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Analysis of the influence of Nature-Based Solutions (NBS) on air quality in industrial areas – case study in Bragança (Portugal)

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Abstract. This research approaches the benefits of NBS, with a focus on tree vegetation, in the industrial zone of Bragança (PT), addressing carbon sequestration and air quality, through microclimatic modelling and simulations with the use of two software, i-Tree and ENVI-met. In this study, three scenarios were created and simulated: Scenario 0, which does not consider the presence of trees; Scenario 1, which reflects the current situation of the study area; and Scenario 2, which consists of the implementation of an additional green space. Thus, using data collected in the field and secondary meteorological data, simulations were performed for the base line year (2022) and for a projected scenario (2052) to compare the effects of vegetation over time. The simulation results suggest that the introduction of trees in industrial areas has the potential to double pollutant removal and annual CO_2 uptake and increase storage by approximately 40%. For the hourly CO_2 flux, it is estimated that carbon uptake can be increased by up to 200%. Considering the use of these two software, i-Tree provides global annual and monthly analyses from a simpler and accessible interface, while ENVI-met allows the hourly simulation of each day from a more complex and robust system, providing more detailed results. Although results lack full validation, the use of these two software provide relevant decision-making support information and may help to foster urban greening strategies.

1 Introduction

Associated with urban growth and economic development, the installation of industrial zones may generate negative environmental impacts, such as air pollution. The emission of toxic and/or pollutant gases, from the industrial production process, is a recurrent environmental liability controlled by specific air quality legislation. However, even with this emission control backed by laws, there are still adverse effects on human health, such as respiratory infections, lung diseases and cardiovascular problems [1, 2].

According to the European Environment Agency (EEA), in 2019, 307,000 persons died prematurely in Europe from exposure to pollutants and fine particles, and at least 58% of these deaths could have been avoided if emission levels were lower [3]. In addition to problems related to human health, gas emissions by industries also interfere with the climate, as some of their waste gases, such as carbon dioxide (CO_2) for example, are considered Greenhouse Gases (GHGs), which in turn contribute to Global Warming [1, 4].

Besides the relationship with the global climate, industries interfere directly in the urban climate of the region and in the microclimate of the area where they are installed [5]. Being located mainly close to large urban centres, in places with limited presence of natural green areas, many buildings and a constant flow of vehicles, make the microclimate of such territories warmer with an increase in the levels of atmospheric pollutants [6].

One way to mitigate the effects of industrial areas on urban climate and microclimate is through the implementation of Nature-Based Solutions (NBS), which are interventions that foster ecosystem restoration and conservation, climate adaptation services and control of impacts of anthropic actions using solutions inspired by natural resources [7, 8]. The benefits arising from SBN implementation include the environmental, social, and economic perspectives, providing natural restoration, human well-being, and increased resilience for anthropogenic infrastructure systems [9].

One of the ways to measure and predict the benefits caused by SBNs is through microclimate modelling [10]. In this sense, two software, ENVI-met and i-Tree, both allow modelling and simulation of the benefits of vegetation in urban environments. ENVI-met is based on a holistic, three-dimensional microclimate model, and simulates the climatological interactions between

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surfaces, plants, and atmosphere [11]. iTree is a software package that provides tools for system analysis and the benefits of urban and rural forestry, quantifying the forest infrastructure and environmental benefits provided by trees [12].

Such software has been used for significant microclimate modelling, especially when there is a need to expose the effects of trees on atmospheric factors. This is demonstrated by Buccolieri et al. (2020) [13], who used both ENVI-met and i-Tree to perform microclimate modelling in a district in southern Italy. Simona et al. (2018) [14], on the other hand, used ENVI-met to model transpiration and leaf temperature of urban trees, in order to contrast with measured data. In addition, Pança (2021) [15], Pace (2020) [16], Costa, (2020) [17], Alves (2020) [18] and Simon (2016) [19] are among the several researchers who used ENVI-met or i-Tree as essential tools for their academic research, demonstrating the efficiency of these software for this type of analysis.

This research aimed to analyse the potential influence of Nature Based Solutions (NBS) in the industrial area of Bragança-PT, considering air quality, temperature, CO_2 absorption and storage, through microclimatic modelling and simulation, focusing on the benefits of urban vegetation, using ENVI-met and I-Tree.

2 Methodology

2.1 Study area

The focus of this work was an area of approximately 4.3 ha located in the industrial zone of the city of Bragança, in the northeast of Portugal. Such area is composed mainly by commerce and industries, having few green areas, with extensive paved areas and spaces of exposed soil. This area (Figure 1) received interventions within the framework of INTERREG POCTEP INDNATUR project, promoted by the University of Valladolid, which had the objective to rehabilitate industrial areas, aiming the adaptation to climate change and the improvement of life quality from nature-based solutions [20].

Fig. 1. Study area.

2.2 i-Tree tool

i-Tree software seeks to evaluate the benefits of ecosystem services generated by trees, is based on an inventory of trees to obtain the results. Therefore, in this study, a complete inventory of all trees present in the public spaces of the studied area was made, considering two mandatory primary variables: species name and diameter at breast height (DBH); and six secondary variables: land use, total height of the trees, height to the base of the crown, crown width, percentage of missing crown and exposure to light from the crown. Data collection in the field took place in July and October 2022.

As input variables for the simulation, information regarding the city location of the study area was collected, in addition to data from meteorological and atmospheric pollution stations in the vicinity. Such data was collected directly by the system from pre-defined cities and stations already registered in i-Tree. Therefore, there is no possibility of inserting such information into the project by the user. For this research, the closest meteorological and air pollution station to the study area was identified in Ourense, approximately 180 km from the study city.

The Forecast tool was also used, which allows simulating the evolution of the studied urban vegetation for a predetermined period. Table 1 shows the parameter values used to forecast the scenarios of this research.

Table 1. Parameters used in the Forecast function.

Basic parameters	Values
Expected number of years	30
Frost-free days per year	303
Basic annual mortality rate for healthy trees	1.0%
Basic annual mortality rate for diseased trees	5.0%
Basic annual mortality rate for dying trees	10.0%

2.2.1 i-Tree scenarios

Three distinct scenarios were considered in i-Tree. The first one (Scenario 0) refers to a hypothetical situation where there is no tree in the study area. In this sense, as the parameter inputs in the system refer only to trees, there was no simulation. The second scenario, Scenario 1, refers to the current situation with the presence of vegetation, mostly herbaceous in free plots. A forecast was also performed for this scenario, obtaining quantitative results regarding the possible ecosystem benefits that would be obtained if the area when kept unaltered.

Finally, the last scenario, Scenario 2, refers to a hypothetical situation where part of the study area would be converted into an urban park of approximately 1.9 hectares. Such a project was proposed for the purposes of this research, considering an area of the region that is not used and that could serve a better purpose. For this scenario, the addition of 124 tree specimens was considered, according to the proposed project, having each one of them the four parameters (species, DBH, land use, total height of the trees). The specimens chosen were based on species already existing in the area and on studies on urban forests, as done by Alegria (2018). The number of trees was the result of the construction of the proposed project design. For this situation, the forecast was also performed.

2.3 ENVI-met tool

ENVI-met is a software which requires a licence associated with a monetary cost. It allows the modelling and three-dimensional microclimatic simulation of an area from the definition of the elements that make up the place studied. Therefore, the characteristics of the terrain, buildings, vegetation, soil, and surfaces were collected and inserted in the model composition. Additional data inputs included meteorological and concentrations of atmospheric pollutants.

The model was built in 2D view from modules called Grids, in the size 5x5x1 meters for the plans X, Y and Z, respectively. The dimensions applied in the model were 74 grids for the X plan, 55 grids for the Y and 30 for the Z. In addition, the reference of the elevation level at sea level was set as 740 meters. The insertion of the elements that compose the urban grid was made in a segregated layer regarding buildings, vegetation (pre-defined by the system), and soil and surface.

The mandatory ENVI-met parameters refer to general information for the simulation, including date, start time, duration, and meteorological information. In this research, the simulation was performed for July 11, 2022, and July 11, 2052 (30-year forecast), starting at 00:00 and lasting for 25 hours. Regarding meteorological data, the values expressed in Table 2 were used, and were obtained from on-site measurements through simple meteorological stations fixed in the study area, which continuously measured the parameters below for seven months.

Table 2. Meteorological parameters used in ENVI-met.

Parameters	Values
Value and time of the maximum temperature	38,0 ºC and 15:00 h
Value and time of the minimum temperature	18,0 ºC and 06:00 h
Value and time of the maximum relative humidity	53,0 % and 06:00 h
Value and time of the minimum relative humidity	12,0 % and 17:00 h
Wind speed	2,7 m/s
Wind direction	270 º

Regarding the optional parameters, it was used the session referring to the atmospheric pollution. For this purpose, we chose to consider the standard background air pollutants, where concentrations were obtained from the i-Tree records: NO (0.0 μg/m³); NO_2 (2.0 μg/m³); O_3 (65.0 μg/m³); PM_{10} (3.0 μg/m³); $PM_{2.5}$ (1.0 μg/m³); and CO (249.0 μg/m³).

The time required for the simulations in ENVI-met is influenced by the size and resolution of the area being modelled, the running time set for the simulation, and the processing capacity of the computer. The average time taken to run each of the simulations in this research was approximately 30 hours. The results obtained are files that can be used to obtain 2D and 3D hourly thematic maps referring to different themes, and in this research, the atmosphere and vegetation data were used.

2.3.1 ENVI-met scenarios

As for i-Tree, three scenarios were considered for ENVI-met. Scenario 0, which represents the hypothetical situation where no trees exist in the study area, with a simulation of year 2022. In this case, all the other elements that composed the urban grid were represented, such as: concrete surface (grey); asphalt surface (black); grass cover from 25 to 50 cm (light green); unseeded frank sandy soil surface (brown); broken brick soil surface (orange); and finally, buildings (grey) being represented by the highest elevation elements. The 3D model obtained from this scenario is presented in Figure 2.

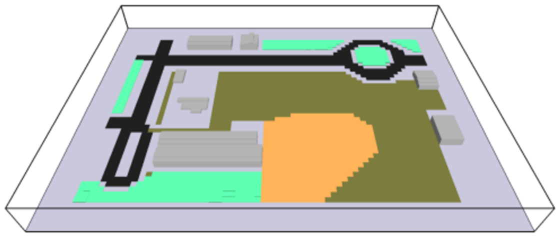

Fig. 2. Scenario 0 from ENVI-met.

The second scenario built, Scenario 1, in turn, is the most representative in terms of the current reality. It is basically composed of all the elements present in Scenario 0, with the addition of 58 3D plants that represent the arboreal specimens present in the study area, which are segregated into: 28 specimens of *Liquidambar styraciflua*; 12 specimens of *Quercus rubra*; 12 specimens of *Platanus occidentalis*; 2 specimens of *Celtis australis*; 2 specimens of *Liriodendron tulipifera*; 1 specimen of *Aesculus hippocastanum*; 1 specimen of *Zanthoxylum clava-herculis*.

The 3D model obtained from this scenario is presented in Figure 3. The same scenario was also used in the future simulations of 2052, however, attention was paid to the adaptation of the specimens indicated above, so that it represented trees in a more advanced stage of development.

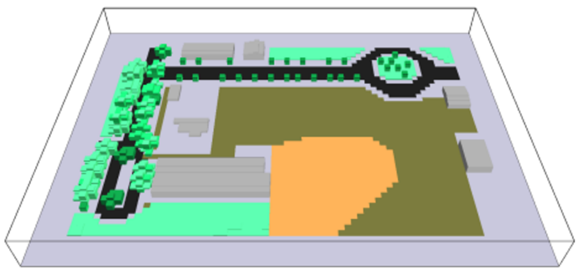

Fig. 3. Scenario 1 from ENVI-met.

Finally, the third scenario, Scenario 2, aggregates all the elements present in the previous scenarios, plus other resources necessary to the hypothetical situation of transformation of a vacant area into an urban park. For this, it was foreseen the insertion of a pedestrian pathways and 124 arboreal specimens including: 33 *Liquidambar styraciflua*; 19 *Cupressus macrocarpa*; 19 *Pinus strobus*; 6 *Liriodendro tulipifera*; 12 *Castanea sativa*; 7 *Acer saccharinum*; 9 *Quercus rubra*; 9 *Platanus occidentalis*; and 10 *Quercus robur*.

The aim of diversifying the species is to increase the biodiversity. Furthermore, this model was also used for forecasting simulations for 2052, paying attention to the issue of species development. The 3D model obtained from this scenario is presented in Figure 4.

Fig. 4. Scenario 2 from ENVI-met.

3 Results and discussions

3.1 i-Tree results

The i-Tree results were segregated into composition and structure, pollutant removal and CO_2 absorption and storage, making it possible to carry out a comparison between the scenarios studied in order to assess the benefits of SBN in each simulated year.

The input data of i-Tree consists only in the tree parameters, but as scenario 0 corresponds to a hypothetical situation of non-existence of trees, it was not possible to perform a simulation in the system. Therefore, the results obtained with i-Tree for this situation and for a future scenario are null, demonstrating a limitation of the system in not considering other elements that compose the environment.

3.1.1 Composition and structure

The system provides several results at the individual tree level and at the global level. Table 3 shows the overall results of the simulations in relation to three parameters chosen as relevant to the research.

Table 3. Overall i-Tree results on composition and structure.

Parameter	2022		2052	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Tree population	58 units	182 units	47 units	138 units
Leaf area	2009 m²	3471 m²	-	-
Leaf biomass	-	-	47.09 t	47.82 t

In a comparison between the two scenarios for the year 2022, it is noted that the increase in the number of trees also leads to an immediate increase of 73% in the foliar area of the study area. Regarding the year 2052, the system performs the prediction of the tree population considering the mortality of trees. In addition, it was noted that the overall leaf biomass increased (219%) due to the evolution of specimens that were considered young in 2022.

3.1.2 Pollutant removal

The results obtained by i-Tree regarding this parameter were based on pollution data available from the nearest registered meteorological station (in this case located in Ourense, approximately 180 km from Bragança). The system estimates such removals considering different methodologies, references, and models for the different types of pollutants considered in the analysis. Table 4 presents the general results for each year and simulated scenario.

Table 4. Overall i-Tree results on pollutant removal.

Parameter	2022		2052	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Pollutant removal	2.6 Kg/year	5.2 Kg/year	167 Kg (in 30 years)	329 Kg (in 30 years)
Associated value	1.14 €/year	2.20 €/year	72,13 €	138,86 €

The analysed removed pollutants include ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), $PM_{2.5}$ and PM_{10}, which are substances that can be harmful to human health, in addition to volatile organic compounds (VOC) that are emitted by plants and are precursors of tropospheric ozone, which leads to the increase of this pollutant in the atmosphere.

It is noted that, in general terms, the simulations indicated that for the year 2022, the implementation of SBN can generate an immediate increase of 98.9% in the removal of annual pollutants. For the year 2052, this value increases to 118.3%.

In absolute quantitative terms, O_3 is the pollutant most removed by trees, followed by PM_{10}, both for the year 2022 and 2052. However, comparing the removal of pollutants between the two scenarios, it is noted that for 2022 $PM_{2.5}$ was proportionally the pollutant most absorbed proportionally, while for 2052 it was PM_{10}, with the removal of particles occurring mainly through deposition on leaves.

3.1.3 Absorption and storage of CO_2

The absorption of CO_2 takes place from new growth of the plant each year or through photosynthesis. The amount of carbon dioxide sequestered depends on the health and size of the plant specimen. Table 5 and 6 presents the general results of this theme for each simulated scenario and year.

Table 5. Overall results of i-Tree on CO_2 absorption.

Parameter	2022		2052	
	Scenario 1	Scenari o 2	Scenari o 1	Scenari o 2
Absorption of CO_2 equivalent	510 Kg/year	1000 Kg/year	84.3 t	91.5 t
Associated value	22.48 €/year	43.34 €/year	-	-

Table 6. Overall results of i-Tree on CO_2 storage.

Parameter	2022		2052	
	Scenario 1	Scenari o 2	Scenari o 1	Scenari o 2
Storage CO_2 equivalent	4.800 Kg	6.900 Kg	88.9 t (in 30 years)	89.5 t (in 30 years)
Associated value	204,33 €	300,94 €	-	-

Comparing the two scenarios for the year 2022, it was estimated that the increment of trees in the study area can increase 94% of carbon absorption and 47% in carbon storage. For the scenario foreseen for 2052, these numbers are not as expressive, but still indicate an increase in relation to the two parameters.

3.2 ENVI-met results

In order to relate with the results obtained by i-Tree, the CO_2 flux of the plants (mg/m².s) was evaluated. In addition, the temperature (ºC) was also analysed, as such variable is a good indication of the cooling effects of vegetation. In terms of air pollution, a limitation of ENVI-met is that specific results on this topic are only available from the insertion of a pollutant source in the model construction, i.e., when a source of pollutant emission is added directly in the model area. Only the insertion of background pollutants, as was done, does not result in specific maps and does not allow a more in-depth analysis of this topic.

The results obtained from the ENVI-met simulations provide hourly thematic maps. Therefore, the maps for the three scenarios were analysed at 15:00, as this is the time of expected higher temperatures, broken down by parameter and by year.

3.2.1 CO_2 flux plants

Plants, in general, absorb CO_2 from the atmosphere during the process of photosynthesis, which occurs during the day, and emit it during the night in the process of respiration. In this sense, the CO_2 flux balance can be represented with a negative sign when it comes to absorption of carbon dioxide, and positive when it comes to emission of this gas [14].

The maps obtained from ENVI-met can be seen in Figures 5, 6 and 7.

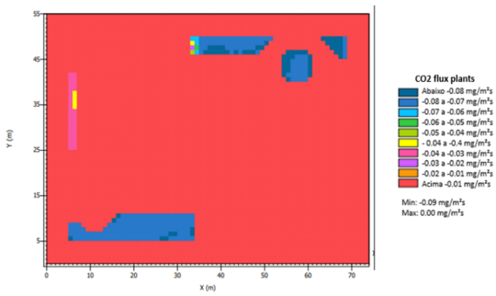

Fig. 5. CO_2 flux plants for scenario 0 in 2022.

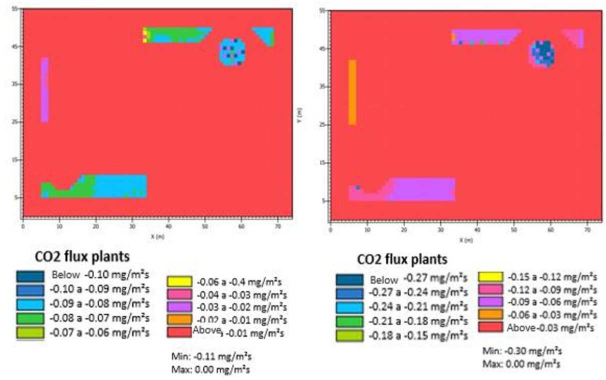

Fig. 6. CO_2 flux plants for scenario 1 in 2022 and 2052, respectively.

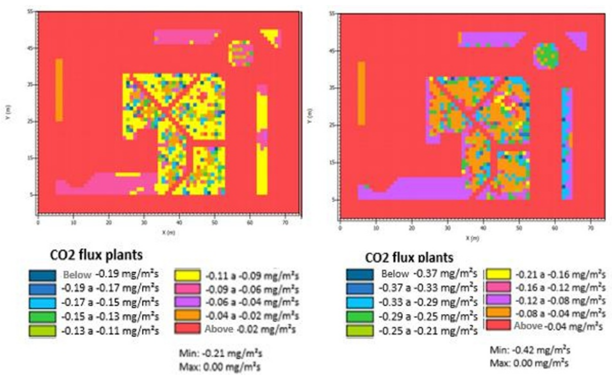

Fig. 7. CO_2 flux plants for scenario 2 in 2022 and 2052, respectively.

From the areas and the average CO_2 flux values of each colour indicated on the map, it was possible to obtain an hourly CO_2 uptake result for each scenario. The results are presented in Table 7.

Table 7. ENVI-met CO_2 absorption results.

Scenario	Absorption of CO_2	
	2022	2052
Scenario 0	2.81 Kg/h	-
Scenario 1	2.73 Kg/h	4.85 Kg/h
Scenario 2	9.00 Kg/h	13.85 Kg/h

The hourly absorption of CO_2 in the scenarios is mainly related to the grassed areas and the arboreal specimens. For the year 2022 it can be noted that when comparing the absorption between scenario 0 and scenario 1 there was a small difference, which could be explained by the fact that trees in the study area were very young. However, between scenarios 1 and 2, an increase of approximately 230% in the immediate absorption of CO_2 is observed, as a consequence of the insertion of trees in the model. For the year 2052, it is also noted the general increase in the hourly absorption of CO_2 from the development of trees.

3.2.2 Temperature

The Figures 8, 9 and 10 show the thematic maps of the three scenarios in the two simulated years.

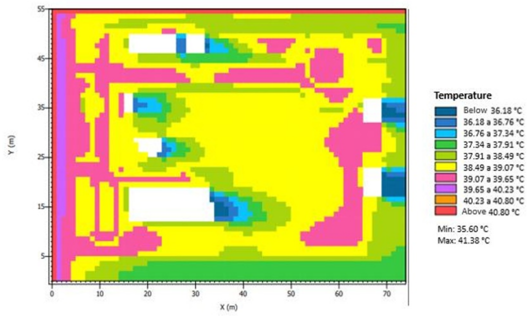

Fig. 8. Temperature for scenario 0 in 2022.

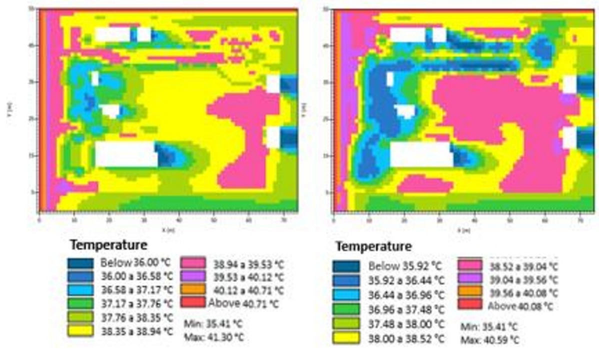

Fig. 9. Temperature for scenario 1 in 2022 and 2052, respectively.

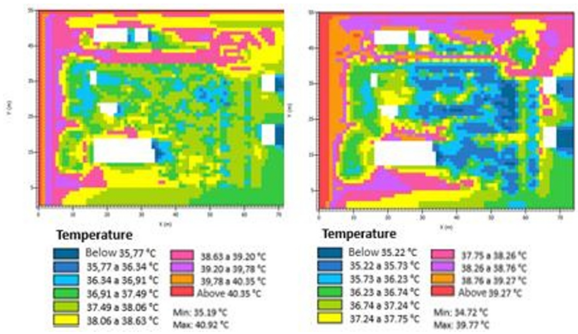

Fig. 10. Temperature for scenario 2 in 2022 and 2052, respectively.

From observation of the thematic maps of temperature, it was possible to note the clear increase of cooler areas where vegetation was present, in addition, it was also obtained the averages of minimum and maximum temperatures of each scenario for comparison purposes. The results are presented in Table 8.

Table 8. Results of maximum and minimum temperatures by ENVI-met.

Scenario	2022		2052	
	T min	T max	T min	T max
Scenario 0	35.89 °C	39.36 °C	-	-
Scenario 1	35.71 °C	39.24 °C	35.67 °C	38.78 °C
Scenario 2	35.48 °C	38.35 °C	34.97 °C	38.51 °C

With the analysis of the data presented above it is noted that the maximum and minimum temperatures decrease from the insertion of SBN. The values are also influenced by the degree of development of the trees, showing that more developed plants can further influence the cooling of the local temperature. It is noteworthy that the values studied were for the time of highest temperature and with high incidence of sunlight, representing a time of greatest stress in the environment.

3.3 Comparison between i-Tree and ENVI-met

The software used in this study were chosen due to the similarity air quality results provided. The quantitative comparison of the results obtained by the systems used is possible but requires further data processing by ENVI-met. Although the results are similar, the methodologies of the two systems are not compatible, so the comparison shown in Table 9 mainly involves the application and the general characteristics of the two software.

Table 9. Comparison between i-Tree and ENVI-me [11, 12].

	i-Tree	ENVI-met
What it simulates	Ecosystem benefits of trees	Microclimate, pollutant dispersion, solar analysis, building physics, thermal comfort, humidity, and wind flow.
Context of analysis	Trees in urban and rural areas	Mainly three-dimensional urban context
Price	Free	Licences from € 290.00 to € 2,900.00 (free demo version)
Level of difficulty	Easy to use, simple and affordable	Complex, more robust and more difficult
Type of results	Quantitative data in the form of reports, graphs and tables	Quantitative in the form of thematic maps thematic maps
Characteristics of the results	Simple, global and direct	Complex and specific
Temporal analysis	Dynamic model where elements evolve with time	Static model where elements do not undergo temporal changes. Evolution requires the definition of new scenarios.

3.4 Data validation

Data validation of a simulation is important to verify the veracity and reliability of the simulated results. For the i-Tree software, data validation for this research was not feasible, since the meteorological data used in the simulation was collected from a meteorological station far from the city of Bragança.

As for ENVI-met, the only simulation that could be validated is the one referring to Scenario 1 in the year 2022. As temperature data were collected on site with a sensor located in the centre of the study area, the average value of air temperature collected in the field for the day 11/07/2022 at 15:00 was compared with the value simulated by the software on the same day and time.

The sensor is located mainly in the yellow colour zone, which corresponds to a maximum temperature of 38.94 ºC. On the other hand, the measured data for the time interval of 15:00 on 07/11/2022 reached a temperature of 38.36 ºC. Comparing such values, it is noted the proximity between the two, with a deviation of less than 1 ºC, being this a high level of accuracy, and can be considered a model representative of reality.

4 Conclusion

From this research it was possible to expect that the introduction of nature-based solutions, more specifically trees, is advantageous in terms of air quality. This was proven with the quantitative simulated results obtained with i-Tree and ENVI-met.

The degree of development of the tree population proved to be a determining factor in the quantitative simulations for pollutants removal, CO_2 absorbed and stored, and air temperature. Thus, the importance of future temporal analysis of the vegetation is emphasized when aiming to measure the ecosystemic benefits generated by trees.

Although it is remarkable the environmental advantages of scenario 2, which involves the implementation of a functional green area, this is a project that would require a certain investment. Considering that the area would have to be acquired by the public authority and revitalized, it is estimated that approximately 400,000 euros of investment would be required (considering market research for the value of the land, tree seedlings and equipment to be deployed). Although this is a relatively high amount, in the long run the benefits for the population would be of great value.

After working with both software, we conclude that i-Tree is a simpler tool, more accessible to the civil society and is indicated to obtain more global results for a certain area. However, as it does not consider the whole range of complexity that makes up an urban environment, it may result in under or overestimated values.

ENVI-met, on the other hand, is a holistic software package aimed at 3D microclimate modelling limited urban environments. It requires additional technical knowledge and is indicated for more local specific, and individualized analyses, with several parameters available for complex and robust simulation. However, it does not perform forecasts, and for that it is necessary to adapt and build additional 3D models, which are more time consuming.

Both systems have advantages and limitations, and the use of each one will depend on the objectives to be achieved and the availability of primary data. Both tools can and should be used for decision-making in SBN related interventions, as both provide estimates of the environmental performance of a given intervention considering different scenarios.

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