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Changes in Air Water Vapour Pressure, Relative Humidity and Carbon Dioxide Concentration in Summer on the City Outskirts

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ABSTRACT

Urban greenery contributes to improve air quality through carbon dioxide sequestration and to increase air humidity by transpiration. These processes are dependent on diurnal physiological activity of vegetation as well as its spatial distribution. In our study we aimed to find out (1) how urban greenery can change the atmospheric conditions during a day and (2) if there is a difference between a housing estate interior with abundant greenery and a wide street of heavy traffic. The examination was carried out a suburban district of Warsaw, in two sites of contrasting characteristics: in a street with heavy traffic during rush hours and in a housing estate nearby. Gas measurements were carried out using an infrared gas analyser included in a portable photosynthesis system on two sunny days in July 2021. On each day measurements of air water vapour pressure and atmospheric carbon dioxide were taken in both locations from early morning to the evening. The results showed that water vapour pressure in the air increased from ca. 12 to nearly 18 hPa from 6:45 a.m. to 9:00–9:30 a.m., respectively, and then gradually decreased until 7:00 p.m. on both measurement days. Carbon dioxide concentration in the atmosphere in the early morning hours exceeded 430–450 ppm and then decreased to 400 ppm or even less than 360 ppm depending on the day. We concluded that the site characteristics had not an important effect on relative humidity and carbon dioxide concentration, but vapour pressure deficit was higher in the street.

Keywords: diurnal changes, ecosystem services, housing estate, urban greenery, urban vegetation, vapour pressure deficit.

INTRODUCTION

Ecosystem services provided by urban greenery include carbon dioxide sequestration and air cooling through transpiration [Haase et al., 2014; Fares et al., 2017; Veerkamp et al., 2021]. Plants remove CO_2 from the atmosphere during the process of photosynthesis and accumulate as organic carbon in numerous forms: roots, trunks, stems, branches, leaves and fruit. Carbon compounds accumulated in roots, trunks and branches provide building material for woody plants for many years, but small organs such as twigs, leaves and fruit remain may become a litter in green areas of a city. Biomass residues deposited in the soil may serve additionally as a temporary reservoir for carbon. Particularly trees play important role in removing CO_2 from the atmosphere because they provide a long-term deposit of carbon dioxide [Fares et al., 2017; Nowak et al., 2018], however, shrubs and woody vines also utilise carbon as a building material for several years. Another consequence of plant activity is transpiration which is an element of the whole-plant water use. Transpiration supports water uptake from the soil, transport of water from roots to leaves allows for delivery of nutrients and signalling agents (hormones, etc.) to the tissues [Scharwies and Dinneny, 2019]. Transpiration performed by urban trees effectively contributes to mitigate effects of heat in cities [Gillner et al., 2015; Tsoka et al., 2018]. The energy (i.e., latent heat) used to evaporate water transpired by trees consumes heat energy (i.e., sensible heat) in the local environment that would otherwise raise air temperature and, instead, cools leaf surfaces and nearby air temperatures by advection [Winbourne et al., 2020]. This is of great importance for reducing heat stress for residents. In consequence, urban trees and urban greenery in total contribute to health safety and reduction of mortality caused by high temperatures [Jungman et al., 2023]. Thus, developing urban forests and green areas in cities is recommended as an appropriate policy in order to offset CO_2 emissions [Weissert et al., 2014] and to mitigate the effect of urban heat island [Tsoka et al., 2018; Hewitt et al., 2020; Senosiain, 2020].

The potential of urban greenery for carbon dioxide sequestration and for microclimate improvement was assessed using different approaches. In several papers the contribution of trees serving as a carbon sink was estimated by using tree species-specific allometric equations or standard wood method to estimate the average biomass in the sample plots [Gratani et al., 2019; Tsedeke et al., 2021]. Different models were used, e.g. UFORE, i-Tree Eco, i-Tree Streets, CUFR Tree Carbon Calculator (CTCC), which may underestimate or overestimate C storage and sequestration [Russo et al., 2014], however, there is no doubt that gradual CO_2 fixation in urban areas is performed. Urban carbon storage was also assessed combining data from sampling urban forest plots and Landsat ETM + data [Shen et al., 2020; Jiang et al., 2023]. These methods enable to estimate total amounts of carbon sequestration over specified periods of time (e.g. subsequent years) but do not enable to show the impact of this process on the local environmental conditions. The effect of carbon dioxide removing provided by urban greenery was assessed using infrared gas analysers or combined measuring devices as eddy covariance method [Pan et al., 2016; Takano and Ueyama, 2021]. Eddy covariance allows to show fluxes of CO_2 and other gases at specific time intervals [Pawlak and Fortuniak, 2016]. This micrometeorological technique allows to quantify large scale net ecosystem carbon exchange over time periods, ranging from hours to years [Baldocchi, 2014]. Infrared gas analysers were previously used as portable devices temporarily installed at different sites or in cars for mobile measurements [Takano and Ueyama, 2021]. There are also different methods allowing for assessing transpiration rates and a cooling effect of urban forests. Remote sensing, e.g. monitoring high-resolution satellite land surface temperatures (LSTs) and land-cover data indicate significant impact of green areas on the distribution of the cooling effect [Schwaab et al., 2021]. ENVI-met dynamic simulations provide complex surface-vegetation-air interactions in the urban environment [Tsoka et al., 2018; Jiang et al., 2023]. Ground-based studies on trees' transpiration involve techniques adopted from physiological methodology. Tree transpiration was formerly estimated using sap flow sensors which monitor in real-time the movement of water in an individual tree stem. Sap flow measurements can provide an estimate of transpiration or can be combined with an estimation of total area of hydraulically conductive tissue in a tree trunk to assess the rate of transpiration [Tan et al., 2020]. Transpiration of urban trees was also assessed in combination with stomatal activity using porometers which provide the actual rate of transpiration at a given time [Tan et al., 2020]. A porometer consists of a small chamber containing a humidity sensor which is clamped to the leaf surface and either the time required for an increase in humidity between two preselected levels or the change in humidity for a given time interval is determined. More precise measurements of transpiration (and parallelly CO_2 assimilation) are provided by infrared gas analysers (IRGA) which detect the real-time record of CO_2 and H_2O concentrations in an analysis cell and calculate the difference between them and concentrations of these gases in a reference cell filled with the ambient air. Infrared gas analysers allowed to compare transpiration rates in different tree species in urban environment including streets [Gillner et al., 2015; Konarska et al., 2016].

In recent papers many authors showed differences in CO_2 (or CO_2 fluxes) and micrometeorological conditions between city centres and suburbs or rural areas [e.g. Takano and Ueyama, 2021]. Differences in carbon dioxide concentration were also found between particular urban sites [Gratani et al., 2019b]. A typical pattern of photosynthetic activity of plants shows the highest performance at mid-day. However, high solar radiation and high temperature in hot summer days may force plants to close their stomata in order to avoid water stress in plant tissues and photodamage of photosynthetic apparatus [Sabir and Yazar, 2015, Martin-StPaul et al., 2017]. This results in depletion of transpiration rate and CO_2 assimilation. Thus, the impact of vegetation on the composition of atmospheric air may depend on the rise of air temperature during a day. Local conditions also affect the transpiration activity in urban trees [Rahman et al., 2017]. Zhou et al. [2017] showed that the cooling effect of trees may depend on tree density and the size of area covered by trees. Moreover, tree species differ for net CO_2 assimilation [Fini et al., 2023]. Thus, the combination of weather, site conditions and vegetation composition and abundance may influence the diurnal pattern of water vapour and carbon dioxide changes in urban atmosphere.

The infrared gas analysers used for photosynthesis measurements in plants, by measuring the CO_2 and H_2O concentrations in a reference cell, also enables to track the current carbon dioxide and vapour content in the ambient air. In our study on urban shrubs the photosynthetic performance in different locations was compared. The aim of the study was to assess daily photosynthetic activity of urban shrubs in the full growing season. In this paper we present the results of the measurements of CO_2 and H_2O concentrations in the ambient air as a result of reference measurements by IRGA. We aimed to find out (1) how urban greenery can change the atmospheric conditions during a day and (2) if there is a difference between a housing estate interior with abundant greenery and a wide street of heavy traffic.

MATERIALS AND METHODS

The research was carried out in Ursynów (52°09′N, 21°02′E, 98 m asl), a suburban district of Warsaw, Poland. In 2007-2016 the annual mean temperature in Warsaw was 9,4°C with a temperature range from −1.5°C (January) to 20.1°C (July), annual and monthly precipitation in July of 565 and 93 mm, respectively. Ursynów is mostly a residential district with a high proportion of green areas. Measurements were taken in two sites of contrasting characteristics: (1) on the inter-lane lawn strip in Al. Komisji Edukacji Narodowej, a street with heavy traffic during rush hours (KEN), (2) in a housing estate nearby with 4- up to 10-storey residential buildings scattered irregularly and surrounded by a rich composition of trees and ornamental shrubs (HE) (Figure 1). KEN is an avenue with irregular tree plantings, including young and mature trees of *Platanus ×hispanica*, *Acer* sp. and *Populus* sp., however, there are no trees in the close neighbourhood of the studied inter-lane lawn strip but groups of shrubs (Figure 1b). Vegetation in HE includes lawns, young and mature trees and shrubs of ca. 50 species, mostly deciduous.

Gas measurements were carried out using TARGAS-1 Portable Photosynthesis System (PP-Systems, Amesbury, MA, USA) on two sunny days, 20th and 23rd of July 2021. The device contains a precise CO_2/H_2O gas analyser which can be used as part of a leaf gas exchange system with a leaf cuvette or as a self-contained instrument for continuous measurement of CO_2 and H_2O in air. The latter was applied in our study. The device allows for continuous air sampling, as a built-in pump introduces fresh sample gas to the infrared gas analyser during the time of measurements. Both gases CO_2 and H_2O in air sample are measured together, according to the information from the producer, the effect called ʻforeign gas broadening’ (FGB), as well as temperature and pressure effects are automatically corrected by TARGAS-1 (PP Systems 2016. TARGAS-1 Portable Photosynthesis System Operation Manual. Version 1.01). Changes in ambient CO_2 content and H_2O vapour pressure in the atmosphere were measured around ornamental shrubs of ca. 2–3 m height. Air samples were collected at a height of 2.3 m. TARGAS-1 Portable Photosynthesis System enables to collect records every second which results in a huge amount of data. Due to the abundance of records, partially discontinuous, we decided to choose for analyses 7 minutes at approximately regular intervals from 6:45 a.m. to 7:00 p.m. (further denoted as 19:00) and included in calculations the initial 10 seconds of each minute (7×10 seconds interspersed by 50 seconds, 70 records per each time set). The additional parameters, vapour pressure deficit and relative humidity, were calculated by the device. Due to technical constraints, air temperature was not recorded. Thus, we used leaf temperature from a shaded part of shrub as an indicator of ambient temperature.

Meteorological data were obtained from Meteo Station of the Warsaw University of Life Sciences (SGGW), Energy Management Department (Source: SGGW Warszawa, sggw.meteo.waw.pl), located ca. 1500 and 1700 m away from HE and KEN, respectively (Figure 2). Differences

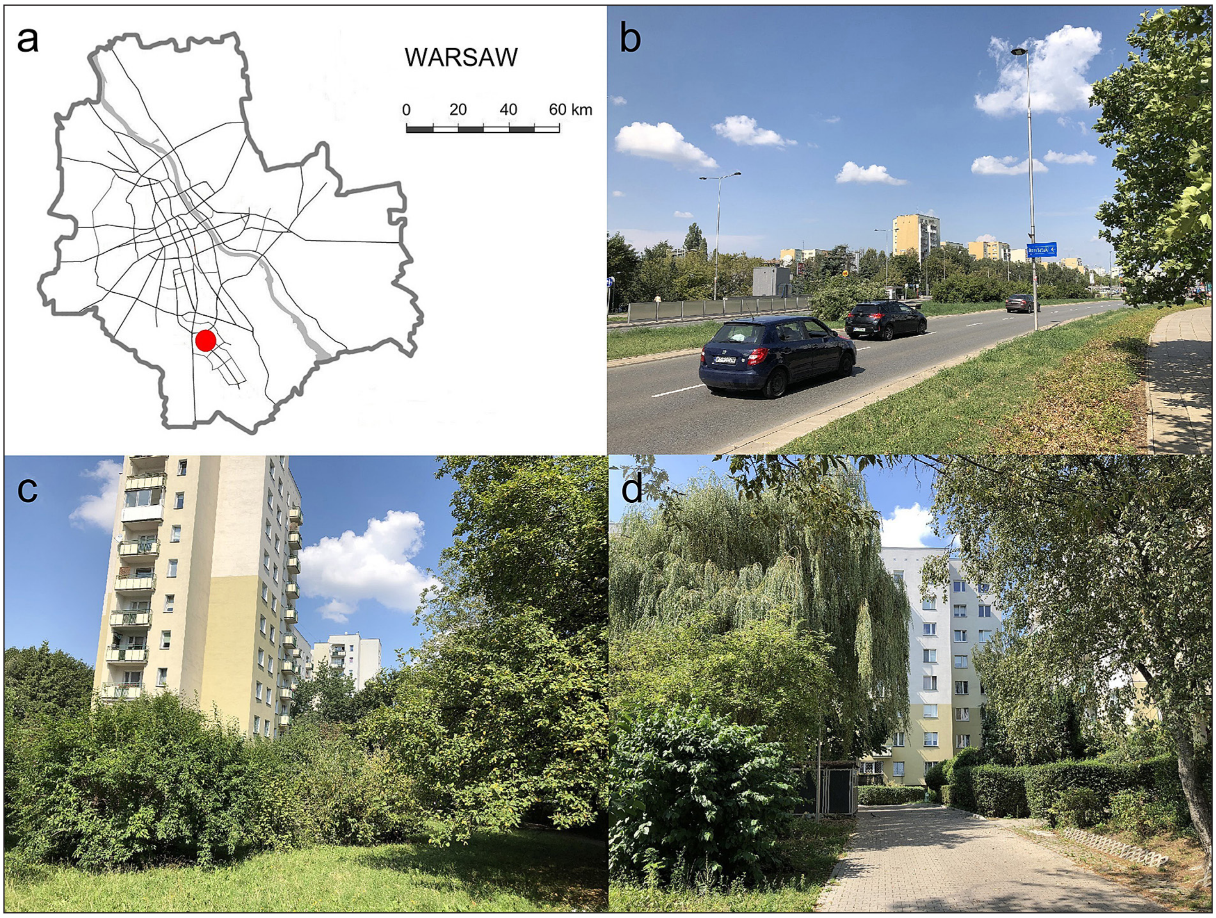

Figure 1. Location (a) and photographs of study sites: Al. Komisji Edukacji Narodowej (KEN, b) and housing estate (HE, c and d)

of the means were tested by two-way analysis of variance (ANOVA) and Tukey test for multiple comparisons, the effects of site and time were compared on each measurement day separately. Statistical tests and graphs were performed using a statistical software STATISTICA version 13.0 software (TIBCO Software Inc., USA).

RESULTS

On the first day of measurements the highest mean CO_2 concentration of 437.6 ppm was found early morning in KEN, followed by the concentration of 419.3 ppm in HE. At 9:00 mean CO_2 concentration in KEN decreased to 357 ppm and since 10:00 remained in a range 324–345 ppm until the evening in both sites. In most cases differences between the measurements were significant except in KEN at 12:00 and in HE at 16:00 and 18:30 (Figure 3a). On the second day the initial average CO_2 concentration in KEN was 453.9, then decreased up to its minimum at 10:30 (393.7 ppm) and finally remained almost unchanged in both sites. Diurnal differences between maximum and minimum mean values collected on 20th and 23rd of July gained ca. 113 and 60 ppm, respectively (Figure 3a and 3b). The results showed very low variability therefore 95% confidence intervals are not visible in the graphs.

Atmospheric vapour pressure was the lowest in the early morning hours (6:45), then rapidly increased gaining in average 17 and 17.3 hPa at about 9:00 on July 20th and 23rd, respectively, with maximum values exceeding 18 hPa. Afterwards the decrease of vapour pressure during a day was more pronounced in HE on both measurement days (Figure 4a and 4b). Differences between sites were significant ($p < 0.001$) except the measurements at 9:00 and 10:00 on the first day.

Vapour pressure deficit was low in the early morning hours but started to increase since 9:00 and 9:30 on June 20th and 23rd, respectively. However, on the second day of measurements

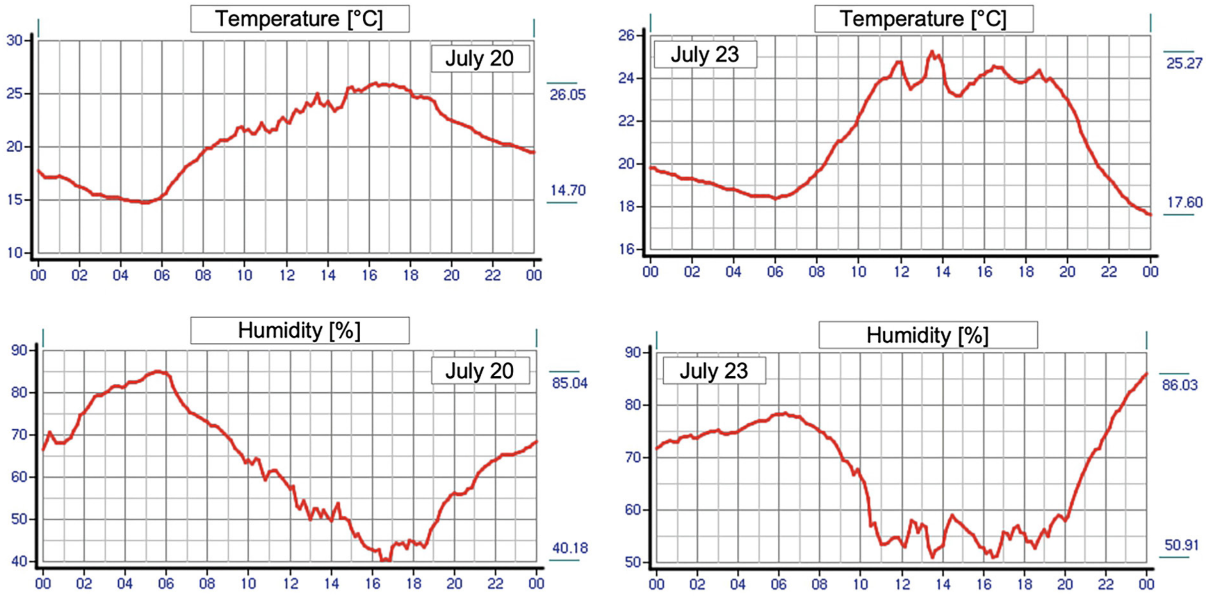

Figure 2. The 24-h cycle of climatic data of air temperature and relative humidity measured at Meteo Station of the Warsaw University of Life Sciences, Energy Management Department

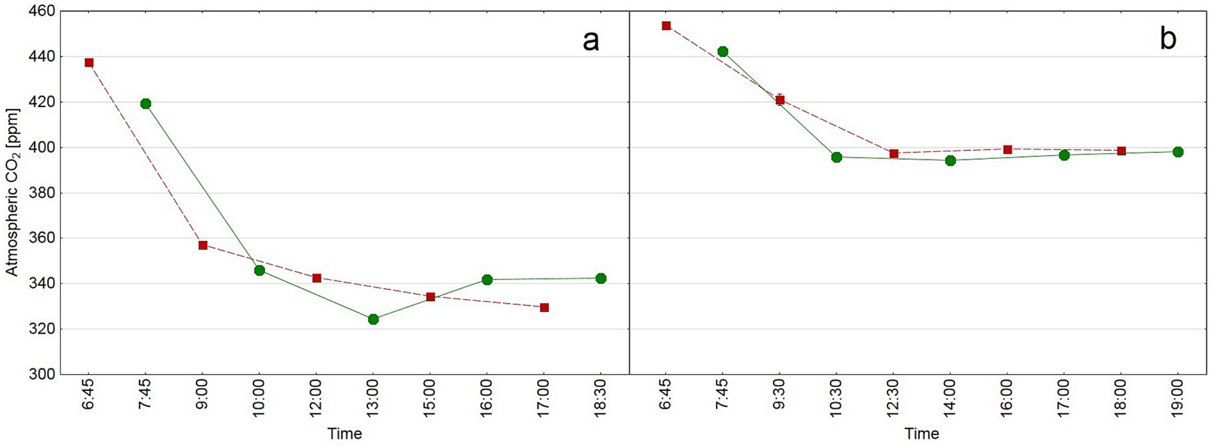

Figure 3. Atmospheric CO_2 concentration in the street with heavy traffic (KEN, red squares) and in the housing estate (HE, green circles), on July 20th (a) and July 23rd (b), 2021 (means, whiskers indicate 95% confidence intervals)

VPD gained its maximum in the early afternoon and then gradually decreased (Figure 5a and 5b). The patterns of VPD changes indicate significantly lower values of VPD in housing estate except the time of intense increase between 9:00 and 13:00. Diurnal pattern of relative humidity was similar in both sites on both days (Figure 6a and 6b), showing initial increase in the street until 9:00–9:30 and then gradual decrease in both sites. In in the housing estate initial values at 7:30 were significantly higher than in the next hours on both days. Mean leaf temperature in the early morning did not exceed 20°C and 22°C on the first and second day, respectively (Figure 7a and 7b). Then it increased gradually exceeding 26°C at 12:00–12:30 in the street on both days and in the housing estate on the first day of measurements. The pattern of temperature changes was similar in both sites and days, but in the afternoon higher values were found in the street.

DISCUSSION

City structure provides differential spatial end environmental conditions. Differences in air quality between central parts and outskirts were previously reported [Takano and Ueyama, 2021; Wu et

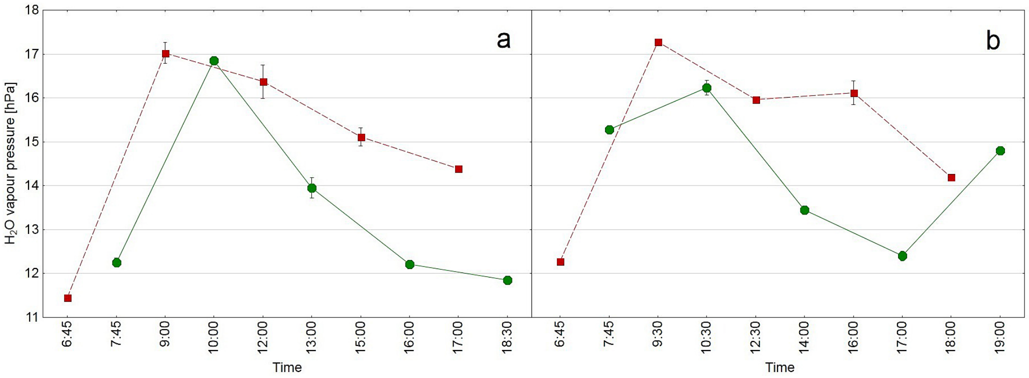

Figure 4. Atmospheric vapour pressure in the street with heavy traffic (KEN, red squares) and in the housing estate (HE, green circles), on July 20th (a) and July 23rd (b), 2021 (means, whiskers indicate 95% confidence intervals)

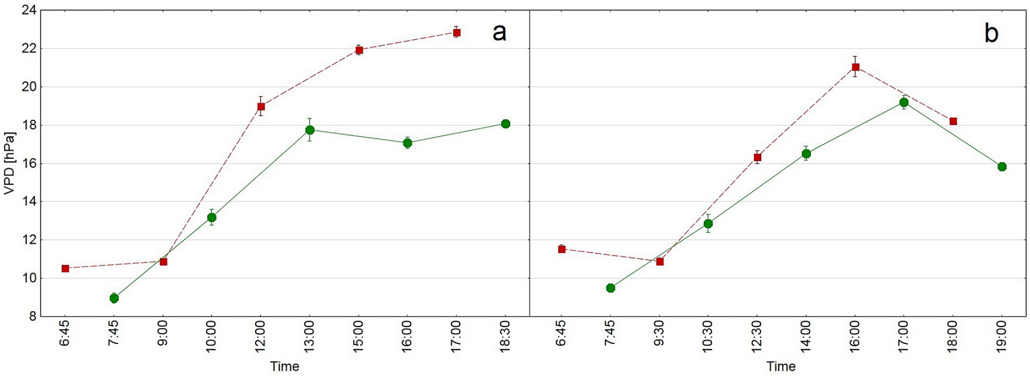

Figure 5. Vapour pressure deficit (VPD) in the street with heavy traffic (KEN, red squares) and in the housing estate (HE, green circles) on July 20th (a) and July 23rd (b), 2021 (means, whiskers indicate 95% confidence intervals)

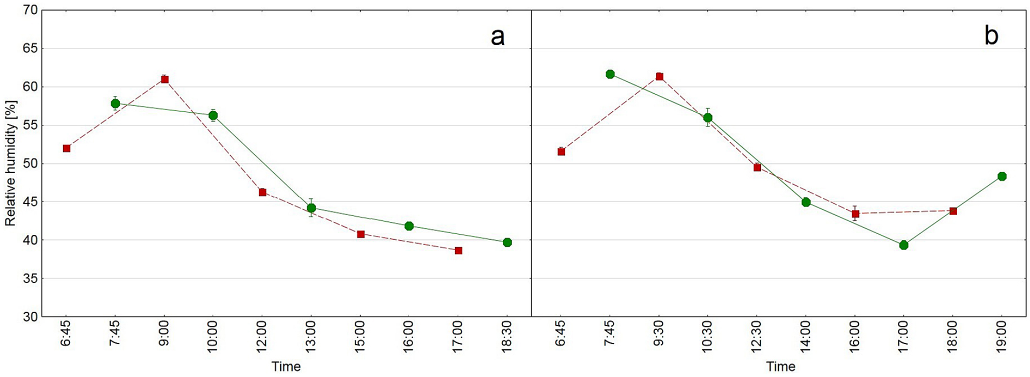

Figure 6. Relative humidity in the street with heavy traffic (KEN, red squares) and in the housing estate (HE, green circles) on July 20th (a) and July 23rd (b), 2021 (means, whiskers indicate 95% confidence intervals)

al., 2023]. Differences were also detected within the same district but in different streets [Rakowska et al., 2014; Salem et al., 2017]. Many papers prove that the main source of CO_2 emissions in urban areas is the fuel combustion associated with transport, followed by energy use in households and public buildings, as well as manufacturing and industry however the nocturnal respiration of urban greenery is also considered as a source of nigh CO_2 emission [Weissert et al., 2014]. The quality of atmospheric air in the streets and their neighbourhood is strongly affected by pollution from road traffic [Salem et

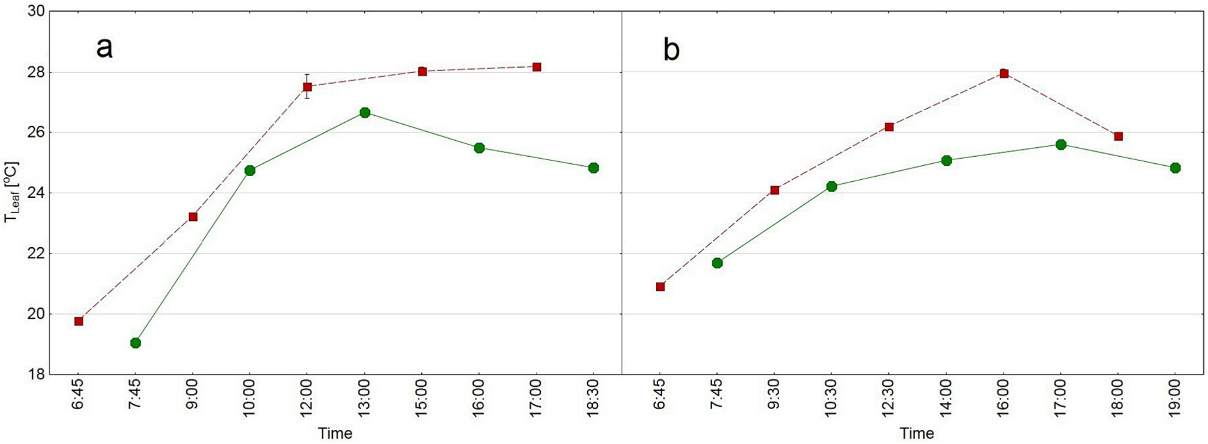

Figure 7. Leaf temperature in the street with heavy traffic (KEN, red squares) and in the housing estate (HE, green circles) on July 20th (a) and July 23rd (b), 2021 (means, whiskers indicate 95% confidence intervals)

al., 2017, Jiang et al., 2023]. Gratani et al. [2019a] found significant differences in CO_2 concentration between interior of a hospital area and neighbouring streets. Thus, in our study it was expected that CO_2 concentrations will be higher in the two-lane street than inside the housing estate. We conducted our study in a peripheral district with a high share of greenery accompanying housing estates. This may have contributed to the lack of differences between the street and the housing estate. Nevertheless, atmospheric carbon dioxide concentration due to assimilation during daytime showed the pattern similar to that observed in other studies [Velasco et al., 2013; Weissert et al., 2014; Gratani et al., 2019a]. Once the daytime photosynthetic activity starts, the CO_2 concentration gradually decreases until 9:00-9:30. In the study by Ward et al. [2015] performed in suburban district CO_2 concentration increased during morning hours and gained a visible peak at about 8:00 which was explained as a result of heavy traffic in the morning rush hours. Many residents of Ursynów commute to work in the city centre, however, (1) the district is well connected thanks to a metro line, (2) the number of residents usually decreases during summer holidays, and (3) the 2021 was the second year of coronavirus pandemic, which resulted in many employees working online. The maximum CO_2 concentration measured in our study at early morning hours gained 437–454 ppm on both days of measurements, while the minimum was 324 and 394 ppm, on 20th and 23rd July, respectively, so, the diurnal differences gained ca. 113 and 60 ppm, respectively. According to Gratani et al. [2019b], carbon dioxide concentration at 8:30 (in the range of ca. 420–500 ppm) was higher than at 11:30 a.m. (ca. 400–450 ppm) in the area of Sapienza University Campus in Rome, Italy. Jiang et al. [2023] found that green areas diminish atmospheric CO_2 concentration by 0 to ca. 6 ppm and by 6 to 12 ppm and more on lawns/open space gardens and urban forests, respectively, while in streets and residential area CO_2 concentration increases up to 5 ppm and more. As the Sixth Assessment Report by IPCC shows, in 2019 average atmospheric CO_2 concentrations gained 410 ppm and were higher than at any time in at least 2 million years [IPCC, 2023]. Our measurements done only on two summer days do not answer whether the extensive vegetation in the studied area contributes to the decrease of average CO_2 concentration or rather mitigates the effects of urban CO_2 emissions which exceed the mean value reported by IPCC. In our previous measurements conducted once a month in 2018 atmospheric humidity increased and CO_2 concentration decreased from May to October at noon hours (data not published). This is consistent with results shown by Gratani et al. [2019a]. Comparing patterns obtained both in summer and winter by other researchers [Ward et al., 2015; Gratani et al., 2019a] we may ascertain that extensive vegetation in housing estates plays the important role in CO_2 reduction in urban areas during the growing season.

Transpiration from trees (and other plants) has a significant contribution to the saturation of the atmosphere with water vapour. According to Matasov et al. [2020], a single tree in a high-latitude city may transpire daily in average 1.74–2.90 kg H_2O per hour in July, which makes approximately 41–70 kg H_2O per 24 hours. The rate of transpiration contribution depends not only on species composition [Cregg et al., 2023] but also on soil moisture, tree size and tree or vegetation density

[Forrester, 2015]. Transpiration is also highly correlated with current microclimatic conditions, e.g. irradiance and temperature [Sabir and Yazar, 2015; Konarska et al., 2016]. At the leaf level, transpiration rates are controlled both physiologically by stomatal conductance and physically by gas exchange between leaves and the surrounding air [Winbourne et al., 2020]. When plants receive enough amounts of water, a correlation between transpiration and VPD exists [Tan et al., 2020]. Midday high temperature and high vapour pressure deficit often result in decrease in stomatal conductance and, consequently in transpiration at noon and/or early afternoon due to temporal drought stress in leaf tissues caused by insufficient water supply from roots [Tuzet et al., 2003; Sabir et al., 2015; Yan et al., 2016]. This contributes to the diurnal pattern of water vapour pressure. In our study atmospheric vapour pressure increased since early morning hours until 9:00 (17–17.3 hPa) and then gradually decreased until the late afternoon. The pattern was similar for both sites, however in late afternoon hours the vapour pressure was lower in the housing estate. Indeed, in sunny days when air temperature increases, the air moisture decreases [Gillner et al., 2015]. In our study diurnal pattern of relative humidity was similar in both sites on both days. However, higher VPD combined with higher atmospheric vapour pressure in the street with heavy traffic (KEN) was bound with the higher air temperatures in that site (which was confirmed by the leaf temperature) due to the relationship between atmospheric vapour pressure, VPD and air temperature. This shows that in open areas without trees the air temperature raises more than in housing estate interiors densely covered by vegetation [Manickathan et al., 2018]. However, even though the transpiration from urban vegetation does not fully compensate for midday VPD mitigation, the morning contribution of transpiration has a significant impact on site-specific microclimate [Rahman et al., 2017].

CONCLUSIONS

The contribution of urban vegetation to improvement of environmental conditions was previously widely discussed with different findings. It is generally agreed that in countries of northern latitudes vegetation do not remove carbon dioxide from atmosphere during the winter. However, some contribution during growing seasons exists. Our study conducted in the suburban district of the city of nearly 2 million inhabitants showed that due to summer photosynthetic activity abundant vegetation has a potential to remove a significant amount of carbon dioxide. The contribution for increasing atmospheric humidity is also evident, however, is highly moderated by microclimatic variables including temperature and wind. Once the stomata and leaf gas exchange are activated in the morning the vapour pressure in the air increases, however, increasing air temperature and other microclimatic factors influence the further pattern of atmospheric water vapour, vapour pressure deficit and relative humidity. Nevertheless, inside the housing estate with buildings surrounded by greenery the vapour pressure deficit and temperature were lower than in the street. More abundant vegetation contributes significantly to the improvement of microclimatic conditions in the city. In future research a comparison of different types of housing estate structure (blocks of flats with public gardens, terraced house estates with private gardens, green roofs etc.) may give valuable guidelines for city planners how to shape residential areas.

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