



Street design scenarios using vegetation for sustainable thermal comfort in Erzurum, Turkey

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Abstract

Urbanization models that do not comply with the planning criteria are affecting human lives. In urban areas, street trees have positive contributions to the ecosystem and human thermal comfort. In this study, the thermal comfort of the main streets that connect people to each other and provide access and transportation has been thermally explored. Cumhuriyet Street, which is one of the vibrant streets in Erzurum, was selected as a case study scenario in the winter and summer periods in 2018 by using the ENVI-met V. 4.4.2 winter model. A different green scenario is proposed, and the best thermal comfort scenario in both seasons is determined. The results show that, in the summer period, the air temperature of the greener street scenario is about 1.0 °C cooler than the existing condition and about 2.0 °C warmer in the winter period. Physiological equivalent temperature (PET) value was better in narrow canyon streets in winter months, but in wide canyon streets in summer months. The green scenarios of wide canyon streets positively affect the outdoor thermal comfort in both seasons. These results clearly imply that green streets are an appropriate strategy for city streets that suffer from discomfort levels in cold winter and hot summer periods. It has been concluded that it is possible to increase thermal comfort through improvement in the open space in street and more suitable plant preferences for livable urbanization. Planning streets in a new city characterized by summer and winter seasons should take into consideration an accurate decision for providing a thermal comfort level and healthy urbanization.

Keywords Outdoor thermal comfort · Street design · Green scenario · Winter cities · ENVI-met

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Introduction

Today, it is well known that the most intensively used areas in the cities are transportation axes. But, it is also commonly accepted that urban open green spaces and street trees have positive effects in reducing the negative effects in the cities and in improving the thermal comfort of the site. One of the biggest urban planning difficulties in the future is to develop and protect cities as livable and sustainable places and to offer urban areas of the same quality to the growing population. For people living in cities, good quality of life largely depends on the quality and naturalness of the urban environment.

Urban canyon in the city is typically defined with the shape of a simple rectangle, commonly used for urban climate studies such as thermal comfort, wind flow, and air pollution (Oke 1988; Arnfield 2003; Mochida and Lun 2008; Salata et al. 2017). It was emphasized that

urban canyons have an important effect on outdoor thermal comfort, and building heights and densities should be taken into consideration in urban planning (Chokhachian et al. 2020). The characteristic of a street canyon is determined by the width of the road and by the length and the floor heights of the surrounding buildings. Falasca et al. (2019) stated that the sky visibility rate, street canyon, and wind movement affect thermal comfort. Street corridors are connected to intersections such as parks, schools, city centers, shopping centers, and other pedestrian roads (Lerman et al. 2014). In general, pedestrian corridors are also defined as streets that connect areas within the city center or city center to central residential areas (Delso et al. 2017). Outdoor spaces that constitute the urban environment are different from interior spaces; an individual walking on the pedestrian path is affected by solar radiation, which affects the thermal comfort level of humans (Xie et al. 2018).

It was reported that increasing the average height of the buildings (aspect ratio), blocking solar radiation, and ensuring shading can contribute to improving the thermal environment (Pearlmutter et al. 2007; Cao et al. 2015; Chokhachian et al. 2020; Ma et al. 2020).

In most studies, all these parameters are discussed separately, and no basic comparative evaluation is made for urban design. Studies are conducted on geometric features of streets such as aspect ratios, street orientation, thermal comfort, energy flow, and wind area (Ali-Toudert and Mayer 2007; Andrade and Alcoforado 2008; Chen et al. 2012; Bottillo et al. 2014; Yilmaz et al. 2018a; Mutlu et al. 2018). Cooling benefits of urban vegetation in summers period are widely examined in city trees, city parks, green roofs, and building facades (Tsoka et al. 2017, 2018; Yilmaz et al. 2018b; Gómez et al. 2018; Josephine et al. 2019). Other studies are generally conducted on structural coating materials based on their physical properties (Yilmaz et al. 2016; Djekic et al. 2018; Maharroof et al. 2020). Different hardened, ground materials used for summer and winter on the sidewalks, and the effects on thermal comfort were also examined (Rosso et al. 2018). In addition, these studies consider more than one parameter affecting the thermal comfort. Most of these parameters focus on urban geometry along with trees, green roofs, and surface albedo (Emmanuel et al. 2007; Alexandri and Jones 2008; Shashua-Bar et al. 2012; Ma et al. 2020). ENVI-met model analysis was performed on the street canyon formed by street width and building heights to investigate the thermal comfort effect. It has been determined that street canyons with high asymmetrical aspect ratios cool the environment in summer (Qaid and Ossen 2015).

Research confirms that vegetation can improve environmental temperature, humidity, radiation, and recreation (Ozhanci et al. 2014; Gómez et al. 2018). Although vegetation will block solar radiation, the air temperature will not be considerably affected because of wind circulation, but mean radiant temperature will be noticeably decreased. Moreover, the size and type of vegetation will affect air temperature. Sometimes, vegetation can increase the air temperature (Park et al. 2012; Josephine et al. 2019). In addition, the vegetation will prevent the spread of long-wave radiation from the ground to the sky. This feature improves the thermal stability of the vegetated area. Meanwhile, the vegetation releases water through the leaves through perspiration, thereby increasing the humidity in their immediate environment (Svensson et al. 2003; Ng and Cheng 2012; Yang et al. 2018; Irmak et al. 2018). In addition, trees can mitigate heat stress in urban areas through shade and give a cooling effect through a natural evapotranspiration process (Mayer et al. 2009; Bowler et al. 2010; Shashua-Bar et al. 2011; Srivani and Hokao 2013). The sweat rate is positively correlated with the cooling rate of the air, and less intensive cooling in a non-vegetative reference region shows that tree sweating contributes to cooling shortly after sunset. This shows that the cooling effect is high during night hours (Konarska et al. 2016).

Trees play a vital role in urban environments. In addition, trees have esthetic benefits and other vegetation helps to alleviate the effects of the urban heat island by reducing the heat flow leading to increased heat flow through evapotranspiration and low air temperatures (Anyanwu and Kanu 2006; Tan et al. 2016). In terms of air temperature studies, cool places are closely linked to much vegetation (Lindén 2011; Middel et al. 2012; Alavipanah et al. 2015; Fan et al. 2015; Norton et al. 2015). Harlan et al. (2006) show that increased urban vegetation is strongly associated with improved thermal comfort conditions, especially during heatwaves. Increasing vegetation in cities is therefore one of the key approaches in reducing both air and heat radiations (Bowler et al. 2010; Norton et al. 2015; Simon et al. 2018).

In winter, people need to relax and breathe outdoors. In order to perform this action, thermal comfort improvement works must be done in outdoor streets. However, studies on this subject are very limited (Zhang et al. 2018; Yang et al. 2018; Mutlu et al. 2018; Ma et al. 2020). In summer, the factors affecting thermal comfort are different than those in winter. Perceptions about environmental features such as trees and water bodies in urban parks are effective in the assessment of thermal comfort in summer rather than

in winter. The difference is probably due to the fact that people prefer to have more trees and water bodies in the summer time. In terms of outdoor thermal comfort, trees can provide a cooling effect and shade to reduce sunlight, thus providing a cooling effect during the hot summer months (Shashua-Bar et al. 2011; Klemm et al. 2015; Yilmaz et al. 2019). In contrast, people prefer less cooling in winter and more solar radiation. For example, changes in air temperature and thermal sensation cause more changes in thermal comfort in summer than in winter (Chan and Chau 2019).

In urban areas, livability has become the center of almost all studies in recent years. Although the term urban viability is widely used today, it often lacks an exact meaning (Fu et al. 2019). Kashef (2016) summarizes three different aspects of urban viability research (design, planning, and global ranking surveys) and advocates an interdisciplinary understanding that potentially evaluates all aspects of urban viability. Although these recommendations are conceptually attractive, they often lack practical applicability. Urban planners and other urban scientists have carefully considered the viability of cities as a balanced and harmonious economic mode such as economic, social, cultural, land use, and environmental developments in cities (Flores et al. 1998; Asgarzadeh et al. 2012; Liu et al. 2014; Kazemi et al. 2018). A livable city is a place that provides adequate and well-livable conditions (both natural and cultural) in urban planning and land use. A livable city is also a city with reasonable land use models that meet the material and spiritual life needs of residents (Dumbaugh and Gattis 2005; Chen et al. 2016; Liu et al. 2014) and support the long-term development needs of both the city and its inhabitants.

Erzurum, the largest city in the Eastern Anatolia Region in Turkey, has a dense population with increasing vehicle traffic. Thus, crowded sidewalks and roadways have had a negative effect on people. It is very important that people walk safely in the city streets and feel more comfortable in terms of thermal comfort. For this purpose, Erzurum City Center was chosen as the most frequently used street working area over all four seasons. The Köppen-Geiger climate classification, developed by Wladimir Petrovich Köppen (Köppen 1918) and improved by Rudolf Geiger, is one of the most widely used classification systems. Turkey has three of the five main climate types represented in the Köppen-Geiger classification system. Erzurum Province is located in the main climate class (D class; cold, humid, middle-latitude/terrestrial dilemma) (Öztürk et al. 2017). Winter months are quite cold in Erzurum, which is categorized as “cold winter city” according to Köppen climate criteria.

The aim of this research is to examine the thermal comfort effect of plants, namely by adding trees to the streets. This study helps to improve the outdoor thermal comfort in the stage of the urban planning and landscape street design for a more livable effective city. People do not want to go out unless they have an urgent need to do so. Therefore, the purpose of the study is to develop landscape design scenarios for people to travel comfortably in summer and winter without being disturbed by the cold and the heat. How can outdoor thermal comfort be improved on pedestrian paths and streets? Do trees contribute to the improvement of outdoor thermal comfort? Again, does the sky view factor (SVF), which shows the road width-to-floor height ratio in the street canyon, have an effect? The answers to the questions were attempted to be investigated. In the open space here, it is aimed to determine how deciduous trees affect the thermal comfort of the street. Accordingly, for best results, it is important to transfer the design into the planning decisions.

Methodology

Case study

Erzurum City is geographically located at latitude 39° 57' 23" North and 41° 10' 12" East. Cumhuriyet Street, the busiest and most intense main street of the city, was preferred to represent Erzurum streets. This is because this street is the place that the local people most commonly use. The current street has not been diverted, but the vegetative design is intended to change thermal comfort positively in summer and winter. Birch (*Betula* spp.) was used in simulations to determine the effect of planted street on outdoor thermal comfort. This tree grows naturally in the city and adapts to the ambient conditions.

Features of selected streets and climate condition

Turkey's most violent climate takes place in this region. The springs are rainy, summers are hot and dry, and winters are cold and snowy. The average annual temperature is 5.7 °C, and the coldest month average is -8.4 °C. The hottest month average is 18.8 °C. During approximately 220 days of the year, the average temperature remains below 8.0 °C. The average annual rainfall is recorded as 432 mm, and the rainfall is irregular. The relative humidity is 60.3% (MGM 2018). Especially in winter, it has intense air pollution, while the effect of hot air with short-wave sun rays is seen in summer. Long-term climate data for the case study area were obtained from the Meteorology Regional Directorate Station (1929–2018). Average climate values for these years are also given in Table 1. The presence of pedestrian-friendly streets plays an important role in living criteria. It is particularly important that

Table 1 Climate data for Erzurum (MGM 2018)

Erzurum	Average						Highest temperature (°C)	Lowest temperature (°C)
	Temperature (°C)	Highest temperature (°C)	Lowest temperature (°C)	Sun time (h)	Rainy days	Monthly total rainfall (mm)		
January	-9.2	-4.0	-14.0	3.2	11.3	22.5	8.0	-36.0
February	-7.7	-2.4	-12.6	4.4	11.1	26.8	10.6	-37.0
March	-2.4	2.6	-7.1	5.1	12.4	34.9	21.4	-33.2
April	5.4	10.9	0.0	6.3	13.7	53.0	26.5	-22.4
May	10.7	16.8	4.4	7.9	16.2	73.8	29.6	-7.1
June	14.9	21.7	7.3	10.2	11.0	49.0	32.2	-5.6
July	19.3	26.5	11.2	11.2	6.7	26.6	35.6	-1.8
August	19.5	27.2	11.2	10.7	5.2	17.7	36.5	-1.1
September	14.7	22.6	6.5	9.0	5.2	23.5	33.3	-6.8
October	8.1	15.1	1.8	6.8	9.7	48.3	27.0	-14.1
November	1.0	6.8	-3.7	4.8	9.3	33.1	20.7	-34.3
December	-5.9	-1.0	-10.3	3.1	10.7	22.8	14.0	-37.2
Annual	5.7	11.9	-0.4	82.7	122.5	432.0	36.5	-37.2

The measurement period is 1929–2018

streets and pavements have the desired technical equipment as well as thermal comfort values for pedestrian-friendly transport.

Cumhuriyet Street is the main road people have been using intensively since the beginning of the 1900s. This

leads to both heavy traffic and pedestrian circulation. Two points with different features are identified on the same street. These determined points are named as “street 1” and “street 2.” Two areas with different characteristics were selected on the main street passing through the city center.

Fig. 1 The current environmental status of street 1 and street 2 areas in Erzurum

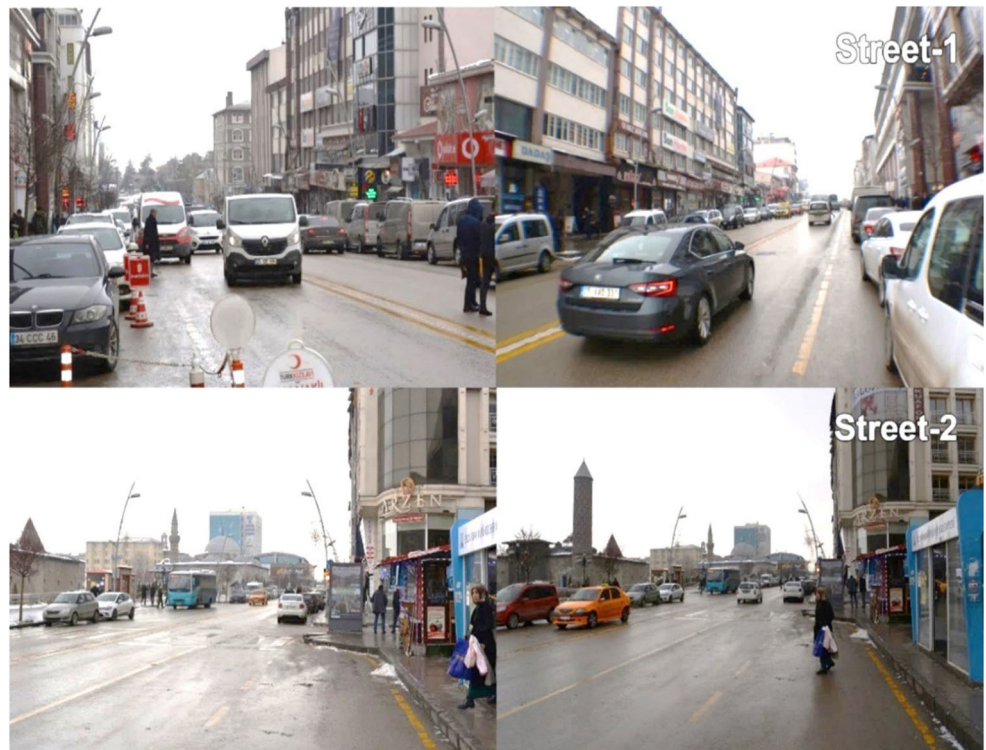
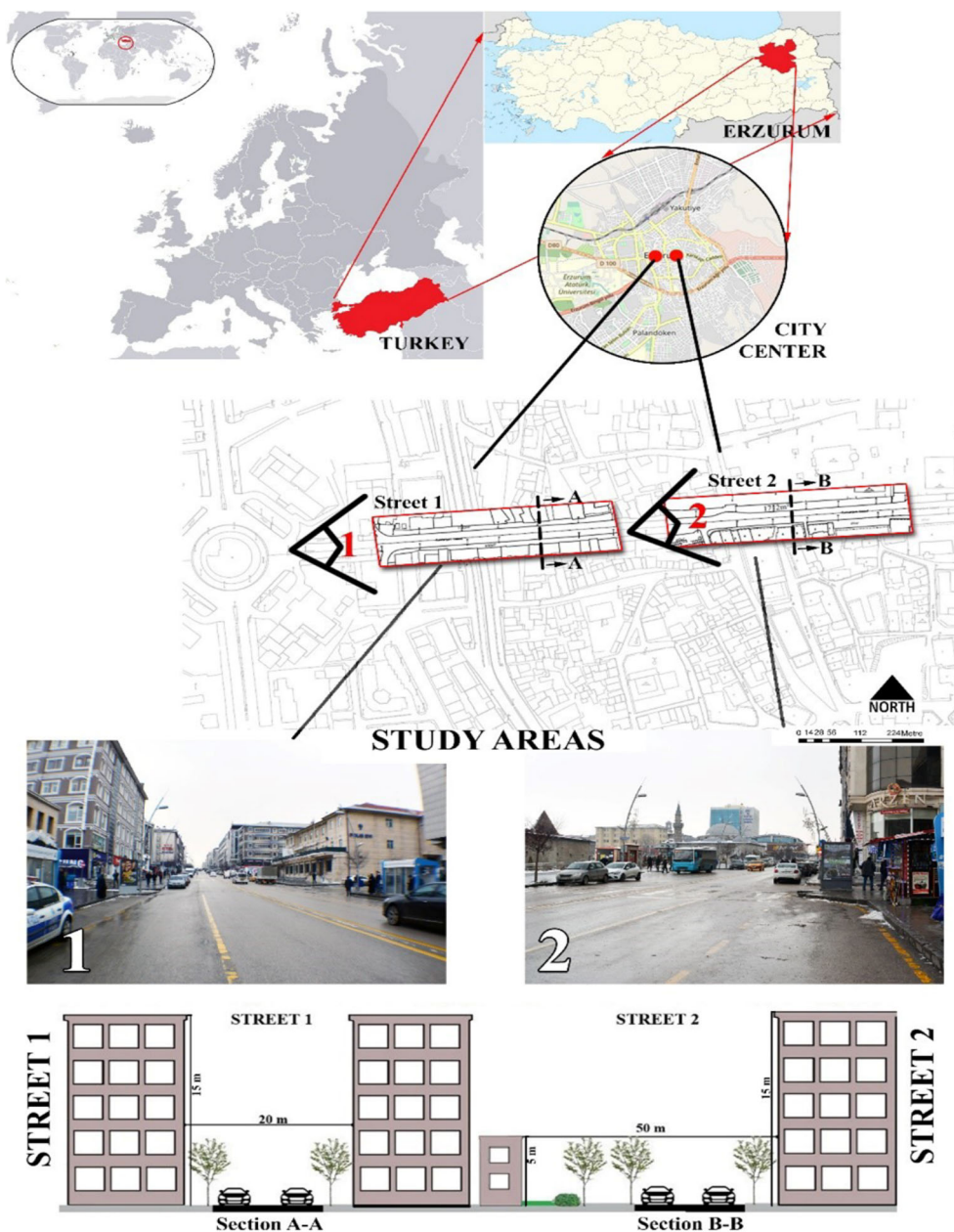


Fig. 2 Locations of street 1 and street 2 areas in Erzurum



In the area, the coordinates of street 1 are $39^{\circ} 54' 20.65''$ N– $41^{\circ} 16' 10.91''$ E and those of street 2 are $39^{\circ} 54' 21.47''$ N– $41^{\circ} 16' 19.25''$ E. Street 1 and street 2 are in the east-west direction. Since the main street is located in this direction and there is a low possibility for changing the direction of the road in this area, different alternatives have not been tried. There are madrasas, parks, shopping centers, and shops around the street. Sidewalk is available on both sides of the street (Fig. 1). Preferred stations for study location and analysis (Fig. 2) are street 1 and street 2.

Street 1

It is defined as the area with approximately 2–5 story buildings on both sides. The width of the street was measured as approximately 20 m. This street is narrower than street 2. There is a sidewalk on both sides of the street. There are ornamental trees along the street, but they are not the desired size yet with the age of 7–8 years.

Street 2

This street is wide. It is the area with a park and open green area on one side and 3–5 story buildings on the other. At this point in the street, the width reaches about 50 m. On the north of this street, there is a large area of pocket parking. It is united with the garden area of a historical building (Fig. 2).

Long-term climate data for the study area were obtained from the Meteorology Regional Directorate Station (1929–2018). Average climate values for these years are also given in Table 1.

Field measurement and collecting data

The microclimate data to be used in the ENVI-met V. 4.4.2 winter model was recorded with the meteorological station installed right on the street. Davis Vantage Pro2 device was used for measuring the meteorological data (Fig. 3). This device is used by Turkey's General Directorate of Meteorology, and the device is preferred because it can record detailed information.

For this purpose, the hottest and coldest months were preferred according to the data of the study area for many years (15 January 2018 and 15 August 2018). In these measurements, air temperature (°C), humidity (%), wind speed (m/s), and wind direction were recorded. Measurements were taken at a height of 1.5 m from the ground level. Microclimate data recorded for the 24-h winter and summer day measured by the device are provided.

SVF

People's thermal comfort in the outdoor environment will be affected by different street canyon parameters including aspect ratio SVF. In the street canyon, the aspect ratio (H/W)

expresses the ratio between the average height of the building and the street width (Oke 1988).

The SVF values were recorded in the hottest month and the coldest month to determine the thermal comfort in the street canyon and how the scenario affects outdoor thermal comfort in current street situation. These values were determined by coming to the middle of both streets, turning north and attaching the fisheye lens to the camera at a height of 1.0 m from the ground (Matzarakis and Matuschek 2011) (Fig. 3). The fisheye lens used for this purpose features RayPro 52 mm 0.25X ProHD FishEye + 12.5 Diopter Macro Lens. On both sides of the street, the SVF measurements were taken with a Nikon D5200 camera. Eye-level shots were made from the middle of the street by turning to the north in the area (fisheye lens + Nikon D5200). The SVF of street 1 and street 2 was analyzed by the RayMan Pro 2.1 computer model (Matzarakis et al. 1999; Yilmaz et al. 2018b). The results of this analysis include values between 0 and 1. When the sky view factor reaches 1, it means the proportion of sky reaches 100% in the sky hemisphere. In street 1, which has a narrow canyon feature, the SVF value is low, while in street 2, which has a wide canyon feature due to open area width, the SVF value is higher. *Physiological equivalent temperature* (PET) is a thermal comfort index produced in the heat balance of the human body (Höppe 1999). It is a personal and geographical event that does not remain constant in space and time. The RayMan model (Matzarakis et al. 1999; Mayer et al. 2009) simulates the flow of short- and long-wave radiations from a three-dimensional environment in simple and complex environments that can be transferred to a synthetic parameter, also called average radiant temperature (T_{mrt}). Maintaining the air temperature (T_a , °C), relative humidity (RH, %), wind speed (WV, m/s), and T_{mrt} produced by the RayMan Pro 2.1 model is considered the same as the index calculated by the PET program by Höppe (1999). The values in Table 2 include the values obtained by Matzarakis et al. (1999) based on an

Fig. 3 Meteorological station Davis Vantage Pro 2 and fisheye lens + Nikon Camera D5200



Table 2 PET value ranges (Matzarakis et al. 1999)

PET (°C)	Thermal sensitivity	Grade of physiological stress
> 4.0	Very cold	Extreme cold stress
4.1–8.0	Cold	Strong cold stress
8.1–13.0	Cool	Moderate cold stress
13.1–18.0	Slightly cool	Slightly cold stress
18.1–23.0	Neutral (comfortable)	No thermal stress
23.1–29.0	Slightly warm	Slightly heat stress
29.1–35.0	Warm	Moderate heat stress
35.1–41.0	Hot	Strong heat stress
> 41.0	Very hot	Extreme heat stress

average European man. PET evaluations in the study were calculated according to these standards. In addition to the PET, the study analyzes the predicted mean vote (PMV) and the mean radiant temperature (T_{mrt} , °C), and the data of these parameters were collected from the ENVI-met output data of the different street scenarios.

ENVI-met V. 4.4.2 winter soft model

The study aims to estimate the different proposed effects of microclimate street scenarios in summer and winter times using a numerical simulation. The model developed by Bruse (2017) is a prognostic non-hydrostatic model composed of a three-dimensional main model and one-dimensional atmospheric boundary layer model. ENVI-met is a high-resolution microclimate model, a grid-based climate model designed to simulate ground, façade, vegetation, and air relations in urban areas. Typical horizontal resolution ranges from 0.5 to 5 m and $90 \times 90 \times 30$, which enables near-accurate modeling of microclimatic parameters. Air temperature (T_a , °C), humidity (RH, %), wind speed (m/s), and wind direction simulate short and long radiation waves as well as pollutants in the air. ENVI-met has been used in many studies to evaluate urban settlements and microclimate condition ranges (Tsoka et al. 2018; Maharroof et al. 2020). Some of the parameters evaluated are simulations containing physical parameters related to plants. These physical parameters include sweating, evaporation, sensitive heat flowing from plant to air, and shading rate. In addition, the software is capable of examining heat and mass changes related to plants and other surfaces. An example of this is the amount of water the plant absorbs from the soil (Salata et al. 2016; Tsoka et al. 2018). The ENVI-met software used has a very high sensitivity in estimating the outdoor thermal environment. The model is a good choice for simulating the different scenarios of this study. However, the low tree type in the model is a disadvantage that should not be ignored, and which future models need to improve.

This would enable future studies to consider different types of trees (Ma et al. 2020).

This study uses the latest complete version of ENVI-met (V 4.4.2 Winter Beta). In order to validate the model, Cumhuriyet Street and the measurement data were used as input data for the ENVI-met model (Fig. 2; Tables 3 and 4). The layout of the area was developed based on a drawing provided by the Erzurum Municipality. The area domain in ENVI-met was as follows: $X = 90$, $Y = 90$, and $Z = 30$. This domain allows for the details of the existing condition objects to be indicated, with a grid cell size of $x = 1$ m, $y = 1$ m, and $z = 1$ m. The heights of the buildings and species of trees were obtained from field measurements. Trees and grass were selected from the database of the model as described in the following:

- AN/*Acer negundo* trees; height of 11 m, crown width of 9 m; used for the middle of the car road traffic islands
- B7/*Betula* spp. trees; height of 6 m, crown width of 7 m; used for pedestrian road
- XX/grass 50 cm aver, dense

Currently, there are asphalt road material and granite material on the pedestrian road. The pavement of streets (GS/granite pavement) and car road (ST/asphalt road) materials were selected from the model database to match existing conditions. The model was rotated out of the grid north by 0° to fit the existing direction of the street. Using values greater than 0.0–0.9 m/s caused a complete change in temperature. This low wind speed is acceptable in this city. The dominant wind direction changes in summer and winter, with the wind blowing from the east-south-east at 0.8 m/s (24 h average) in summer (ESE/112.5°) and from the south-east (SE/135°) at 0.1 m/s (24 h average) in winter. The data in Tables 3 and 4 for air temperature and humidity values were entered into the ENVI-met program on an hourly basis for summer and winter. The data height (1.5 m ground level) was extracted at the same height the measurement data was obtained. The winter simulation ran for 24 h on 15 January 2018 (Table 3) from 0:00 to 0:00, and in the summer on 15 August 2018 (Table 4) from 0:00 to 0:00. Different data were used for summer and winter evaluation.

Proposed street scenarios

Two different scenarios were applied to the two stations on the main street of the city. The first of the scenarios was prepared by adding a deciduous tree species on a middle refuge application on a street surrounded by structures on both sides. The second scenario is street with buildings on one side and parking area on the other side, but deciduous trees were added to the parking area. Both streets are in the same direction and are positioned as a continuation of each other. The plant used in the streets is given in Fig. 4. In these scenarios, based on the

Table 3 Meteorological data of 15 January 2018 (winter day)

Date	Time	Air temperature (°C)	Relative humidity (%)	Wind speed (m/s)	Wind direction
15.01.18	00:00	−2.7	93	0.0	–
15.01.18	1:00	−2.8	93	0.0	–
15.01.18	2:00	−3.2	93	0.0	–
15.01.18	3:00	−3.4	93	0.0	–
15.01.18	4:00	−3.9	92	0.0	–
15.01.18	5:00	−4.0	94	0.0	–
15.01.18	6:00	−3.8	94	0.0	–
15.01.18	7:00	−3.5	94	0.0	–
15.01.18	8:00	−3.3	92	0.0	–
15.01.18	9:00	−1.8	90	0.0	–
15.01.18	10:00	−1.0	84	0.0	ESE
15.01.18	11:00	−1.0	83	0.9	SE
15.01.18	12:00	−0.2	78	0.4	ESE
15.01.18	13:00	−0.1	73	0.4	SE
15.01.18	14:00	−0.3	71	0.4	NNW
15.01.18	15:00	−2.1	83	0.0	W
15.01.18	16:00	−2.8	85	0.0	NW
15.01.18	17:00	−3.6	87	0.0	–
15.01.18	18:00	−3.6	87	0.0	–
15.01.18	19:00	−4.0	86	0.0	–
15.01.18	20:00	−4.5	88	0.0	–
15.01.18	21:00	−4.9	87	0.0	–
15.01.18	22:00	−5.3	85	0.0	–
15.01.18	23:00	−4.9	86	0.0	–

Maximum and minimum values

current situation of street 1 and street 2, 43 deciduous trees were added to both. The number of 25 deciduous plants available on street 2 increased to 68. A deciduous plant was preferred for analysis. This is because scot pine, which is a plant with a coniferous and which grows in the city, prevents pedestrian circulation because it is branched from the bottom. At the same time, scotch pine causes icing in the shade areas in winter, while deciduous plants prevent icing because they allow sun permeability.

ENVI-met model validation

Accuracy analysis of this model was performed (Figs. 5 and 6). The air temperature (T_a , °C) is a significant factor that has been used to validate the model’s performance. Two statistical goodness-of-fit measurements were used to calibrate the observed (O) and the predicted (P) data of both streets for evaluating the model’s performance in winter and summer times. The statistical measurements used were the coefficient of determination (R^2) and the index of agreement (d). Studies have emphasized the usefulness of the index of agreement (d) for evaluating the model performance. The coefficient of determination (R^2) and the index of agreement (d) have values between 0 and 1. A

value of 1 or near 1 indicates that most of the input data are fitting or close to the regression line, whereas a value of 0 or near 0 indicates that most of the variation data is far from the regression line. As can be seen in Figs. 5 and 6 a and b, the values of R^2 and d are high, which represents a good fit value. At the same time, the scatter points do not fit the line and are scattered around the regression line in the positive and negative directions.

The residual plots, which are the distance of each scattered point from the regression line, are acceptable as it represents the small difference between the predicted value (P) and the observed value (O) in both directions. However, the difference between the predicted (P) and the observed (O) data is expected and occurs in many studies based on the simulation model including the ENVI-met model. In this context, higher R^2 value represents the differences between the observed (O) data and the predicted (P) data are smaller and unbiased. Unbiased values, known as the fitted values, are not systematically too high or too low. On the other hand, a higher value of d indicates that the degree of error in the prediction data is very low. The observed (O) and the predicted (P) air temperature in Fig. 5a and b indicates the R^2 for winter (0.81) and R^2 for summer (0.78) in street 1, and that in Fig. 6a and b indicates the $R^2 = 0.92$ for winter and $R^2 = 0.77$ for summer of street 2. The coefficient of

Table 4 Meteorological data of 15 August 2018 (summer day)

Date	Time	Air temperature (°C)	Relative humidity (%)	Wind speed (m/s)	Wind direction
15.08.18	00:00	16.6	63	1.3	ESE
15.08.18	1:00	16.4	65	0.9	N
15.08.18	2:00	16.1	66	0.9	ESE
15.08.18	3:00	15.6	68	0.4	ESE
15.08.18	4:00	15.4	68	0.9	ESE
15.08.18	5:00	15.0	69	1.3	ESE
15.08.18	6:00	15.2	71	1.3	ESE
15.08.18	7:00	16.4	67	1.3	ESE
15.08.18	8:00	17.3	65	1.8	ESE
15.08.18	9:00	19.0	60	1.3	ESE
15.08.18	10:00	20.9	54	1.3	ESE
15.08.18	11:00	21.8	51	1.3	ESE
15.08.18	12:00	23.2	48	1.3	SE
15.08.18	13:00	23.7	46	0.9	ESE
15.08.18	14:00	24.8	41	0.9	ESE
15.08.18	15:00	25.8	38	0.9	ESE
15.08.18	16:00	25.3	38	0.9	ESE
15.08.18	17:00	25.7	36	0.4	ESE
15.08.18	18:00	24.9	37	0.4	ESE
15.08.18	19:00	23.3	42	0.0	ESE
15.08.18	20:00	22.7	45	0.0	ESE
15.08.18	21:00	21.1	47	0.9	ESE
15.08.18	22:00	20.2	50	1.3	ESE
15.08.18	23:00	19.3	55	0.9	ESE

Maximum and minimum values

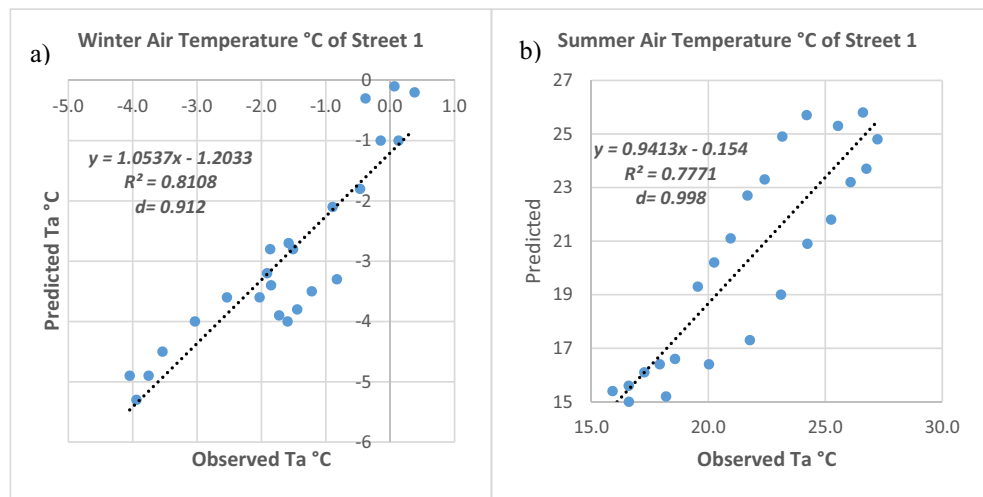
determination (R^2) for all streets in winter and summer times is slightly lower than 1, which means they are statistically significant. Additionally, the index of agreement (d) for street 1 is 0.91

and 0.99 for winter and summer, respectively. The index of agreement (d) for street 2 is 0.88 and 0.99 for winter and summer, respectively. All values are close to 1, which shows that the

Fig. 4 Deciduous birch tree used in streets (*Betula* spp.)



Fig. 5 a, b Observed (O) and predicted (P) air temperature for street 1. a Winter time. b Summer time



correlation is statistically significant, and the model performed perfectly. Based on these results, the software is well validated and the study can be run with this software output.

Result and analysis

Design criteria were determined in order to enable people to walk in thermal comfort spaces and pedestrian-friendly streets. Proposed design scenarios made by increasing the number of trees on the street were analyzed by computer models. It was tried to determine how the street, which has a narrow and wide canyon, affected thermal comfort.

SVF analysis

According to the results of the analysis in street 1, which has a narrow canyon feature, the SVF value is low, while in street 2, which has wide canyon feature due to open area width, the SVF value is higher (Fig. 7). In street 1, due to the narrow street and the surrounding structures, the SVF value was low

and showed a narrow canyon feature, whereas in the larger street 2 area, the SVF value was high and showed a wide canyon feature.

Street 1 shows a narrow canyon, but street 2 shows a wide canyon feature according to the SVF analysis. In the SVF images taken in the street 1 area, the SVF value was found to be 0.448. Due to the fact that there are building structures on both sides of the street, the openness ratio is low.

The SVF value in the middle of street 1 is low (0.448). This is because the street is a narrow canyon and surrounded by building structures on both sides, which led to decreases in the SVF value. In the proposed scenario, the SVF ratio was found to be 0.158 (Fig. 8).

Using the same methods, SVF analysis was performed on street 2. The SVF value obtained from the middle of the street was measured as 0.581. There are 3–5 story buildings on one side of the street and the other side is empty. SVF value is higher than street 1. The average SVF value was determined as 0.258 in the proposed scenario of street 2 (Fig. 9).

Fig. 6 a, b Observed (O) and predicted (P) air temperature for street 2. a Winter time. b Summer time

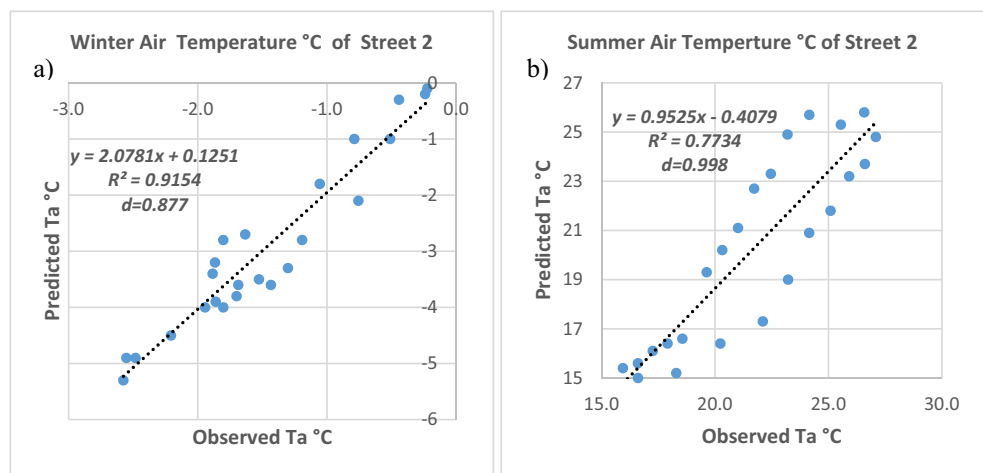
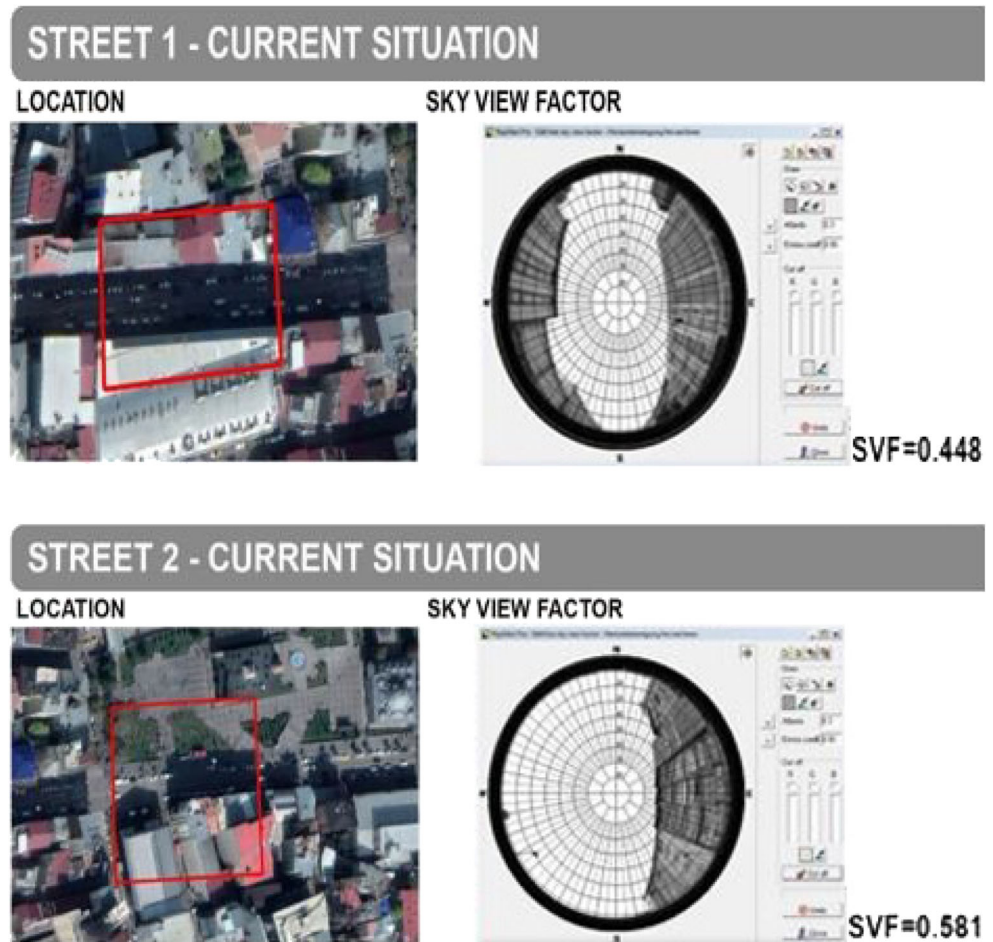


Fig. 7 Current sky view factor of street 1 and street 2 areas in Erzurum



PET analysis

In the ENVI-met model, while 24-h data were sufficient, 1-year data were recorded for PET. The data were recorded with the meteorology station (1.5 m above the ground) installed very close to the street (50 m). PET assessments in the study were conducted in 2018; the highest number of cold stressed days in Erzurum City Center is in January, and the highest number of hot stressed days is in June (Fig. 10). However, when evaluating the study area, the average temperature values between 1929 and 2018 were taken into consideration. Although the PET frequency graph prepared for the study is warmer in June, the values in Table 1 show that there is an exception in 2018. Therefore, evaluations for the study area were determined as January representing winter months and August representing summer months.

Erzurum City is mostly under the influence of cold weather (Fig. 10). The months with the highest PET value are usually July–August. January and December are the months when the thermal comfort values are lowest. According to this figure, in the city where there is a little hot stress in the summer, cold stress is observed intensely in the winter due to the frost. Frost is experienced due to the impact of the moisture created by excessive

snowfall. For this reason, it is very troublesome and difficult for people to spend time outdoors in winter or to walk on the roads.

Current and proposed street 1 and street 2 analysis

The ENVI-met model is often used to find factors affecting street canyon, urban heat island, and outdoor thermal comfort and to analyze the scenarios offered. Seventy-seven percent of the total number of ENVI-met studies has been published during the last 5 years (Tsoka et al. 2018). Efforts were made to determine the conditions under which Cumhuriyet Street has better thermal comfort.

The data used in the ENVI-met model are given in Table 5. The thermal comfort analysis of street 1 and street 2 in both their current situations and suggestion models were done. In the analysis of the current situation, the results of street 1 and street 2 were very similar. Because it was not possible to put a measuring device in the middle of the street and to measure 24 h for summer and winter, the measurements were taken from the station installed near the street. It was not possible to take this measurement from the middle of the heavily used street. Moreover, an increase in vehicle density together with urbanization constitutes negative impact on data obtained.

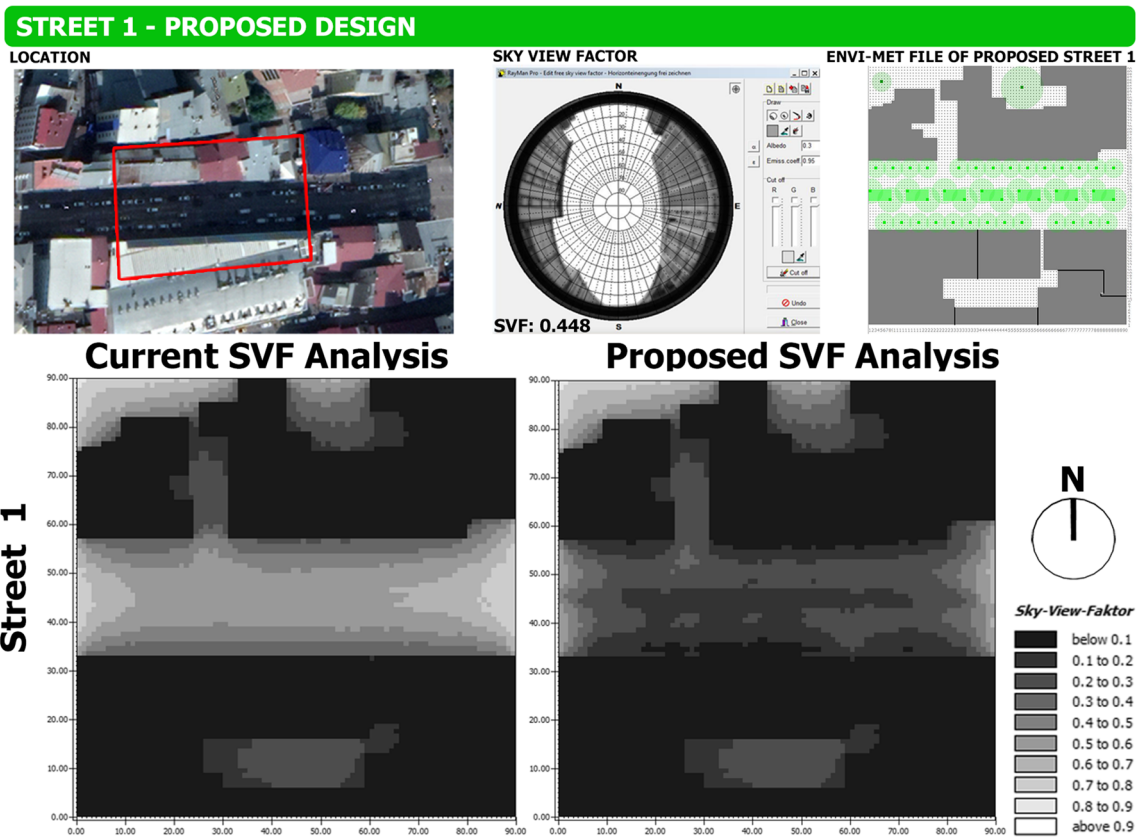


Fig. 8 SVF analysis of the current and proposed situation of street 1

Therefore, the results were similar to the current situation. The ENVI-met program allows for the analysis of weather conditions at a height of 1.5 m from the ground for subsequent assessments. However, the program analysis only covers the

boundary area and inside the drawing. Therefore, the factors outside the drawing are not included in the analysis. This is one of the disadvantages of the program.

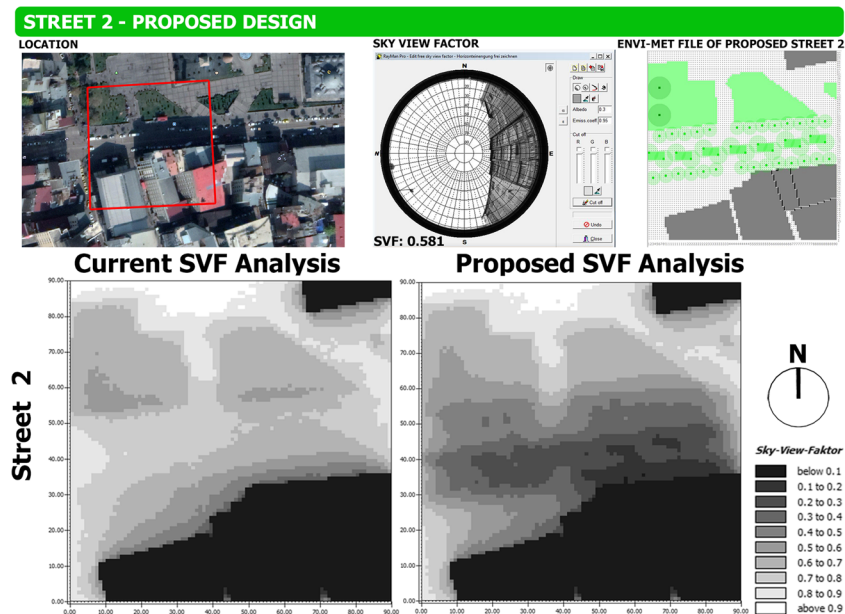
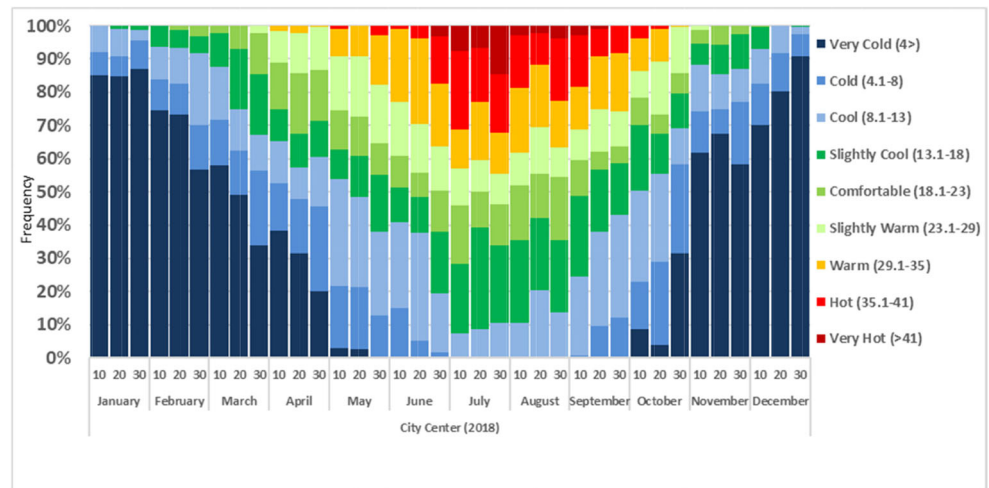


Fig. 9 SVF analysis of the current and proposed situations of street 2

Fig. 10 PET frequency graph of Erzurum City Center for 2018



According to the landscape designs, a maximum of 43 plants could be placed in the area. Similar scenarios created by using plants were used in different studies. In the ENVI-met sub-models, street and vegetation model also analyzed thermal comfort indices (Qaid et al. 2016; Bruse 2017; Tsoka et al. 2018). The ENVI-met program provides a great advantage in visual

materials for the evaluation of landscape designs made in the study area by applying them to the site.

The current state of the streets and the proposed scenarios with 43 added trees were compared for the thermal comfort of the environment. It was obtained that if the trees are used in the right places, they contribute positively to the thermal comfort of the environment (Table 6). Approximately 27% of the area became more thermally comfortable by thermal improvement. The maximum and minimum results of temperature analysis for the current situation and proposed scenarios are given in Table 6.

ENVI-met analysis for the suggestions and current situations of the streets was prepared separately for street 1 and street 2.

Table 5 Data used in the ENVI-met program

Location	Erzurum City Center
Climate type	Mountain ecosystem
Simulation period	Values
Total simulation duration	24 h for 1 landscape design
Spatial resolution	1 m × 1 m × 1 m
Domain size	80 m × 80 m × 30 m
Model rotation	0°
Date	15.01.2018/15.08.2018
Basic meteorological input	Unshaded
Wind speed (m/s)	15.01 (0.0)/15.08 (0.9)
Wind direction (°)	112.5°
Air temperature for 24 h	+ (simple forced)
Relative humidity for 24 h	+ (simple forced)
Lowest air temperature (°C)/h	15.01 (− 5.3/22:00)/15.08 (15.0/05:00)
Highest air temperature (°C)/h	15.01 (− 0.1/13:00)/15.08 (25.8/15:00)
Lowest humidity	15.01 (71%/14:00)/15.08 (36%/17:00)
Highest humidity	15.01 (94%/06:00)/15.08 (71%/06:00)
Sky condition	Clear
Information of designs	
Street 1 current	25-deciduous plant design
Street 2 current	25-deciduous plant design
Street 1 proposed design for summer and winter	43-deciduous plant design
Street 2 proposed design for summer and winter	43-deciduous plant design

For street 1

The air temperature analysis obtained for street 1 is given in Fig. 5. In winter analysis of the current situation, the temperature ranges between − 0.8 and 11.7 °C. When the suggestion for the area was analyzed, the temperature ranges between − 0.8 and 13.3 °C in January 2018 (Fig. 11). The air temperature is at a minimum in winter, the suggestion was − 0.8 °C, and no difference was observed (Fig. 11). However, the maximum value of 11.7 °C temperature increased to 13.3 °C in winter, a temperature increase of 1.6 °C. The area of street 1 in the study area was analyzed for the current and proposed state, respectively, for summer (15 August 2018). In summer analysis of the current situation, the temperature range was between 24.6 and 27.8 °C. When the proposed scenario for the area was analyzed, the temperature range was between 24.4 and 27.3 °C. In the study, it was found that 27% of the area became more thermally comfortable by thermal improvement.

Table 6 Street 1 and street 2 current and proposed temperature analysis of the state

Study areas	Winter months (January 2018)		Summer month (August 2018)	
	Min. (°C)	Max. (°C)	Min. (°C)	Max. (°C)
Street 1 (current)	-0.8	11.7	24.6	27.8
Street 1 (proposed scenario)	-0.8	13.3	24.4	27.3
Street 2 (current)	-0.9	0.9	25.1	27.3
Street 2 (proposed scenario)	-0.9	0.8	24.9	26.5

For street 2

Street 2 was analyzed with ENVI-met for the summer and winter months. The area of street 2 in the study area was analyzed for the current and proposed state, respectively, for winter (15 January 2018). In winter analysis of the current situation, the temperature range was between -0.9 and 0.9 °C. When the suggestion for the area was analyzed, the temperature range was between -0.9 and 0.8 °C in January 2018 (Fig. 12). The area of street 2 in the study area was analyzed for the current and proposed state, respectively, for summer (August 2018). In summer analysis of the current situation, the min-max temperature range was between 25.1 and 27.3 °C. When the proposed scenario for the area was analyzed, the min-max temperature range was between 24.9 and 26.5 °C. In

addition to the present situation, 43 deciduous plants were added on street 2 and ENVI-met analysis was performed. The analysis was made for summer and winter and is given in Fig. 12.

PMV analysis

The recorded microclimate data were used to calculate the thermal comfort values of the senses using the RayMan computer model. For this purpose, the PMV values shown by street 1 and street 2, both in the current situation and in the proposed scenario, were computed (Figs. 13 and 14).

In the calculation of outdoor thermal comfort, the ENVI-met 4.4 winter program and PMV index in the software were used as it is the latest version. The PMV is the most common

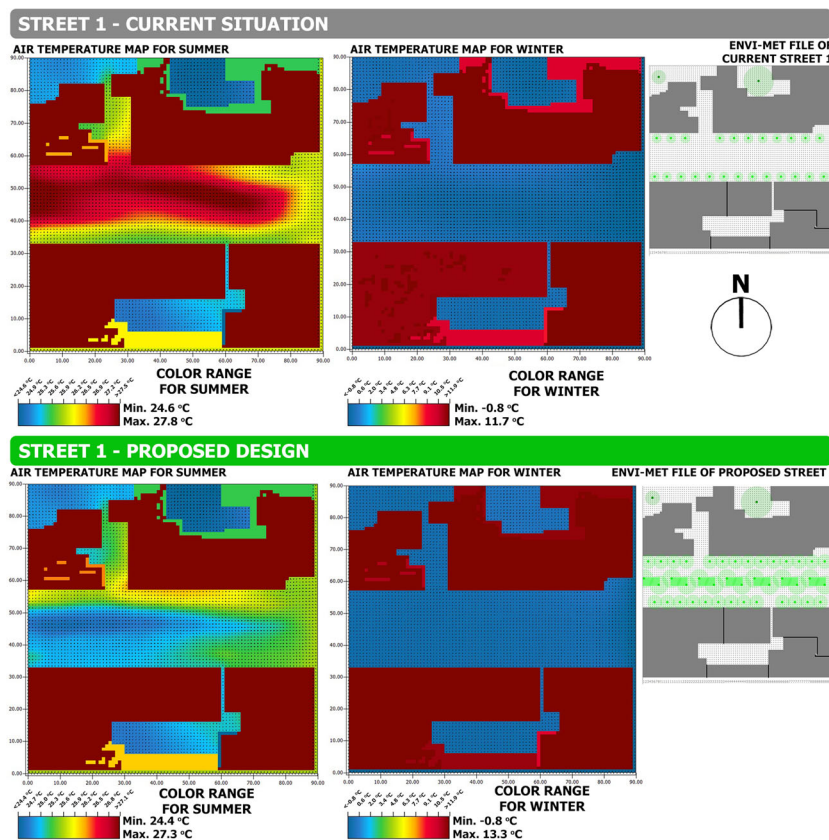


Fig. 11 Street 1 ENVI-met analysis for summer and winter

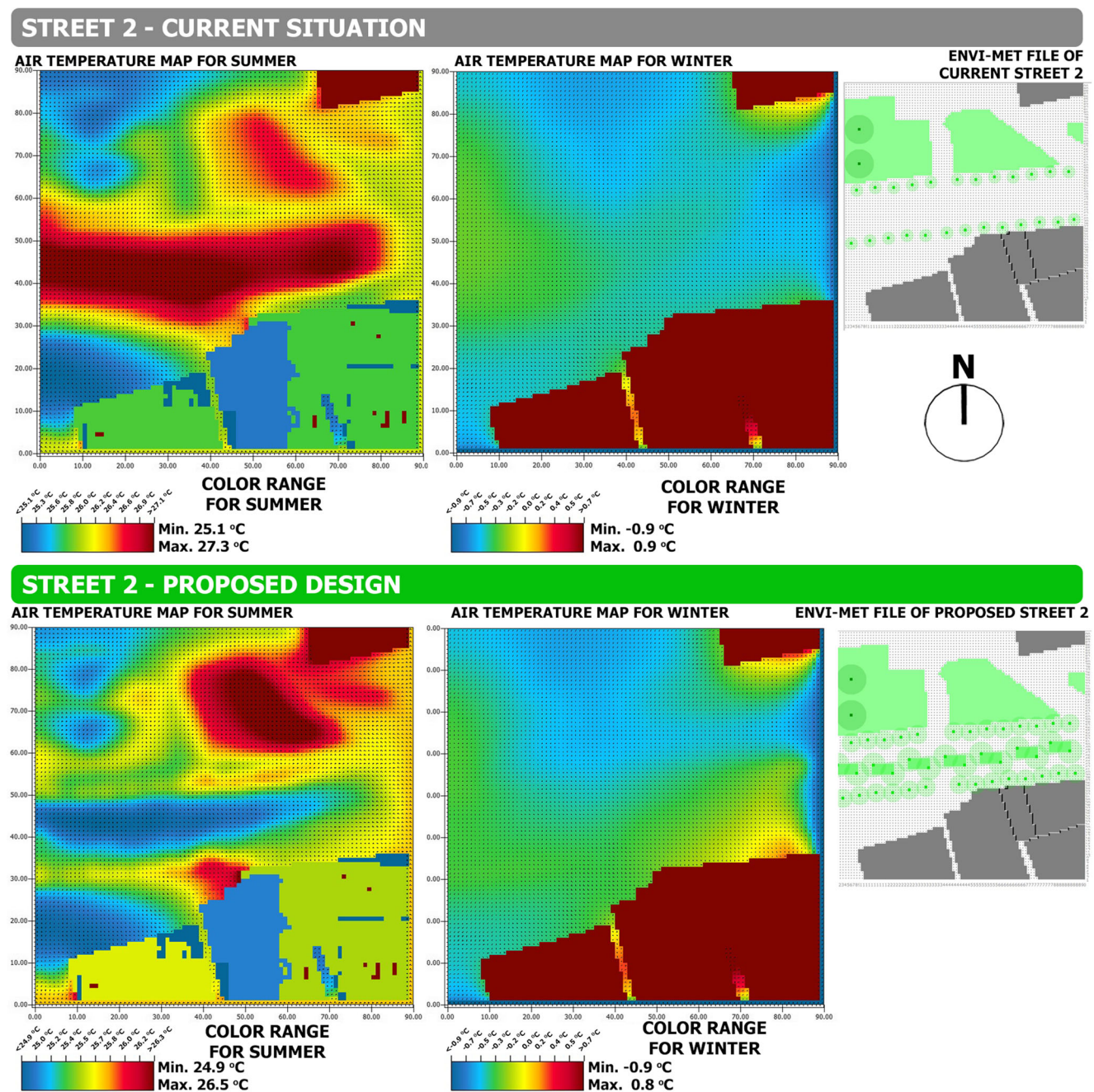


Fig. 12 Street 2, ENVI-met analysis of the current status for summer and winter

index used (Girgis et al. 2016) to define outdoor thermal comfort (Potchter et al. 2018). The PMV values are the analysis that determines outdoor thermal comfort which is interpreted by questioning people (Van Craenendonck et al. 2018). To make PMV analysis, air temperature, relative humidity, wind speed, and the mean radiant temperature values should be known. Also, the average information (age, height, weight, metabolic rate, and clothing coefficient) of the people in the region where thermal comfort is evaluated is required. With this information, the ENVI-met program performs thermal

comfort calculations with the method of Fanger (1972). The outdoor thermal comfort was determined according to the range of values given by Matzarakis et al. (1999) when the PMV results were evaluated. PMV thermal index ranges are shown in Table 7.

Although the standards for PMV were set to 9 December 2018, the maps generated for the analysis were set to 18 December 2018. Summer and winter assessments of street 1 current situation and suggestion scenarios are given in Fig. 13. As shown in the maps, the thermal comfort of the winter

Fig. 13 PMV analysis current and proposed situations of street 1

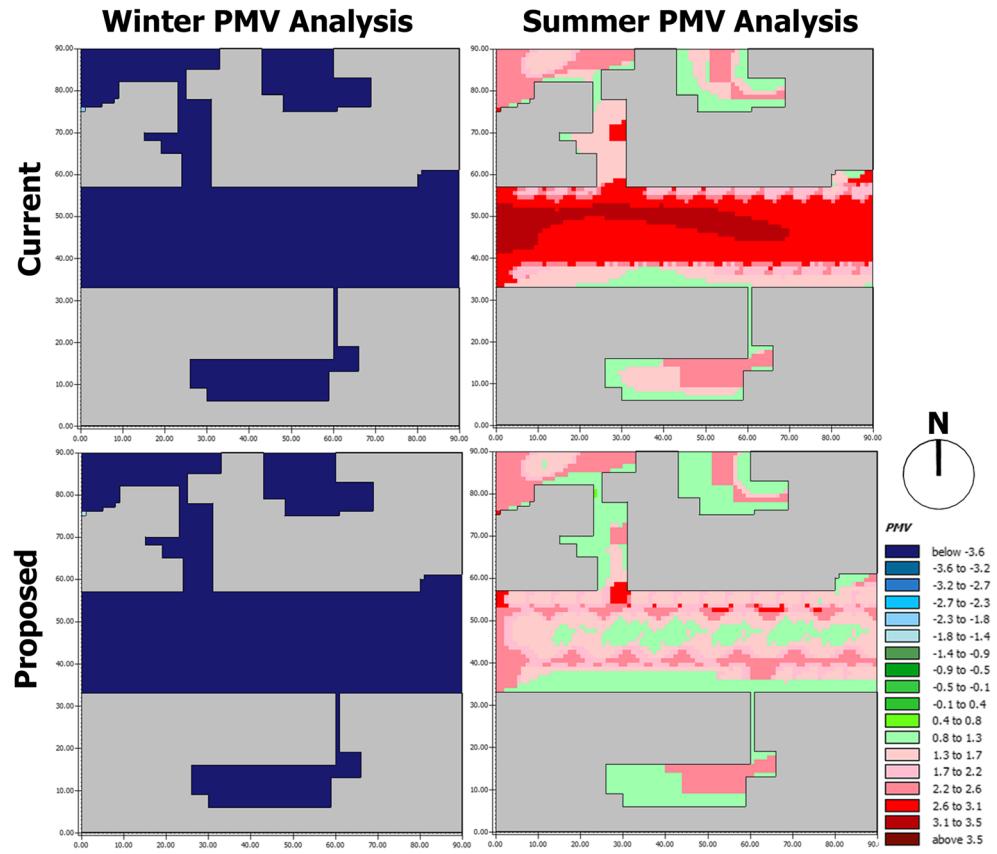


Fig. 14 PMV analysis of current and proposed situations of street 2

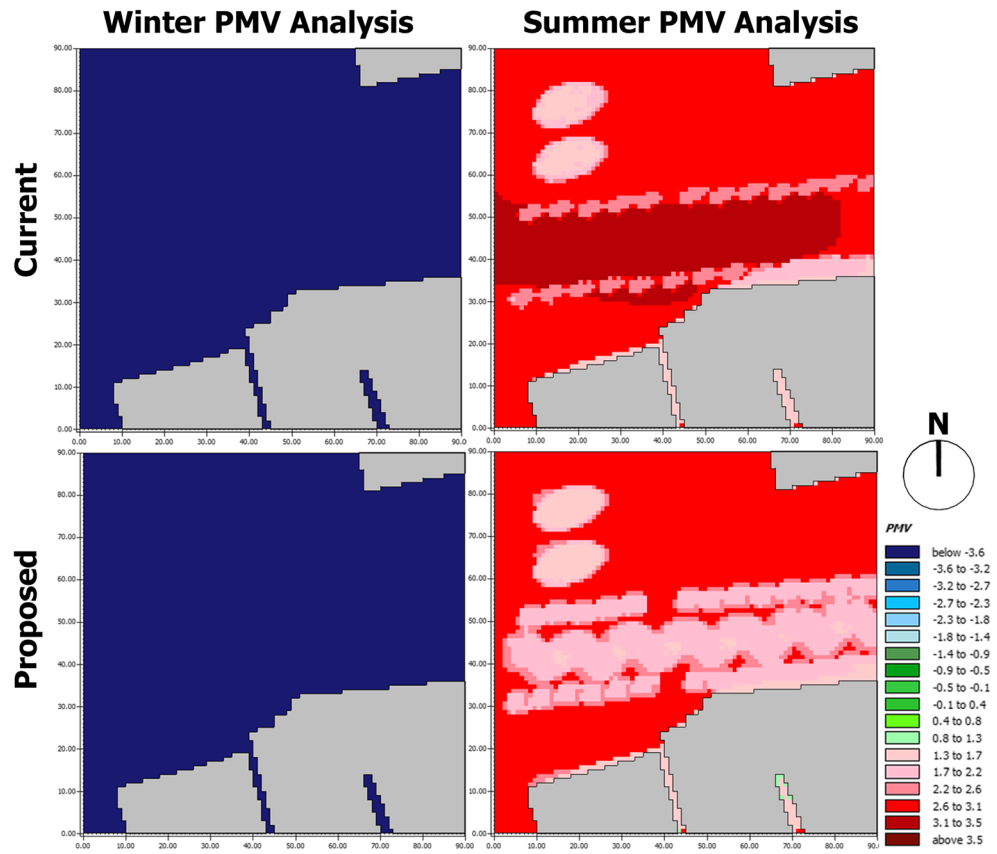











Table 7 The PMV thermal index ranges (Matzarakis et al. 1999)

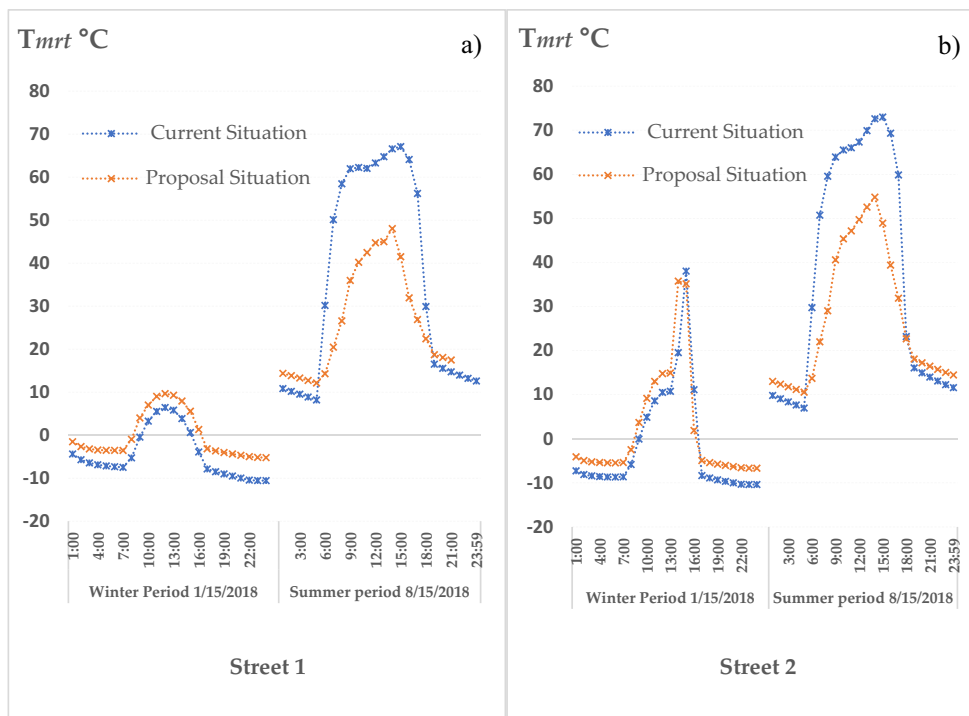
PMV	Thermal perception	Grade of physiological stress	Color Range
< -3.5	Very cold	Extreme cold stress	
-3.5 / -2.5	Cold	Strong cold stress	
-2.5 / -1.5	Cool	Moderate cold stress	
-1.5 / -0.5	Slightly cool	Slight cold stress	
-0.5 / 0.5	Comfortable	No thermal stress	
0.5 / 1.5	Slightly warm	Slight heat stress	
1.5 / 2.5	Warm	Moderate heat stress	
2.5 / 3.5	Hot	Strong heat stress	
3.5 <	Very hot	Extreme heat stress	

months decreased from -5.6 to -5.5 (0.1 improvement), while the evaluation of the summer months decreased from 3.1 to 1.3 (1.8 improvement) (Fig. 13).

Similar analysis was made in street 2. It was found that the current situation worsened (0.7; -4.9 to -5.6) in street 2 PMV values compared with the proposed situation for winter months. The same suggestion scenario was observed to have improved (1.4; 3.2 to 1.8) in terms of thermal comfort in summer (Fig. 14).

Although no survey was conducted in terms of thermal comfort for pedestrians in this study, it was reported by way of outdoor thermal comfort pedestrian surveys that pedestrians preferred areas with more trees (Smith and Henriquez 2019). Conducting a survey in the study area and calibrating the data will be added in subsequent studies.

Fig. 15 a, b The current and proposed situations of T_{mrt} for street 1 and street 2 in winter and summer times



Mean radiant temperature (T_{mrt} , °C) analysis

The mean radiant temperature (T_{mrt} , °C) is affected by the total amount of radiation absorbed by the human body and is directly influenced by urban morphology, street canyon, wind speeds, building facades, and surface materials. The mean radiant temperature is one of the main influenced factors on the outdoor thermal comfort level. It was investigated in the current and proposed scenarios of street 1 and street 2 during the winter and summer periods. As can be seen in Fig. 15 a and b, the T_{mrt} is very high, reaching close to 70.0 °C in both streets in the summertime. It is much lower in winter, reaching 10.0 °C in street 1 and 38.0 °C in street 2. However, in street 1, the T_{mrt} in the proposed situation increased by 4.0 to 5.0 °C in winter and decreased by a maximum of 18.0 °C during the summer period compared to the existing condition, especially in the noontime when the sun is overhead. For street 2, the proposed situation of the T_{mrt} in the winter period increased by a maximum of 5.0 °C during the morning and afternoon times compared with the current situation. But, it seems to be similar to the current condition during noontime from 1:00 pm to 4:00 pm. On the other hand, the T_{mrt} in the summer period in street 2 decreased by a maximum of 20.0 °C at the critical time of the day from 09:00 am to 1:00 pm. It can be concluded that the proposed situation provides a significant thermal comfort sensation for both streets by reducing the T_{mrt} in the summertime and increasing it in wintertime.

Discussion

When the SVF images are considered, the current SVF was found to be 0.45 in street 1 and 0.58 in street 2. The current analysis showed that winter months are colder as the sky visibility ratio increases, as shown by the surrounding open area getting bigger. In addition, the SVF values of the scenarios were determined to be 0.15 for street 1 and 0.25 for street 2. Therefore, a negative thermal comfort development was observed in street 2 for the winter months, while in all other cases, it was found that the SVF ratio decreased and the thermal comfort increased. This situation provides positive progress in thermal comfort, especially in summer months, as the plants minimize the negative effects on thermal comfort with their permeable structure by shedding the leaves in winter and resistance to rapid heating/cooling in cities in summer. In addition, it has been found in different studies that plants increase thermal comfort thanks to moisture retention and perspiration (Irmak et al. 2018; Gómez et al. 2018). Indeed, in a study using the ENVI-met, it was determined that the temperature of urban spaces would increase more in 2100 (Pioppi et al. 2020). Therefore, it is necessary to take precautions in planning to improve outdoor thermal comfort. This requires landscape planners to explore how to create a more

comfortable thermal street in high-density, low-height urban forms and how to choose plant species (Yilmaz et al. 2018b). Similar results and suggestions have been reported by Yang et al. (2018).

The large and open streets with a high SVF value (street 2) are cool in the winter and slightly warm in summer. Although street 1 and street 2 are in the same direction, street 2 is cooler in winter. The reason for this is generally because the air flow is high there (Mochida and Lun 2008; Park et al. 2012; Tan et al. 2016; Morakinyo et al. 2017; Tsoka et al. 2018). The reason for more airflow on street 2 is that there are buildings on one side and parking space on the other side. The fact that one side is open is also described as the circulation movement after the wind blowing from the southwest. It was reported that building heights, densities, and street SVF value in urban space had significant impacts on outdoor thermal comfort (Yilmaz et al. 2018b; Falasca et al. 2019; Chokhachian et al. 2020).

In street 1, ENVI-met analysis was between −0.8 and 11.7 °C for winter months and between 24.6 and 27.8 °C for summer months. The results of the current ENVI-met analysis on street 2 were between −0.9 and 0.9 °C for winter and 25.1 to 27.3 °C for summer. While vegetation in the scenario proposed for street 1 in the study decreases the minimum air temperature in summer by 0.2 °C, it decreases the maximum air temperature by 0.5 °C. The suggested scenario for winter months did not cause a change in minimum temperature but increased the maximum temperature by 1.6 °C. According to other studies, when the number of trees of a campus in Japan was increased by 20%, it was observed that the temperature decreased by 2.9 °C in the summer months (Srivanit and Hokao 2013). It has been stated in different studies that trees on narrow streets retard the speed of the wind (Gromke and Blocken 2015). The positive contributions of green spaces to the urban environment are an undeniable fact (Josephine et al. 2019). As a result of this study, it was determined that the scenario that added trees reduced the temperature of the street by 1.0 °C in the summer and increased by approximately 2.0 °C in the winter. Also, it was observed in another study that increasing the number of trees used in the open area greatly reduced heat stress during the day (Ma et al. 2020). In another similar study, it was observed that the temperature decreased by 0.8 °C when the number of plants was increased by 40% (Tsoka et al. 2017). In a study conducted in Italy, it was observed that when the number of plants was increased by 10%, the temperature decreased by 1.34 °C (Salata et al. 2017). The increase of tree leaves will reduce the variation in the range of PET in the street canyon (Yang et al. 2018). This will also influence the selection of the street tree species.

This study showed that plant designs, which are suggested for both streets, decrease the ambient temperature; in turn, the PMV values significantly decreased, especially in winter. But, in some cases, trees that are positioned incorrectly along the

street can also prevent free airflow along the street, resulting in a higher PMV. Street design would need to adopt more customized strategies such as the types of shading and ventilation in conjunction with street openness. Both temperature and thermal comfort (PMV) are influenced more by the street aspect ratio (Maharroof et al. 2020). In the proposed scenario of street 1, the air temperature increased by 1.6 °C in winter months. This is important in the city of Erzurum in the cold winter months. People on the sidewalks of this street are more important in terms of walking more comfortably in winter. Again, during the summer months, there is a cooling effect of 0.5 °C maximum.

In street 2, which has a wide canyon feature, a temperature drop of 0.8 °C is observed in the scenario where trees are added, especially for summer months. This is usually due to the shading of trees, blocking sunlight (Tsoka et al. 2018), or because of the better air circulation in the wide area. Vegetation also prevents long-wave radiation from flowing from the ground to the sky, which reduces reflection (Yang et al. 2018; Irmak et al. 2018). Wide canyon provides wind velocity in open spaces. Therefore, in the analysis performed on the street in the same direction, the open area was found to be 10.8 °C cooler at a maximum temperature in winter. In summer, it is cooler at a maximum temperature of 0.5 °C. These areas on the street provide the mobility of the wind and reduce the air temperature of the environment (Nordh and Østby 2013; Lin et al. 2017; Mutlu et al. 2018).

The scenario proposed for street 1 in the study decreases the temperature in summer by 0.2 °C in minimum and decreases the temperature by 0.8 °C in maximum. The suggested scenario for winter months did not cause a change in minimum temperature but decreased the maximum temperature by 0.1 °C. Deciduous trees (*Betula* spp.) added in both scenarios reduced the SVF rate. The plants used improved thermal comfort by 1.8 °C on street 1 and 1.4 °C on street 2, reducing the heat stress of the summer with the reduced SVF rate. The results of the analysis show that when the number of plants on the street is increased, the temperature increases in winter and decreases in summer (Yilmaz et al. 2018a; Irmak et al. 2018; Mutlu et al. 2018). An increased number of plants pursuant to the scenario proposed for street 2 (open area) have decreased the temperature in winter. The reason for this is the steady wind speed and higher wind mobility as compared to the other street. The correct design should be made for the positive contribution of plants to the thermal comfort of the environment. Zhang et al. (2018) have stated that the wind was blocked and decelerated under the trees. For this reason, plants should be positioned according to the wind direction.

Conclusion

For livable cities, pedestrian access is important. People should be able to walk in both summer and winter months without being affected by heat and cold. The creation of pedestrian-friendly streets for people is necessary in terms of the city's readability. As a result of this study, it is seen that planting can change the thermal comfort of the environment.

Using the right trees in the right place affects thermal comfort. In cold climate regions such as Erzurum, light-permeable deciduous should be preferred. These form the shade (canopy) in the summer and cool the environment, thus providing the permeability of sunlight in winter and supporting the heating of the space. The open spaces on the street, in the form of pocket parks, cool the environment in both summer and winter. However, deciduous semi-permeable trees have a positive effect on the thermal comfort of the street in both the summer and winter months.

As a result of the analysis of the climate values with the correct method and the physical plan decisions, it is considered to be very important in terms of achieving the standards that the urban livability conditions, including the cities with extreme climatic conditions, can be improved. Although they differ from each other, the scenarios including vegetation positively contribute to the thermal comfort of the environment both in summers and in winters. In conclusion, it is recommended that correct planning should include an ecological approach and consideration of microclimates, streets in winter cities are planned parallel to the predominant wind direction, deciduous tree vegetation should branch from above, and open space area is preferred.

This study has addressed only two of many typical street canyon spatial forms. Different pavement materials, tree species, and street directions can also be tried. Actually, many factors affect the situation. Creating a more complex model or more than the recommended scenarios will help the result have broader compatibility.

The results showed that we should consider different kinds of proposed scenarios in future studies. More livable areas should be redesigned or reorganized by landscape architecture and urban planners. It has been concluded that it is possible to increase thermal comfort by improving with open area and correct plant preferences for livable urbanization. It can also be beneficial for policymakers, urban planners, and landscape architects to design resilient urban street design and landscape trees by using user-friendly sustainable simulations.

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