Sustainable Cities and Society 120 (2025) 106128

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Tree growth simulation in Geographic Information Systems: Coupling CityTree and ArcGIS for solar radiation analysis

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ARTICLE INFO

Keywords:
Digital twin
Urban green infrastructure
Tree growth
CityTree
Ecosystem services
Solar radiation

ABSTRACT

Cities must undergo a sustainable transformation as they rapidly expand with urban heat and CO_2 emissions increasing. Urban development with a detailed digital twin is crucial for managing this multilayered transformation. This paper proposes an approach to integrate urban tree growth in such digital twins. By coupling Geographic Information Systems (GIS) with a tree growth model our methodology predicts the growth of trees for 20 years. This allows the local assessment of future Ecosystem Services from trees and supports their long-term management. The *CityTree* model is used to simulate tree growth in a 500,000 m^2 case study area in Munich, Germany. The derived crown diameter and height increments are implemented in ArcGIS to assess the resulting impact on solar radiation. 20 years of tree growth reduced the solar radiation on the ground by 6.1%, whereas on the building roofs, the reduction was 1.0%. The increase in cooling energy due to tree growth exceeded the reduction of usable solar energy from buildings' roofs by a factor of almost 50. The methodology for 3D tree growth projection in GIS saves monitoring resources for urban tree management and improves the accuracy of digital twin models.

1. Introduction

Cities constitute a small share compared to the earth's total land area, but their urbanization process is felt globally regarding climate change, environmental problems, natural disasters, etc. (Boyko, Cooper, & Dunn, 2020). By 2050, 68% of the global population will live in urban areas (Kohlhase, 2013). Urban heat is one of humanity's main concerns, which will increase even further in the future due to climate change and urbanization (Zhang, Tan, Zhang, & Chen, 2024). Mechanical–electrical systems that support the thermal comfort of human beings reinforce the Urban Heat Island (UHI) effect even more (Hartmann et al., 2023). Due to this effect, the core city portions and adjacent places with a high density experience higher temperatures than the city's outskirts. Rising global temperatures and the UHI effect in cities will make cities less liveable in the future (Antonopoulos, Trusty, & Shandas, 2019) and lead to increasing CO_2 emissions (Zhang et al., 2023).

Therefore, sustainable cities are the need of the time. These are conceptualized as urban systems that include production, consumption, infrastructures, and landscapes that enable the livability of humans with significantly less impact on nature (Cohen, 2017). Frequently, a misconception is that a sustainable city means to make cities look green. Still, in reality, it is a combination of green, gray, and blue with permeable surfaces, spacious squares, canals, water bodies, trees, hedges, parks, etc. (Chan, Imura, Nakamura, & Ao, 2016). Urban Green Infrastructure (UGI) is a crucial element of sustainable urban development, which has multiple advantages on the ecological, social, and economic aspects of keeping a city liveable (Hansen et al., 2018). UGI can mitigate the negative effects of high density and climate change by reducing the UHI effect through evapotranspiration and shading (Rötzer et al., 2020). Besides improving thermal comfort, UGI reduces water runoff, absorbs air pollution, provides social benefits, and stores carbon (Nowak & Crane, 2002; Rötzer, Rahman, Moser-Reischl, Pauleit, & Pretzsch, 2019). UGI for a sustainable city is to be planned strategically (Hansen et al., 2018), and its future development is critical to successfully utilizing the UGI to deliver the named Ecosystem Services (ESS). The changing climates in the cities, such as increasing temperature and increasing precipitation, can greatly affect tree growth, which reflects on ESS in the city area (Easterling et al., 2000; Keenan, 2015; Rötzer, Seifert, Gayler, Priesack, & Pretzsch, 2012;

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https://doi.org/10.1016/j.scs.2025.106128
Received 21 August 2024; Received in revised form 4 December 2024; Accepted 6 January 2025
Available online 10 January 2025

Wang, Zhang, Chen, Zhang, & Han, 2024). With these ESS, UGI plays a crucial role in reducing the UHI effect and improving the living conditions of humans in the urban environment (Kong et al., 2017; Zölch, Maderspacher, Wamsler, & Pauleit, 2016). Trees have a long lifespan and constitute the more significant part of UGI (Rötzer et al., 2019). Hence, tree growth and development should be an integral part of city planning to effectively utilize the ESS from UGI. Tree properties like crown dimension, leaf area, tree height, biomass, etc., are important information for determining various ESS (Haase et al., 2014; McPherson, 1998; Rötzer et al., 2019). However, UGI cannot provide all these benefits immediately after planting, but needs time to grow and fully develop its physical structure. Therefore, the future growth projection of UGI is an important aspect of successfully utilizing ESS.

City planning and data management are crucial for decision-making and risk mitigation. With the future being dependent on digitalization and City Information Modelling, the digital twin of cities proves to be an effective tool for city management and planning to accomplish the goal of a sustainable transformation (Souza & Bueno, 2022; Therias & Rafiee, 2023). The digital twins of cities bundle the data and knowledge from different city stakeholders, sharing multiple pieces of information and integrating this information into the digital model (Cheshmehzangi, Batty, Allam, & Jones, 2024). Building a digital twin of a city requires multidisciplinary data and interdisciplinary collaboration among stakeholders (Soltanifard, Farhadi, & Mansourian, 2024). The integration of 3D data of cities' gray infrastructure comprising buildings and road networks to coordinate infrastructure management, land use management, and transportation management has been evolving quickly in recent years (Dantas, Sousa, & Melo, 2019). With new file formats, such as IFC and CityGML, there is improvement in data exchange with semantic information across different platforms (Deng, Cheng, & Anumba, 2016; Laat & van Berlo, 2011). Along with data on gray infrastructures, accurate data on the UGI in 3D formats is needed to create a more realistic digital twin of the city for evaluating sustainability aspects (Chen et al., 2023), as UGI and the built environment influence each other (Reitberger, Pattnaik et al., 2024). Generating data on UGI is continuously improving, for instance, through the use of Very High Resolution (VHR) remote sensing (Leichtle, Zehner, Kühnl, Martin, & Taubenböck, 2021). However, compared to buildings, trees are dynamically evolving over their lifespan (Franceschi et al., 2022; Rötzer et al., 2019). Digital twins can integrate such dynamics through simulation models based on existing data (Therias & Rafiee, 2023), which makes them suited to integrate tree growth models. Thereby, efforts to collect data on urban trees are reduced as geometries can be updated through simulation, and monitoring periods can be enlarged. Further, this allows future predictions for the whole city, e. g., to investigate changing radiation availability due to changing tree dimensions and the impacts on renewable energy production. Process-based tree growth models have been developed, which are based on age, species type, and other physical growth parameters. For instance, the *CityTree* model is an equation-based urban tree growth model that has proven valid in predicting the growth of various species of trees and their ESS in Central Europe, specifically Munich, Germany (Rötzer et al., 2019). With such urban tree growth models, there is a possibility of predicting the growth and development of single trees in urban regions without continuous physical data collection.

Currently, cities spend a lot of labor to keep their tree population accurately monitored. Recent tree growth models allow the derivation of updated tree dimensions based on previous measurements. However, they are hardly integrated into cities' tree monitoring systems. Hence, the goal of this paper is to develop a methodology for obtaining future tree dimensions, which can be used to improve the quality of City Information Models. This allows urban planners to overview the changes in the ESS of urban trees due to their growth using a bottom-up approach. We showcase the usage by analyzing the impact of tree growth on changes in solar radiation on building roofs and streetscapes in a case study area in Munich, Germany. The goal of our case study application is to quantify the effect of tree growth on outdoor thermal comfort and renewable energy production on building roofs. The theoretical framework outlined in the introduction is summarized in Fig. 1. Section 2 introduces the state of the art regarding each framework part. Thereby it sets the stage for our methodology to couple tree growth simulation and 3D City Models (Section 3.2). Results are presented in Section 4 for the tree growth projections, followed by the solar radiation and evapotranspiration simulations. Discussion (Section 5) and conclusion (Section 6) interpret and reflect on the results to derive recommendations for urban tree management.

2. State of the art

Collecting and managing tree data has always been crucial for forest and urban tree management. Researchers have created maps of tree species distribution in forest regions across Europe to understand and manage the tree data (Beck et al., 2020). GIS was often more utilized in modern agriculture practices (Bill, Nash, & Grenzdörffer, 2012). Researchers explored GIS-based studies to assess the suitability of tree crops for different types of terrains, as it gave scope for a holistic approach to the management and development of trees (Tsiaras & Domakinis, 2023). To improve the management of urban trees and make them visible, studies related to GIS methods were implemented for individual tree modeling in urban areas. These methods helped to provide an alternative to field-based data collection and incorporate more data for tree valuation (Cimburova, Blumentrath, & Barton, 2023). Isa and Othman (2012) prove that GIS-based tools used to assess trees can be more efficient with smart data management than the conventional approaches (Isa & Othman, 2012). With remote sensing and laser-scanning, more complex data of the urban environments and forests can be captured in GIS platforms (Tiede, 2005). The ArcGIS platform has developed tools that combine Light Detection and Ranging (LIDAR) data to enable the analysis and calculation of 2D and 3D data of forests, trees, terrains, drainage patterns, and more. These developments enable researchers to combine the spatial data with ESS assessment models to derive quantifiable data related to the trees' ESS (Dwyer & Miller, 1999).

Urban trees include all trees within the urban limits, such as the trees in public areas, residential and private properties in the city limits, green parks, government properties, and commercial spaces (Miller, Hauer, & Werner, 2015). The growth conditions of urban trees are diverse across the cities, and they are exposed to adverse environmental influences at the growing sites compared to forest trees (Rötzer et al., 2020). Very-High spatial Resolution (VHR) Remote sensing techniques are used to gather data on urban trees and their surroundings (Leichtle et al., 2021). Unlike the buildings, the trees grow, and their dimensions change continuously. Surveying the trees periodically is time and resource-consuming, especially for the trees on private properties (Schrenk et al., 2021). Hence, tree representation in digital twins is often outdated. Additionally, urban planning involves consideration periods of several decades, which requires future tree dimensions. Several models for tree growth prediction have been developed, which will be further explained in the Methods Section 3.2.1.

Solar potential estimation of buildings started with architectural simulations with limited data (Kristl & Krainer, 2001). For a more comprehensive examination of urban structures incorporating a vast amount of data, GIS-based techniques, such as solar energy planning, have emerged as a valuable adjunct to facilitate large-scale energy planning for urban areas. Still, these approaches were limited to 2D context (Gadsden, Rylatt, Lomas, & Robinson, 2003). Even further, there has been the development of 3D city models, which allows the assessment of the photovoltaic (PV) potentials of each building while considering the effects of neighboring buildings (Hofierka & Kaňuk, 2009). The major shortcoming of such studies is the exclusion of

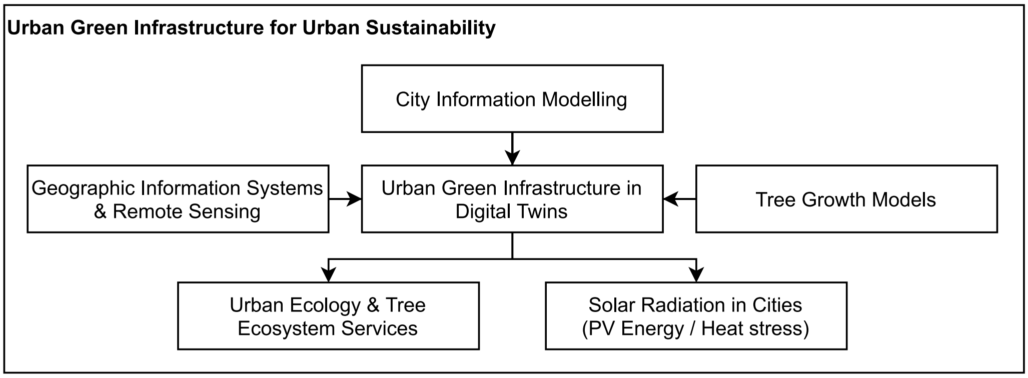

Fig. 1. Theoretical framework of the paper, integrating the main components for urban sustainability related to green infrastructure.

non-building elements like vegetation. Studies by Dereli et al. (2013) suggest that tree position and their growth influence the performance of PV modules placed on adjacent low-rise buildings and tree shading (Dereli, Yücedağ, & Pearce, 2013). There have also been findings that urban trees near buildings can improve the microclimate and reduce the cooling energy demand of buildings (McPherson & Simpson, 2003; Reitberger, Theilig, Vollmer, Takser, & Lang, 2023). Hence, recent studies incorporate urban trees into the 3D models to assess their impact on buildings' solar potentials and provide more realistic data. For instance, the effect of trees on rooftop solar radiation of residential buildings (Ko, 2014) and buildings' roofs and façades was investigated (Behnisch, Münzinger, Poglitsch, Willenborg, & Kolbe, 2020).

Besides providing additional shade, trees cool down the air temperature through the process of evapotranspiration (Rahman, Moser, Rötzer, & Pauleit, 2017a; Shashua-Bar, Potchter, Bitan, Boltansky, & Yaakov, 2010). Thereby, trees release water vapor into the surrounding atmosphere, which raises air humidity but cools the local environment by shifting the partitioning of incoming solar irradiation from sensible heat to latent heat (Taha, 1997). It is a crucial physiological activity that maintains the vitality of trees and provides evaporative cooling to help dissipate heat (Wang et al., 2011). Through transpiration, trees cool themselves and reduce the surrounding air temperatures, with a specific study in Munich demonstrating a peak cooling effect of 3.5 °C (Rahman, Moser, Rötzer, & Pauleit, 2017b). Therefore, trees can be drivers of a trade-off between outdoor thermal comfort and renewable energy production, as they improve the first through shading and evapotranspiration but might impair the latter through shading on PV panels (Reitberger, Palm, Palm and Lang, 2024).

3. Material and methods

In the following Section 3.1, we introduce the site considered for our study and explain the available datasets and meteorological boundary conditions. After that, the generic methodology for coupling tree growth simulation and GIS is introduced in Section 3.2.

3.1. Case study data

The site considered for the case study is located in the city of Munich (48∘8′N, 11∘35′E, elevation of 520 m above sea level). Munich is the third-largest city in Germany and the capital of the Bavarian state of Germany. Its population is over 1.4 million, and the area is around 311 km^2. Munich combines cold and warm months, with an annual mean temperature of 9.5 °C from 1971 to 2000 (this data is intended to give an impression of the city's climatic condition and is not used for the simulation parts of this study). The coldest temperature average of January in Munich during this period was 0.3 °C, and the warmest temperature average was 18.9 °C in July (German Weather Service (DWD), 2024b). The yearly average precipitation in Munich is 954 mm, mostly received during summer (Jochner, Alves-Eigenheer, Menzel, & Morellato, 2013). The winter is often drier, and precipitation averages can reach a minimum of 46 mm in January (Rahman et al., 2017a). Munich's urban forest structure has been analyzed using GIS, showing that trees and shrubs covered 18% of the city's area, with a close link between vegetation patterns and land use zoning (Pauleit & Duhme, 2000b). Munich's city planning is based on many green open spaces and uniform-height buildings, with only a few buildings taller than 100 m (Jochner et al., 2013). The case study site measures 500,000 m^2 and contains 2783 trees (1794 deciduous, 989 conifers). It is selected because of its central position in the city, which makes it vulnerable to urban heat. Further, the site contains streetscapes as well as open spaces and squares, which allows an investigation of several types of urban spaces. Fig. 2 shows the location of Munich and the case study area.

The primary data for the case study model came from the State Office for Digitization, Broadband and Surveying in Bavaria (LDBV, 2024). It was made available as part of the *Geomass Data* project. Based on this data, the Leibnitz Institute for Ecological and Regional Development in Dresden created the tree model. The vegetation data used for the Munich area is the laser-scan data collected in 2012. The average point density in the urban area is 4.6 pts/m^2 (Münzinger, Prechtel, & Behnisch, 2022). This data is used to create comprehensive and realistic models of the urban tree population in the CityGML scheme for integration into 3D city models (LDBV, 2024). The vegetation data is available in the reference system ETRS89/UTM Zone 32N (EPSG:25832) in CityGML format and contains various attributes, including location, diameter at breast height (dbh) [m], crown diameter (cd) [m], species type (conifer or deciduous), and height [m] (Münzinger et al., 2022). The vegetation files were available in patches of land in Munich. The building data is publicly available from the Bavarian OpenData website (Opendata, 2024). For this research, multiple software was used as the datasets were stored in different file formats and needed to be compiled into a single model. The primary tools used are ArcGIS (version 3.2.1) from Esri, Python, and *CityTree* (version 4.1) (Rötzer et al., 2019). As soils in cities vary greatly and their nutrient content is largely unknown, all known growth models for urban trees do not take soils and their nutrient content into account. Therefore, sandy loam was chosen as the soil type for this study. The suburban soil condition of Munich was set as follows: field capacity: 25 vol-%, maximum rooting depth: 80 cm, permanent wilting point: 8 vol-% (Rötzer et al., 2019).

Since there was no data defining surface sealing in a high-resolution scale in Munich, the tree growth is simulated for different surface sealing conditions (0%, 60%, and 95%) to investigate the results' sensitivity to this parameter. The tree species chosen for the study is small-leaved lime (*Tilia cordata*) since the vegetation data contained only the species type (conifer or deciduous) rather than the species name. *Tilia cordata* is a deciduous tree that is among the most seen trees in central European

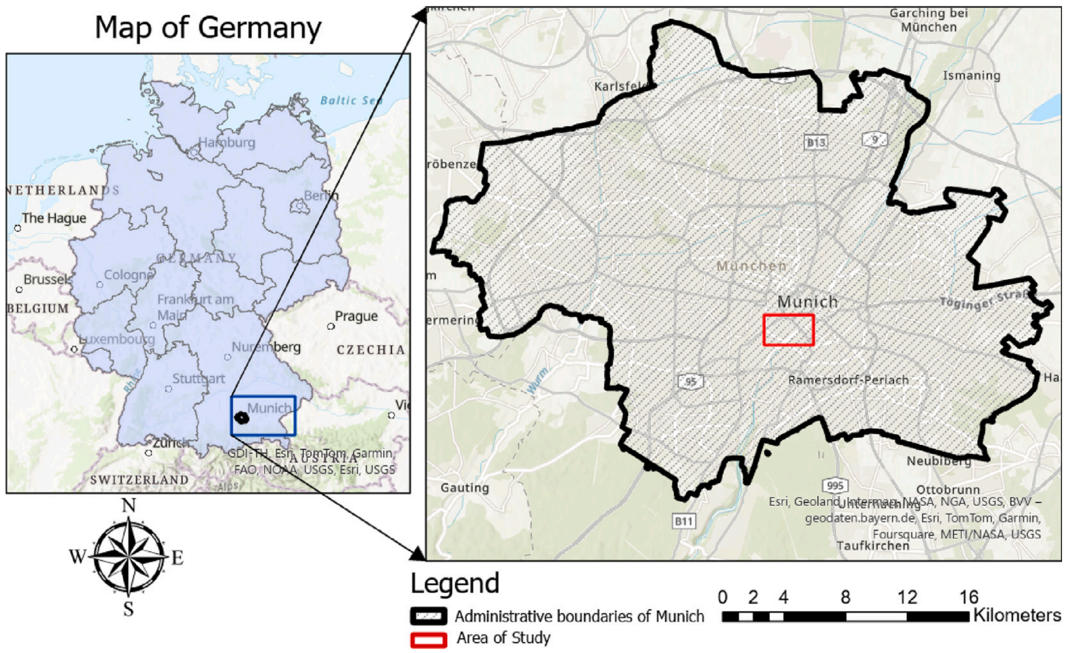

Fig. 2. Location of Munich and the case study area derived from the Open Data of Munich from ArcGIS. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

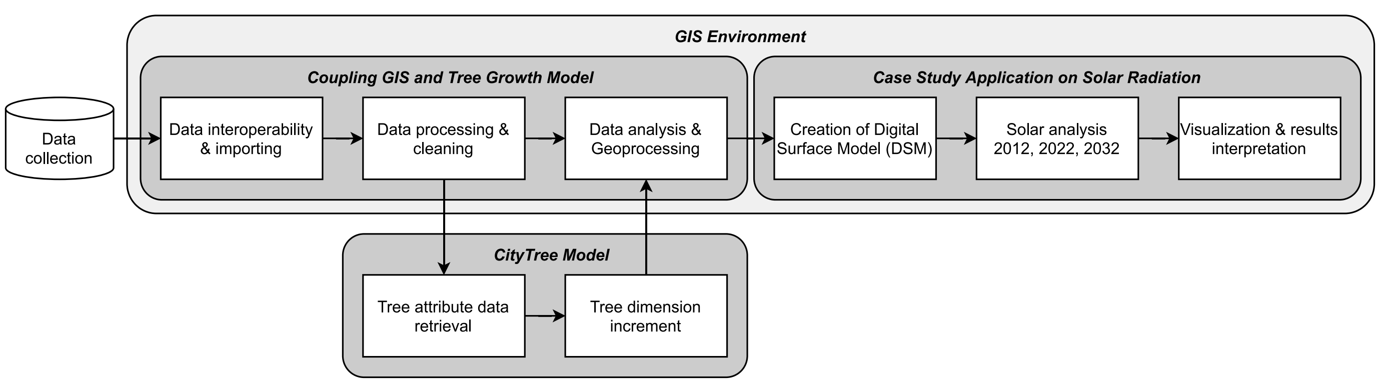

Fig. 3. Methodological framework for coupling GIS and the tree growth model *CityTree* for a solar analysis case study.

urban areas (Rahman et al., 2019) and exhibits a progressive increment in dbh annually. Its growth was validated well during the development of the *CityTree* model (Rötzer et al., 2019).

3.2. Methods

The main goal of the proposed workflow is to couple GIS with a tree growth model. We showcase the usage by investigating the impact of tree growth on solar radiation and evapotranspiration. To achieve this, we first merge multiple file types available from open-source data and the laser-scan data of Munich city's vegetation and buildings. Second, we derive the necessary information on all trees in the case study area to run tree growth simulations for each individual tree. Third, we calculate solar exposure and evapotranspiration after applying tree growth to the GIS model. Fig. 3 summarizes the methodological steps to accomplish this task. The following subsections explain the application in our case study, going through tree growth model selection, data preparation, tree growth projection, and solar exposure calculation.

3.2.1. Tree growth model selection

The foundation of process-based tree growth models are atmosphere-plant-soil interactions described by physical and biochemical reaction processes (Rötzer et al., 2019). The *CityTree* model is one of the few models developed on these principles. In contrast, other urban tree growth models, such as *i-Tree*, *UFORE*, *CityGreen*, etc., are parameterized based on empirical approaches and are, therefore, difficult to apply outside their system boundaries or conditions (Rötzer et al., 2020). The *CityTree* model is founded upon a comprehensive understanding of the physical, chemical, and biological processes that govern tree growth. The model employs physiological equations and uses environmental conditions to calculate the biomass increment of different tree species, which makes this model unique (Rötzer et al., 2019). It allows the assessment of tree growth and ESS based on different climatic, soil, atmospheric, and site conditions. This is based on structural tree data and a rough soil characterization. In addition to the concentration of CO_2 in the atmosphere, the following monthly climate data represent the driving forces: temperature, radiation, air humidity, wind speed, and precipitation. The model includes a water balance model to calculate the actual evapotranspiration, interception, and runoff, with the soil properties serving as the basis for these calculations. Furthermore, the estimation of ESS provided by urban trees, including carbon storage, reduction of rainwater runoff, shading, and cooling by transpiration, is feasible. By employing the already validated growth model *CityTree*, it is also possible to conduct studies on tree growth and ESS under varying surface sealing conditions.

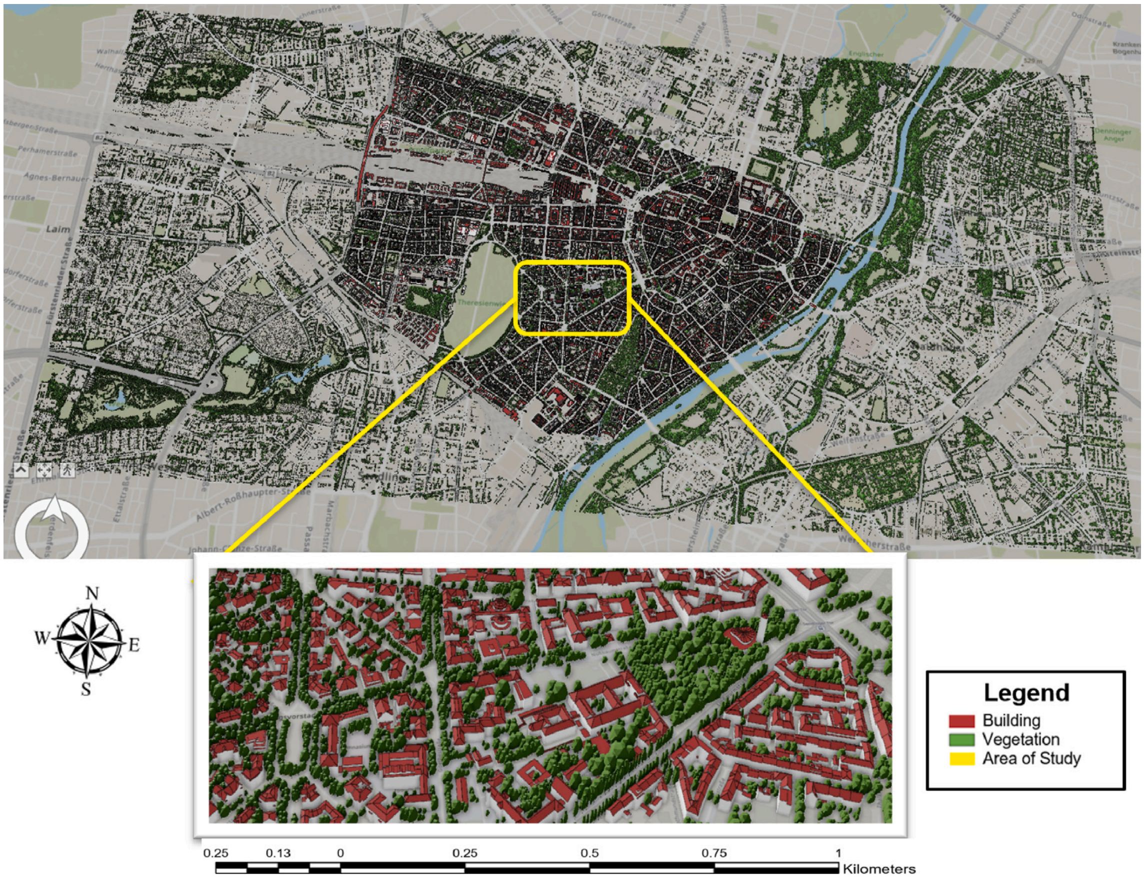

Fig. 4. Imported vegetation patch (Münzinger et al., 2022) and buildings (Opendata, 2024) in ArcGIS. The case study area is marked in yellow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

This parameter affects urban areas' environmental quality, trees' root development, and drainage issues (Pauleit & Duhme, 2000a). However, the impact of nutrient effects, such as nitrogen or phosphorus supply, on tree growth has not yet been incorporated.

The *CityTree* model is used for this study because, as a process-based tree growth model, it must not be adapted to different environmental conditions. In addition, it was chosen due to its proven effectiveness in simulating urban tree growth in Central Europe. The model was validated for the Central European climatic and urban site-specific conditions ranging from sites with high precipitation amounts (Rötzer et al., 2019) to warm and dry cities (Rötzer et al., 2021). The validation studies include independent data sets on dbh increment and transpiration measured with dendrometers and sap flow sensors. These validation studies confirm a strong agreement between simulated and observed values. Specifically, Rötzer et al. (2019) validated *CityTree* for *Tilia cordata* and *Robinia pseudoacacia* using high-resolution data across multiple Munich sites, each with unique soil sealing levels and meteorological inputs (Rötzer et al., 2019). Rötzer et al. (2021) highlight the model's ability to simulate drought responses and ESS, such as carbon sequestration and cooling, under high-stress urban conditions (Rötzer et al., 2021). To our knowledge, *CityTree* has not been combined with GIS-based tools to investigate the effect of tree growth in large-scale urban areas.

3.2.2. Data preparation

The data regarding the physical and spatial characteristics of Munich city was gathered from open sources (Opendata, 2024) and laser-scanned data (Münzinger et al., 2022). The vegetation and building datasets were available in files representing different patches of land across Munich. The vegetation data and building datasets were separately imported into the GIS platform using the interoperability tools in the Esri ArcGIS platform. The vegetation data was imported from the Geography Markup Language (GML) format to point feature using the quick import function in the interoperability tools. This retained the parametric properties and data from the CityGML file. The vegetation data was projected with a topographic base map in the coordinate system ETRS 1989 UTM Zone 32N. This creates a geodatabase of the imported file, which is added to the map in ArcGIS for further analysis. The imported data is cross-checked with the base maps, including the elevation of the features set on the ground in the properties section. All the layers in the map are set to the same projected coordinate system. The imported data is clipped using geoprocessing tools according to the study area. The attribute table of the data is updated with new fields. The attribute table fields are also modified to remove irrelevant data for further geoprocessing analysis and to take results from the *CityTree* model using Python coding. The point features of the trees are represented in 3D format using the 3D symbology template of *European Beech* (Esri, 2024a) since there was no 3D template for *Tilia cordata*. The chosen template illustrates similar physical aspects of *Tilia cordata*. The 3D tree data is dynamically symbolized in the GIS platform using the information from the attribute table of the tree data, with height and width governed by each tree's height and crown diameter. The attribute tables are updated accordingly to make them compatible with analysis in ArcGIS.

The building data was imported from the CityGML format to the multipatch feature layer in ArcGIS using the interoperability tools (Esri, 2024b). The projected coordinate system ETRS 1989 UTM Zone 32N successfully integrates multiple building models into the GIS platform, adhering to the topographic base map. The building elements were in segregated multipatch formats of the building surfaces, such as roofs and walls. These surfaces were combined to create the whole building unit for analysis. New fields are included in the attribute table to

Table 1
Chosen inputs for the *CityTree* model regarding weather and seasonal conditions over the year.

Month	Radiation [J/cm^2]	Temperature [°C]	Rel humidity [%]	Wind speed [m/s]	Precipitation [mm]
1	371	0.9	80	2.7	52
2	614	1.9	76	2.7	46
3	962	5.7	71	2.9	61
4	1396	10.2	65	2.6	56
5	1674	14.3	67	2.5	107
6	1845	17.8	67	2.4	121
7	1855	19.6	66	2.5	119
8	1653	19.4	68	2.2	116
9	1177	14.7	75	2.2	78
10	744	10.1	80	2.3	67
11	417	4.9	83	2.4	58
12	311	1.8	82	2.7	59
Annual means:	**1085**	**10.1**	**73**	**2.5**	**78.3**

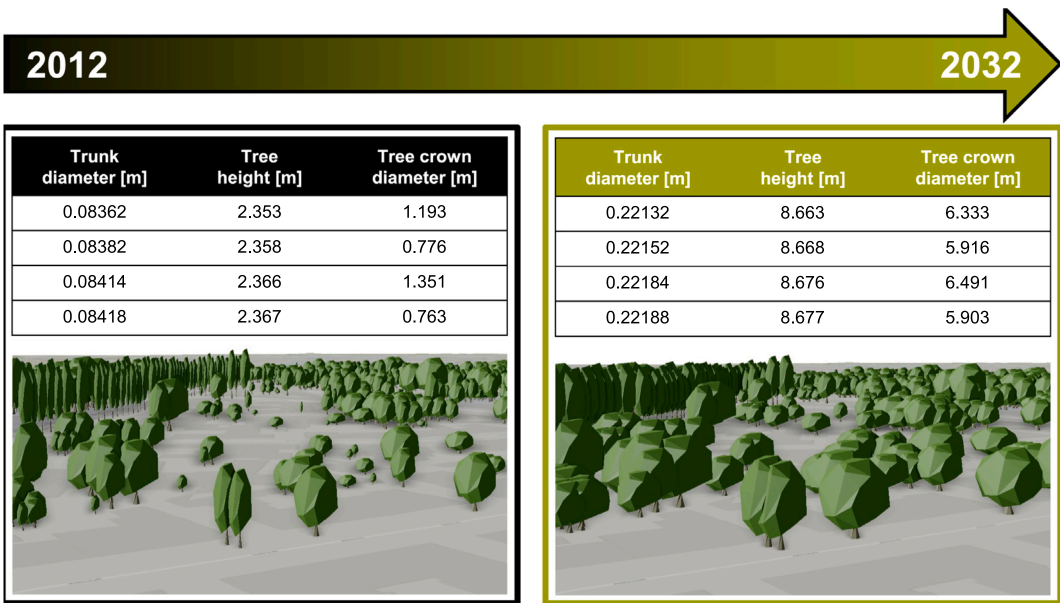

Fig. 5. Illustration of tree growth from 2012 to 2032 predicted with *CityTree* and visualized in ArcGIS.

make the imported CityGML data compatible with solar analysis in the ArcGIS platform. Fig. 4 depicts the imported vegetation and buildings in the GIS platform.

3.2.3. Tree growth projection

Tree growth for individual trees was derived using the *CityTree* model, which calculates and applies the incremental change rate of each tree's physical parameters to the GIS model on a yearly base. The vegetation data was collected in 2012, and the tree growth was projected for 20 years until 2032. Munich's site-specific and meteorological data was applied in the *CityTree* model to derive each tree's growth from 2012 to 2032 (Moser, Rahman, Pretzsch, Pauleit, & Rötzer, 2017; Rahman et al., 2019; Rahman, Moser, Gold, Rötzer, & Pauleit, 2018; Rahman et al., 2017a). The monthly meteorological inputs to *CityTree* are kept constant for each simulation year. The seasonal variation is summarized in Table 1 and kept constant for all growing years. Each tree's growth was simulated, and growth parameters were defined for the tree species *Tilia cordata*.

The growth of the trees was updated annually in the vegetation data by creating a new feature layer in the ArcGIS platform. The increase in the physical change was also updated with the dynamic symbolization of the feature layer in ArcGIS. The tree growth simulations of *Tilia cordata* species from 2012 to 2032 were performed for three different surface sealing conditions: 0%, 60%, and 95%. An example of tree growth from 2012 to 2032 is visually depicted in Fig. 5.

3.2.4. Solar exposure calculation

For the solar analysis in ArcGIS, a Digital Surface Model (DSM) of the case study area was created (Esri, 2024c). The DSM was developed by combining three raster files based on the elevation property of each raster. The three raster layers are: building elevation raster, vegetation elevation raster, and ground elevation raster. The raster files were created based on the elevation of each attribute of the corresponding feature layer in ArcGIS. In the coordinate system used, ETRS 1989 UTM Zone 32N, the raster files were generated for the tree and building data using the geoprocessing tool "Feature to Raster" in ArcGIS with maximum elevation as the field value for the generated output raster. The output resolution of 3.85 m of the tree raster file derived from the default setting in ArcGIS is also used to generate other raster files. The buildings' roofs considered in this study are taken as a flat surface to get a general view of the effects of tree growth without detailed consideration of pitched roofs or any special consideration of roofs facing directions for maximum solar radiation. Since the tree and building data had information on the elevation of the ground point of each feature, an interpolation technique using a geoprocessing tool in ArcGIS is used to derive the ground elevation raster. These three rasters are merged using the geoprocessing tool "Mosaic to new Raster" with the merging operator as "maximum" (the output cell value of the overlapping areas will be the maximum value of the overlapping cells) to create a DSM of the exact resolution as the input raster files. Fig. 6 shows the different raster files created from the features and the DSM obtained by combining the three raster files.

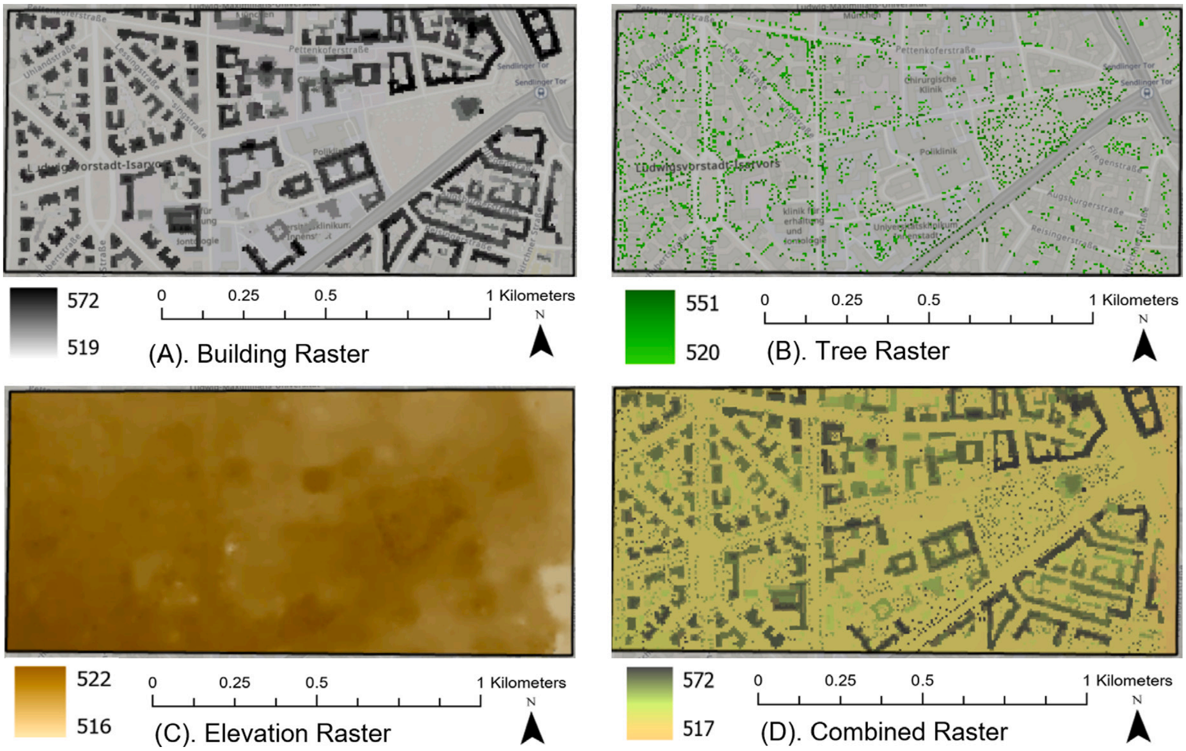

Fig. 6. A: Elevation raster of buildings, B: Elevation raster of tree feature (for the year 2032 with 60% surface sealing tree growth condition), C: Elevation raster of the ground, D: Combined raster representing the Digital Surface Model of the study area.

The area selected for a detailed solar study measures approximately 500,000 m^2. The spatial analysis tools in ArcGIS were used to perform the solar analysis on this chosen area, emphasizing the interaction of buildings and vegetation data based on the climatic data with the global horizontal irradiance. The climatic and meteorological data was inputted for Munich (Moser et al., 2017; Rahman et al., 2017a). The rest of the radiation and topographic parameters were set as per the solar radiation analysis documentation of ArcGIS Pro (Esri, 2024d). With these data, solar exposure for the ground surfaces and the solar potential of buildings' roofs was determined. Solar radiation analysis was done in this chosen area for 2012, 2022, and 2032. In DSMs of various years, the only changing variable was the tree raster, which is attributed to the tree growth for the respective year. The solar analysis was also done for tree growth conditions with varying surface sealing. The input data was visualized in GIS tools to generate results of simulation and radiation exposure maps to interpret the data for comparative analysis. The results are given in kWh/m^2 of ground and building roof area.

4. Results

We present our results first for the tree growth projections (Section 4.1), followed by the changes in solar exposure due to tree growth over 20 years (Section 4.2). Finally, the cooling potential increment is investigated in Section 4.3.

4.1. Tree growth projection

Using the *CityTree* model, we predicted the changes in diameter at breast height (dbh) and crown diameter (cd) of *Tilia cordata*, based on three different surface sealing conditions (0%, 60%, and 90%). *CityTree* outputs yearly increment rates for the different geometry aspects. These increment rates sum up to the dimensional change of the tree over the considered period (e. g. 20 years of tree growth). *CityTree* differentiates tree growth by dbh-classes, i.e., smaller trees show different growth patterns than older and larger trees. The dbh-classes range from below 10 cm to above 90 cm in steps of 10 cm. The increment rates of dbh and cd relative to the dbh-class of the tree species are higher in 0% surface sealing conditions compared to higher surface sealing conditions (Rötzer et al., 2019), see Fig. 7 (A + B). In contrast, the tree height grows similarly across all surface sealing conditions (Fig. 7 (C)).

The right part of Fig. 7 shows the changes in various physical attributes of a single *Tilia cordata* tree in a low dbh-class (8.3 cm) at 0%, 60%, and 95% soil sealing at three points in time. For cd and dbh, the growth rate is higher in the lower surface sealing conditions. Within 20 years of projecting the tree growth, there is a considerable dimension change in cd and dbh for various surface sealing conditions. With the lower surface sealing condition, bigger crown diameters are observed. For the height increment of the tree, there is a slight contrast in terms of growth pattern as observed in the case of cd and dbh. The increment rate of the tree height according to the *CityTree* model in various surface sealing conditions is similar. The growth increment rate is predominant in lower dbh-classes. Regarding the height increment rate patterns of the tree, it is found that in the lower surface sealing conditions, the growth rate in terms of the dbh tends to be at a higher pace than in the higher surface sealing conditions. This results in the tree growing in lower surface sealing conditions getting into higher dbh-classes than the trees growing in higher surface sealing conditions over the same time period. Also, the height increment rates in the higher dbh-classes are lesser than in lower dbh-classes, which resulted in a slight increase in tree height in higher surface sealing conditions. Overall, the varying surface sealing conditions exhibited different growth rates regarding dbh, cd, and tree height. In higher surface sealing conditions, *Tilia cordata* grows slender and is slightly taller than in lower surface sealing conditions. The cd was higher in the lower surface sealing condition than in the higher surface sealing condition.

For a detailed interpretation of how tree growth changes for different surface sealing conditions over the years, we have taken an example of a particular *Tilia cordata* tree growing from the lower dbh-class of

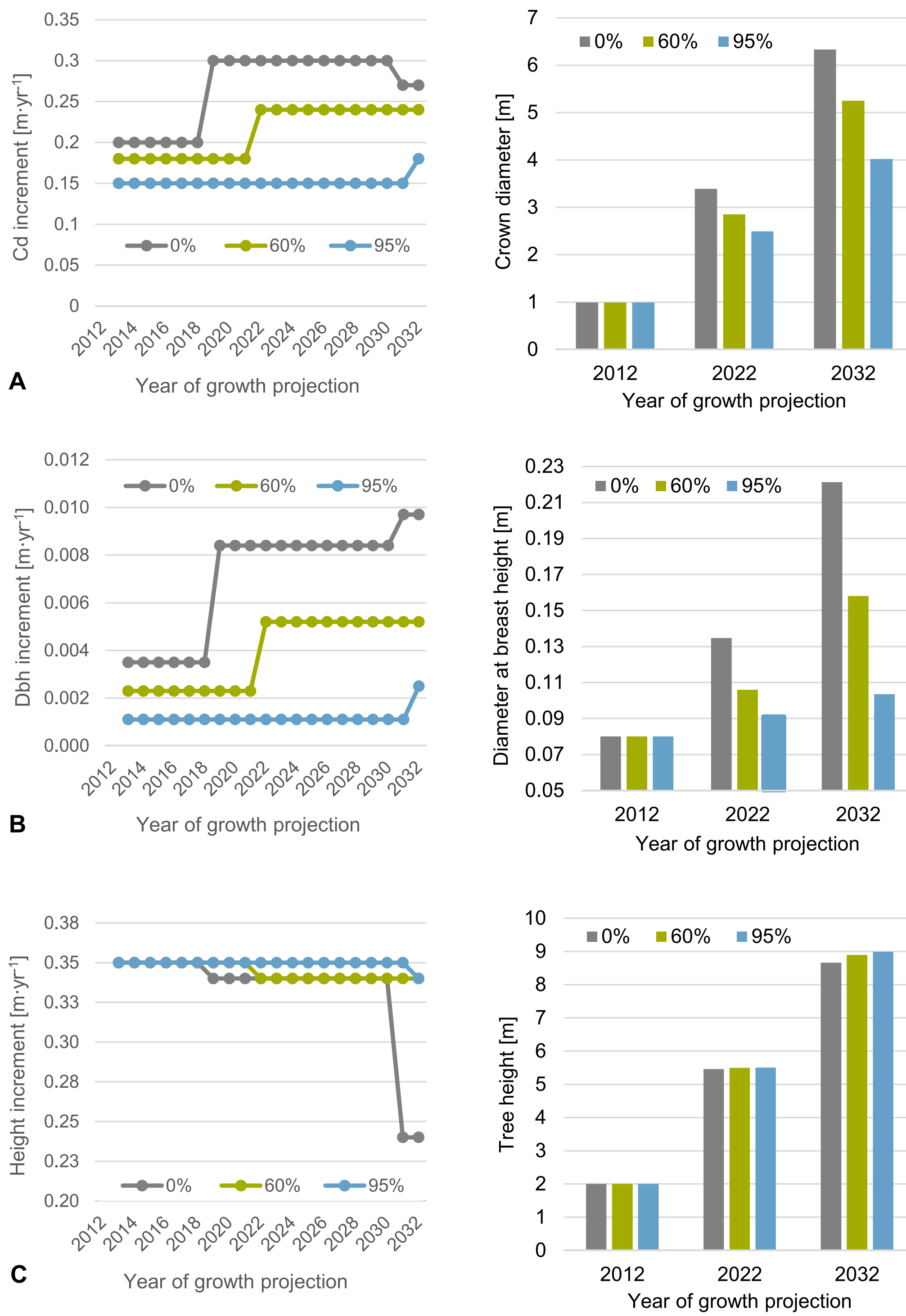

Fig. 7. A: crown diameter (cd), B: diameter at breast height (dbh), C: height (h) of a single *Tilia cordata* tree at 0%, 60%, and 95% soil sealing at three points in time explained with their change in individual increment rate over the course of years.

10 cm to 100 cm. According to the *CityTree* model, the growth rate of the tree's physical attribute dbh is predominant in the lower dbh-class (see Fig. 8). Meanwhile, the height increment rate remains similar for different surface sealing conditions across the dbh classes of the tree.

4.2. Solar exposure with tree growth projections

The solar radiation on the building roofs and open ground surfaces is separately derived using the geoprocessing tools in ArcGIS. This separation helps to understand the contradictory effects of tree growth, which can reduce the solar radiation on the ground and simultaneously reduce the energy output produced from PV panels. With the tree growth over the years, the trees grow in height, which can result in changes in the elevation of various points in the DSM. This changes shadow cast on the ground surfaces and roofs due to increased height and crown diameter. In higher surface sealing conditions, trees tend to be slightly taller than trees simulated in lower surface sealing conditions (see Section 4.1). This leads to slight changes in the effect of solar radiation on the buildings' roofs. To understand how solar radiation changes over the years, we use the mean solar radiation

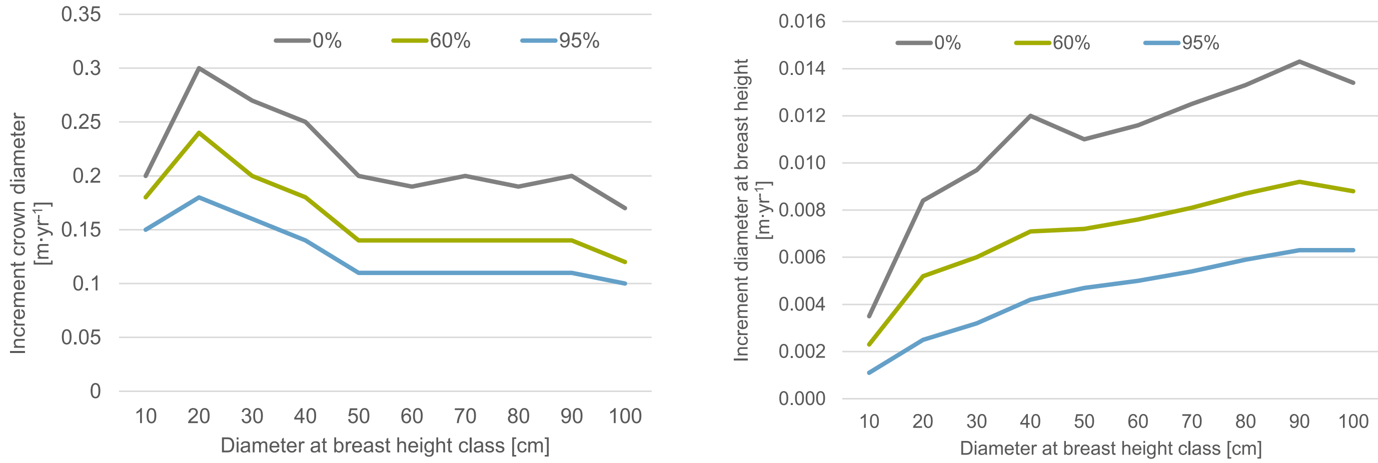

Fig. 8. Yearly crown diameter increment (left) and diameter at breast height increment (right) depending on dbh-class and soil sealing for *Tilia cordata* simulated with *CityTree* (Rötzer et al., 2019).

intensities calculated for a particular year and total solar radiation energy received in the study area for a particular year to give a holistic view of the energy variations. GWh (Gigawatt hour) unit is used in consideration of total solar radiation energy throughout the year in the area of study, and kWh/m^2 (Kilowatt hour per square meter) signifies the mean radiation intensity in the study area.

The illustrative parameters for the comparison are derived from the solar exposure analysis of 2012, 2022, and 2032 with varying tree growth conditions. Fig. 9 depicts the resulting solar exposure map of the case study area. It shows the subtraction of the 2032 solar exposure raster with the 2012 solar exposure to highlight the regions where the solar radiation differs significantly due to 20 years of tree growth. Places where trees are located can be easily recognized by the reduced solar radiation (blue shading). The growth of the trees also leads to an increase in the amount of solar radiation in some areas (red shading). This results from the increase in tree height, which changes the shadow cast by the crown and is not completely offset by the increase in the crown diameter. In streets and open spaces, there is a slight reduction in solar radiation. Strong reductions are observed in the area of tree groups as crown shadows increase, and additional overlaps occur. Fig. 10 shows the distribution of solar radiation changes for the 0%, 60%, and 95% scenarios over ground and building roof DSM grid cells. The ground raster shows higher variation compared to the building roof raster. Further, in the building roof raster, more zero-values are observed. This is to be expected, as not all trees reach the height of building roofs, and therefore, only a few can influence the corresponding solar radiation. In the 60% scenario, there is a reduction of solar radiation with a mean of -22.32 kWh/m^2 over all raster cells observable. The standard deviation in this scenario is ± 48.42 kWh/m^2. Most of the grid cells remain similar, and there are only a few spots in the case study area where the change exceeds 150 kWh/m^2. The maximum decrease and increase are -564.62 kWh/m^2 and $+547.32$ kWh/m^2, respectively.

Looking at the absolute values, the mean solar radiation on the ground and roof surfaces for 2012 is 640.3 kWh/m^2 and 592.8 kWh/m^2, respectively. With the tree growth projected to 2032, the mean solar radiation intensity on the ground and roof surfaces reduced to 612.7 kWh/m^2 and 585.9 kWh/m^2. On the ground, there was a deficiency of 28.3 kWh/m^2. The deficiency on the buildings' roofs after 20 years is 6.9 kWh/m^2, as visualized in Fig. 11 (left). The total solar radiation energy incident on the ground for 2012 is calculated to be 173 GWh compared to 162.4 GWh in 2032. Due to tree growth, there has been a decrease in solar radiation incidents on the ground of 10.6 GWh from 2012 to 2032. In the case of the roofs, total solar radiation for 2012 is 95.6 GWh compared to 94.6 GWh in 2032, a deficiency of 1.0 GWh. Fig. 11 (right) visualizes the total solar radiation results.

Table 2
Mean solar radiation on roofs for different years in 0%, 60%, and 90% surface sealing conditions (unit = kWh/m^2).

Surface sealing	Year 2012	Year 2022	Year 2032
0%	592.8	589.6	586.3
60%	592.8	589.6	585.9
95%	592.8	589.5	585.8

The mean solar radiation intensity change was simulated for three tree growth conditions: 0%, 60%, and 95% surface sealing to give an impression of the uncertainty of results due to unknown imperviousness conditions. Higher surface sealing conditions exhibit more reduction in the incident solar radiation on buildings' roofs due to the slender tree growth with slightly taller trees compared to the tree growth condition in lower surface sealing. Table 2 summarizes the mean solar radiation results for the respective years and surface sealing conditions. The mean solar radiation for 2032 with 95% surface sealing is 585.8 kWh/m^2 compared to 586.3 kWh/m^2 with 0% surface sealing. This means a slight reduction of 0.5 kWh/m^2 of solar radiation on roofs when trees grow in 95% surface sealing condition compared to 0% surface sealing. As shown before, the solar radiation reduction between 2012 and 2032 is calculated as 6.9 kWh/m^2. Hence, considering tree growth is more important than knowing the exact surface sealing conditions for *Tilia cordata* trees when it comes to long-term solar radiation analysis on building roofs.

4.3. Cooling through evapotranspiration from trees

Using the *CityTree* model, the evapotranspiration energy equivalent from the trees located in the 500,000 m^2 case study area is calculated for the 60% surface sealing condition. The resulting increase in evapotranspirative cooling energy can be used to interpret the reduction in solar energy yields in the later discussion. With the tree growth, the leaf area also increases, resulting in higher evapotranspiration from the trees. The summer evapotranspiration energy was derived from the *CityTree* model for every single tree and summed up. The results for the case study area show an increase in annual evapotranspiration energy by 21.4 GWh from 2012 to 2032 due to tree growth. The summer evapotranspiration energy increased by 10.5 GWh from 2012 to 2032. Fig. 12 depicts the increase in evapotranspiration energy for various years with tree growth.

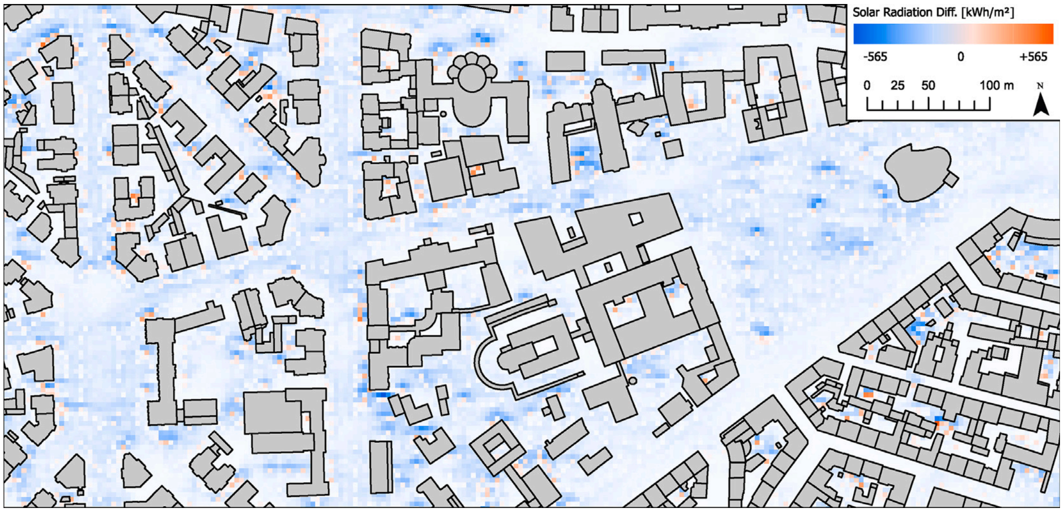

Fig. 9. Difference of solar radiation between 2012 and 2032 due to tree growth. Changes result from tree growth simulated with *CityTree* in 60% surface sealing condition. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

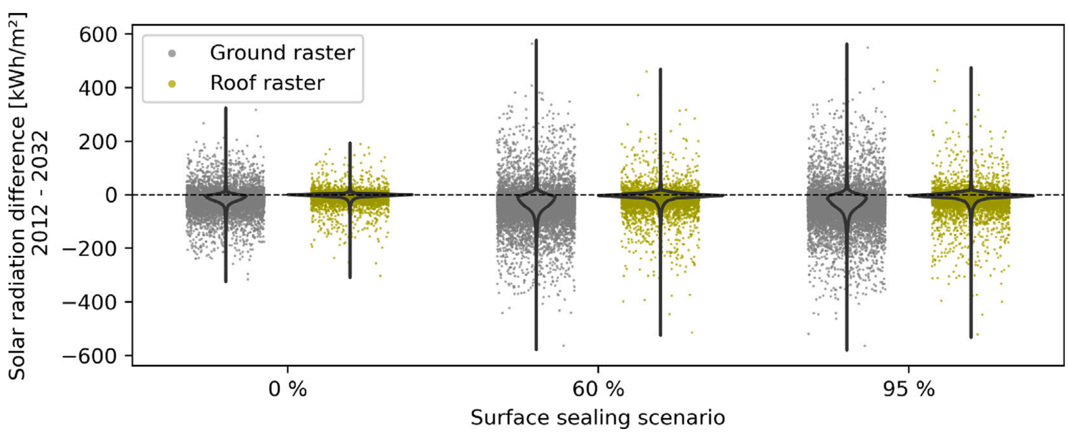

Fig. 10. Distribution of solar radiation difference from 2012 to 2032 due to tree growth in varying surface sealing conditions. The results are grouped by the ground and building roof rasters.

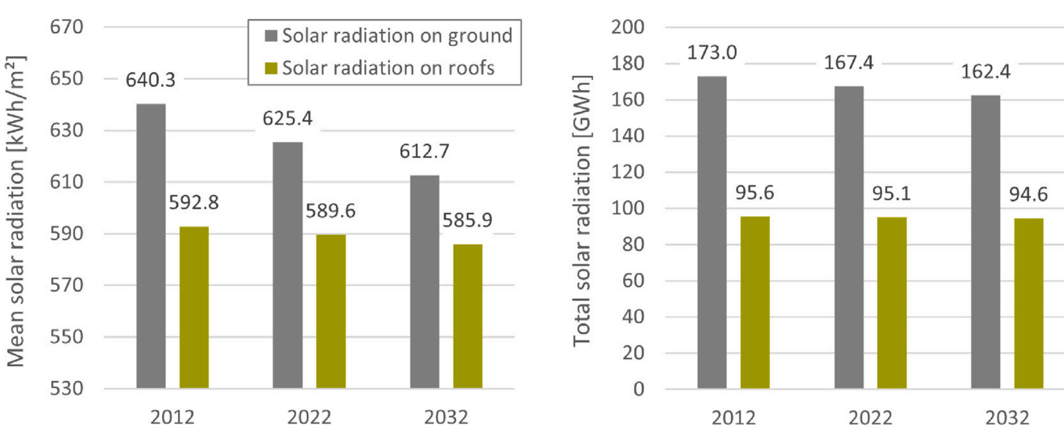

Fig. 11. Mean solar radiation (left) and total solar radiation (right) on ground and roofs for various years in 60% surface sealing condition.

5. Discussion

First, we interpret the results regarding the impact of surface sealing conditions on tree growth to understand the impact of growth patterns on solar radiation. The results for solar radiation and evapotranspiration changes due to tree growth follow accordingly and the emerging trade-off is discussed. Finally, we give the limitations of our study.

5.1. Tree growth in different surface sealing conditions

Integrating tree growth with the digital twin creates a more realistic representation of the city to effectively manage trees' ESS provision. Section 4.1 signifies how tree growth changes for different urban conditions and how various growth parameters change over the years. In higher surface sealing conditions, the trees grow in slender form rather

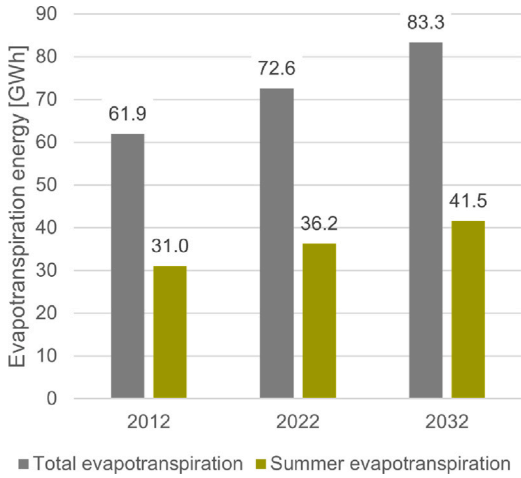

Fig. 12. Change in evapotranspiration energy due to tree growth from 2012 to 2032 in 60% surface sealing conditions.

than in broader shape, which can be attributed to the lower infiltration potential in the areas with higher surface sealing (Pauleit & Duhme, 2000a; Rahman et al., 2019). The results show that reducing the surface sealing can increase the chances of growing thicker and broader trees, which can yield more shade on pathways and ground, as well as cooling the adjacent buildings in summer. These trends were similarly observed in the studies done for the species *Celtis australis* grown in different paving conditions (Fini et al., 2022). In impervious pavings, the growth was more slender than in unpaved bare soil conditions, in which the height increment rate was slightly higher in impermeable conditions. In contrast, the annual dbh increment and cd increment rates are predominant in the bare soil growth condition. Also, permeable paving conditions are much more suitable for the growth of tree roots and affect the vegetation water uptake due to increased evaporation and infiltration fluxes (Fini et al., 2022; Sela, Svoray, & Assouline, 2015). Hence, when aiming for improved outdoor thermal comfort, tree managers should reduce soil sealing around existing trees to allow the trees to develop a broader shape, which yields more shade on streetscapes.

Besides site characteristics, human interaction is among the key factors that influence the health of urban trees. Urban planners, environmental scientists, and policymakers play a crucial role in maintaining it. Urban trees, which generally require maintenance, can have shorter life spans compared to those growing in natural environments (Bühler, Kristoffersen, & Larsen, 2007; Lawrence, Escobedo, Staudhammer, & Zipperer, 2012; Mullaney, Lucke, & Trueman, 2015). Higher surface sealing can limit the water and nutrient availability of urban trees. Also, higher surface sealing can cause increased daytime temperature on the upper part of the soil and ground surface, affecting the tree health and the microclimate of that particular region (Craul, 1992; Kozlowski, 1985; Mullaney et al., 2015). With the increasing importance of tree information databases for urban areas, tree growth monitoring and maintenance is crucial for the sustainable management of urban trees and decision-making with multi-faceted information for overall city development (Schrenk et al., 2021). Tree growth and maintenance are essential for reaping the maximum ESS for the urban environment. Pavements must be designed accordingly to ensure proper permeability, ensuring better ESS provision (Mullaney et al., 2015). In higher surface sealing conditions, trees tend to grow in unhealthy patterns if there is less maintenance to the trees, causing a decrease in ESS. This can result in shading reduction attributed to lesser crown growth and comparatively lesser evapotranspiration cooling as anticipated from the tree's actual potential. With street experiments in the mobility sector gaining traction, landscaping the streets and public areas with proper UGI is also a need of the future (Smeds & Papa, 2023). Hence, in streets and possible tree locations, surface sealing should be reduced to improve the growth and ESS of trees.

5.2. Solar radiation analysis with vegetation and building data

From Section 4.2, the reduction in mean solar radiation and total solar radiation on the ground surfaces is higher than on the buildings' roofs. In the comparative analysis of solar radiation on the ground surface in 2012 and 2032 with projected tree growth, the reduction in total solar radiation on the ground is 6.1%. On the roofs, the reduction of solar radiation from 2012 and 2032 due to tree growth is 1.0%. Hence, the changes in shading are more predominant on the ground surface, which can create a better microclimate in pedestrian areas and open spaces. Similar GIS studies evaluated the effect of trees and buildings to identify the shading impact on outdoor spaces, which determined that both the buildings and trees significantly impacted the shading effect on outdoor spaces (Takebayashi, Kasahara, Tanabe, & Kouyama, 2017). Others show that the effect of trees on solar radiation varies across land uses, with single-family residential areas experiencing the greatest reduction (Tooke, Coops, & Voogt, 2009). Studies also affirm that trees improve the microclimate and shading in open spaces (Darvish, Eghbali, & Eghbali, 2021; Reitberger et al., 2023). Researchers highlight the importance of 3D shading analysis, including vegetation and buildings, to gain a deeper understanding of land surface temperature and to mitigate the UHI effect (Park, Guldmann, & Liu, 2021).

From the value engineering perspective, the cooling potential of trees in urban areas and their development can be equated with a reduction in solar energy potential from the buildings due to tree growth. From Section 4.2, the reduction in solar energy potential of roofs from 2012 to 2032 is 1.0 GWh due to tree growth. Considering PV modules to have an efficiency of 20%, the net solar energy that can be effectively converted to electricity from 1.0 GWh is 0.2 GWh. This energy is far less than the cooling energy equivalent increase from the trees due to evapotranspiration (10.6 GWh). With the increasing focus on renewable energy to counter climatic changes, research on multiscalar energy assessment using GIS for large areas focuses on evaluating PV potentials (Vecchi & Berardi, 2024). These GIS-based approaches give more clarity in analyzing geospatial data in the purview of solar exposure (Choi, Suh, & Kim, 2019). The reduction in usable solar radiation potential on the roof surfaces of buildings due to tree growth found in our study is small. It is compensated well by the evapotranspiration ESS of the trees. Ko (2014) studied the effect of urban trees on potential PV energy from residential buildings. The author shows that the density and physical attributes of trees impact rooftop solar potential with trees accounting for a total reduction of 1.8% (Ko, 2014). In our study conducted in Munich, we found that tree growth led to a reduction in usable solar energy from buildings, amounting to approximately 1.0%. Different tree growth conditions influence the incidence of solar radiation intensities on buildings. Higher surface sealing conditions resulted in slightly taller trees, which resulted in a slight reduction of solar radiation on the roofs compared to lower surface sealing tree growth conditions. Hence, low surface sealing conditions are preferable for broad and thick tree crowns, improving shading and outdoor thermal comfort on the ground and maintaining PV potentials on roofs.

5.3. Trade-off between cooling and renewable energy potential

According to Section 4.3, the total evapotranspiration energy equivalent from trees increased by 21.4 GWh, and summer evapotranspiration energy increased by 10.5 GWh from 2012 to 2032 due to tree growth in our 500,000 m^2 case study area. To give a better impression of these values, we compare them to the overall incoming solar radiation in the area. In Munich average global radiation income is approximately 1,150 kWh/m^2 and therefore 575 GWh for our case study area (German Weather Service (DWD), 2024a). Hence, the summer evapotranspiration is about 1.8% of the energy income through solar radiation. However, the cooling effect provided by evapotranspiration mechanisms is much more localized. It varies in time and space, with tree morphology, species characteristics, above and below-ground site conditions having considerable influence (Georgi & Zafiriadis, 2006; Pattnaik et al., 2024). Therefore, coordinating new tree plantings with the existing tree development is an important local measure to improve outdoor thermal comfort, although the influence on a larger scale is comparably small.

As discussed in Section 5.2, extended shading through tree growth can negatively affect the PV potential of buildings' roofs. However, there are also positive effects on buildings' energy demand through trees. The results of our case study corroborate studies on the effectiveness of trees in reducing the energy demand of buildings by reducing the artificial cooling demands (Laband, 2009; McPherson & Simpson, 2003). Several studies emphasize the advantages of planting trees with offsets in the range of 4 to 5 m in the south, west, and east direction of the buildings to increase the effectiveness of shading and cooling on the buildings (Donovan & Butry, 2009; McPherson & Simpson, 2003; Zielonko-Jung & Janiak, 2022). At the same time, the comparative analysis of tree planting costs compared with the energy savings from urban trees encourages planting more urban trees (Huang, Akbari, Taha, & Rosenfeld, 1987; McPherson & Simpson, 2003).

This identifies tree growth as one of the possible drivers of the trade-off between outdoor thermal comfort and renewable energy production. On the one hand, tree growth increases cooling effects through evapotranspiration and by shading pedestrians. On the other hand, it may lead to shaded PV surfaces, thereby reducing renewable energy production. This trade-off has also been identified regarding new tree plantings in other studies (Reitberger, Palm et al., 2024). Our case study extends this to the growth conditions of existing trees and shows that existing trees can also influence this trade-off. To balance the inherent conflict, urban planners must understand the interactions caused by trees and explore possible building-tree configurations. This could enhance the overall transpirational cooling, thereby improving thermal comfort for pedestrians while simultaneously minimizing the negative effects of PV shading.

5.4. Limitations of the study

The vegetation data used in this study only concerned the species type, namely deciduous and conifer. Therefore, tree growth had to be generalized with *Tilia cordata* species for the whole vegetation of the case study area rather than the actual scenario of mixed species of different conifer and deciduous varieties. Other tree species have different growth patterns and ESS. Thus, the uncertainty in the tree dimensions increases as the simulation period increases. This is partly compensated by selecting the highly occurring *Tilia cordata* species.

Weather conditions play an important role in tree growth. The *CityTree* model allows to consider monthly averages to account for seasonal changes. However, we only considered one average condition for all simulation years from 2012 to 2032. This excludes extremely hot or dry years that might heavily impact tree growth and increase tree mortality.

Data on the elevation of the ground and streets between the trees and buildings was unavailable. For the solar study and the creation of a DSM, a new raster file was created to define the elevation of the ground between the buildings and trees. The elevation of the ground was created using the z-coordinates of the trees. The z-coordinates of trees represented the approximate elevation of the ground at the base of the trees. By interpolation using geoprocessing tools in ArcGIS, the ground elevation raster is a derived raster file rather than the actual elevation data of the ground at the respective point. Further, the DSM raster of 3.85 m limits the results in terms of accuracy and leads to neglecting smaller variations in height. This includes simplifying the tree crown shape, represented as a rectangular raster of the DSM at the top of the trees according to the crown diameter. Although this paper focuses on the effect of tree growth on solar radiation, this simplification may lead to an overestimation of the shaded area and thereby increase the absolute tree shading impact. The raster of building roofs was created using CityGML data. This data allows differentiating between pitched and flat roofs. However, pitched roofs had to be simplified into flat roofs to create the raster file in ArcGIS. Therefore, the absolute solar radiation on these roofs differs from the actual situation.

The tree growth is validated solely based on the *CityTree* growth model and comparative results from other scientific works. The physical or real-world validation of the tree growth was not within the scope of this study. Trees' nutrient cycles and supply are not included in the *CityTree* model. However, urban trees that grow in highly sealed areas, such as street canyons and public squares, often lack adequate nutrients to meet their needs (Meineke, Dunn, Sexton, & Frank, 2013; Rötzer et al., 2021). This nutrient limitation can hinder growth by reducing biomass production and leaf development, ultimately leading to a lower provision of ESS (Gessler, Schaub, & McDowell, 2017). In addition to supporting metabolic processes and tree growth, nutrient uptake plays a role in ESS by removing nutrients from stormwater runoff (Denman, May, & Moore, 2016). Incorporating these nutrient dynamics into urban tree growth simulations could enhance our understanding of ESS in urban environments.

6. Conclusion

This study successfully coupled a GIS-based City Information Model with a tree growth model to derive more realistic and recent tree dimensions for the planning and management of urban tree development. The usability of the proposed methodology was exemplified by investigating tree growth impact on solar exposure for an area of 500,000 m^2 in Munich, Germany. The changes in trees' dimensions due to their growth were derived using the *CityTree* model and integrated into the ArcGIS platform. Thereby, remote sensing tree data from 2012 was projected to 2032. The simulated 20 years of tree growth reduced the solar exposure of the case study's ground surface (streets and open spaces) by 6.1%, whereas on buildings' roofs, the reduction was 1.0%. This implies that future tree growth improves outdoor thermal comfort through extended shading while reducing radiation on building surfaces. The loss of renewable energy generation potential was small compared to the additional cooling potential (shading + evapotranspiration) resulting from tree growth.

Urban planners should concentrate on creating sufficient growing conditions for existing trees to maximize their contribution to outdoor thermal comfort in the future. The results of this paper show that in discussions where trade-offs between existing trees and renewable energy generation through PV arise, these should be considered on a case-by-case basis. Nevertheless, the advantages of ESS through tree growth frequently exceed the potential decline in PV potential in the future. In places where the trade-off is expected to be significant, such as high tree densities or trees close to buildings, selecting tree species with a suitable growth geometry can help mitigate the trade-off. A detailed simulation should examine the resulting shadow casting on buildings and streetscapes.

Different tree growth conditions of species *Tilia cordata* showed varying tree dimension development. In higher surface sealing conditions, the trees tend to grow in slender patterns, whereas in lower surface sealing conditions, the trend of tree growth was broader and more uniform. These tree growth conditions affected the solar exposure and the trees' ESS. The study results enforce the need to reduce surface sealing around trees to gain their full outdoor cooling potential. The trees grow to a broad shape only when provided sufficient space and permeable surroundings for water uptake.

The tree growth prediction and integration of UGI into the digital twin of Munich city gave insights into various aspects of the ESS provided by the trees and their interaction with gray infrastructure. To allow such an analysis, cities must collect sufficient data on UGI conditions. The proposed approach reduces the resources for ongoing data collection by predicting trees' future dimensions based on one-time sensing. Thereby, only newly planted and removed trees need to be updated in a city's UGI database. This allows cities to create a more accurate digital twin and to model future tree dimensions to observe their implications on today's city management. Such a holistic model offers long-term recommendations for energy utilization, PV panel installations, and UGI development. This helps urban planners to optimize their tree-planting strategies and to deploy resources in a targeted manner. Once it is clear that tree growth will ensure sufficient shading of the outdoor space in the future, new tree planting can focus on other, more vulnerable areas of the city.

Another aspect of projecting tree growth is the assessment of the health and maintenance conditions of trees in urban areas. The proposed methodology can help urban tree managers to derive future scenarios regarding tree development and compare them with recently captured remote sensing data of the trees. This allows the identification of areas where growing conditions are not as expected. Such knowledge can guide urban planners in developing interventions to improve local growing conditions. This enables better management of urban trees and enhances the utilization of their potential ESS.

Future research should focus on improving the usability of urban tree models in GIS. Our study showed how tree growth can be considered through a coupling approach, but for urban tree management also other aspects like tree mortality are relevant. Hence, extending this study with tree mortality models would be a valuable step to investigate radiation changes due to tree growth and mortality in parallel. Another aspect of solar radiation simulation are façade PV systems, which are getting more and more attention in cities. Extending the scope of this study to building façades would, therefore, be a valuable contribution to identify suitable vertical PV surfaces. The tree growth predictions from the *CityTree* model could be enhanced by considering more local tree growth conditions, such as neighboring buildings, and their impact on tree dimensions and ESS. The usability of data from high-resolving remote sensing methodologies should also be explored. Thereby, more individual growing conditions for every tree can be considered in the growth simulation. This allows a better investigation of urban areas where highly sealed surfaces harm tree growth. Furthermore, methodologies that allow determining tree species from such remote sensing data would improve the tree growth simulation accuracy. Through the described advancements, the trade-off between PV potential reduction and additional cooling can be explored in a high spatial resolution, allowing urban planners to derive local measures to enhance urban tree growth while keeping the impact on PV systems to a minimum. To achieve this, a systemic approach to the challenges of urban planning is essential.

Abbreviations

cd: Crown diameter
dbh: Diameter at breast height
DSM: Digital Surface Model
ESS: Ecosystem Services
GIS: Geographical Information System
GML: Geography Markup Language
LIDAR: Light Detection and Ranging
UGI: Urban Green Infrastructure
UHI: Urban Heat Island
VHR: Very High Resolution

CRediT authorship contribution statement

Roland Reitberger: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation, Conceptualization. **Vinayak Prem Kooniyara:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Leila Parhizgar:** Writing – review & editing, Resources, Methodology. **Thomas Roetzer:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Werner Lang:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Funding

This work was carried out within the Research Training Group *Urban Green Infrastructure*, funded by the German Research Foundation under grant 437788427 – RTG 2679.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors want to thank the State Office for Digitization, Broadband and Surveying and Leibnitz Institute for Ecological and Regional Development (Markus Münzinger) for providing the vegetation data for this study.

Data availability

Data will be made available on request.

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