Enhancing Urban Greenery: Integrating Environmental Data into 3D Urban Tree Models

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Abstract: This paper addresses the imperative of understanding the environmental impact of urban plant species for sustainable urban development. It introduces a novel method integrating additional environmental data into urban trees, focusing on carbon sequestration and solar radiation. Using Grasshopper and digital 3D tree models, a CO_2 calculator is developed, providing precise estimates of sequestration potential. By integrating surface temperature reductions caused by tree shadows with CO_2 data, urban planners gain valuable insights for making informed decisions. Results include a user-friendly interface offering recommendations and visualizations for suitable tree species. The discussion emphasizes the significance of data integration, while the conclusion advocates for broader research in evolving urban landscapes, promoting sustainable design knowledge.

Keywords: Urban greenery, environmental data, urban heat islands, data-driven design, carbon sequestration, thermal analysis of trees analysis, decision support

1 Introduction

As the world's population continues to concentrate in urban areas, urban green spaces are increasingly important for supporting healthy, resilient, and liveable cities (BOWLER et al. 2010, GOLDERBERG et al. 2018). Urban trees, in particular, are key elements in sustainability, contributing to carbon sequestration, air purification, and urban cooling (GAGO et al. 2013, SALMOND et al. 2016, ORDÓÑEZ et al. 2023). Urban areas face numerous challenges, including the development of urban heat islands, which are pockets of higher temperatures in cities compared to their surrounding rural areas (TAHA 1997). These heat islands can lead to increased energy consumption, heat-related health issues, and decreased overall quality of life (PATZ et al. 2005). In this context, the role of urban green spaces and trees becomes even more critical, as they can help mitigate the adverse effects of urban heat islands (MARANDO et al. 2022). However, to maximize trees' potential, we must have a deeper understanding of their climate-related footprint and their relationship with the built environment (TRATALOS 2007, ROY et al. 2012). New databases are developing to quantify the Carbon sequestration of plants, for instance iTree or in the form of software like ENVI-met. However, this kind of data and analysis is not integrated systematically into a design tool. This paper introduces a novel method integrating environmental data into urban trees, focusing on the climate change mitigation contributions of carbon sequestration and the climate adaptation benefits of reducing solar radiation through shading.

The achievements of the research are as follows:

1) Grasshopper integrated carbon sequestration tool to calculate the carbon sequestration of different species providing data visualization for decision making.
2) Method for the calculation of land surface temperature based on projected shadows from urban trees to better understand the trees' capacity to mitigate urban heat islands using Ladybug tools in Grasshopper (LADYBUG TOOLS 2013).

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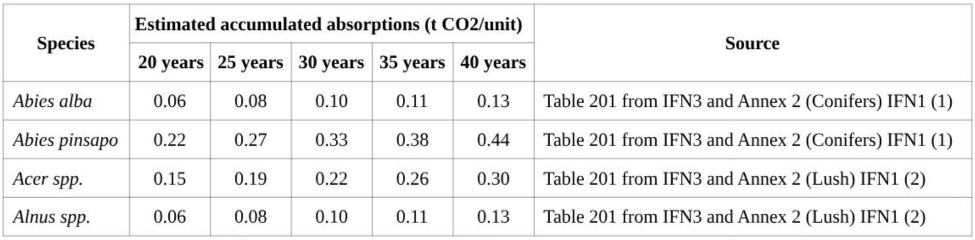
2 Methods

Our research leverages the capabilities of Grasshopper (Grasshopper 2009), a powerful parametric design tool, to develop a CO_2 calculator that seamlessly integrates with digital 3D tree models inside Rhino and Lands Design environment (Rhino 7 Mcneel 2021, Lands Design Asuni 2020). This calculator employs an algorithm that takes into account factors such as tree species, age, and the period over which the carbon sequestration rate is calculated (which we will call the period of calculation). In our research, we combined CO_2 data with data that specify the impact of urban trees on the reduction of the land surface temperature. A unified data model enables a wider view of the environmental performance of urban trees. This model can be extended in the future.

2.1 Carbon Sequestration Analysis Method

The CO_2 calculator is a pivotal component of our research. It employs detailed data on tree species and their growth patterns to provide a precise estimate of carbon sequestration potential. All the data used for this calculator has been obtained from the Spanish “Ministry for the Ecological Transition and the Demographic challenge”, which provides information about how much carbon dioxide each species sequestrates depending on its age (Spanish Ministry For The Ecological Transition And The Demographic Challenge 2023). Analysis results are calculated in the unit of tons of CO_2.

Table 1: Example for the extracted dataset obtained from the Spanish “Ministry for the Ecological Transition and the Demographic challenge”.



Species	Estimated accumulated absorptions (t CO2/unit)					Source
	20 years	25 years	30 years	35 years	40 years	
Abies alba	0.06	0.08	0.10	0.11	0.13	Table 201 from IFN3 and Annex 2 (Conifers) IFN1 (1)
Abies pinsapo	0.22	0.27	0.33	0.38	0.44	Table 201 from IFN3 and Annex 2 (Conifers) IFN1 (1)
Acer spp.	0.15	0.19	0.22	0.26	0.30	Table 201 from IFN3 and Annex 2 (Lush) IFN1 (2)
Alnus spp.	0.06	0.08	0.10	0.11	0.13	Table 201 from IFN3 and Annex 2 (Lush) IFN1 (2)

Leveraging this data, we've crafted a Grasshopper algorithm that generates individual graphs for each tree species. On these graphs, the X-axis corresponds to carbon sequestration values, while the Y-axis represents the age of the species. By employing interpolation, we can accurately ascertain carbon sequestration values for each plant species within the 0 to 50-year age range. This way we can calculate the carbon sequestration for each species within a period defined by the user (for the next or past 20 or 30 years for example) (Fig. 1).

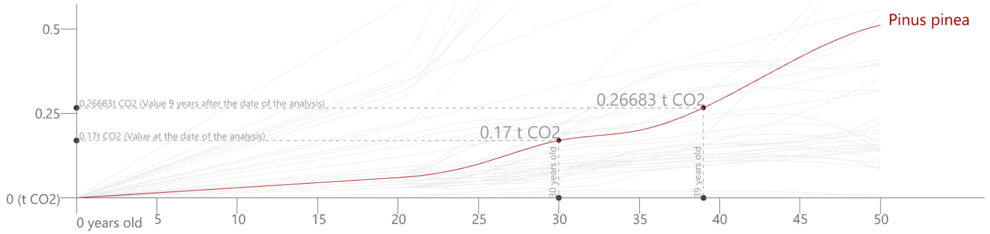
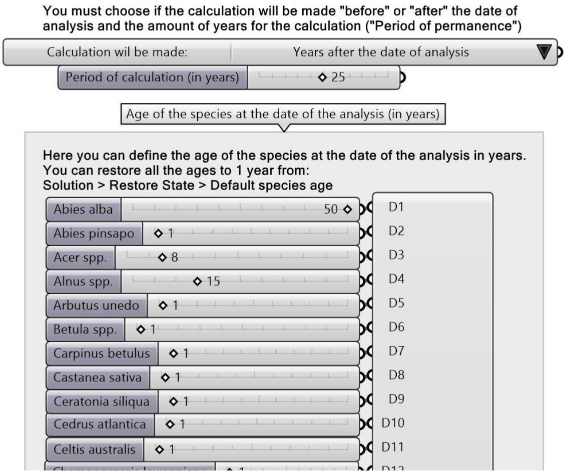


Fig. 1: Example graph provided by our CO_2 calculator to display the information used during the carbon sequestration analysis. For instance, the plant species Pinus pinea has sequestered 0.17 tons of CO_2 when it is 30 years old and 0.27 tons of CO_2 when it is 39 years old. That means that the carbon sequestration accumulated during a period of 9 years (between 30 and 39 years) is the difference between 0.26683 and 0.17 which is 0.09683 tons of CO_2.

The users of our CO_2 calculator are landscape designers and urban planners. To operate our tool, they need to create a BIM model using the Lands Design BIM software for Rhino, and choose the plants to be taken into account for analysis. At this stage, the analysis is limited to a list of 61 species but it will be extended in the future. Once they have created their plant objects in CAD, they need to define the age of each plant species (in years) and input the period for the simulation (in years). The tool has a user-friendly interface that allows for an intuitive selection of input parameters (Fig. 2). In the final step, all plant species that are part of the input 3D BIM model are automatically considered in the CO_2 calculator.


You must choose if the calculation will be made "before" or "after" the date of analysis and the amount of years for the calculation ("Period of permanence")

Calculation wil be made: Years after the date of analysis

Period of calculation (in years) 25

Age of the species at the date of the analysis (in years)

Here you can define the age of the species at the date of the analysis in years.
You can restore all the ages to 1 year from:
Solution > Restore State > Default species age

Abies alba 50
Abies pinsapo 1
Acer spp. 8
Alnus spp. 15
Arbutus unedo 1
Betula spp. 1
Carpinus betulus 1
Castanea sativa 1
Ceratonia siliqua 1
Cedrus atlantica 1
Celtis australis 1

Fig. 2:
CO_2 calculator user interface to input plant species of your BIM project, their individual ages, and the time period for the analysis

In summary, our tool enables urban planners to get real-time feedback about carbon sequestration of the plants used in their landscape architecture projects. This information helps to make more informed decisions about which tree species are best suited for a particular urban setting or specific mitigation objectives. Furthermore, it offers insights into the timeline for carbon sequestration, aiding in long-term carbon mitigation planning. Our tool is a free Grasshopper Add-on and publicly available on Food4Rhino, an online app store for Rhino and Grasshopper-related software plugins (CO2 ABSORPTION CALCULATOR FOOD4RHINO 2023). Since its upload in 2023, we have a test group of more than 285 users.

2.2 Land Surface Temperature Analysis Methods for Tree Objects

Urban trees serve as natural cooling devices by providing shade and reducing ambient temperatures through a process called transpiration. In our methodology, we prioritized the examination of the shading characteristics exhibited by urban trees. Understanding and mitigating the urban heat island (UHI) phenomenon hinges significantly on comprehending the role of land surface temperature. UHIs occur when urban areas experience higher temperatures compared to their rural surroundings, primarily due to human activities and built infrastructure. Monitoring land surface temperature provides crucial insights into the intensity and spatial distribution of UHIs, helping urban planners and policymakers devise effective strategies for mitigating heat-related challenges. Accurate land surface temperature data aids in the identification of heat-prone areas within cities, guiding the implementation of green infrastructure and other measures to enhance urban resilience and improve the overall quality of life for residents. In this context, we developed an algorithm in Grasshopper using Ladybug tools, a Grasshopper plugin for environmental analysis, that calculates land surface temperature values on BIM models of urban trees (LADYBUG TOOLS 2013). The analysis results, presented in section 3, provide information about the tree's capacity to lower land surface temperature in a certain area of the city and the impact of urban trees on mitigating UHIs during different seasons of the year. For our calculations, we used the UTCI thermal comfort model (Universal Thermal Climate Index) in Ladybug tools (Fig. 3). It is strictly for the outdoors and outputs the "feels-like" temperature metrics used by meteorologists (LADYBUG TOOLS 2013). UTCI requires an URL where climate data resides to open context specific weather files (EPW files), which include mean radiant temperature (MRT) which equals air temperature, relative humidity values, and values for meteorological wind velocity (velocity at 10 m is 1,5 times the speed felt at ground). The model outputs the UTCI index together with the ground surface temperatures in degrees Celsius (e. g., +3 = Strong Heat Stress 32 <= UTCI < 38). The model considers another input called "ground reference", a single number between 0 and 1 that represents the reflectance of the floor. For concrete the input value would be one 1 while the value 0.25 is characteristic of outdoor grass or dry bare soil.

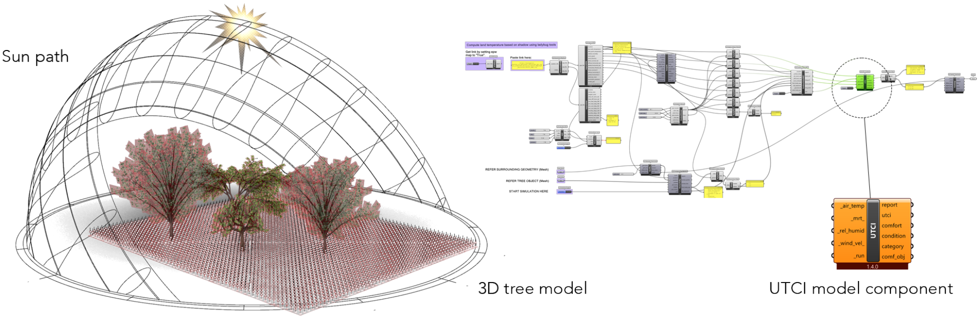


Fig. 3: The input for the land-surface temperature calculation are 3D tree models and their surroundings, a specific location to determine the altitude and azimuth of the sun, and the analysis period

Analysis results can be downloaded as a numerical dataset in a predefined resolution (e. g., 1 m^2) and are displayed as color gradients on the digital 3D model. In summary, the analysis method presented provides valuable feedback to urban planners and policymakers to better understand the effectiveness of their design decision concerning mitigating UHIs. The Grasshopper definition is free and publicly available on Food4Rhino (COMPUTE LAND SURFACE TEMPERATURE BASED ON SHADOWS FROM TREE OBJECTS 2023). The Grasshopper definition was downloaded more than 300 times.

2.3 About the Synthesis of these two Analysis Methods

Urban trees provide really important services, simultaneously, in two different aspects of climate control – reducing the driver, GHG concentrations, through sequestration, and reducing the effects, UHI, through shading. Thus, by understanding the two measures side- by-side, we empower urban planners and landscape architects to make data-informed decisions regarding tree selection and placement. This understanding allows for an easier analysis of a tree's contribution to mitigating UHIs. By visualizing land surface temperatures as a color gradient as well as carbon sequestration values for each plant species in tons, the method fills the gap between sustainable design and digital modeling, paving the way for greener urban landscapes. Future steps include the development and observation of further environmental analysis algorithms, e. g., to calculate tree-specific evaporation values, the impact of wind speed on trees, natural and artificial irrigation systems, water flow, and watershed to gain a more precise picture of the role and dynamics of urban trees to mitigate urban heat islands. In the following section, we will demonstrate our initial results using an example from a landscape architecture project.

3 Results of Complementary Environmental Data to Urban Tree Models

One of the key outcomes of our research is the development of a user-friendly interface for the calculation of CO_2 absorption of custom landscape projects (Section 2.1). The tool provides real-time analysis of how much CO_2 is stored over the years in your design. Thus, it is an essential decision-support aid for environmental analysis in CAD for urban planners and designers. It empowers users to access and use the environmental data for more effectively modeling trees with a defined environmental objective. The interface provides visual feedback on the potential impact of selected trees on carbon sequestration. By creating a user-friendly interface in Grasshopper for landscape architects and urban planners, we aim to promote a data-driven and more informed design approach for enhancing urban greenery. In this section, we show our results using an example project (Fig: 4). The project is an urban park designed with Lands Design and Rhino that includes different plant species.

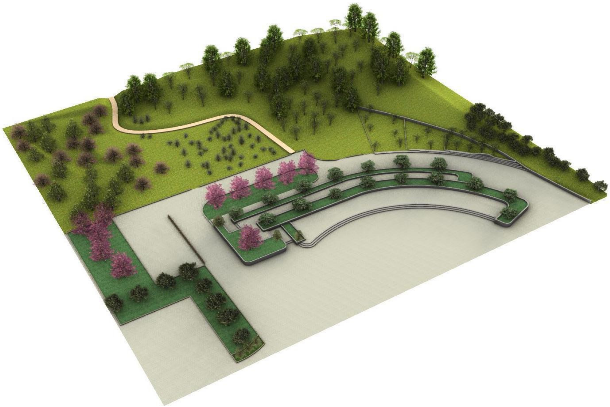
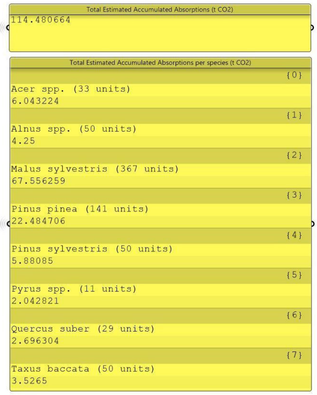


Fig. 4: Example of a landscape design project developed using Lands Design and Rhino. The project has 8 plant species: *Acer platanoides “Crimson King”* (8 years old), *Alnus cordata* (15 years old), *Malus sylvestris* (9 years old), *Pinus pinea* (30 years old), *Pinus sylvestris* (13 years old), *Pyrus salicifolia* (11 years old), *Quercus suber* (6 years old) and *Taxus baccata* (7 years old).

In our example, we performed with our CO_2 calculator, a carbon sequestration analysis from the date of the analysis to 25 years later. To make the calculation, we have defined the age of each plant species at the date of the analysis. As a result, we get the total carbon sequestration for the park design in addition to the carbon sequestration for each plant species based on the number of plants of each species we have in the design (Fig. 5). The amount of carbon dioxide is calculated in tons.



```
Total Estimated Accumulated Absorptions (t CO2)
114.480664

Total Estimated Accumulated Absorptions per species (t CO2)
{0}
Acer spp. (33 units)
6.043224
{1}
Alnus spp. (50 units)
4.25
{2}
Malus sylvestris (367 units)
67.556259
{3}
Pinus pinea (141 units)
22.484706
{4}
Pinus sylvestris (50 units)
5.88085
{5}
Pyrus spp. (11 units)
2.042821
{6}
Quercus suber (29 units)
2.696304
{7}
Taxus baccata (50 units)
3.5265
```

Fig. 5:
Analysis results are displayed (in t) within Grasshopper panels. The upper panel in this figure shows the total estimated accumulated carbon dioxide absorptions (in tons). The values in each line of the panel show the resulting values per species. All values can be exported to a .txt file to be used as additional environmental data for your landscape project (CO2 ABSORPTION CALCULATOR FOOD4RHINO 2023).

Additionally, the calculator returns a graph that provides precise information about different sequestration values per plant species, i. e., which plant sequesters more carbon dioxide so that the user can decide which plant species needs to be modified (Fig. 6).

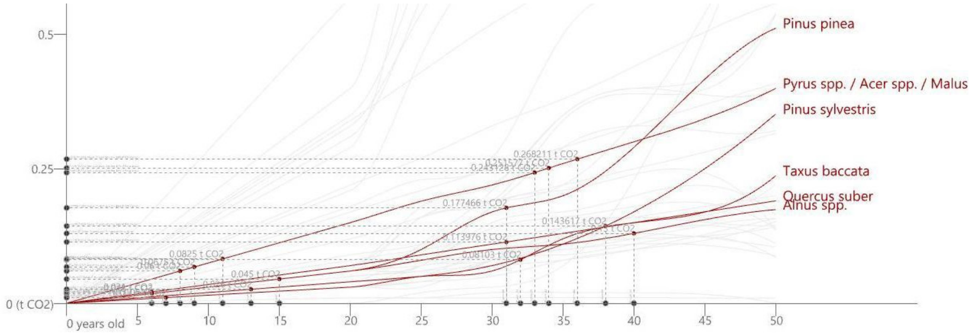
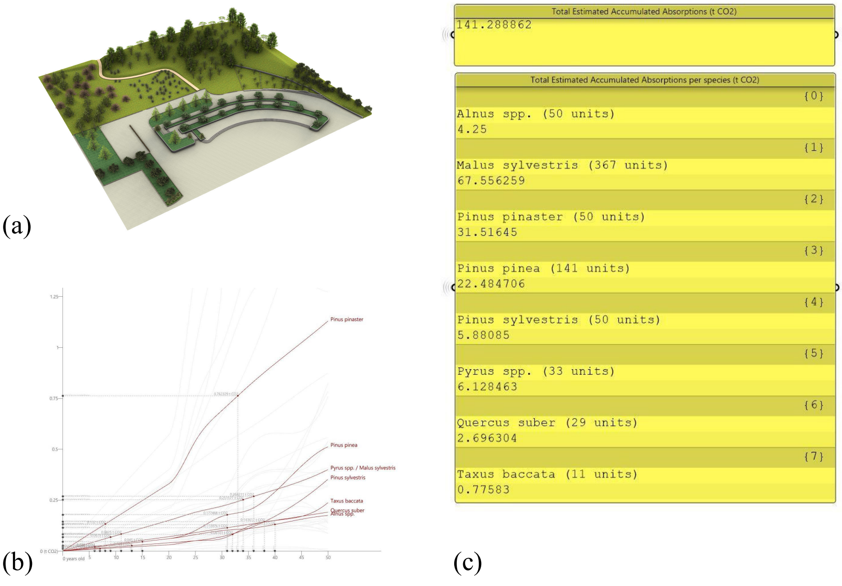


Fig. 6: Resulting graph of the carbon sequestration analysis performed with the CO_2 calculator for our example design

Based on these results, the user can determine which species they would like to change to improve their design based on the criteria of higher carbon sequestration values. Therefore, in the following design iteration, we changed the plant species Acer platanoides 'Crimson King' by Pinus pinaster accordingly. The results and improvements are shown below (Fig. 7).



Total Estimated Accumulated Absorptions (t CO2)

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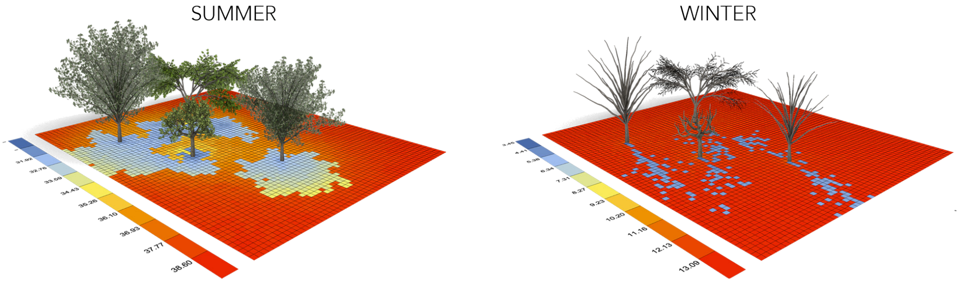
141.288862
```

Total Estimated Accumulated Absorptions per species (t CO2)

```
{0}
Alnus spp. (50 units)
4.25
{1}
Malus sylvestris (367 units)
67.556259
{2}
Pinus pinaster (50 units)
31.51645
{3}
Pinus pinea (141 units)
22.484706
{4}
Pinus sylvestris (50 units)
5.88085
{5}
Pyrus spp. (33 units)
6.128463
{6}
Quercus suber (29 units)
2.696304
{7}
Taxus baccata (11 units)
0.77583
```

Fig. 7: Our results show (a) the adjusted design outcome which has improved its capacity to store 23.42% more carbon dioxide (instead of 11.48t, 14.29t), (b) a graph that represents the changes made (*Pinus pinaster* is showing in its graph an overall higher carbon sequestration than the previously used plant species, *Acer platanoides 'Crimson King')*, and (c) numerical values for each tree species of the optimised design.

Elevated land surface temperatures in densely populated areas contribute to the intensification of UHIs, highlighting the importance of monitoring and addressing this thermal phenomenon for sustainable urban planning. Concerning the second part of our research (Section 2.2), we developed an algorithm that provides numerical information about land surface temperature changes depending on the age, species, and location of urban trees within a city. In particular, groups of urban trees have an expansive canopy that strategically blocks and diffuses sunlight, creating an ideal environment for temperature moderation and enhanced comfort in its vicinity. The developed algorithm is a Grasshopper definition using Ladybug tools that understand global geometry inputs of urban tree models including landscape architecture projects. In our example, we used a smaller group of trees that formed a canopy. Our calculations show that land surface temperatures in this example can be reduced by 7 °C from 38.8 °C (date July 15, location Madrid) to 31.7 °C (Fig. 8a). In the wintertime, the tree canopy, though bare of leaves, still provides valuable structural elements that contribute to windbreak and snow accumulation but it loses its capacity to block sunlight. In this sense, trees serve as perfect devices in winter by shedding leaves, allowing sunlight to penetrate and warm the urban environment when heat is needed most. Our results show that during winter (date January 15, location Madrid), the shaded areas are reduced by 80% and that land surface temperatures remain at 13.09 °C under the leafless canopy (Fig. 8b). Only in shaded areas, the temperature is reduced.



(a) (b)

Fig. 8: These figures illustrate the practical application of our land surface temperature analysis method at different analysis periods in (a) summer and (b) winter, and the value it adds to urban landscape design

The land surface temperature analysis of urban trees reveals their efficacy as climate regulators, showcasing their vital role in mitigating UHIs. Our Grasshopper definition analyses 3D models of trees to provide a rapid and straightforward feedback mechanism through the trees' ability to influence land surface temperatures. Thus, it is a practical tool for sustainable urban planning. Recognizing the impact of urban tree placement becomes instrumental in leveraging these natural solutions to effectively combat and mitigate the adverse effects of UHI. By visually representing the environmental impact of trees, we empower urban planners and landscape architects to make sustainable choices that benefit both the environment and urban communities. In summary, both analysis approaches introduce an innovative methodology for incorporating environmental data into urban tree modeling, emphasizing the importance of considering the land surface temperature in urban areas and carbon sequestration. By providing an accessible interface for decision support, we enable more sustainable urban landscapes, paving the way for future research and data integration in the field of digital landscape design. This research is a stepping stone toward creating greener, more sustainable cities and ensuring a healthier, more resilient future for urban environments.

4 Discussion

The presented methods hold significant implications for advancing sustainable urban development, as they address the critical need for understanding and incorporating the environmental impact of urban trees. By focusing on carbon sequestration and land surface temperature analysis, the research endeavors to bridge the gap between design, data, and sustainability. The calculated carbon sequestration potential, facilitated by the developed Grasshopper-based CO_2 calculator, is a noteworthy outcome. The tool's incorporation of detailed data on tree species, growth patterns, and ecological factors provides a nuanced understanding for urban planners, aiding informed decisions about suitable tree species for specific urban contexts. This depth of analysis extends to considerations of photosynthesis rates, biomass accumulation, and carbon storage, contributing to effective long-term carbon mitigation planning. The benefit of working with a unified data model enables us to understand the complementary aspects (surface temperature values with CO_2 data) of trees' contributions to climate change and climate amelioration. The meticulous digital model for land surface temperature calculation, grounded in Ladybug tools, considers geographical location, seasonal variations, and tree placement. This integration allows urban planners to make data-informed decisions regarding tree selection and placement, particularly in mitigating UHIs. The development of a user-friendly interface is a pivotal contribution, acknowledging the essential role of accessibility in environmental analysis. The interface serves as a decision support tool for urban planners and designers, catering to both professionals and non-experts. Its interactivity and intuitiveness empower users to input specific parameters and receive recommendations for suitable tree species, fostering a seamless bridge between research insights and practical application. The visualizations presented, such as the 3D tree model with CO_2 data and the land surface temperature impact illustration, vividly demonstrate the method's practical application. These visual representations offer valuable insights into the environmental benefits of different tree species, aiding decision-makers in tree selection, placement, and maintenance. It must be said that the data obtained to make the carbon sequestration calculation corresponds to Spanish species planted in Spanish climatic zones, so in case this calculator is used abroad, an assimilation between species and climatic zones should be done. In showcasing the capacity of trees to lower land surface temperature in urban contexts, the method provides a tangible understanding of the impact of an informed placement of tree canopies in urban environments. The practical application of these visualizations empowers urban planners and landscape architects to make informed, sustainable choices for the benefit of both the environment and urban communities. However, the current version of the CO_2 calculator only uses data for the Iberian Peninsula, while the surface temperature analysis can be applied to locations worldwide. In summary, this research marks a significant step towards creating greener and more sustainable cities. The innovative method presented, coupled with the user-friendly interface and impactful visualizations, contributes to an easier understanding of urban tree dynamics. The discussion underscores the potential of this approach in shaping future research and data integration within the realm of digital landscape design, fostering a healthier and more resilient future for urban environments.

5 Conclusion and Outlook

In conclusion, our work represents a significant step forward in adding essential data to parametric 3D tree models. The integration of land surface temperature analysis and CO_2 data enhances our understanding of the environmental impact of urban greenery, aiding decision-makers in creating more sustainable and resilient cities. While we have focused on CO_2 calculation and land surface temperature analysis, there is a clear need for further research and data integration, including parameters such as evaporation, water retention, and spatio- temporal dynamics of urban tree growth. The dynamic nature of urban environments demands continuous adaptation and innovation. As cities evolve, so too must our approach to urban greenery. To achieve resilient and sustainable urban landscapes, we need to consider a broader spectrum of factors that influence the urban ecosystem. As we delve deeper into this domain, we anticipate that more comprehensive and data-driven decision support tools will emerge, reshaping the way we design and manage urban landscapes. Our research emphasizes the importance of creating a knowledge base that supports the sustainable design of urban green spaces, and we encourage further collaboration and innovation in this area.

Acknowledgement

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