future climate conditions, holistic planning and research can work out synergies between the different fields and help understand the complex interactions better.

This research focuses on the microclimate, defined as the distinct climatic conditions that are specific to a particular area. They often vary considerably within distances of a few meters, especially in an urban context. The microclimate in urban areas depends on numerous factors that urban planners can influence. These include the urban geometry, the building density, the surface albedo and material of the surroundings, the wind flow, and water bodies. Green infrastructure (GI), in particular, significantly impacts microclimate and thermal comfort (Wang et al., 2021). The ecosystem services provided by urban vegetation go beyond shade provision and encompass broader ecological functions such as carbon fixation, cooling by transpiration, and runoff reduction. Due to the unique characteristics of each site, case studies and small-scale simulations are crucial for sustainable urban planning. Given the emerging challenges of climate change, understanding and predicting the microclimatic conditions is becoming increasingly important. This requires site-specific simulations and, as stated above, a holistic approach in simulations to assess the possible future microclimate.

A research field to further explore in this domain is the dynamic modeling of tree growth for future scenarios as well as the thermal comfort for future scenarios. Such simulations need to include the water cycle and soil moisture availability and incorporate dynamic growth patterns to account for the effects of climate change on heat stress. Long-term green infrastructure planning is critical as it takes into account the changing effects of climate on tree development and thermal comfort. Understanding these interactions is key to fostering urban ecosystems that can withstand environmental change.

The case study used in this thesis is a practical project in close cooperation with research partners. It focuses on an ecologically progressive neighborhood in Debring near Bamberg, with the aim of creating ecologically positive urban areas. This Bavarian region, located in a warm-temperate climate zone, is experiencing climate changes, particularly hotter and drier summers that intensify heat waves and alter precipitation patterns (Bayerisches Landesamt für Umwelt, 2022). These changes pose risks to health, agriculture, and infrastructure and emphasize the need for adaptation strategies.

The approximately 6,000 m^2 project site in Debring-Stegaurach is currently undeveloped and borders a residential neighborhood. The development plan foresees the development of a residential area with an area of 3,000 - 5,000 m^2 and approximately 30-65 residential units. This neighborhood will integrate different forms of housing, communal spaces, and various amenities such as a daycare center, mobility services such as e-bike/ car sharing, cooperation with social institutions, and mixed-use commercial space.

The project is guided by its ECO+ design principles and landscape architectural perspectives, which emphasize ecological improvements. It is anticipated that the post-construction ecological value of the site will exceed its pre-construction condition. Efforts will be made to preserve and enrich habitats for protected species, with a focus on improving shading and evaporation to increase living comfort. The multifunctionality of the design aims to promote a close connection between people and nature and is in line with the broader objectives of addressing climate challenges and improving quality of life.

The ECO+ project site serves as the focal case study area for this thesis, providing a practical example for the study of microclimatic conditions. Case studies are an essential research method in the field of microclimate simulations, enabling detailed insights into specific environmental contexts. This approach is particularly relevant given the significant regional variations in climatic conditions. Tailored analysis is required to validate general guidelines effectively. Furthermore, as these factors have a strong influence on microclimate, the study emphasizes the importance of understanding regional differences in vegetation. This consideration is crucial for the informed transfer of any ecological recommendations to ensure their applicability in different settings.

2.2 Literature Review

Green infrastructure and outdoor thermal comfort

Extensive research has been conducted on the impact of urban green infrastructure on outdoor thermal comfort. It has been established that green infrastructure often mitigates heat stress and provides various ecosystem services. The effectiveness of urban vegetation varies based on its arrangement and quantity. Its interactions with the environment are complex; therefore, modeling the influence and growth of vegetation is essential for adapted urban planning and creating outdoor thermal comfort.

Sun et al. (2017) employed numerical simulations to explore the potential of a ring-shaped park in Beijing to improve thermal comfort. Their study, which used the PET index for evaluation, showed that green infrastructure could ease heat stress, with urban green spaces typically offering better thermal comfort. Regression analyses indicated that taller trees significantly enhance thermal comfort, whereas hardened ground surfaces have a negative effect.

Spangenberg et al. (2008) examined the effects of city-wide green space interventions. They found that extensive, connected green belts mitigate Urban Heat Island effects more effectively than isolated green spaces. While trees in street canyons had a limited impact on air temperature and reduced wind speeds, they significantly lowered mean radiant and surface temperatures, which showed more influence on PET than the lower wind speed.

A review of the general effects of green infrastructure and quantification of its impact was published by Clark et al. (2010). The review highlighted the role of urban vegetation in influencing stormwater runoff. In the absence of GI, pavement increases surface temperatures and disrupts the ecosystem. However, when GI is incorporated, it reduces urban surface temperatures, thereby lowering runoff temperatures again. The study also points out that the shade provided by mature trees reduces the energy required for cooling. It also examines the role of green roofs, which are found to act similarly to insulation. The effectiveness of this insulation depends on soil moisture. However, the study also notes that the more insulating a building material is, the smaller the impact of the green roof. This raises questions about the efficiency of green roofs in some instances.

The appropriate urban green infrastructure strategy for different scales were determined with numerical methods by Wang et al. (2021). The research addresses urban overheating in Guangzhou, China, using an approach that combines Local Climate Zone (LCZ) classification with ENVI-met microclimate simulations. The study identified specific zones with high surface urban heat island (SUHI) intensities and evaluated street trees and green roofs as green infrastructure strategies for these areas. The findings revealed that increasing green cover by 10% with grove and street trees significantly mitigates urban overheating. In contrast, adding extensive green roofs has minimal impact on pedestrian-level thermal comfort and can potentially worsen the SUHI effect. This study emphasizes the importance of tailored UGI strategies based on local urban characteristics for effectively reducing urban heat.

In summary, while the positive impact of green infrastructure on urban microclimates and thermal comfort is clear, more research is needed to optimize these measures for sustained thermal comfort, particularly in the context of future climate scenarios.

Tree modeling

Fauk and Schneider (2023) explored how urban trees can be modeled to estimate their ecosystem services, highlighting their role in enhancing urban ecosystems and climate moderation. A summary of interactions trees have with their environment is illustrated in Figure 2.1. Trees absorb solar radiation, provide shade, and reduce heat on streets and buildings, thereby lessening temperature-related health risks.
Their transpiration contributes to cooling the environment. Trees support biodiversity, provide habitat, and play an important role in air purification. In addition, they absorb and retain rainwater, improve soil water holding capacity, and prevent runoff. Thus, they contribute to effective urban water management and increase resilience to floods and droughts. Their model is based on statistical methods to predict urban tree growth. It accounts for various factors influencing growth, including species, dimensions like diameter at breast height (dbh), height, crown diameter, nutrient conditions, local and regional climate, surrounding environment (sealed and unsealed areas), competition, and a mortality model. The conclusion reached was that a definitive abiotic optimum for tree growth could not be determined. This suggests a need for ongoing refinement of growth function parameters in the model.

An improved growth function could also be achieved by a different modeling approach. Arora (2002) emphasizes the importance of dynamic vegetation modeling in climate and hydrological studies. He discusses the necessity of considering vegetation's interaction with atmospheric CO_2, as vegetation both absorbs CO_2 during photosynthesis and releases it during respiration and decomposition. Elevated CO_2 levels can increase plant growth and alter vegetation structure, thus affecting the CO_2 exchange with the atmosphere. Accurately modeling these dynamics is essential for understanding and predicting atmospheric CO_2 trends, which in turn aids in forecasting climate change impacts. Integrating hydrology into the tree growth model is also crucial.

Vegetation plays a key role in the water cycle. It affects evapotranspiration rates, soil moisture levels, and runoff patterns. Dynamic modeling of these aspects can enhance predictions and management of water resources, especially under changing climatic conditions. Furthermore, soil-vegetation Interactions need to be accounted for. The health and growth of vegetation are influenced by soil conditions, including moisture and nutrient levels. Dynamic modeling captures the bidirectional relationship between soil and vegetation, improving our understanding of how changes in one can affect the other.

Arora (2002) states that to model tree growth dynamically, a soil-vegetation-atmosphere transfer (SVAT) schemes is necessary. The SVAT schemes emphasize the role of vegetation in the water and energy balance by considering its physiological properties, particularly the leaf area index (LAI) and stomatal conductance, which model evapotranspiration. For effective SVAT schemes and hydrological modeling, it is important to include representations of photosynthesis, autotrophic respiration, resource allocation, and plant phenology. Additionally, soil nutrient availability, as nitrogen is the primary limiting nutrient for plant growth.

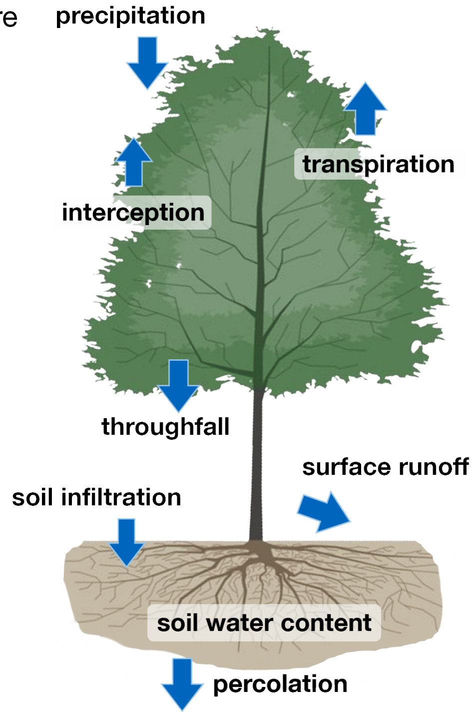


Figure 2.1: Tree interactions with its environment adapted from Rötzer on CityTree, 2023

Another factor to consider is the long-term dynamic of tree growth and modeling. A study by Zhang et al. (2021) investigates the divergent responses of vegetation growth to soil moisture (SM) availability in Central Asia during dry and wet periods. This study displays the interplay between vegetation phenology and hydroclimatic variations on a decadal scale. The research found that soil moisture greatly affects plant growth. During dry periods, plants react strongly and quickly to changes in soil moisture, with a delay of about a month. In wet periods, the response is slower and varies in different places. Higher temperatures and less humidity in dry periods also cause plants to start growing earlier in the year, which can change the length of the growing season depending on how much water is available. This shows that the growing season in this region is changing and becoming less predictable due to varying water and weather conditions. They underscore the need to consider these factors in predicting regional vegetation growth, especially under increasingly warmer and drier climates in water-stressed areas.

The study of tree growth modeling covers a range of complex interactions and factors. There are two primary modeling approaches: empirical models, which rely on measurements and statistics, and process-based tree models, which incorporate tree physiology to convert carbon assimilation and allocation into growth rates. While modeling in forestry is more developed, the modeling of urban trees still requires further advancements. One key challenge is the need for long-term studies to accurately validate tree growth. Another challenge for model parameterization arises from the wide range of tree species, each having individual growth patterns and behavioral responses (Peper et al., 2001). Additionally, determining the age of a tree accurately can be challenging, typically involving an examination of its annual rings.

2.3 Model descriptions

In this study, two software models were selected for the simulation of thermal comfort and tree growth. The first, ENVI-met, is used for the simulation of thermal comfort. This model was chosen because it is widely recognized and commercially available as a comprehensive microclimate model that takes into account dynamic plant-atmosphere interactions. ENVI-met has already been used and validated in numerous microclimate simulation studies (Sun et al., 2017). The second software, CityTree, is a specialized urban tree model developed by Professor Thomas Rötzer of the Chair of Forest Growth and Yield Science at the Technical University of Munich. This software was made available by the chair for use in this work. In order to model the future climatic conditions, climate projection data was obtained using the Meteonorm software. This section presents the selected programs and describes their modeling approaches.

2.3.1 Description of ENVI-met

ENVI-met is a sophisticated environmental modeling software initially developed for the simulation of surface-plant-air interactions. This commercial software is often used in early design stages to assess the impact of urban planning, simplifying informed decision-making in sustainable urban development, green infrastructure planning, and climate change mitigation strategies. It is often used to assess green architecture's impact and efficiency and simulate outdoor human thermal comfort.

As a high-resolution 3D software, ENVI-met models the complex interactions between architectural structures, vegetation, and atmospheric conditions in a complex way. It works as a grid-based computational fluid dynamics (CFD) model and uses advanced numerical algorithms to accurately simulate even the most complex interactions. The software allows the creation of highly detailed model areas, typically simulated with a horizontal resolution of 1-10 meters.ENVI-met as a CFD model uses a finite difference method on an essentially uniform mesh (which can be altered only in the vertical direction using so-called telescoping grids (see section 3.3).

ENVI-met's holistic approach covers a wide range of environmental interactions. It includes a solar analysis and simulates the heat flows through walls and roofs. In this process, the software calculates the impacts of solar radiation, taking into account shading effects, reflections, and the influence of various building materials and vegetation. It also models wind fields, considering the drag foIt solves the Reynolds-Averaged-Navier-Stokes (RANS) equations for each spatial grid cell at every time step.rces caused by vegetation and urban structures. The software also calculates particle dispersion and chemical reactions within the NO-NO_2-O_3 cycle.

Regarding the soil and vegetation module, ENVI-met considers the exchange processes within the soil and with vegetation. This includes the determination of evapotranspiration and the sensible heat flux of plants, including a complete simulation of all plant physical parameters, such as the photosynthetic rate of leaves. In addition, the effects of water bodies are calculated, as well as an extended calculation of the hydraulic water exchange in the soil, which contains the water uptake by the roots and the plant's water supply.

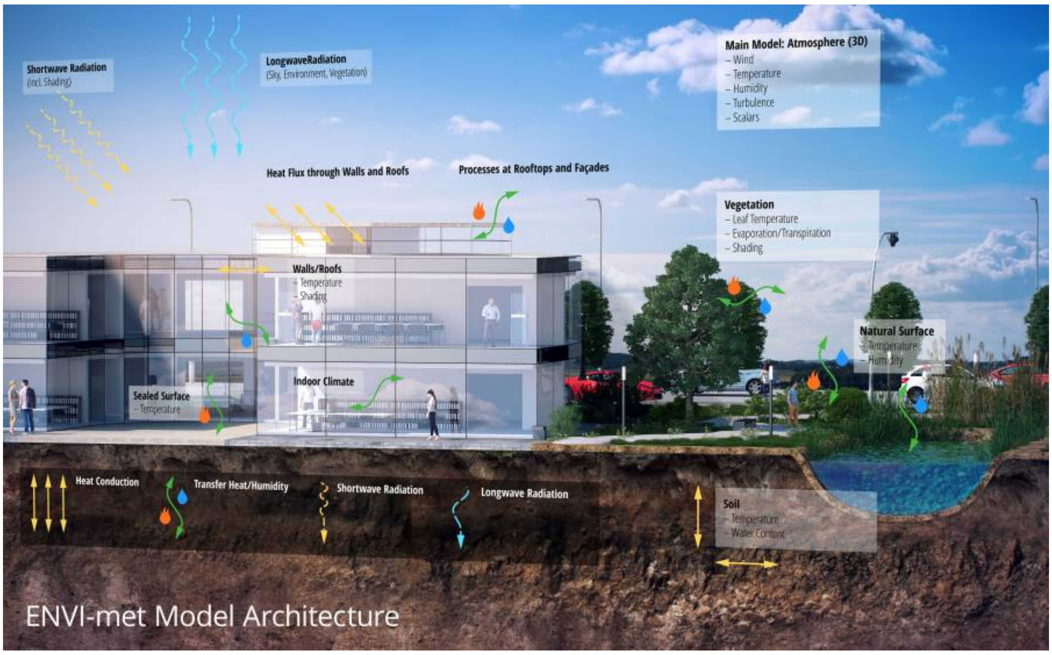


Figure 2.2: ENVI-met model architecture [ENVI-met website, 2023, https://www.envi-met.info/doku.php?id=intro:modelconcept]

In Figure 2.2, the model architecture with its environmental interactions is illustrated.

ENVI-met is typically applied for a simulation time frame of 24 h to 48 h and a default time-step of 2-10 seconds for the calculation. The typical horizontal resolution of 1 m to 10 m allows the analysis of small-scale interactions between buildings, plants, surfaces, and the atmosphere (ENVI-met website, 2023). The results are output in hourly intervals, containing atmospheric conditions, building information, pollutant concentrations, radiation fluxes, soil state and vegetation details.

Vegetation model *Albero*

The Albero tree manager is a specialized tool for creating and editing tree representations in ENVI-met. It has an extensive database of tree species from temperate and boreal climate zones. Users can either use the existing tree models or modify them as needed. The latest version uses the sophisticated Lindenmayer system to construct the plant geometry. This system depicts different tree species' branches and leaf structures more realistically. Thanks to the detailed geometry, characteristics like the shading pattern, the radiation absorption, and wind flow that greatly influence its interaction with the environment are considered. These factors lead to a more refined leaf area density (LAD) distribution in each cell. The developers conducted research showing that this geometry results in significant differences between tree types and radiative transfers, which is important for improving the simulation's microclimatic effects of trees (Simon et al., 2020). Since the Lindenmayer system applies an algorithm to build the tree geometry, it is not possible to directly adjust the tree height and diameter as a value.

In the model area, each plant is treated as a distinct species with its water balance control and a response system for heat and water stress. The model includes interactions like heat and water vapor exchange between plant leaves and the atmosphere. The hydraulic model considers water extraction from the soil via the plant root distribution. A complex ray tracing algorithm assesses the plants' impact on solar radiation (shading) and long-wave radiation exchange (thermal shielding). Factors like plant health, soil water supply, and additional variables regulate the transpiration rate and leaf temperature.

2.3.2 Description of CityTree

The CityTree model was developed by Rötzer in 2019, focusing on the physiological growth of urban trees. It models and outputs the biomass growth and ecological functions of a single tree for one year. The model analyzes various aspects of the tree's physiology and ecosystem services. The input parameters include the tree's species, age, dimensions, and various soil characteristics. Additionally, it needs monthly meteorological data, atmospheric CO_2 concentration, the location's coordinates, and the percentage of sealed surfaces at the site. The model operates on a monthly resolution, processing and integrating environmental data with the tree's characteristics to simulate its growth and ecosystem services. The model's structure is divided into modules, each responsible for different aspects of tree physiology and environmental interaction. A significant part of the model is the water balance module that simulates the entire water cycle's impact on the tree, including aspects like stomatal closure and leaf conductivity. Tree data from six Central European cities was used as a data basis for the model development and parameterization. The model's accuracy was validated with high-resolution data from four sites in Munich (Rötzer et al., 2019).

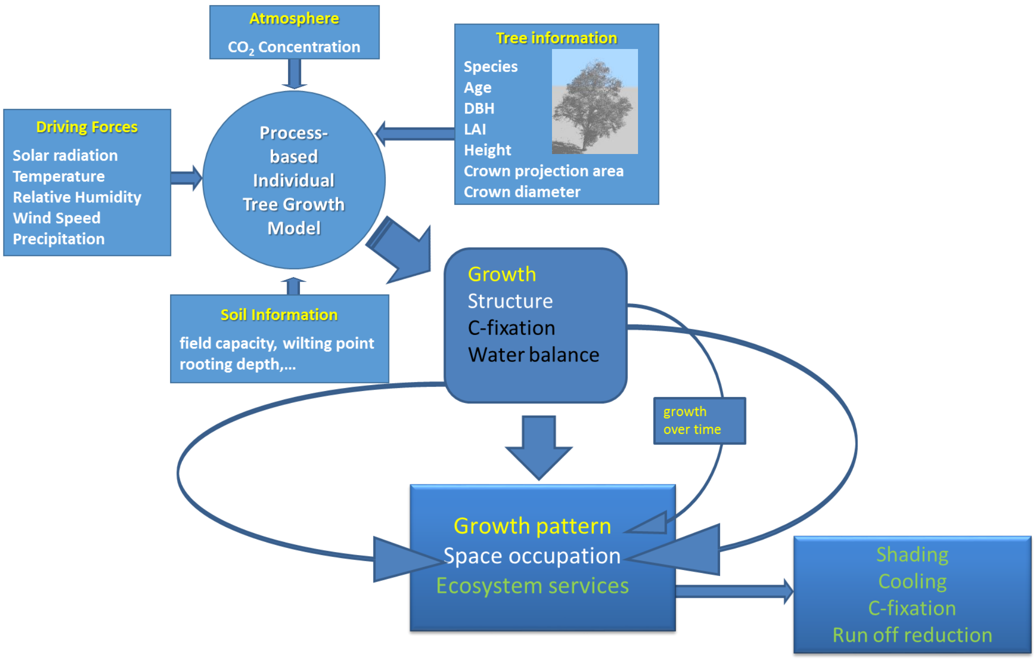


Figure 2.3: CityTree model components [Rötzer 2023]

2.4 Climate Projection models

Climate projections are crucial for understanding possible future developments in the earth's climate. These projections are based on simplified but plausible scenarios of how the future might develop. The scenarios are created using coherent and consistent assumptions about various factors such as demographics, economics, energy, and land use. A projection is then a potential future development of one or more scenarios, often calculated using models. Projections differ from forecasts as they are based on assumptions about future socio-economic and technological developments that may or may not occur. They work on an "if-then" basis: if a scenario occurs, then a particular development will follow.

The Intergovernmental Panel on Climate Change (IPCC) has commissioned and approved several scenarios for climate research. The research community carries out the development of new scenarios. These scenarios are regularly updated to take account of new research and data and to support the increasing complexity of integrated assessment and climate models. In the IPCC's 5th Assessment Report, finalized in 2013/14, the climate projections are the so-called Representative Concentration Pathways (RCPs). RCPs outline possible pathways of greenhouse gas concentrations and their combined effect with aerosols on radiative forcing. Radiative forcing is measured in watts per square meter and can be explained in simplified terms as an additional energy supply for the earth.

There are several RCPs, as described by IPCC Data Distribution Center (2019):

- **RCP 2.6**, where radiative forcing peaks at about 3 W/m^2 before 2100 and then decreases
- **RCP 4.5**, intermediate stabilization paths where radiative forcing stabilizes at about 4.5 W/m^2 after 2100
- **RCP 6.0**, intermediate stabilization paths where radiative forcing stabilizes at about 6.0 W/m^2 after 2100
- **RCP 8.5**, a high path in which radiative forcing exceeds 8.5 W/m^2 by 2100 and continues to rise

A further refined set of projections is now known as Shared Socioeconomic Pathways (SSPs). These SSPs differ from the earlier RCPs, which primarily focused on the concentration of greenhouse gases in the atmosphere. The SSPs take into account socioeconomic factors that influence these emissions. They outline various scenarios of societal development, including aspects like economic and population growth, energy usage, and land use. Five scenarios were developed, spanning a spectrum of sustainable development to heavy fossil fuel dependency scenarios.

In this thesis, Meteonorm was used to get precise climate projections for the study site in Bamberg. The software obtains specific climate projections through downscaling. This technique adjusts large-scale climate data to the local scale, ensuring accuracy for Bamberg. Due to the available choices in Meteonorm and its provision of data in a monthly mean format, the RCP scenarios were chosen for this thesis. This ensured that the meteorological projections were both accessible and tailored to the specific needs of the study. The projections available from Meteonorm were the RCP 2.6, 4.5 and 8.5 scenarios. For the simulations in this thesis, the two scenarios 4.5 and

8.5 were chosen. RCP 4.5 reflects significant but not extreme mitigation efforts, while RCP 8.5 is a more extreme scenario that tests the resilience and effectiveness of GI measures in a future with high greenhouse gas emissions. Both scenarios differ from the current situation in order to represent a broader range of GI impacts.

2.5 Thermal comfort indices

Human thermal comfort is a multifaceted concept influenced by a combination of environmental factors, personal activities, and clothing. Environmental factors include mean radiant temperature, relative humidity, air temperature, and wind speed, while personal factors encompass an individual's clothing insulation and activity levels.

To quantify thermal comfort, several indices have been developed (Ghani et al., 2021). For this thesis, the Universal Thermal Climate Index (UTCI) was chosen to evaluate simulation results due to its intuitive representation of 'perceived temperature'. This index is approved by EU COST Action 730 and employs a simplified regression model by Peter Broede to serve as a stationary thermal comfort measure for a standard person in a typical setting. The UTCI provides a comprehensive description of how outdoor temperature influences humans, including solar radiation, wind, and humidity. It incorporates factors like clothing insulation and metabolic rate.

The heat stress categories defined by the UTCI illustrate varying degrees of thermal comfort (see Figure 2.4): 9 °C - 26 °C is considered no thermal stress, 26 °C - 32 °C as moderate, 32 °C - 38 °C as strong, 38 °C - 46 °C as very strong heat stress and everything above 46 °C is classified as extreme heat stress.

UTCI (°C)	Heat stress category
> 46	extreme
38 - 46	very strong
32 - 38	strong
26 - 32	moderate
9 - 26	no thermal stress
0 - 9	slightly cold

Figure 2.4: Heat stress categories UTCI

The use of UTCI in this research is key for its universal applicability in describing the physiological effects of the environment on people, which is crucial for developing strategies to ensure comfort in urban spaces.

3. Methodology: Model Setup and Simulations

This chapter describes the methodology and workflow of the conducted simulations. The methodological framework of this thesis is the numerical simulation of microclimatic conditions of the study area to assess future thermal comfort. Typical for microclimate studies, the simulations are carried out on a particularly hot summer day, and different scenarios are evaluated. The thermal comfort and the influence of the vegetation are analyzed by comparing two climate projection scenarios. In order to take plant growth into account, the vegetation model is adjusted at different time intervals. Simulating the construction area of a project in Bamberg as a case study demonstrates the practical application of this research.

As the microclimate varies substantially, a guiding principle of microclimate analyses must be to integrate all processes and interactions of the urban environment. The more accurate and comprehensive the model is built, the better the approximation of the conditions in reality becomes. The software used in this study views the urban environment as a holistic system and considers a multitude of interacting processes. This is a crucial approach to understanding and modeling our environment, but it results in very complex simulations that require input data from diverse fields. Numerous programs must be used to convert, prepare, or modify the data and geometry to eventually construct the model area. This complexity comes with great effort and time cost for the simulation setup. Additionally, the computational expense for microclimate analyses is very costly as well. The most important steps and programs used to carry out the simulations are outlined in this chapter.

Figure 3.1 below gives a schematic overview of the workflow of the modeling process and the programs used.

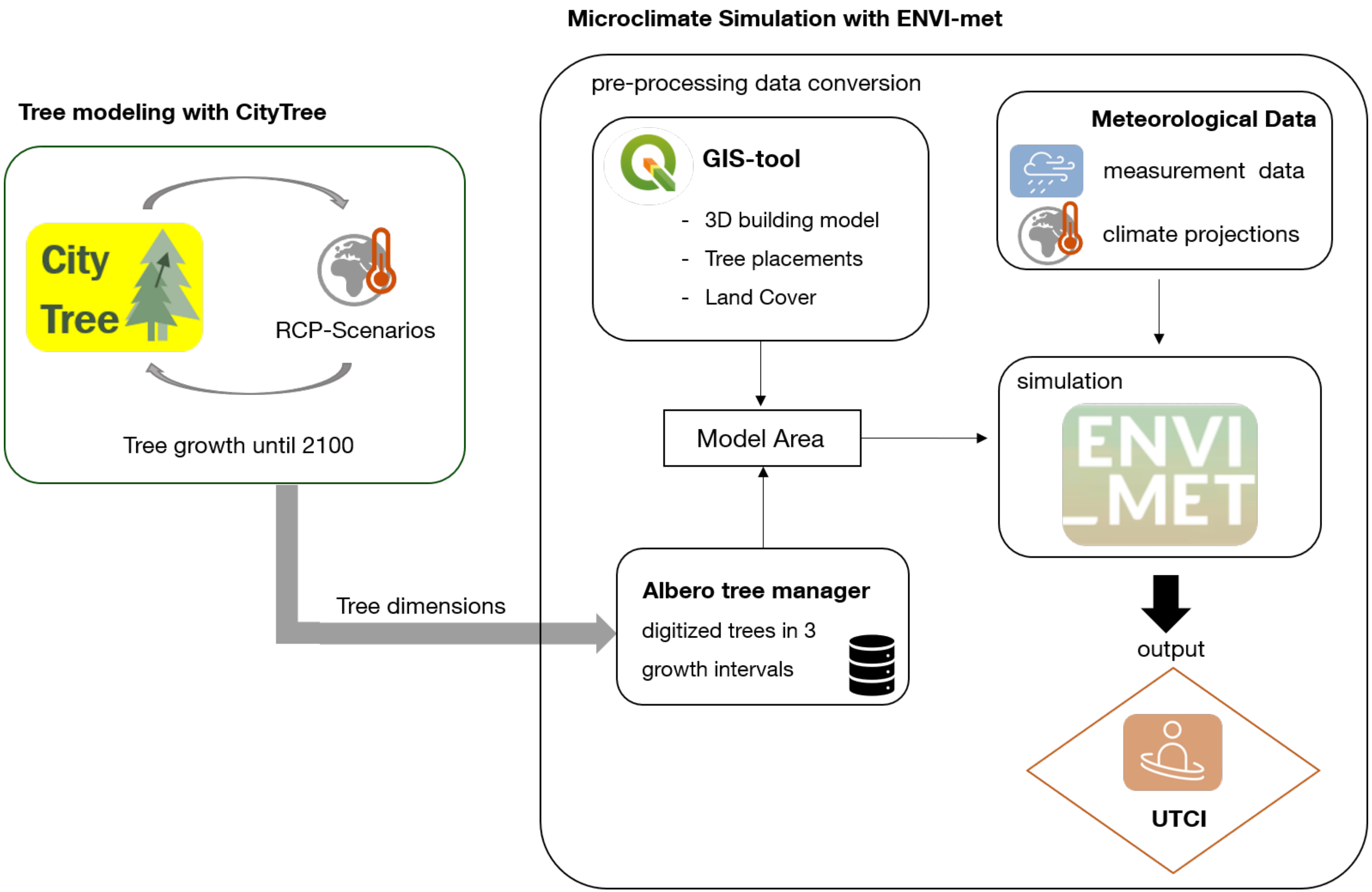


Figure 3.1: Workflow of the simulation process and the models utilized

3.1 Model setup and input data ENVI-met

As mentioned in the section Model descriptions, the software ENVI-met is used to carry out the microclimate simulations. A description of the software ENVI-met and its principles can be found in section 2.3.1. The input data, their sources, and the parameters used for setting up the simulation will be described in the subsequent sections, along with an explanation of how they were entered into the model. Digitizing the model area is challenging to describe chronologically but can be categorically divided into different steps based on the types of elements that need to be digitized and according to their data type.

The ENVI-met suite is a collection of integrated programs segmented roughly according to the simulation workflow. For data pre-processing, the suite features *Monde*, a GIS-based tool for digitizing the model area, and *Spaces*, which transforms this area into the required grid-based model for simulation. For the simulation setup and configuration, a dedicated program guides the creation of the simulation files, complemented by another one that initiates the simulation run. Post-simulation, *BIO-met* is utilized to derive thermal comfort indices from the output values. The suite offers *Leonardo* for result analysis and visualization. In parallel, database programs within the suite manage the storage of material and vegetation properties. The database program within the suite dedicated to trees is named *Albero*. The paragraph in section 2.3.1 provides more detail on the tree modeling with Albero and their representation in the simulation. Additionally, a few plugins are available that improve the modeling process with their extended functionalities, contributing to enhanced capabilities and efficiency.

Georeferencing and building geometry

Firstly, the geolocation of the study area and the building geometry were digitized by converting the architectural plans. The model area was created with the 'QGIS to ENVI-met' plugin. QGIS is an acronym for Quantum Geographic Information System and is a freely available and open-source GIS software by the Open Source Geospatial Foundation. QGIS supplies powerful digitalization capabilities for geodata and supports various data types, such as vector and raster data, satellite imagery, and terrain models. This plugin expands the capabilities of ENVI-met with valuable geospatial tools and replaces the program *Monde* for the digitization of the model area.

The property of the research project ECO+ is located in Stegaurach, south-west of the city Bamberg in northern Bavaria, Germany. The planners provided an architectural drawing of the planned buildings and some existing developments. The foreseen locations of the trees were also provided by the planners. These CAD drawings of the architectural and landscape plans were received in a .dwg file format. The first step was to convert the plans into geospatial data. QGIS can read the layers of the dwg file, and then the elements of the layers can be exported into shapefiles. A shapefile is a widely used file format for storing geographical features like points, lines, and polygons, along with their attributes. A conversion to the shapefile format is needed to georeference the model area. The next step after the conversion and the sorting out of the needed geometries for the modeling area was the georeferencing of the files. Therefore, data from another source was required. The State Office for Digitisation, Broadband and Surveying provides a free 3D model of existing buildings in Bavaria. This model is already georeferenced and was downloaded freely from the BayernAtlas website (Bayerische Vermessungsverwaltung, 2023). The 3D model is available in a Level of Detail 2 which refers to a medium detailed representation that includes accurate building footprints and roof shapes. Using the 3D building model, the architectural plans were georeferenced within QGIS. The building model from the Bavarian geo-portal was also used to obtain the building heights of the surrounding already existing construction.

Figure 3.2 below shows the project site in Stegaurach as a Google Satellite image and the model area marked by a yellow frame.

Figure 3.2: Property of the project ECO+ in Stegaurach, model area marked in yellow [Screenshot of Google Satellite in QGIS]

Surfaces and Landcover

ENVI-met allows for very detailed modeling, with the ability to set building materials for each wall, select and create soil profiles, add water, and refine vegetation into simple vegetation such as grass and shrubs or 3D vegetation for trees. Since the focus of the thesis is on outdoor thermal comfort and there was no information available on the building materials of the surroundings, the ENVI-met default wall and roof material was applied to the building model. The default building surfaces adequately represent the low-rise urban area; however, land cover surfaces were specified given the focus on outdoor conditions. The land cover was determined using Google satellite imagery and existing plans. In QGIS, the land cover types were then digitized as polygon shapefiles assigned the corresponding location in the model area. The landcover types were categorized as follows: sealed surfaces such as roads and paved courtyards were categorized as concrete pavement, the general soil profile was sandy loam, and the gardens and other green areas were covered with the simple plant type of grass. As designed in the landscape plan, areas of the project property were further divided into the simple plant types of high grass, low grass, and shrubs. In QGIS, the land cover type is attributed to each shapefile element in the attribute table as an ENVI-ID that corresponds to an item in the ENVI-met database.

Trees

The vegetation in the form of trees was digitized using the ENVI-met program *Albero*. This program has already been introduced in section 2.3.1. The tree geometry and characteristics are digitized in this program and stored in the database. Each database entry is given a unique 'ENVI-ID', which is requested during the simulation. In the GIS program, the trees are represented as points in the shapefile, indicating the location of each tree. The ENVI-ID is linked to the location of the tree as an attribute, and the tree is only explicitly modeled later on in the grid-based program.

The species and height of the existing trees were mainly selected from the satellite images. Some trees were mapped and identified by the Chair of Green Technologies in Landscape Architecture, also involved in the ECO+ project. Based on the diameter and color of the trees visible in the satellite image, tree species common to northern Bavaria were assumed. If no approximation was possible, various tree heights and species were randomly assigned to the location of the existing trees. Regarding the newly planted trees, the species Robinia pseudoacacia (Balck locust) was selected for the trees around the buildings because this species has heat-tolerant characteristics (Böll, 2018; Zentrum Stadtnatur und Klimaanpassung, 2022). For the new trees in the garden, a mix with two more species was modeled, the Tila cordata (Small-leaved lime), and Aesculus hippocastanum (Horse chestnut), which are common for this region.

The placement of the existing and new trees according to the green infrastructure plan is shown in Figure 3.3 above. The trees displayed in a light green color exist already, and the dark green trees are to be planted. The GI plan proposes to plant the new trees around the building facades and in several other selected locations. The trees are planted relatively close to the walls, especially west of Building 1 and south of Building 2. North of Building 2 and east of Building 1, the selected locations of the trees show some distance to the facades. The dimensions of these planned trees will be determined based on the results of the CityTree tree growth model. Detailed explanations of the results and the reasons for the selection of tree species can be found in the Section 3.2.

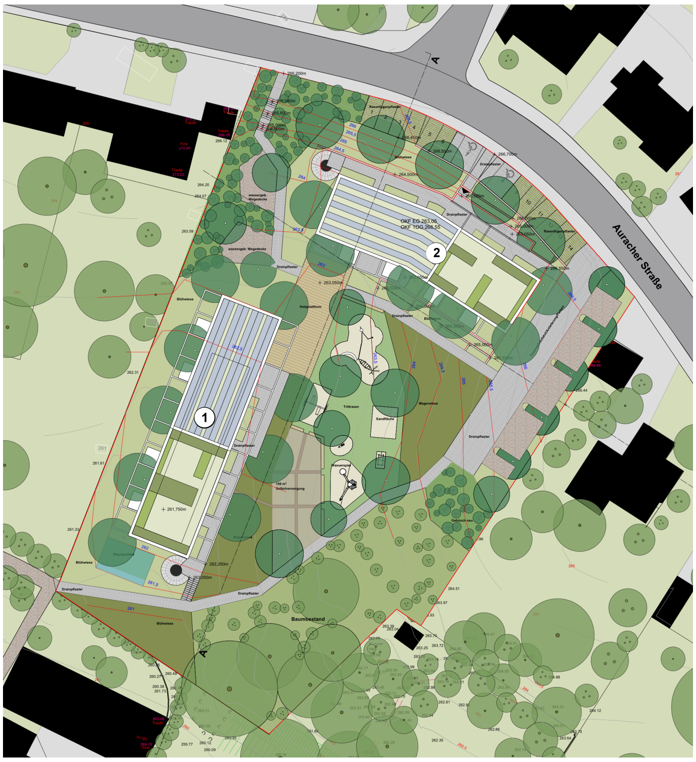


Figure 3.3: Green Infrastructure site plan from ECO+ project with dark green trees newly planted

Meteorological Data

Two different sources were used to obtain the meteorological data, since for some simulations actual measured data was used, and for future scenarios, climate projections were used. The data for the simulation of the actual year 2023 were downloaded from the website of the German Weather Service (DWD), which provides the measured data of its weather stations. The closest weather station to the study area is the 'Bamberg' station, which is located approximately 4.9 km northeast of the property. In order to be able to use the weather data, ENVI-met's *Forcing Manager* is used, which converts the weather data into a suitable format. The forcing manager can import datasets in the form of CSV (Comma-separated values), EPW (EnergyPlus Weather file), or TRY (Test reference Year) files and convert them into a specialized 'forcing file'. The data required includes hourly records of: cloud cover (scaled from 0-8) for high, medium, and low clouds, air temperature (in Kelvin), relative humidity (in percent), wind speed (in meters per second), wind direction (in degrees), and precipitation (in millimeters).

The dataset from the DWD was obtained in a CSV format and the datasets for the future weather data were obtained from Meteonorm as EPW files. Some of the weather data required minor adjustments to ensure the stability of the simulations. For example, in cases where there were abrupt changes in wind direction over short periods of time, modifications were made to maintain a stable simulation environment.

3.2 Dynamic vegetation model

The microclimate simulations with ENVI-met are performed for the current year as well as two points in the future and two different climate scenarios. To achieve the most realistic future conditions, not only the meteorology but also the trees were adapted in their development according to the simulation date and climate scenario. To obtain the tree dimensions of the future, the tree growth model CityTree is used. One driving force of the CityTree model is the monthly weather data for which the climate projections are entered. It is expected that the trees grow differently according to climate scenario. Thus, the dynamic growth of trees is approximated for each climate scenario with CityTree.

A detailed description of the physiologically-based principles of CityTree is provided in the section Description of CityTree. The operation of the model is within a sophisticated Microsoft Excel framework, requiring data input only on one of its sheets. The model calculates the tree's growth and interactions for one year. The output sheet shows tree growth, phenology, productivity, biomass, water balance, cooling by evapotranspiration, and shading. The input data required and used are listed in Table 3.1 below.

Table 3.1: Input parameters for CityTree

Location:	latitude 49.89°, longitude 10.9°
Surface sealing:	22 %
Competition index:	0.60
Soil type:	sandy loam
Field capacity:	25 vol%
Wilting point:	8 vol%
Rooting depth:	100 cm
Species:	Robinia pseudoacacia (black locust)
CO_2 concentration:	420 - 935 ppm, according to scenario
Climate:	monthly means of radiation, temperature, relative humidity, wind speed and precipitation according to scenario
Dbh class:	approimated by age

Since CityTree gives yearly outputs, the initial strategy for simulating dynamic tree growth over an 80-year period involved iterative processing through a custom Excel macro. This macro repetitively used the annual output in tree dimensions as the subsequent year's input, incorporating evolving climatic conditions by updating meteorological data and atmospheric CO_2 every decade. The climate predictions were obtained from Meteonorm as described in section 2.4. However, this iterative method led to implausible results regarding the growth of the tree dimensions, so it was unsuitable for this study. The reasons for the unplausible results could not be determined with the available knowledge about the model, and the development of a fully dynamic version of the CityTree model to fix this issue was beyond the scope of this thesis. However, making the model fully dynamic represents an interesting possibility for future studies. Furthermore, while CityTree shows considerable potential in simulating detailed biomass growth, it is not a spatially explicit model focussing on geometry but rather on ecosystem services. This limits the transfer of the output accuracy obtained for certain aspects into the ENVI-met model.

Because a continuous dynamic model was not applicable to the current CityTree version, a modified, intermittently dynamic modeling approach was chosen. The growth calculations of a tree are divided into 10 dbh classes. The dbh and the tree age are not linked in a linear way. Since the age of a tree is difficult to determine, the dbh is used to classify different growing stages of the tree. Therefore, to approximate the growth of the trees, every dbh class was looked at, and from the difference in growth, the difference in tree dimensions for each scenario was to be derived. As the dbh does not provide direct information about the tree age, literature values were consulted to assume the age (Zentrum Stadtnatur und Klimaanpassung, 2022). According to the age, the meteorological data was input, available in decadal intervals until 2100. The tree growth simulations were performed for the species Tilia cordata (small-leaved lime), Robinia pseudoacacia (black locust), and Aesculus hippocastanum (horse chestnut). The following parameters were updated, and each time the increase in dbh, height, and crown diameter was documented (see appendix A).

- Tree age, estimated based on the dbh correlations as described in the Urban Tree Guideline
- Monthly average weather data, ranging from 2020 to 2100 and updated at ten-year intervals
- Variations in atmospheric CO_2 concentrations as projected in the IPCC Fifth Assessment Report (Figure A.2)

The effects of these updated parameters on dbh, tree height, and crown diameter were documented to assess the impact of different climate scenarios on multiple tree species. The model output of CityTree offers a variety of parameters; however, most of them cannot, unfortunately, be transferred into ENVI-met. Therefore, tree dimensions and not the other outputs available, like ecosystem services or shading, were used because the tree height and crown diameter are the interface where the CityTree results can be inserted into ENVI-met. The results are presented in Section 4.1.

3.3 Simulations

To assess the influence of the planted trees on thermal comfort in future climate conditions, multiple simulations were run with different climate scenarios, different tree growth stages, and without the trees. The simulation years chosen were the current year, 2023, and the years 2050 and 2100. These years were chosen to observe the trees' growth and assess thermal comfort along the construction project's life cycle. The hottest day of each year was determined and used for the simulations respectively. The selection of the hottest day as an indicator is due to its representation of peak heat stress, a significant future risk. The hottest day can vary significantly from year to year, but this choice is driven by the challenges of running microclimate simulations over long periods. Thus, this day was considered the best indicator for comparison.

Concerning the resolution, the grid size of the model must be weighed against the simulation time. For a microclimate simulation, the resolution is generally a few meters. For the project site, which measures approximately 125 meters by 80 meters, the model area was expanded to 202 meters by 204 meters. This expansion beyond the actual study area is needed to mitigate the effects of boundary conditions. A resolution of 2 m was chosen, which was found to be appropriate for capturing the influence of trees on the microclimate.

To avoid numerical errors and decrease simulation time, some adjustments were made to the model extensions in agreement with ENVI-met guidelines. First, ENVI-met recommends that the horizontal distance between the border and the buildings should be either zero or at least the size of the closest building height. Therefore, empty grid cells were added around the area until the spacing met this requirement. The vertical extension of the model is considered good when the model height is at least double the height of the highest element in the domain. This was already applied during the export from QGIS. Secondly, to reduce simulation time, there is the option to use telescoping grids. Telescoping grids increase their size in the z-direction with the height by a given factor. To not disrupt the area of interest, the telescoping was started a few meters above the height of the highest building with a factor of 15 %. Furthermore, the microclimate of an area depends strongly on the previous small-scale meteorological conditions in that area. Therefore it is important to have a good initialization for a simulation that should output realistic results. ENVI-met advises starting a simulation at a time when it can go along with the atmospheric process of the sun. So rather than starting the simulation in the midday heat, it should start in the night or at sunrise. Additionally, to avoid any influence of the initial conditions on the simulation results, a preferable initialization time is 24 hours, if possible.

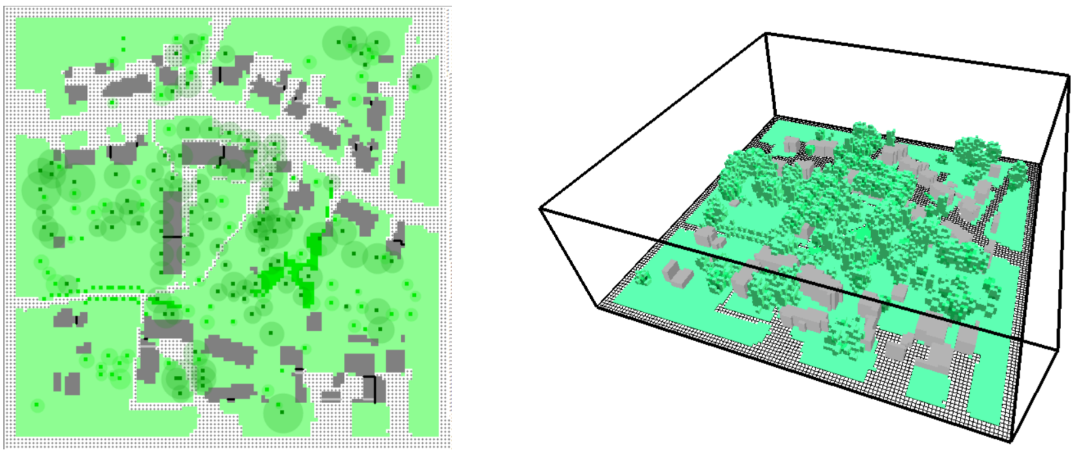
Since the hottest time of the day in the summer is the afternoon when the solar radiation is strong and has already heated up the environment, it was decided to look at the thermal comfort at 2 p.m. in wintertime for the analysis of the results.

With the available science license for ENVI-met, a simulation of about 112 × 111 × 20 grids with the settings used takes around 30 - 45 h of computation to model 40 hours on an Intel Core i7-11800H processor using 16 CPUs.

3.3.1 Example model domain

As an example, all input parameters and model settings for the simulation (Variant 2a) on 25th August 2050 are shown in the following figures.

In Figure 3.4 the building and vegetation model are shown in the program Spaces.



(a) 2D view **(b)** 3D view

Figure 3.4: Spaces file of the model area in 2D and 3D view

Model domain parameters:

- 102 x 101 x 20 grids
- dx = 2 m, dy = 2 m, dz = 2.5 m
- core domain size: 205 m x 201 m
- height of 3D model top: 75.76 m
- telescoping 15 % after 27 m model height
- border grids: + 5 in each direction

Figure 3.5 shows the weather data for 24th August 2050 and Figure 3.6 for 25th August 2050:

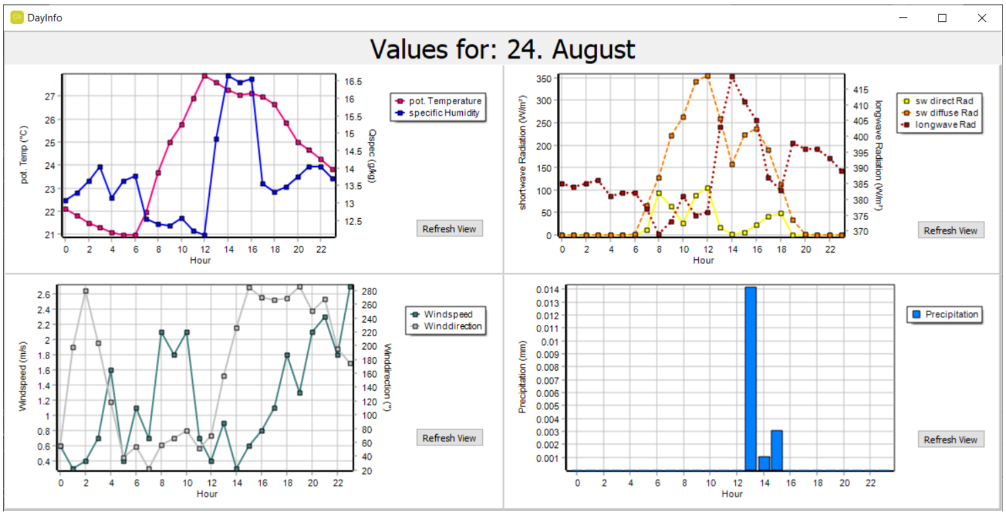


Figure 3.5: Meteorological data RCP 4.5, 24. August 2050

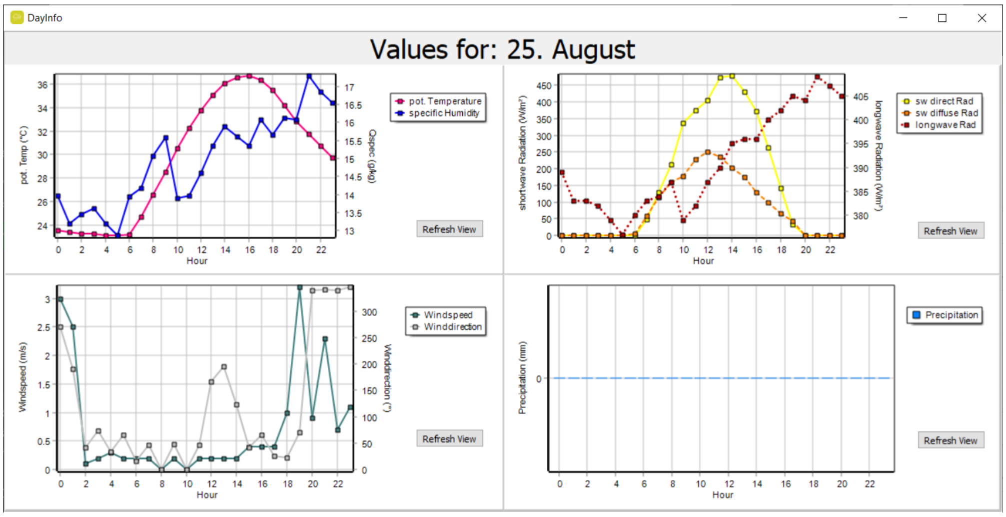


Figure 3.6: Meteorological data RCP 4.5, 25. August 2050

The tree types that were placed next to the facade are shown in Figure 3.7. Based on the results from CityTree, 35 years of growth resulted in tree dimensions of 19.76 m height and 12.5 m tree extent for the species Robinia pseudoacaia.

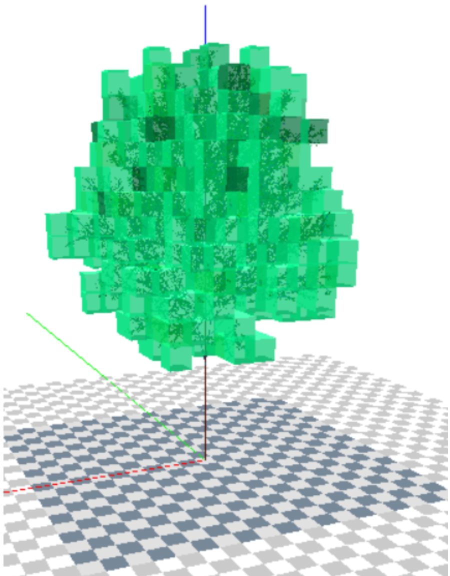


Figure 3.7: Robinia 35 years represented in Albero

The simulation duration was 40 hours, starting on 24.08.2050 at 6 a.m. and ending on 25.08.2050 at 9 p.m. The RCP scenario used was RCP 4.5. All simulations were run on 16 CPU cores with 32 reserved CPU threads and a clock speed of 2.30 GHz with the ENVI-met version 5.6.1. This example simulation took 27 hours and 25 minutes to complete. The thermal comfort index UTCI was calculated from the atmospheric output by ENVI-met's program BIO-met.

3.3.2 Simulation variations

Table 3.2 gives an overview of all simulation variations carried out.

Table 3.2: Simulation variations

Variant	GI	Date	Scenario	Tree age	Tree height	Computation Time
0	No GI	15.07.2023				34.3 h
1	Facade trees	15.07.2023		~10 years	6.9 m	35.2 h
2 a	Facade trees	25.08.2050	RCP 4.5	~35 years	19.7 m	27.4 h
2 a-0	No GI	25.08.2050	RCP 4.5			25.6 h
2 b	Facade trees	11.08.2050	RCP 8.5	~35 years	19.7 m	46.h h
2 b-0	No GI	11.08.2050	RCP 8.5			47.6 h
3 a	Facade trees	21.07.2100	RCP 4.5	~85 years	25.4 m	53.4 h
3 a-0	No GI	21.07.2100	RCP 4.5			39.4 h
3 b	Facade trees	21.07.2100	RCP 8.5	~85 years	25.4 m	31.4 h
3 b-0	No GI	21.07.2100	RCP 8.5			28.9 h

4. Results and Discussion

This chapter presents the results of the simulations carried out. Firstly, the results of the tree growth model CityTree are presented and assessed (section 4.1). These results are used in the ENVI-met simulation. The results of the ENVI-met simulations are presented in the form of a spatial UTCI distribution (section 4.2). The accuracy and efficiency of the results are discussed, and the performance of the different scenarios and tree growth stages are compared to each other.

4.1 Tree growth results

The modeling method and the difficulties in obtaining a fully dynamic model are described in Section 3.2. When simulating, absolute values must be cautiously reviewed, as the model can never fully depict reality. It is better to have a comparison between two model settings. For this study, the two scenarios, RCP 4.5 and RCP 8.5, are used as the comparison settings. They represent different climate conditions. Weather data, especially precipitation and CO_2 concentration are essential for vegetation growth. Thus, the assumption was made that the different future scenarios would lead to differences in the growth of the trees.

The following graphs display the growth increments of Robinia over the years until 2100. In addition to the previously mentioned RCP 4.5 and 8.5 scenarios used in the microclimate simulations, the CityTree model also incorporates the RCP 2.6 scenario for a broader comparison and reference in the tree growth modeling. Furthermore, the simulations were carried out for two other tree species also prevalent in the region, the Little Leaf Lime (Tilia cordata) and the Horse Chestnut (Aesculus hippocastanum). As the tree species is a decisive factor regarding tree growth, multiple species were simulated to evaluate the robustness of the model and to identify any potential flaws. The results of these species can be found in Appendix A. However, this analysis primarily focuses on the Robinia species, as it is the chosen species for the trees surrounding the facade.

The graph in Figure 4.1 illustrates the annual increase in crown diameter of Robinia trees up to the year 2100, in units of meters. The growth ranges between 0.13 m and 0.23 m per year in crown diameter across all climate scenarios. Upon examination, the growth increments show minimal variation between the different scenarios. The differences are less than a centimeter per year, resulting in a maximum difference in growth of about 30 cm over 80 years. While this marginal variance is noticeable, it is not substantial for a tree, considering the natural variability among individual trees and the fact that the underlying calculations are based on averages of numeral trees.

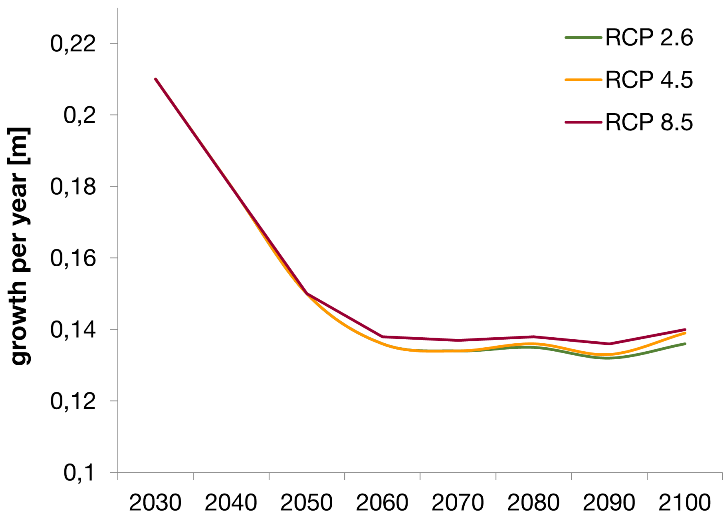


Figure 4.1: Annual crown diameter growth of Robinia pseudoacacia under RCP scenarios 2.6, 4.5, and 8.5

It is noticeable that the growth patterns are identical in all scenarios until 2050, and only afterward variations in growth rates are observed. However, predicting growth in the distant future is subject to considerable uncertainty due to the lack of measurement data for reference. In spite of the uncertainty, it is notable that the RCP 2.6 scenario shows the least growth, while RCP 8.5 shows the most, with RCP 4.5 in between, which is consistent with their respective climate projections. This trend is likely to be influenced by changes in CO_2 since higher CO_2 levels enhance plant growth due to increased photosynthetic activity, a phenomenon known as CO_2 fertilization. However, as stated before, the differences are negligible regarding the size of trees. To conclude, the analysis shows no significant difference in crown diameter growth of Robinia under different climate scenarios.

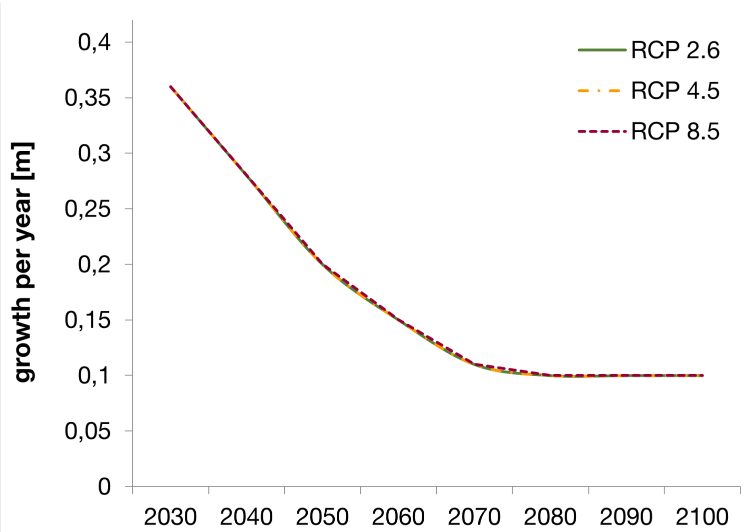


Figure 4.2: Annual height growth of Robinia pseudoacacia under RCP scenarios 2.6, 4.5, and 8.5

The graph in Figure 4.2 shows the documented increments in growth per year of the height for the same species, Robinia. The graph illustrates quickly that no significant differences could be found for the height according to the RCP scenarios. It is remarkable that likewise, for the other species investigated (Figure A.6, Figure A.7), there are no changes per scenario concerning the height growth per year. In contrast to the marginal differences observed in the case of crown diameter, the reason here probably lies in the calculations embedded in the CityTree model. CityTree calculates the biomass growth in total for the tree and then re-allocates growth increments to height, drown diameter, and dbh. In summary, similar to the results for crown diameter growth, the modeling results for the height do not show any significant differences between the climate scenarios.

Although the diameter at breast height cannot be adjusted in ENVI-met, the growth in dbh is examined for a better understanding. The results are shown in Figure 4.3. Similar to the previously examined growth indicators, dbh shows slight differences according to climate scenarios. However, similar trends as for the crown diameter can be observed from 2050 onwards. The growth of the dbh changes in the order of the RCP scenarios, which is probably also due to the changes in the CO_2 concentration.

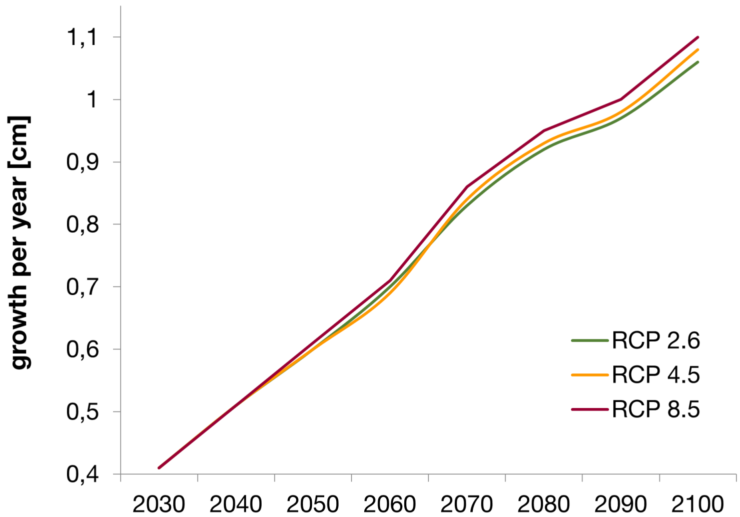


Figure 4.3: ANnual dbh growth of Robinia pseudoacacia under RCP scenarios 2.6, 4.5, and 8.5

The growth results of the Robinia tree presented in the three graphs above indicate that the trees continue to grow and are not negatively affected by the changing climatic conditions in the future (compared to the conditions under the RCP 2.6 scenario, which is more similar to the current conditions). Reasons why this general assumption is not reflected in the results of the CityTree model, could be attributed to potential model deficiencies or the unique characteristics of the Robinia species. The Robinia tree was selected for the tree facade for its drought-resistant qualities, so it likely thrives in the warmest scenario with elevated CO_2 levels. To evaluate if the model's response was predominantly to atmospheric CO_2 levels rather than climate-related stressors, the growth patterns of the two other species were also examined (see Appendix A.1).

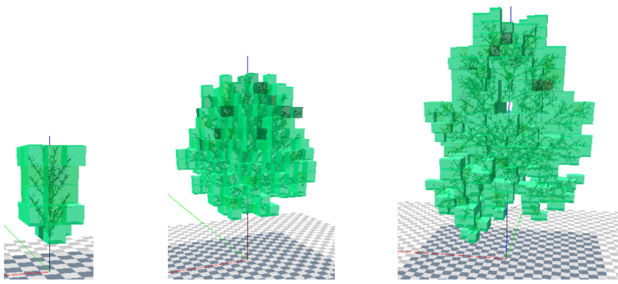
This comparative analysis of the dbh growth of various species revealed that the model does respond to the scenarios. The results for the other species underscore the significance of species selection in relation to climate scenarios. For instance, the heat-tolerant Robinia tree shows the highest growth rates in conditions with the highest CO_2 concentrations and temperatures. Looking at the dbh as an indicator, the horse chestnut, in contrast, displays its best long-term growth under the RCP 4.5 scenario. Initially, its growth peaks under RCP 8.5, but this trend reverses after 2070, leading to the lowest growth rates under RCP 8.5 in the long term. The species Tilia cordata, known for its higher water sensitivity (Zentrum Stadtnatur und Klimaanpassung, 2022), shows similar behavior, with the most favorable growth rates under RCP 4.5 and the lowest growth under the RCP 8.5 scenario from 2070 onwards. Nevertheless, the overall differences between the scenarios for these species are minimal and would need to be more pronounced for modeling differences in the resolution of the ENVI-met simulation.

The marginal differences observed may stem from inaccuracies in the CityTree model, particularly its limitations in incorporating long-term effects. While CityTree simulates annual growth rates, this study required approximations of long-term growth, which the model does not contain. The dynamization of the model, necessary for accounting for extended periods of drought across several years, still needs to be implemented. Consequently, the model's annual growth outputs do not consider droughts impacting the following year. This methodology overlooks the potential lag responses of trees to environmental changes, which may occur over extended periods. Another inaccuracy originates from the intermittent dynamization where the growth is examined for every dbh-class. This means the model reverts to using average dimensions as input, derived from literature values based on present climate conditions for each dbh class.

While the model's limitations in addressing long-term effects and dynamization have been discussed, another aspect to consider for enhancing the model's accuracy is the adaptation of soil characteristics. In the CityTree module, tree growth is influenced by climate data and also soil characteristics. The soil characteristics convey valuable information, such as soil moisture content and field capacity, which influence vegetation growth. Due to the lack of information and suitable future models of the soil conditions, the soil characteristics were not adjusted over time in the model input. For future studies, this could be another parameter to include in order to obtain more precise model results with CityTree.

Continuing the discussion about model inaccuracies and other impactful variables, it is relevant to investigate the meteorological data as an essential part of the model. The climate projections, namely the air temperature and precipitation values, were examined for the scenarios RCP 4.5 and RCP 8.5, as indicators. The quantity of precipitation, as well as its seasonal distribution, are important for tree growth. Comparing the weather projections for the two scenarios, there is a substantial discrepancy in temperature of up to 2.7 degrees Celsius between the scenarios. On the other hand, the difference in the yearly amount of precipitation between the two scenarios averaged over the years 2020-2100, is only 3 mm. The precipitation amount for both scenarios for the location of Bamberg is thus considered very similar. Since the distribution of rainfall over the course of the year is also influential for tree growth, the amounts per month were compared. The averages per month from 2020-2100 were evaluated. The comparison shows that the difference in the distribution over the year was, on average, also only 3 mm monthly between the two scenarios. The biggest differences were found in the months of May and November, with a maximum difference (averaged from 2020-2100) of 6.11 mm in November. This leads to the conclusion that the precipitation patterns are also quite similar between the scenarios. In other Bavarian regions, the climate-induced changes in rainfall sum up to 99 mm, like in Kempten for example (Abschlussbericht S. 61). The regional variations underscore the importance of localized climate data in accurately modeling tree growth.

In summary, the analyses discussed in this section suggest that the minor differences in tree growth between the scenarios are likely due to the similar precipitation patterns observed for both scenarios. The location-specific projections for Bamberg obtained from Meteonorm indicate a relatively stable future in terms of precipitation, which is a favorable outcome. To conclude the model performance of CityTree, it is clear that urban tree growth models require enhancements, particularly in long-term and dynamic modeling capabilities. In the current situation, literature values were needed to verify the dbh class that corresponds to the tree age, which leads to results that are indirectly influenced by current climate conditions. Moreover, drought stress over multiple years needs to be included in the model to reflect the impact of climate change more accurately. As such, predictions about distant future scenarios using current urban tree growth models should be approached with caution. The results of the CityTree simulations are used for the microclimate simulation with ENVI-met. Concerning this matter, it can be concluded that the differences in growth between the two climate scenarios are not significant in general and, particularly here, are not large enough to be able to be considered in the resolution of 2 m of the microclimate simulation. Therefore the same tree dimensions are used for RCP 4.5 and RCP 8.5. The trees created in Albero are based on the dbh-class 10 (as per Leitfaden Stadtbäume data) for initial height, combined with modeled growth increments scaled by the number of years passed. The three growth intervals used for the simulation of the Robinia tree are displayed in Figure 4.4 below.



(a) 2023, 6.9 m height **(b)** 2050, 19.7 m height **(c)** 2100, 25.4 m height

Figure 4.4: Growth intervals modeled in Albero

4.2 Thermal Comfort results

An overview of the simulations carried out is given in Table 3.2. The computation time for the simulations was around 37 h on average. For the purpose of this thesis, the output in the folder 'atmosphere' was used to extract the UTCI for the area. For calculating the UTCI, the BIO-met program from ENVI-met was used, adopting the parameters of an average 35-year-old female in summer clothing.

On average, the total storage requirement for the output of a single simulation is around 8.8 GB, with the atmosphere data occupying about 1.8 GB. The output files can be analyzed in the Leonardo program. This tool enables the spatial visualization of various parameters, such as air temperature e.g., in both 2D and 3D formats. This thesis primarily focuses on the horizontal 2D distribution, considering that in the vertical direction mostly the height relevant to human well-being was of interest. To include as many person groups as possible, the second grid cell at a height of 1.25 m was chosen.

It is important to note that a direct validation of the simulation results against measurements is not possible, as they calculate future conditions. But the results of the spatial distribution can be compared to expectations and to other scenarios. Like this, the validity of the results can be warranted and the effects of the GI can be identified by comparison. In this analysis, the thermal comfort index UTCI is used. Throughout this analysis, when describing conditions as 'hot' or specifying temperatures, it is the UTCI that is being referred to rather than the actual air temperature.

Results 2023 (Variant 0 and Variant 1)

Figure 4.5 presents Simulation Variant 0 on 15th July 2023 at 2 p.m. wintertime, which corresponds to 3 p.m. local time (;ENVI-met does not include daylight-saving in the simulation). This variant models the thermal comfort on the hottest day of the year 2023 in Bamberg, prior to the implementation of any green infrastructure. This scenario represents the current climate conditions in Bamberg, providing a foundation to evaluate how trees impact the area and whether their presence enhances overall thermal comfort on the property.

In this simulation, the UTCI ranges from a minimum of 35.8 °C to a maximum of 46.1 °C. In the unshaded garden area between the buildings, the UTCI varies between 41.7 °C and 46 °C. In contrast, the shaded regions behind the buildings, which are toward the north, show cooler UTCI values ranging from 38.7 °C to 40.2 °C. The wind speed throughout the area is generally low, not exceeding 3 m/s.

An interesting observation from this map is that large trees contribute more to thermal comfort than only the shade from structures. The areas with the best thermal conditions, indicated by a bluer coloration, are those around trees, which can be recognized by their round shape. However, the lowest thermal comfort level across the entire area still falls within the category of strong thermal heat stress (32 °C to 38 °C).

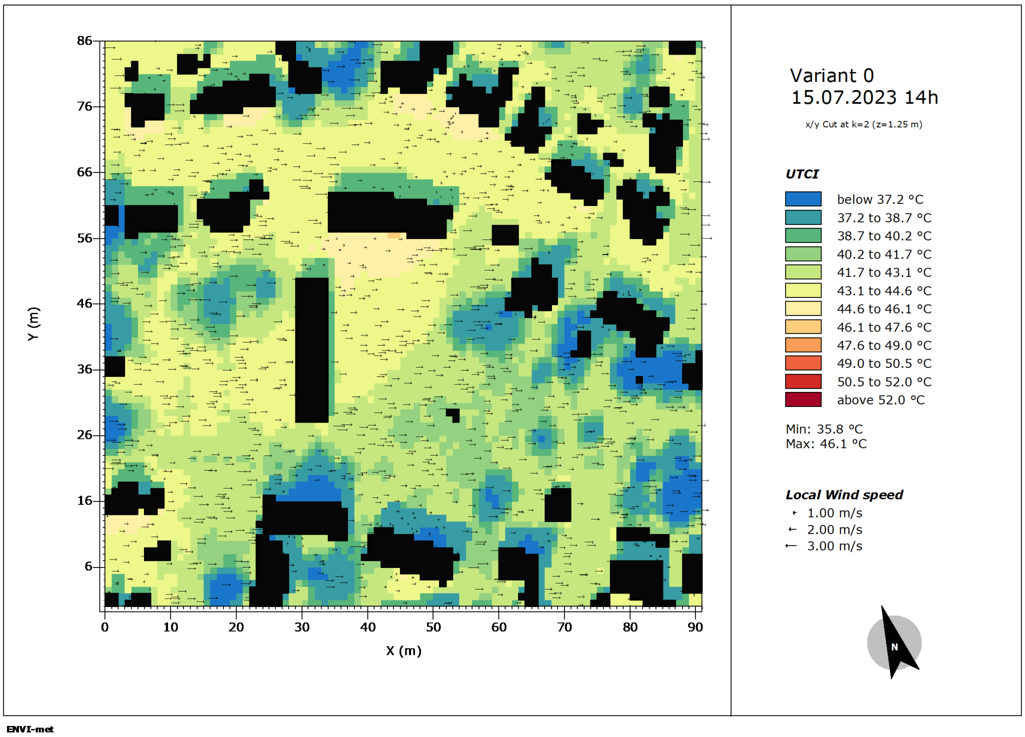


Figure 4.5: Variant 0, UTCI distribution on 15.07.2023, no Green Infrastructure

The map orientation indicates that the sun comes approximately from the bottom of the map, as it is rotated 19° out of the north, but at 2 p.m. the sun is already past the zenith. For clarity in future discussions, the new building located further west, stretching from southwest to northeast, is referred to as Building 1. The other new building perpendicular to it is designated Building 2. Notably, the hottest part of the map is along the long southern facade of Building 2, which is directly exposed to sunlight during this time of day. Additionally, with the wind predominantly coming from the west and being obstructed by Building 1, the wind speed in the corner between the two buildings is relatively lower compared to other areas.

Figure 4.6 shows the simulation Variant 1, run under the same conditions as Variant 0 but with the trees planted in their beginning stage. The time for the analysis is also set at 2 p.m. on 15th July 2023. The height of the Robinia species, which is planted around the facades, is 6.9 m. These newly planted trees make a detectable difference, albeit limited to a very little radius. Their impact is apparent from the small, round areas on the map showing lower UTCI values where the trees are situated. The differences in UTCI detected in the center of the facade trees is about 2.8 - 3.8 K. The influence of the rather young trees covers around 8-10 grid cells on the map, so an area of 6 m x 6 m depending on whether it stands alone or closer to the facade. A map of the spatial comparison between Variant 0 and Variant 1 can be found in the Appendix in Figure A.8. Accordingly, there is an improvement in thermal comfort, but in the overall area it remains marginal and the absolute levels remain considerably high.

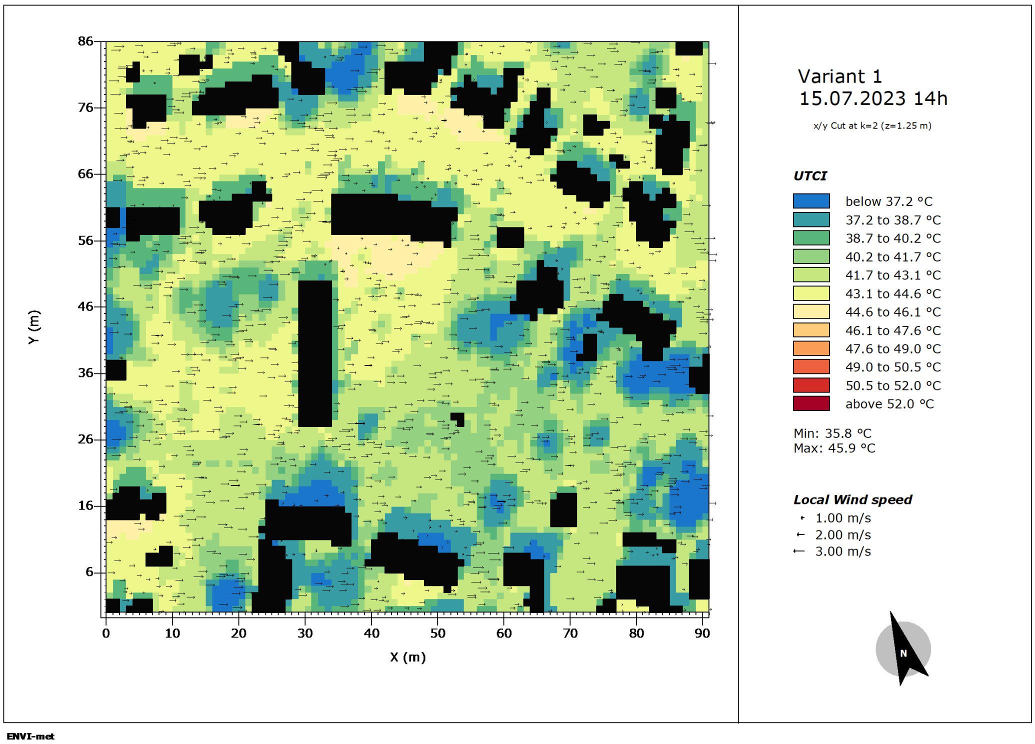


Figure 4.6: Variant 1, UTCI distribution on 15.07.2023, with tree facade

Results 2050 (Variants 2)

The next two figures provide insights into the UTCI distribution for the two different RCP scenarios in 2050. By this time, the trees have grown, reaching a height of approximately 19.7 m. Their significant effect on thermal comfort is noticeable on the map, marked by areas in shades of green and blue with a round shape from the trees.

Figure 4.7 shows Variant 2a, on 25th August 2050, with the climate data of RCP 4.5. In the empty parts of the map without tree cover or other shade-providing structures, the UTCI ranges from 44.6 °C to 46.1 °C. Within shade and within the impact zone of the trees, in contrast, there is a notable improvement in UTCI values which range between 37.2 °C and 40.2 °C. Even compared to the scenario with small trees in 2023, the UTCI could be improved and can be clearly attributed to the planted trees, as round shapes with better thermal comfort can be observed along the facades. This enhancement in thermal comfort is attributed to the increased size and ecosystem services provided by the grown trees. Due to the growth, the UTCI could be improved by around 3 °C at the core of the trees along the building walls compared to 2023.

However, there is a noticeable exception. The southern locations of both buildings display little to no benefit from the nearby planted trees, as indicated by the UTCI distribution on the map. This observation is consistent with the findings for the year

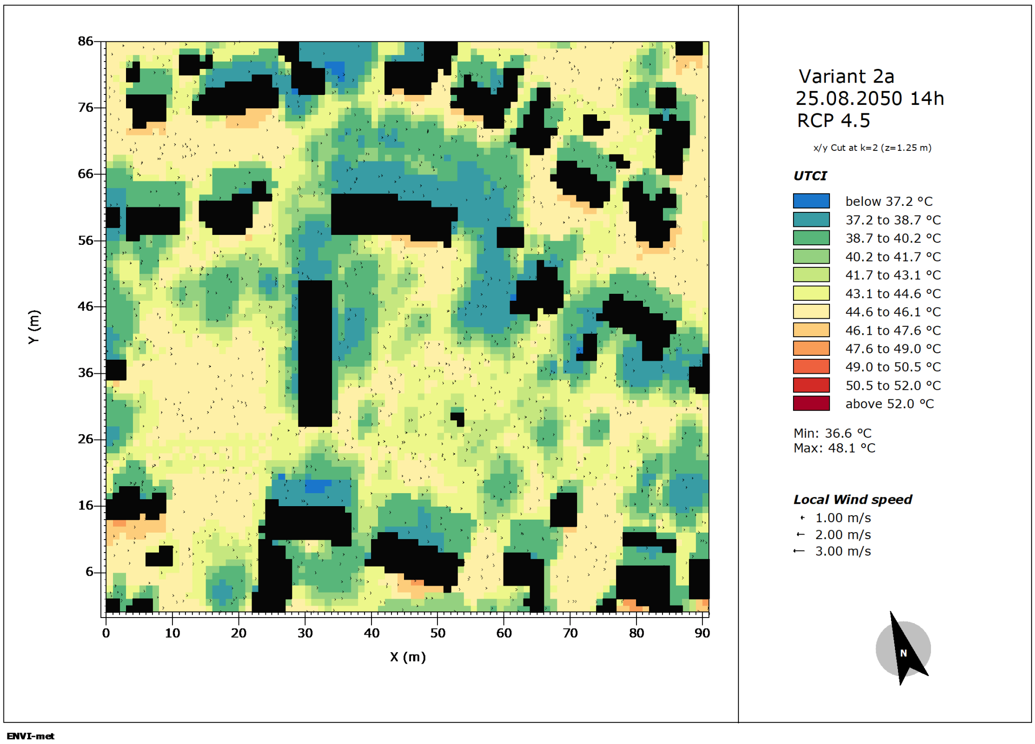


Figure 4.7: Variant 2a, UTCI distribution on 25.08.2050, under RCP 4.5, with tree facade

2023, where the southeastern facade of Building 2 was identified as the most heat-exposed and warmest part of the property. On the southeastern corner of Building 1, no tree was planned, which is reflected in the hotter UTCI values at that location and even further north along the facade, too. Similar to the facade of Building 2, the southern facades of the surrounding buildings worsen thermal discomfort, likely due to the heat radiated by the building materials. The local wind speed is very low on that day.

The second simulation for the year 2050 is presented in Figure 4.8. This Simulation Variant 2b was carried out for 11th August 2050, under the RCP 8.5 climate scenario. The data extracted to the map shows again the spatial UTCI distribution at 2 p.m. and and at a height of 1.25 m. Initial observations reveal that the impact of trees on thermal comfort in this variant is similar to that in Variant 2a, which used the RCP 4.5 scenario. Additionally, the general UTCI values across the map in open fields align with those seen in Variant 2a as well.

A notable distinction in Variant 2b is observed in the regions south of buildings. Compared to Variant 2a, these locations show a markedly aggravated effect of the south-facing facades. The high UTCI values indicate increased heat stress, at these locations specifically in a range of 47.6 °C - 50.5 °C. Another difference to note is that in Variant 2b the wind speed is higher, compared to the near-still conditions in Variant

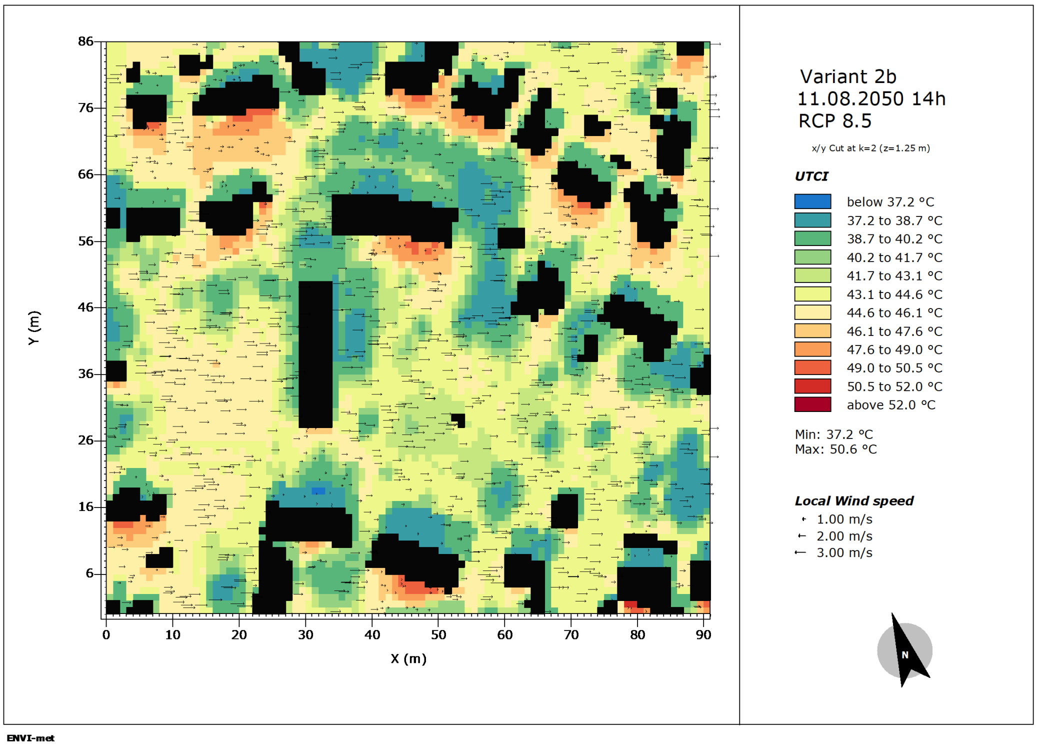


Figure 4.8: Variant 2b, UTCI distribution on 25.08.2050, under RCP 8.5, with tree facade

2a. The increased wind may help explain why the overall UTCI in the RCP 8.5 scenario is only slightly higher than in RCP 4.5, as wind can have a cooling effect and improve thermal comfort. Despite the higher wind speeds, the impact zone of the trees remains largely unaffected, maintaining a similar shape and influence, though the thermal comfort values are somewhat better in the RCP 4.5 scenario. The differences between these two scenarios in the year 2050 are noticeable but not drastic. Comparing the two climate scenarios directly poses a challenge due to their distinct climatic conditions and the fact that only one day per year, the hottest day, is analyzed. For the year 2050, these days are based on different dates in August. However, it is reasonable to observe some similarities between the two results. This can be attributed to the relatively short time span of 27 years between 2023 and 2050, a period in which the projected climate scenarios have not yet diverged drastically.

In addition to comparing the UTCI distribution between different climate scenarios, this simulation is also compared to Variant 2b-0, which models the thermal comfort without any planned GI in the year 2050 under RCP 8.5. The comparative map can be found in Figure A.9. (For Variants 2a and 2a-0, the map could not be created due to limits within Leonardo which only allows to compare model areas with the same amount of grid cells. In Variant 2a, the border grids had to be adjusted to stabilize the simulation.) Compared to the setting without planned GI, the trees improve the thermal comfort by up to 9.3 K, and for the most part, by around 6.7 K. It can be observed that the trees planned further away from the facades have a much larger radius of influence than the ones planned directly on the facade.

Results 2100 (Variants 3)

The simulation results for the year 2100 are displayed in the figures Figure 4.9 and Figure 4.10. Between the previous simulation lie 50 years of climate change, and between the first two variant settings, only 27 years. This extended period has resulted in notably higher temperatures, which are directly visible on the maps. By 2100, the trees have reached a height of 25.4 m, with a slowed growth rate; their height increased by 28 % between 2050 and 2100, compared to more than a doubling from 2023 to 2050.

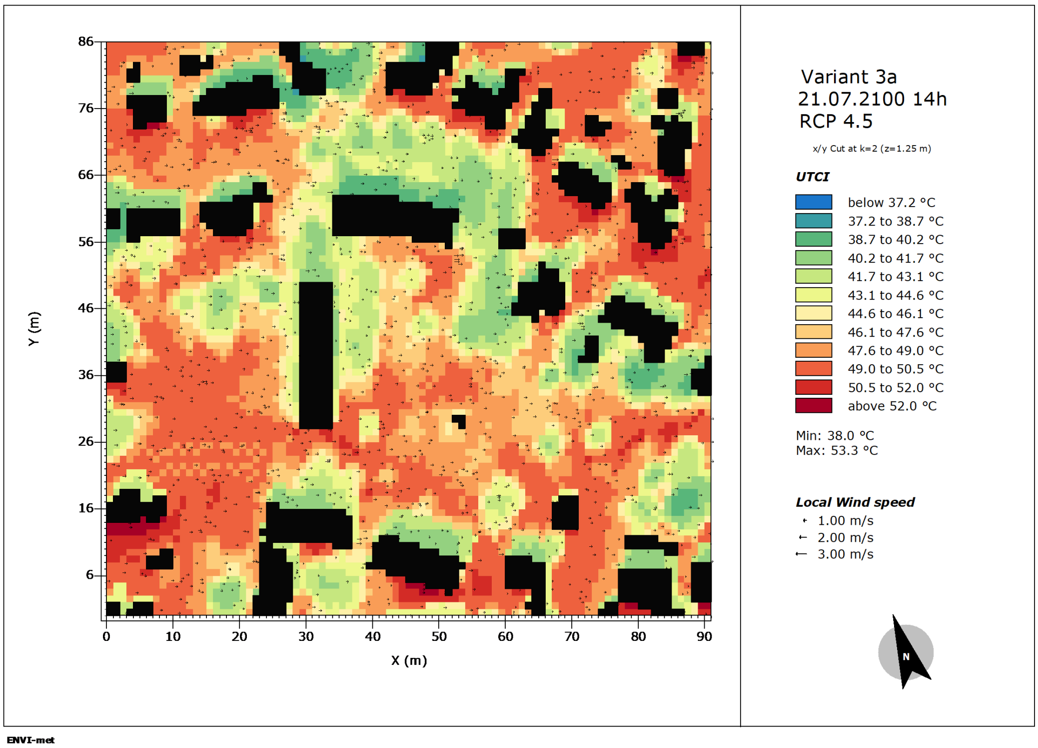


Figure 4.9: Variant 3a, UTCI distribution on 21.07.2100, under RCP 4.5, with tree facade

For the RCP scenario 4.5, which is shown in Figure 4.9 (Variant 3a, 21th July 2100), the UTCI has its minimum with 38 °C in very few grid cells and otherwise performs best in areas that are located north of buildings and include trees. There, the UTCI ranges from 38.7 °C to 40.2 °C. In this scenario, the difference in UTCI between open fields and tree-adjacent areas is about 8 °C. On the southern facades of Buildings 1 and 2, the influence of the trees is hardly noticeable, similar to Variants 2a and 2b. The wind speed on that day is calm. The locations that are within the influence of the trees show a thermal comfort of approximately 38 °C to 45 °C, while unshaded areas not influenced by trees experience UTCI values between 47 °C and 50 °C.

The differences in UTCI between this setting and the simulation without GI amounts to a maximum of 10.7 K difference (see Figure A.10). However, this is only at the center of the trees, and their radius shows differences between 2.6 K - 8.4 K. The greatest improvement due to the presence of the trees is found in the garden between the two buildings, mainly east of Building 1. The trees north of Building 2 also show a significant influence, although slightly less, which could be due to the fact that they are situated north where there is already more shade. The trees on the west facade of Building 1 improve thermal comfort by about 3.7 K to 6.1 K. As observed in the previous variants as well, the improvement of UTCI due to the trees placed southeast of Building 2 show little influence, especially only having a small zone of impact observable on the map.

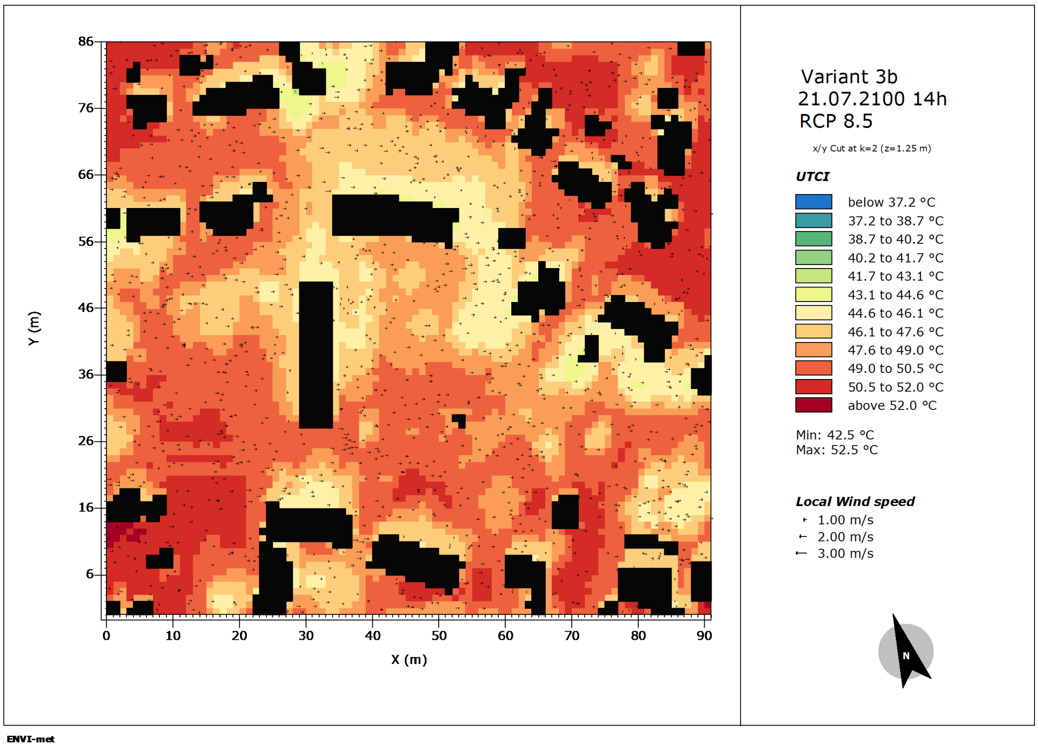


Figure 4.10: Variant 3b, UTCI distribution on 21.07.2100, under RCP 8.5, with tree facade

Figure 4.10 below shows Variant 3b, on 21th July 2100, with the meteorological data of the RCP 8.5 projection. As expected, this setting shows the worst results of thermal comfort, as it is set in the year 2100 with the worst-case climate scenario (RCP 8.5). This variant indicates a reduced impact of trees on thermal comfort compared to other variants, with a smaller difference in thermal comfort between open areas and those near trees. Nonetheless, the beneficial effects of the trees are still observable. However, this suggests that the higher the temperature rises, the less effective green infrastructure becomes. Despite the trees being the oldest and largest in this variant, they are insufficient to create acceptable thermal comfort in this future scenario. Near the trees, the UTCI ranges from 44.6 °C to 47.6 °C.

The observation that the trees have less influence in this scenario is confirmed by the comparison of Variant 3b with Varient 3b-0 without trees (see Figure A.10). The maximum difference found in the comparison is 6 K, which is significantly less than in the comparison of Variant 3a with 3a-0. The distribution of the differences still aligns with the previous analysis, showing the largest improvement in thermal comfort due to trees east of Building 1 and in the passage between the two buildings.

Recommended actions

The spatial analysis of the UTCI distribution of all variants showed some similarities that can be used to derive actions regarding the placement of the trees for this study site. For instance, north of Building 2, it was favorable to have trees planted a bit further from the facade, as the building's shade already contributed significantly to outdoor thermal comfort. Due to the trees planted further from the building, the region of improved thermal comfort could be expanded. Nevertheless, planting trees within this shaded northern area could enhance thermal comfort even further, an important consideration for future planning. Additionally, the decision to plant numerous trees east of Building 1 proved beneficial, as the simulations run without GI measures identified this area as one of the most exposed on the property. The presence of trees greatly improved thermal comfort in the garden area.

Specific attention is needed around the southern facades of buildings. It was observed in the case of Building 1 that the lack of a planned tree at the southeastern corner led to considerable heat stress next to the lower third of the building. Implementing connected green infrastructure might help bridge this gap. The most crucial action is required at the southeast corner of Building 2, where planting trees further from the facade would yield more shade and ecosystem services outdoors, beneficially impacting the building as well as the shade would fall north towards it.

The placement of trees should also be informed by the desired use of outdoor spaces. For example, the trees on the west facade of Building 1 show a much smaller impact zone as they are planted very close to the facade. But if this area is not meant for outdoor activity, optimizing the indoor thermal comfort that trees can provide must be weighed against maximizing their impact on outdoor comfort.

4.3 Development of tree growth and thermal comfort over time

The study analyzed how thermal comfort evolved over time. A specific section of the model area, focused solely on the property of the project, was selected for a detailed examination of the impact of newly planted trees. Details of this particular map section are available in Figure A.14. For this analysis, the UTCI was obtained at a height of 1.25 m, and the average of all grid cells in that area was calculated. This was done for each variant. The results are visualized in the graph shown in Figure 4.11.

The graph demonstrates the growth of trees up to the year 2100. It compares the thermal comfort levels under two climate scenarios: RCP 4.5 (illustrated in blue) and RCP 8.5 (in red). The dotted lines indicate the levels of thermal comfort in the absence of trees for each scenario. In both scenarios, areas without GI show poorer thermal comfort compared to those with GI. For the year 2023, the average UTCI on the property indicates a difference of 0.3 °C between the scenario without GI and the one with the initial stage of the planted trees.

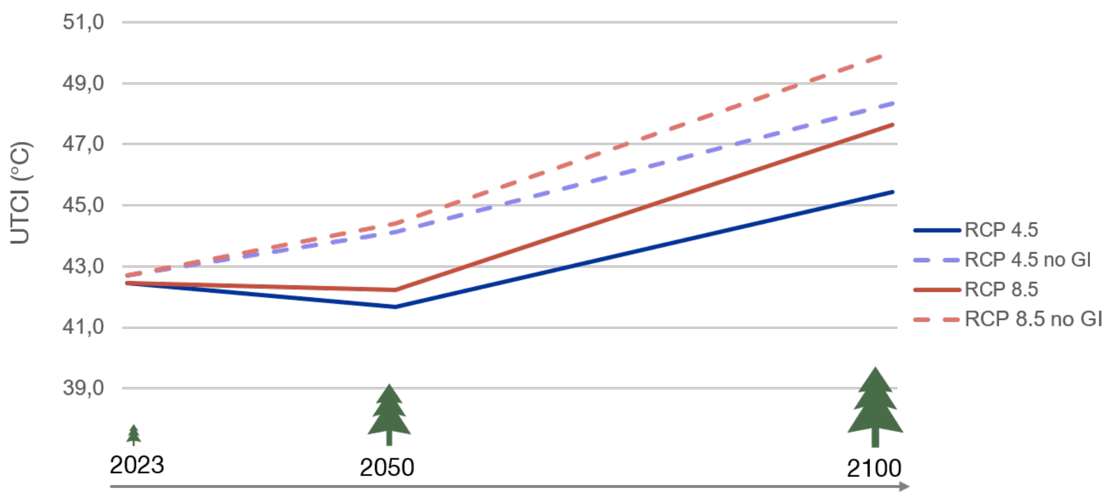


Figure 4.11: Average UTCI at 1.25 m height on the property over time

By 2050, the trees have more than doubled in height compared to 2023. The graph illustrates that, despite rising temperatures due to climate change, trees have been effective in improving thermal comfort. On average, the improvement in UTCI is 2.1 °C for the RCP 4.5 scenario and slightly less at 1.8 °C for RCP 8.5, when comparing the areas with and without trees, respectively. This observation indicates that trees have a more significant impact on thermal comfort in the less severe RCP 4.5 climate scenario.

Although the UTCI for RCP 4.5 is lower than for RCP 8.5, both are categorized as very strong heat stress, averaging 41.6 °C for RCP 4.5 and 41.9 °C for RCP 8.5. The difference between these two scenarios in 2050 is modest, at just 0.3 °C.

In 2100, the average UTCI in the small study area is 45.6 °C for RCP 4.5 with green infrastructure and 47.8 °C for RCP 8.5 with GI. Without GI, these figures rise to 48.1 °C and 50 °C, respectively. As temperatures increase and tree growth is slowing down, trees still improve the UTCI by 2.2 °C to 2.5 °C, but overall thermal comfort decreases. The effectiveness of trees decreases as climate scenarios become hotter. RCP 4.5

with GI shows a greater difference in UTCI compared to the setting without trees than its counterpart RCP 8.5 does. The more severe the climate change, the less effective GI measures are. Interestingly, the RCP 8.5 scenario with trees performs slightly better than RCP 4.5 without trees. This underscores the effectiveness of green infrastructure measures. However, these results are also dependent on the specific area analyzed, which in this case is the whole property, including areas where no new trees were planted, thus evening out some differences.

The average impact of the trees on thermal comfort aligns with findings from other research concerning the order of magnitude. Cheung and Jim (2018) simulated the influence of one tree on UTCI in urban settings with an average result of 2.5 °C UTCI improvement. Cascone and Leuzzo (2023) found slightly higher improvements when investigating the influence of trees on a city square, with 4 °C, and even up to 8 °C when adding shrubs and trees as well. These settings are not directly comparable to this study but validate its results as at the center of the trees, UTCI improvements of around 8 °C were simulated as well.

In conclusion, while trees can enhance thermal comfort, their effectiveness is contingent upon their growth and dimensions being sufficient to counteract increasing heat stress. Trees show rapid growth at the beginning, but this rate decreases over their lifespan. Particularly when crown dimensions plateau, the continuous progression of global warming becomes the more significant factor affecting the environment over time. To more accurately determine the point at which tree effectiveness declines, additional simulation intervals would be necessary, taking into account growth patterns and the point at which a tree maintains its dimensions.

4.4 Challenges and Efficiency

This section delves into the complexities and shortcomings of microclimatic modeling, especially regarding future scenarios. The successful setup of a model delivering UTCI values is a significant achievement, yet it is essential to recognize this process's inherent limitations and efficiency.

The holistic approach to modeling the microclimate posed the challenge of combining different models and methods. Microclimatic modeling is typically feasible in short-term simulations spanning 1-2 days. Extending this to future scenarios and including dynamic tree growth, which ideally requires analysis over multiple years, complicates the modeling process. Therefore, the results only cover extreme climate conditions and peak hours.

Combining the CityTree model results with the ENVI-met system poses unique challenges. The CityTree model, in its current form, needs more complete development, particularly in multi-year dynamization. Therefore, the interesting topic of water availability and its effects is difficult to integrate. Moreover, CityTree's focus on individual trees limits its scope for a broader, property-wide analysis. It would be particularly interesting to explore how climate change influences water availability and, in turn, affects tree growth across the entire property. However, integrating an external water model for tree growth would significantly increase the study's complexity, exceeding this thesis's scope. While ENVI-met includes a water module, modeling long-term effects in ENVI-met is not feasible. Consequently, this study only indirectly considered water availability, using meteorological data from climate projections as input for both CityTree and ENVI-met models. Besides the limitations of each model itself, transferring the accuracy of the CityTree output regarding ecosystem services into ENVI-met is also limited, mainly possible by adjusting tree dimensions.

Data collection and conversion posed a notable challenge in this study. While gathering data was relatively straightforward, converting it for use in different software tools such as QGIS, ENVI-met, and Excel-VBA proved more complex. Gaining proficiency in QGIS, a sophisticated GIS tool, was crucial for developing building and vegetation models in the shapefile format.

The selection of modeling parameters and settings is a significant source of potential error. Actual data was utilized for inputs wherever feasible to mitigate this, ensuring the model area was as detailed as possible based on available information. This approach involved a time-intensive process of modeling various vegetation types within and around the property, constructing the building model, and integrating weather and CO_2 data. Accurately representing the interactions between different micro-environmental factors is essential for a comprehensive simulation.

In terms of enhancing model efficiency, a key area of improvement lies in data conversion. Building Information Modeling (BIM) tools, which already contain detailed information on elements digitized by architects or engineers, could be highly beneficial. For example, vegetation types, building materials, and tree locations could be mapped automatically. However, their conversion capabilities need enhancement to fully realize their potential for GIS applications. This improvement would streamline the process, allowing for more efficient and accurate modeling in future studies.

The time required for computation and initialization was also a significant constraint in the modeling process. It posed the challenge of managing the trade-off between computing time and the size of the model domain. A balance was crucial: a larger model area minimized boundary condition influence and ensured stability, but increased domain size meant longer computing times. This necessitated strategic decisions on whether to aim for a smaller, more efficient model or to construct larger areas to reduce the need for extensive adjustments.

In summary, this study's most inefficient aspect was the pre-processing and data-gathering phase, which required proficiency in various programs. If data conversion tools can improve this aspect, the other challenges and limitations of the models can be partly overcome by exploring further settings and simulations. Despite these challenges, the developed model successfully delivers valuable insights into the impact of urban green infrastructure and climate change on thermal comfort. Future models could benefit from more streamlined data integration and a more robust approach to modeling complex environmental interactions.

5. Conclusion and Outlook

The study investigated how planned vegetation would develop under future water and climate scenarios. This topic was addressed by modeling tree growth with the CityTree model. Meteorological conditions were altered every decade to simulate climate change. In future studies, altering soil characteristics could also be explored, as they play a significant role in reflecting climate and water variability. However, in this study, adjusting these characteristics over time was not possible due to the absence of predictive models for future soil conditions.

The analysis of this thesis found that the development of vegetation strongly depends on location-specific climate predictions. Specifically for Bamberg, the study found that the tree growth does not significantly differ under the two climate projections (RCP 4.5 and RCP 8.5). However, these results might vary in different locations, as the literature about tree growth indicates. Future simulations would benefit from improving the dynamization of CityTree and incorporating a water projection model similar to climate projections. Currently, the modeling of interactions with CO_2 levels, hydrological models, and soil models do not have the sophistication necessary to accurately predict *future* growth. One challenge is to effectively integrate all these interactions into a coherent model base. Enhancing computational power might help address this issue.

The other integral topic that was investigated in this thesis is the question of how green infrastructures need to be planned so that outdoor thermal comfort is still provided in the future. Regarding this topic, the study's findings indicate that under both climate projections, adequate thermal comfort (as measured by the UTCI in degrees Celsius) will not be achieved in 2050 or 2100. It is important to note that the simulations also did not result in sufficient thermal comfort for the year 2023, which was based on actual measured weather data. However, this assessment is based on modeling the hottest day of the year, and it should be remembered that on several other summer days, pleasant thermal comfort might presumably be attainable.

It is also crucial to understand that absolute values from simulations do not necessarily represent reality. The comparative analysis between different climate scenarios suggests that the planning of green infrastructure significantly improves thermal comfort but must consider the location-specific environment.

In conclusion, the GI measures should incorporate as many trees as possible, selecting the tree species based on literature and local climate projections for tree growth to account for the impact these factors have on the species. It is particularly important to focus on planning GI in areas that are vulnerable and exposed to heat, to maximize their cooling effects. In this case study, the most critical location is the southeastern facade of Building 2.

Furthermore, when planting trees, their distance from buildings should be considered to ensure a larger impact zone for thermal comfort. However, this should be balanced with the concept of integrating trees with building facades. The tree facade is an alternative approach to facade greening, which involves integrating large, leafy trees close to building exteriors to provide natural shading and cooling, thereby enhancing the building's energy efficiency and creating a dynamic, green urban aesthetic.

Discussing tree development in relation to climate change presents challenges, especially as this study found that tree growth dimensions were similar across different climate scenarios. While this is an intriguing observation for this specific case study, it underscores the need for further research at other locations. Future studies should also explore the integration of hydrological models, including groundwater levels. Like this, not only single tree growth but also competition between multiple trees is considered. This would expand our understanding of the adaptability and effectiveness of trees in different climatic conditions.

To summarize, the findings in this research confirm the current knowledge about green infrastructures. Each tree provides significantly improved thermal comfort when selecting species that are suitable for the local climate. The GI measures should focus on areas that are particularly susceptible to heat, such as south-facing areas. While tree development across different climate scenarios showed similar dimensions, the specific impacts of each scenario were apparent in the mean UTCI values across the area. Future research should further explore tree growth under varying precipitation projections and explore the precise placement of trees to maximize both indoor and outdoor thermal comfort.

The value of green infrastructure in managing urban heat is demonstrated, offering new and specific insights for the particular case study. While it is arguable to undergo the effort of the simulations to reaffirm existing general guidelines, its importance lies in the nuanced understanding it provides about the impact of specific climate scenarios on urban green spaces. Beyond thermal comfort, this research importantly identifies and addresses current limitations in long-term urban tree growth modeling, offering insights into areas of improvement. This case study is crucial to the field, with a holistic modeling approach that contributes to more targeted and effective GI strategies for local environments.

List of Figures

2.1 Tree interactions with its environment adapted from Rötzer on CityTree, 2023 11
2.2 ENVI-met model architecture [ENVI-met website, 2023, https://www.envi-met.info/doku.php?id=intro:modelconcept] 13
2.3 CityTree model components [Rötzer 2023] 15
2.4 Heat stress categories UTCI 17

3.1 Workflow of the simulation process and the models utilized 19
3.2 Property of the project ECO+ in Stegaurach, model area marked in yellow [Screenshot of Google Satellite in QGIS] 21
3.3 Green Infrastructure site plan from ECO+ project with dark green trees newly planted 23
3.4 Spaces file of the model area in 2D and 3D view 27
3.5 Meteorological data RCP 4.5, 24. August 2050 28
3.6 Meteorological data RCP 4.5, 25. August 2050 28
3.7 Robinia 35 years represented in Albero 29

4.1 Annual crown diameter growth of Robinia pseudoacacia under RCP scenarios 2.6, 4.5, and 8.5 32
4.2 Annual height growth of Robinia pseudoacacia under RCP scenarios 2.6, 4.5, and 8.5 32
4.3 ANnual dbh growth of Robinia pseudoacacia under RCP scenarios 2.6, 4.5, and 8.5 33
4.4 Growth intervals modeled in Albero 35
4.5 Variant 0, UTCI distribution on 15.07.2023, no Green Infrastructure 37
4.6 Variant 1, UTCI distribution on 15.07.2023, with tree facade 38
4.7 Variant 2a, UTCI distribution on 25.08.2050, under RCP 4.5, with tree facade 39
4.8 Variant 2b, UTCI distribution on 25.08.2050, under RCP 8.5, with tree facade 40
4.9 Variant 3a, UTCI distribution on 21.07.2100, under RCP 4.5, with tree facade 41
4.10 Variant 3b, UTCI distribution on 21.07.2100, under RCP 8.5, with tree facade 42
4.11 Average UTCI at 1.25 m height on the property over time 44

A.1 Excerpt from 'Leitfaden für Stadtbäume', showing dbh and age class . . 56
A.2 Excerpt from 'IPCC WG1 AR5 Annex II', CO_2 projections for RCPs 56
A.3 Robinia pseudoacacia CityTree calculation input and results according to RCP scenario 57
A.4 Tilia cordata CityTree calculation input and results according to RCP scenario 58
A.5 Aesculus hippocastanum CityTree calculation input and results according to RCP scenario 59
A.6 Dimension growth of Aesculus hippocastanum calculated with CityTree according to different RCP scenarios 60
A.7 Dimension growth of Tilia cordata calculated with CityTree according to different RCP scenarios 60
A.8 Difference Variant 0 with Variant 1 61
A.9 Difference Variant 2b with Variant 2b0 61
A.10 Difference Variant 3a with Variant 3a0, and Variant 3b with Variant 3b0 . . 61
A.11 Spatial UTCI distribution for the year 2023, Variant 0 and Variant 1 62
A.12 Spatial UTCI distribution for the year 2050, Variant 2a, 2a-0, 2b and 2b-0 62
A.13 Spatial UTCI distribution for the year 2100, Variant 3a, 3a-0, 3b and 3b-0 63
A.14 Area for average temporal development 63

List of Tables

3.1 Input parameters for CityTree 24
3.2 Simulation variations 30

Bibliography

Arora, V. (2002). Modeling vegetation as a dynamic component in soil-vegetation-atmosphere transfer schemes and hydrological models. *Reviews of Geophysics*, *40*(2), 3-1-3–26. https://doi.org/10.1029/2001RG000103

Bayerische Vermessungsverwaltung. (2023). Bayernatlas. Retrieved January 7, 2024, from https://geodaten.bayern.de/opengeodata/OpenDataDetail.html?pn=lod2

Bayerisches Landesamt für Umwelt. (2022). *Bayerns klima im wandel, heute und in der zukunft* (4th).

Böll, S. (2018). Stadtbäume der zukunft [Sonderdruck aus: Veitshöchheimer Berichte 184, 2018, S. 75-85]. https://www.lwg.bayern.de

Cascone, S., & Leuzzo, A. (2023). Thermal comfort in the built environment: A digital workflow for the comparison of different green infrastructure strategies. *Atmosphere*, *14*(4), 685. https://doi.org/10.3390/atmos14040685

Cheung, P. K., & Jim, C. Y. (2018). Comparing the cooling effects of a tree and a concrete shelter using pet and utci. *Building and Environment*, *130*, 49–61. https://doi.org/10.1016/j.buildenv.2017.12.013

Clark, C., Busiek, B., & Adriaens, P. (2010). Quantifying thermal impacts of green infrastructure: Review and gaps. *Proceedings of the Water Environment Federation*, *2010*(2), 69–77. https://doi.org/10.2175/193864710798285381

ENVI-met website. (2023). Envi-met: 3d-simulationssoftware zur hochauflösenden modellierung von städtischem mikroklima für eine klimaneutrale stadtentwicklung und grünplanung. Retrieved January 7, 2024, from https://www.envi-met.com/de/software/#gettoknow

Fauk, T., & Schneider, P. (2023). Modeling urban tree growth as a part of the green infrastructure to estimate ecosystem services in urban planning. *Frontiers in Environmental Science*, *11*. https://doi.org/10.3389/fenvs.2023.1090652

Gatto, E., Buccolieri, R., Aarrevaara, E., Ippolito, F., Emmanuel, R., Perronace, L., & Santiago, J. L. (2020). Impact of urban vegetation on outdoor thermal comfort: Comparison between a mediterranean city (lecce, italy) and a northern european city (lahti, finland). *Forests*, *11*(2), 228. https://doi.org/10.3390/f11020228

Ghani, S., Mahgoub, A. O., Bakochristou, F., & ElBialy, E. A. (2021). Assessment of thermal comfort indices in an open air-conditioned stadium in hot and arid environment. *Journal of Building Engineering*, *40*, 102378. https://doi.org/10.1016/j.jobe.2021.102378

IPCC Data Distribution Center. (2019). Scenario process for ar5: Representative concentration pathways. Retrieved January 7, 2024, from https://sedac.ciesin.columbia.edu/ddc/ar5_scenario_process/RCPs.html

Klemm, W., Heusinkveld, B. G., Lenzholzer, S., & van Hove, B. (2015). Street greenery and its physical and psychological impact on thermal comfort. *Landscape and Urban Planning*, *138*, 87–98. https://doi.org/10.1016/j.landurbplan.2015.02.009

Peper, P., McPherson, E. G., & Mori, S. (2001). Equations for predicting diameter, height, crown width, and leaf area of san joaquin valley street trees. *Arboriculture & Urban Forestry*, *27*(6), 306–317. https://doi.org/10.48044/jauf.2001.034

Rötzer, T., Rahman, M. A., Moser-Reischl, A., Pauleit, S., & Pretzsch, H. (2019). Process based simulation of tree growth and ecosystem services of urban trees under present and future climate conditions. *The Science of the total environment*, *676*, 651–664. https://doi.org/10.1016/j.scitotenv.2019.04.235

Simon, H., Sinsel, T., & Bruse, M. (2020). Introduction of fractal-based tree digitalization and accurate in-canopy radiation transfer modelling to the microclimate model envi-met. *Forests*, *11*(8), 869. https://doi.org/10.3390/f11080869

Spangenberg, J. H., Shinzato, P., Johansson, E., & Duarte, D. (2008). Simulation of the influence of vegetation on microclimate and thermal comfort in the city of são paulo. *Revista da Sociedade Brasileira de Arborização Urbana*, *3*(2), 1. https://doi.org/10.5380/revsbau.v3i2.66265

Sun, S., Xu, X., Lao, Z., Liu, W., Li, Z., Higueras García, E., He, L., & Zhu, J. (2017). Evaluating the impact of urban green space and landscape design parameters on thermal comfort in hot summer by numerical simulation. *Building and Environment*, *123*, 277–288. https://doi.org/10.1016/j.buildenv.2017.07.010

Wang, Y., Ni, Z., Hu, M., Chen, S., & Xia, B. (2021). A practical approach of urban green infrastructure planning to mitigate urban overheating: A case study of guangzhou. *Journal of Cleaner Production*, *287*, 124995. https://doi.org/10.1016/j.jclepro.2020.124995

Zentrum Stadtnatur und Klimaanpassung (Ed.). (2022). *Leitfaden zu stadtbäumen in bayern: Handlungsempfehlungen aus dem projekt stadtbäume im klimawandel – wuchsverhalten, umweltleistungen und perspektiven*. Zentrum Stadtnatur und Klimaanpassung.

Zhang, W., Li, Y., Wu, X., Chen, Y., Chen, A., Schwalm, C. R., & Kimball, J. S. (2021). Divergent response of vegetation growth to soil water availability in dry and wet periods over central asia. *Journal of Geophysical Research: Biogeosciences*, *126*(6). https://doi.org/10.1029/2020JG005912

APPENDIX

A Calculations CityTree

Winterlinde *(Tilia cordata)*

Altersklasse [Jahre]	10	20	30	40	50	60	70	80	90	100
BHD [cm]	7,2	14,5	22,2	30,3	38,5	47,0	55,6	64,4	73,3	82,3
Baumhöhe [m]	5,8	8,6	11,1	13,3	15,3	17,2	19,0	20,7	22,3	23,9
Kronenlänge [m]	3,8	6,0	8,1	10,0	11,9	13,7	15,5	17,2	18,9	20,6
Kronendurchmesser [m]	3,3	5,1	6,9	8,6	10,3	11,9	13,4	15,0	16,5	18,0

Scheinakazie *(Robinia pseudoacacia)*

Altersklasse [Jahre]	10	20	30	40	50	60	70	80	90	100
BHD [cm]	11,0	21,1	31,1	41,2	51,2	61,3	71,3	81,4	91,4	101,5
Baumhöhe [m]	9,3	12,1	14,2	15,8	17,3	18,6	19,8	20,9	21,9	22,8
Kronenlänge [m]	6,1	8,4	10,2	11,8	13,1	14,4	15,5	16,6	17,6	18,6
Kronendurchmesser [m]	5,0	7,0	8,7	10,2	11,5	12,7	13,8	14,9	15,9	16,9

Rosskastanie *(Aesculus hippocastanum)*

Altersklasse [Jahre]	10	20	30	40	50	60	70	80	90	100
BHD [cm]	6,9	13,6	23,1	31,5	40,5	48,3	54,7	60,7	66,4	71,5
Baumhöhe [m]	4,7	6,9	9,0	11,2	12,5	13,9	15,4	16,6	17,9	18,8
Kronenlänge [m]	2,4	4,5	6,2	8,6	9,8	11,1	12,2	12,9	14,6	15,0
Kronendurchmesser [m]	2,0	4,4	6,2	7,8	9,0	9,8	10,5	11,2	11,6	12,3

Tabelle 6: Kenngrößen der Bäume in zehn Altersklassen für die Baumarten Winterlinde *(T. cordata)*, Scheinakazie (*R. pseudoacacia)*, Platane *(P. x acerifolia)* und Rosskastanie *(A. hippocastanum)*. Angegeben ist das Mittel einer Altersklasse, d. h., dass z. B. in der Altersklasse 20 alle Bäume mit einem Alter zwischen 16 und 25 Jahren enthalten sind. Die Grundlage dieser Werte sind Messungen in den sechs bayerischen Städten.

Figure A.1: Excerpt from 'Leitfaden für Stadtbäume', showing dbh and age class

Annex II **Climate System Scenario Tables**

AII.4: Abundances of the Well-Mixed Greenhouse Gases

Table AII.4.1 | CO_2 abundance (ppm)

Year	Observed	RCP2.6	RCP4.5	RCP6.0	RCP8.5	A2	B1	IS92a	Min	RCP8.5&	Max
PI	278 ± 2	278	278	278	278	278	278	278			
2011obs	390.5 ± 0.3										
2000		368.9	368.9	368.9	368.9	368	368	368			
2005		378.8	378.8	378.8	378.8					378.8	
2010		389.3	389.1	389.1	389.3	388	387	388	366	394	413
2020		412.1	411.1	409.4	415.8	416	411	414	386	425	449
2030		430.8	435.0	428.9	448.8	448	434	442	412	461	496
2040		440.2	460.8	450.7	489.4	486	460	472	443	504	555
2050		442.7	486.5	477.7	540.5	527	485	504	482	559	627
2060		441.7	508.9	510.6	603.5	574	506	538	530	625	713
2070		437.5	524.3	549.8	677.1	628	522	575	588	703	810
2080		431.6	531.1	594.3	758.2	690	534	615	651	790	914
2090		426.0	533.7	635.6	844.8	762	542	662	722	885	1026
2100		420.9	538.4	669.7	935.9	846	544	713	794	985 ± 97	1142

Notes:

For observations (2011obs) see Chapter 2; and for projections see Box 1.1 (Figure 2), Sections 6.4.3.1, 11.3.1.1, 11.3.5.1.1. RCPn.n refers to values taken directly from the published RCP scenarios using the MAGICC model (Meinshausen et al., 2011a; 2011b). These are harmonized to match observations up to 2005 (378.8 ppm) and project future abundances thereafter. RCP8.5& shows the average and assessed 90% confidence interval for year 2100, plus the min-max full range derived from the CMIP5 archive for all years (P. Friedlingstein, based on Friedlingstein et al., 2006). 11 ESMs participated (BCC-CSM-1, CanESM2, CESM1-BGC, GFDL-ESM2G, HadGem-2ES, INMCM4, IPSLCM5-LR, MIROC-ESM, MPI-ESM-LR, MRI-ESM1, and Nor-ESM1-ME), running the RCP8.5 anthropogenic emission scenario forced by the RCP8.5 climate change scenario (see Figure 12.36). All abundances are mid-year. Projected values for SRES A2 and B1 and IS92 are the average of reference models taken from the TAR Appendix II.

Figure A.2: Excerpt from 'IPCC WG1 AR5 Annex II', CO_2 projections for RCPs

RCP **2.6**

Baumart: Robinia pseudoacacia

		~ Alter	Wetterdatensatz	CO_2 [ppm]	inc dbh [cm]	inc height [m]	inc cd [m]
					8,4	6,9	3,3
dbh class:	<10	<10	2020	412,1	0,3	0,42	0,23
	10-**20**	<20	2030	430,8	0,41	0,36	0,21
	20-**30**	<30	2040	440,2	0,51	0,28	0,18
	30-**40**	<40	2050	442,7	0,6	0,2	0,15
	40-**50**	<50	2060	441,7	0,7	0,15	0,14
	50-**60**	<60	2070	437,5	0,83	0,11	0,13
	60-**70**	<70	2080	431,6	0,92	0,1	0,13
	70-**80**	<80	2090	426	0,97	0,1	0,13
	80-**90**	<90	2100	420,9	1,06	0,1	0,14

RCP **4.5**

Baumart: Robinia pseudoacacia

		~ Alter	Wetterdatensatz	CO_2 [ppm]	inc dbh [cm]	inc height [m]	inc cd [m]
					8,4	6,9	3,3
dbh class:	<10	<10	2020	411,1	0,3	0,42	0,23
	10-**20**	<20	2030	435	0,41	0,36	0,21
	20-**30**	<30	2040	460,8	0,51	0,28	0,18
	30-**40**	<40	2050	486,5	0,6	0,2	0,15
	40-**50**	<50	2060	508,9	0,69	0,15	0,14
	50-**60**	<60	2070	524,3	0,84	0,11	0,13
	60-**70**	<70	2080	531,1	0,93	0,1	0,14
	70-**80**	<80	2090	533,7	0,98	0,1	0,13
	80-**90**	<90	2100	538,4	1,08	0,1	0,14

RCP **8.5**

Baumart: Robinia pseudoacacia

		~ Alter	Wetterdatensatz	CO_2 [ppm]	inc dbh [cm]	inc height [m]	inc cd [m]
					8,4	6,9	3,3
dbh class:	<10	<10	2020	415,8	0,31	0,42	0,23
	10-**20**	<20	2030	448,8	0,41	0,36	0,21
	20-**30**	<30	2040	489,4	0,51	0,28	0,18
	30-**40**	<40	2050	540,5	0,61	0,2	0,15
	40-**50**	<50	2060	603,5	0,71	0,15	0,14
	50-**60**	<60	2070	677,1	0,86	0,11	0,14
	60-**70**	<70	2080	758,2	0,95	0,1	0,14
	70-**80**	<80	2090	844,8	1	0,1	0,14
	80-**90**	<90	2100	935,9	1,1	0,1	0,14

Figure A.3: Robinia pseudoacacia CityTree calculation input and results according to RCP scenario

RCP **2.6**

Baumart: Tilia Cordata

		~ Alter	Wetterdatensatz	CO_2 [ppm]	inc dbh [cm]	inc height [m]	inc cd [m]
					8,2	6,1	2,7
dbh class:	<10	10	2020	412,1	0,24	0,35	0,18
	10-**20**	20	2030	430,8	0,57	0,34	0,25
	20-**30**	30	2040	440,2	0,68	0,24	0,22
	30-**40**	40	2050	442,7	0,8	0,16	0,2
	! 30-**40**	50	2060	441,7	0,8	0,16	0,2
	40-**50**	60	2070	437,5	0,8	0,1	0,16
	50-**60**	70	2080	431,6	0,84	0,1	0,15
	60-**70**	80	2090	426	0,91	0,1	0,15
	70-**80**	90	2100	420,9	0,96	0,1	0,15

RCP **4.5**

Baumart: Tilia Cordata

		~ Alter	Wetterdatensatz	CO_2 [ppm]	inc dbh [cm]	inc height [m]	inc cd [m]
					8,2	6,1	2,7
dbh class:	<10	10	2020	411,1	0,24	0,35	0,18
	10-**20**	20	2030	435	0,57	0,34	0,25
	20-**30**	30	2040	460,8	0,67	0,24	0,22
	30-**40**	40	2050	486,5	0,8	0,16	0,2
	! 30-**40**	50	2060	508,9	0,8	0,16	0,2
	40-**50**	60	2070	524,3	0,81	0,1	0,16
	50-**60**	70	2080	531,1	0,86	0,1	0,15
	60-**70**	80	2090	533,7	0,92	0,1	0,15
	70-**80**	90	2100	538,4	0,99	0,1	0,15

RCP **8.5**

Baumart: Tilia Cordata

		~ Alter	Wetterdatensatz	CO_2 [ppm]	inc dbh [cm]	inc height [m]	inc cd [m]
					8,2	6,1	2,7
dbh class:	<10	10	2020	415,8	0,24	0,35	0,18
	10-**20**	20	2030	448,8	0,58	0,34	0,25
	20-**30**	30	2040	489,4	0,68	0,24	0,22
	30-**40**	40	2050	540,5	0,8	0,16	0,2
	! 30-**40**	50	2060	603,5	0,81	0,16	0,2
	40-**50**	60	2070	677,1	0,8	0,1	0,16
	50-**60**	70	2080	758,2	0,81	0,1	0,15
	60-**70**	80	2090	844,8	0,86	0,1	0,15
	70-**80**	90	2100	935,9	0,89	0,1	0,14

Figure A.4: Tilia cordata CityTree calculation input and results according to RCP scenario

RCP **2.6**

Baumart:	Aesculus hippocastanum

		~ Alter	Wetterdatensatz	CO_2 [ppm]	inc dbh [cm]	inc height [m]	inc cd [m]
					8	5,1	2,5
dbh class:	<10	10	2020	412,1	0,22	0,2	0,14
	10-**20**	20	2030	430,8	0,43	0,21	0,18
	20-**30**	30	2040	440,2	0,53	0,19	0,16
	30-**40**	40	2050	442,7	0,65	0,15	0,15
	40-**50**	50	2060	441,7	0,74	0,12	0,14
	! 40-**50**	60	2070	437,5	0,75	0,12	0,14
	50-**60**	70	2080	431,6	0,8	0,1	0,12
	60-**70**	80	2090	426	0,83	0,1	0,12
	! 60-**70**	90	2100	420,9	0,83	0,1	0,12

RCP **4.5**

Baumart:	Aesculus hippocastanum

		~ Alter	Wetterdatensatz	CO_2 [ppm]	inc dbh [cm]	inc height [m]	inc cd [m]
					8	5,1	2,5
dbh class:	<10	10	2020	411,1	0,22	0,2	0,14
	10-**20**	20	2030	435	0,43	0,21	0,17
	20-**30**	30	2040	460,8	0,53	0,19	0,16
	30-**40**	40	2050	486,5	0,65	0,15	0,15
	40-**50**	50	2060	508,9	0,75	0,12	0,14
	! 40-**50**	60	2070	524,3	0,76	0,12	0,14
	50-**60**	70	2080	531,1	0,82	0,1	0,12
	60-**70**	80	2090	533,7	0,86	0,1	0,12
	! 60-**70**	90	2100	538,4	0,86	0,1	0,12

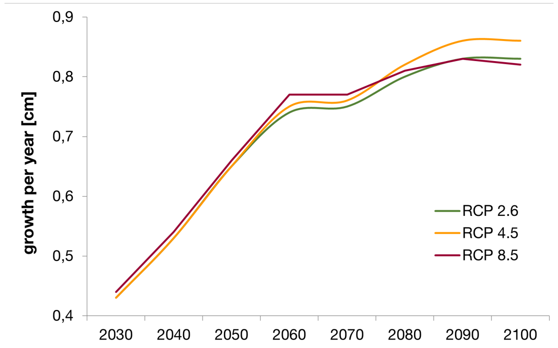
RCP **8.5**

Baumart:	Aesculus hippocastanum

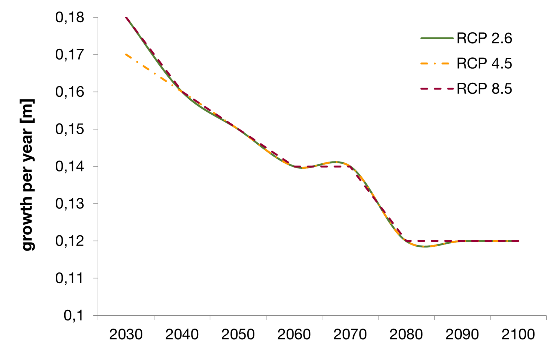
		~ Alter	Wetterdatensatz	CO_2 [ppm]	inc dbh [cm]	inc height [m]	inc cd [m]
					8	5,1	2,5
dbh class:	<10	10	2020	415,8	0,22	0,2	0,14
	10-**20**	20	2030	448,8	0,44	0,21	0,18
	20-**30**	30	2040	489,4	0,54	0,19	0,16
	30-**40**	40	2050	540,5	0,66	0,15	0,15
	40-**50**	50	2060	603,5	0,77	0,12	0,14
	! 40-**50**	60	2070	677,1	0,77	0,12	0,14
	50-**60**	70	2080	758,2	0,81	0,1	0,12
	60-**70**	80	2090	844,8	0,83	0,1	0,12
	! 60-**70**	90	2100	935,9	0,82	0,1	0,12

Figure A.5: Aesculus hippocastanum CityTree calculation input and results according to RCP scenario

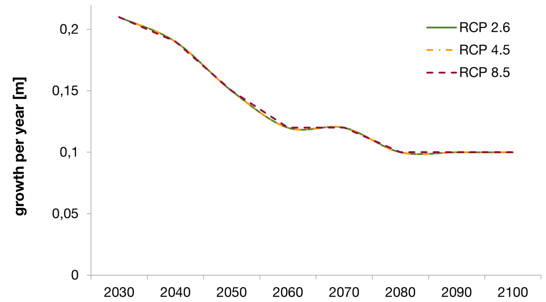
A.1 Growth graphs for Tilia cordata and Aesculus hippocastanum



(a) diameter at breast height

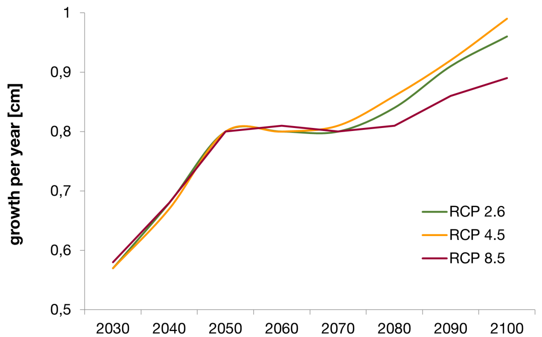


(b) crown diameter

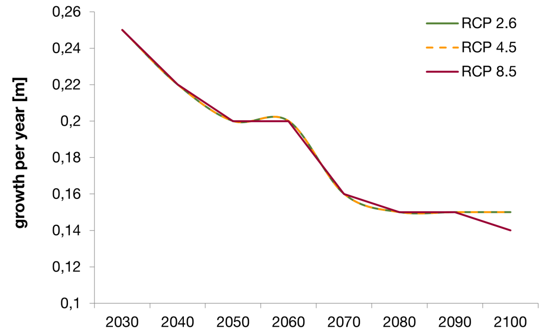


(c) height

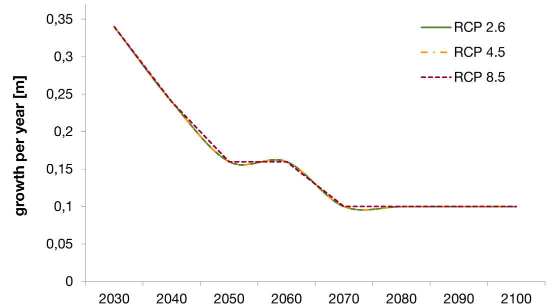
Figure A.6: Dimension growth of Aesculus hippocastanum calculated with CityTree according to different RCP scenarios



(a) diameter at breast height



(b) crown diameter



(c) height

Figure A.7: Dimension growth of Tilia cordata calculated with CityTree according to different RCP scenarios

B Difference comparison maps UTCI with and without trees

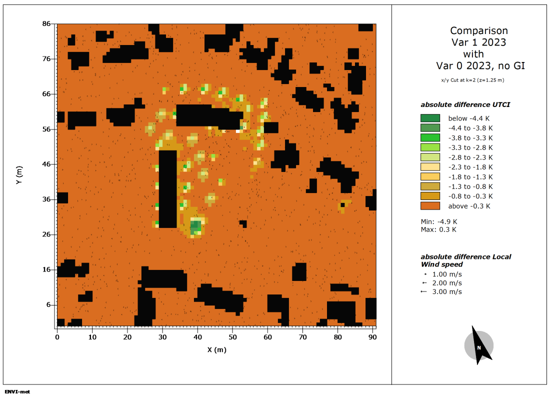


Figure A.8: Difference Variant 0 with Variant 1

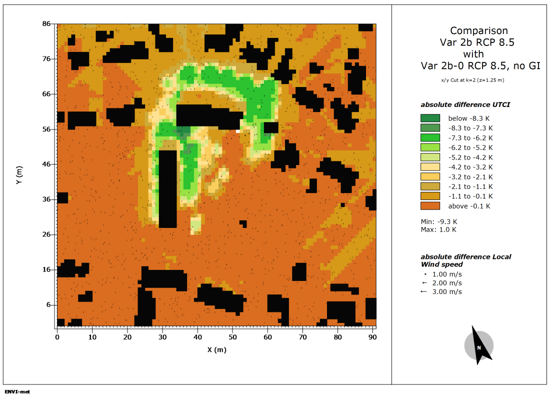


Figure A.9: Difference Variant 2b with Variant 2b0

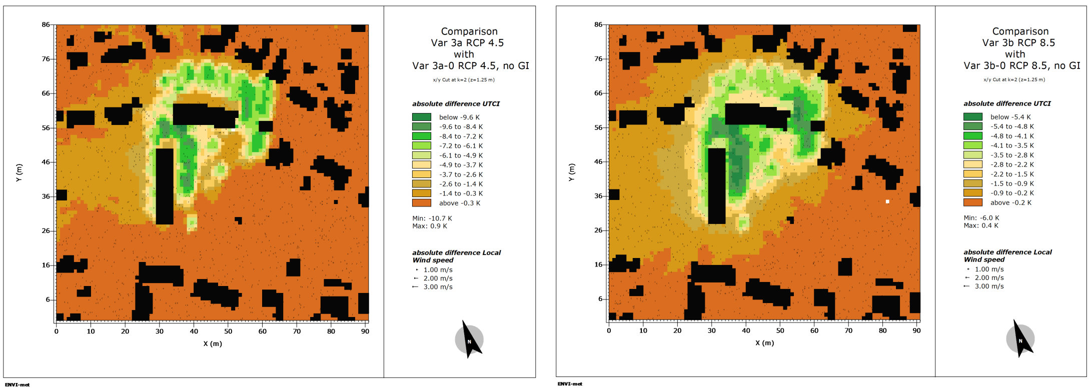
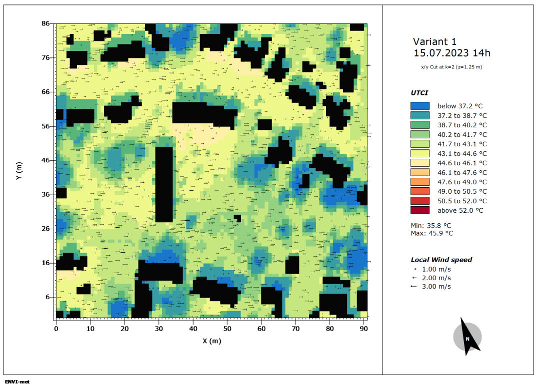
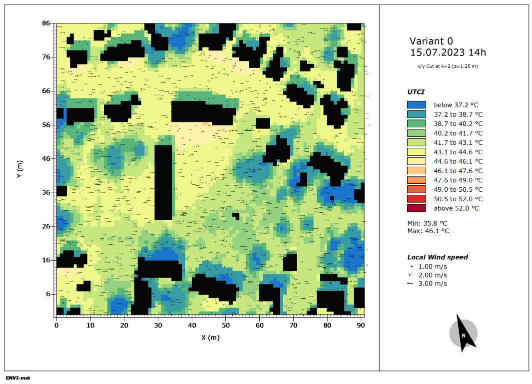


Figure A.10: Difference Variant 3a with Variant 3a0, and Variant 3b with Variant 3b0

C Spatial UTCI distribution of all simulation variants

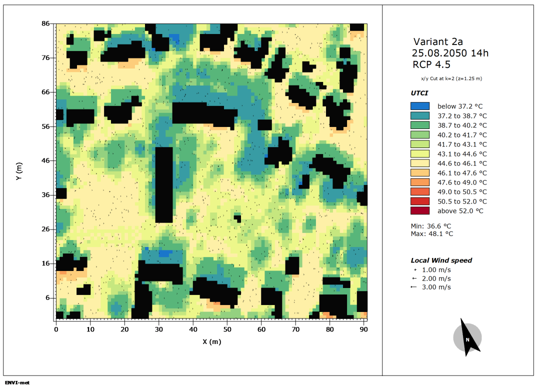


(a) Variant 1, 2023, trees at initial stage

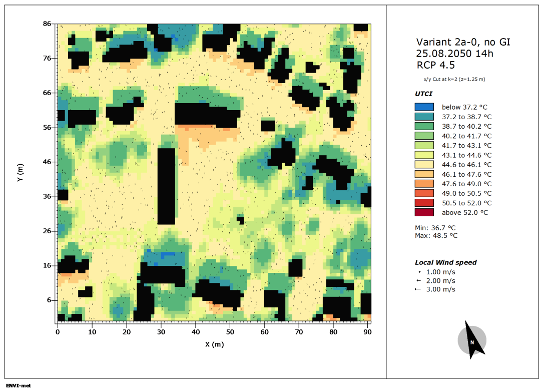


(b) Variant 0, 2023 no GI

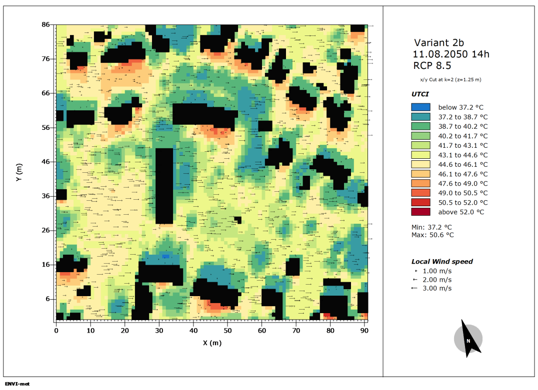
Figure A.11: Spatial UTCI distribution for the year 2023, Variant 0 and Variant 1



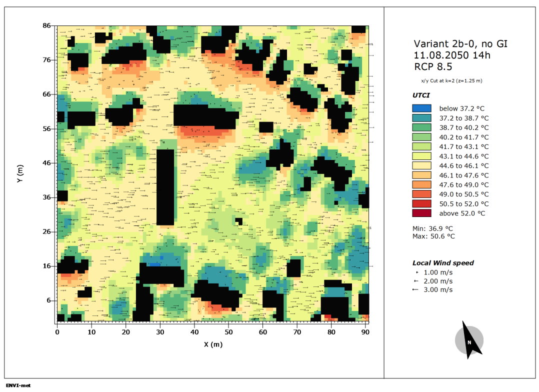
(a) Variant 2a, 2050, RCP 4.5



(b) Variant 2a-0, 2050, RCP 4.5, no GI

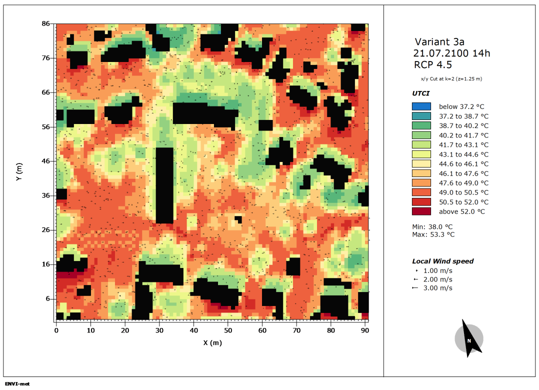


(c) Variant 2b, 2050, RCP 8.5

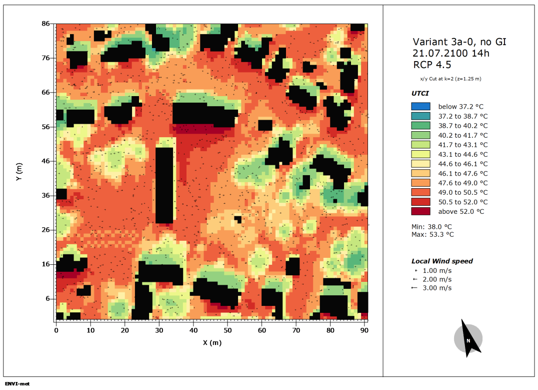


(d) Variant 2b-0, 2050, RCP 8.5, no GI

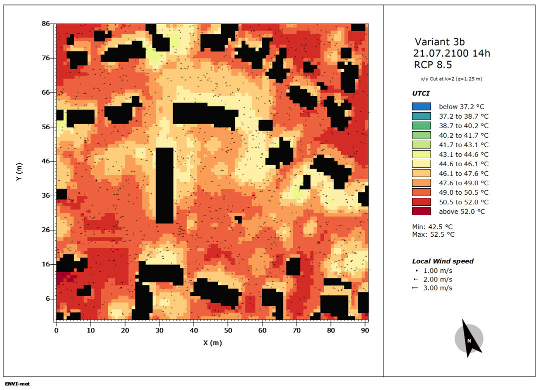
Figure A.12: Spatial UTCI distribution for the year 2050, Variant 2a, 2a-0, 2b and 2b-0



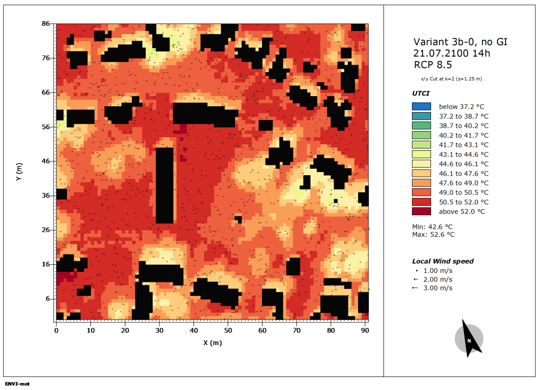
(a) Variant 3a, 2100, RCP 4.5



(b) Variant 3a-0, 2100, RCP 4.5, no GI



(c) Variant 3b, 2100, RCP 8.5



(d) Variant 3b-0, 2100, RCP 8.5, no GI

Figure A.13: Spatial UTCI distribution for the year 2100, Variant 3a, 3a-0, 3b and 3b-0

C.1 Area for average temporal development

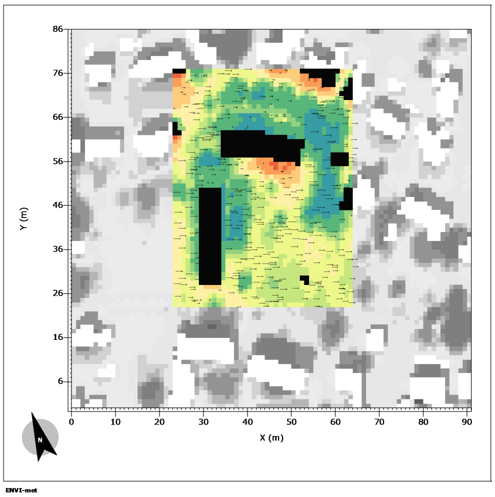


Figure A.14: Area for average temporal development