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Daytime cooling efficiencies of urban trees derived from surface temperature are much higher than those for air temperature

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Abstract

Accurately capturing the impact of urban trees on temperature can help optimize urban heat mitigation strategies. Recently, there has been a widespread use of remotely sensed land surface temperature (T_s) to quantify the cooling efficiency (CE) of urban trees. However, remotely sensed T_s reflects heat radiation from the surface of an object seen from the point of view of the thermal sensor, which is not a good proxy for the air

temperature (T_a) perceived by humans. The extent to which the CEs derived from T_s reflect the true experiences of urban residents remains unclear. Therefore, this study systematically compared the T_s-based CE (CE_{Ts}) with the T_a-based CE (CE_{Ta}) in 392 European urban clusters. CE_{Ts} and CE_{Ta} were defined as the reduction in T_s and T_a, respectively, for every 1% increase in fractional tree cover (FTC). The results show that the increase in FTC has a substantial impact on reducing T_s and T_a in most cities during the daytime. However, at night, the response of T_s and T_a to increased FTC appears to be much weaker and ambiguous. On average, for European cities, daytime CE_{Ts} reaches 0.075 °C $\%^{-1}$, which is significantly higher (by an order of magnitude) than the corresponding CE_{Ta} of 0.006 °C $\%^{-1}$. In contrast, the average nighttime CE_{Ts} and CE_{Ta} for European cities are similar, both approximating zero. Overall, urban trees can lower daytime temperatures, but the impact of their cooling effect, particularly concerning public health implications, is notably amplified when using remotely sensed T_s estimates compared to in situ T_a measurements. Our findings provide critical insights into the realistic benefits of alleviating urban heat through tree planting.

Keywords: Urban heat islands; green space; in situ measurements; ecosystem service; mitigation strategies

1.Introduction

The process of urbanization, marked by changes in land cover and the release of anthropogenic heat emissions, typically results in elevated temperatures within urban

areas, giving rise to the phenomenon known as the urban heat island (UHI) effect (Grimm *et al* 2008, Kalnay and Cai 2003, Zhang *et al* 2022b). This additional urban warming can have negative impacts on various aspects of urban environments, including vegetation growth, the hydrological cycle, and the soil quality (Gui *et al* 2019, Zhou *et al* 2018, Zou *et al* 2021). Moreover, urban heat can pose a risk to the well-being of urban residents, influencing their indoor and outdoor thermal comfort and even leading to added mortality (Iungman *et al* 2023, Ren *et al* 2023, Zhou *et al* 2018). Therefore, urban heat and strategies for its mitigation have garnered increased attention in recent years (Chakraborty *et al* 2022c, Hsu *et al* 2021, Liu *et al* 2023, Schneider *et al* 2023, Tuholske *et al* 2021, Yang *et al* 2023, Yao *et al* 2018, Zhou *et al* 2018). Increasing vegetation cover, particularly through the tree planting, is a feasible and commonly used approach for alleviating urban heat (Iungman *et al* 2023, Schwaab *et al* 2021, Zhang *et al* 2023). Trees outperform other vegetation in terms of evapotranspiration and shading, rendering them effective in mitigating elevated temperatures (Liu *et al* 2021, Zhang *et al* 2023, Zhou *et al* 2017). Consequently, the study of the cooling effect (CE) of trees is a prominent and actively researched topic in the field of urban climate.

Traditionally, the efficiency of trees' cooling is quantified by directly comparing the air temperature (T_a) between areas with and without trees using in-situ measurements (Akbari *et al* 1990, Richards *et al* 2020, Yan *et al* 2020, Zhang *et al* 2020). Such approach offers the advantage of continuous, long-term observations and yields results, specifically T_a, that align closely with human perception (Goldblatt *et al*

2021). However, in situ measurements of the thermal environment (e.g. weather stations or mobile transects) are usually characterized by spatial discontinuities and limited coverage, making them too costly for extensive large-scale analyses (Jiao *et al* 2017, Loughner *et al* 2012, Meili *et al* 2021, Peters *et al* 2010, Richards *et al* 2020, Wang *et al* 2018, Wang *et al* 2012, Wujeska-Klause and Pfautsch 2020, Yan *et al* 2020, Zhang *et al* 2020). With the proliferation of satellite observations, remotely sensed land surface temperature (T_s) has been often used for quantifying the CE of urban trees due to its advantages of spatial continuity (Wang *et al* 2019, Wang *et al* 2020, Yang *et al* 2022). Nevertheless, it is crucial to acknowledge that a distinction exists between remotely sensed T_s observations and in situ T_a measurements (Chakraborty *et al* 2017, Goldblatt *et al* 2021, Janatian *et al* 2017, Jin and Dickinson 2010, Jin 2012, Naserikia *et al* 2023, Venter *et al* 2021, Zhang *et al* 2014).

The differences between T_s and T_a are primarily evident in two aspects. Firstly, T_s and T_a vary in magnitude and spatial distributions, originating from factors like radiation, heat transfer, and storage processes (Cao *et al* 2021, Mutiibwa *et al* 2015). Solar radiation absorbed by surface materials with high emissivity results in a significant increase in surface temperature, whereas air, with its lower emissivity, is less efficient at absorbing and radiating energy (Harde 2013, Li *et al* 2013). Heat transfer via conduction and convection contributes to temperature interaction, but the efficiency of this process is limited by air's low thermal conductivity (Lu *et al* 2014, Zhou *et al* 2012). The higher thermal capacity of surface materials enables them to absorb more heat during the day compared to air, thereby amplifying temperature discrepancies

between the surface and the surrounding air (Mohajerani *et al* 2017). Secondly, T_s and T_a represent different components of the environment, with distinct impacts on human comfort. T_s is typically not directly experienced by urban pedestrians since we do not come into direct contact with the surfaces using our bare skin (Goldblatt *et al* 2021, Haeri *et al* 2023). Moreover, T_s measurements often relate to elevated locations like rooftops, walls, and tree canopies, areas typically less frequented by humans for daily activities (Battisti *et al* 2018, Haeri *et al* 2023, Vanos *et al* 2016). As a result, the trees' CE derived through T_s may not appropriately capture the public health impacts on urban inhabitants, which are typically more aligned with T_a as perceived by humans (Chakraborty *et al* 2022c, Novick and Katul 2020).

Although multiple numerical modeling studies have estimated the CE of urban trees (Krayenhoff *et al* 2021), observational estimates are much rarer (Chakraborty *et al* 2022c, Ziter *et al* 2019), partly due to the dearth of dense T_a measurements within cities (Zaitchik and Tuholske 2021). As a result, many researchers have quantified the CE of urban trees using the remotely sensed T_s observations and considered the slope of T_s versus tree cover fraction as the estimated CE (Chakraborty *et al* 2022a, Chinchilla *et al* 2021, Schwaab *et al* 2021, Wang *et al* 2019, Wang *et al* 2020, Zhao *et al* 2023a, Zhou *et al* 2021). Since T_s and T_a are different, we would also expect substantial differences in T_a-based CE (CE_{Ta}) and T_s-based CE (CE_{Ts}). Knowledge about how CE_{Ts} deviates from CE_{Ta} is critical for gaining a more physiologically-relevant understanding of the role played by trees in shaping the urban thermal environment. However, there is still a lack of large-scale and quantitative assessments of the relationship and

difference between CE_{Ts} and CE_{Ta}. The study by Chakraborty et al. (2022a) is the only relevant one, but it utilizes a vegetation index instead of a tree cover fraction, rendering the two measurements not directly comparable (Zeng *et al* 2023).

Hence, by using a spatiotemporally matched in situ T_a and remotely sensed T_s datasets, we calculated CE_{Ta} and CE_{Ts}, respectively, in 392 European urban clusters. Subsequently, we conducted a comparative analysis of the differences between CE_{Ta} and CE_{Ts} in terms of spatial distribution and day-night contrast. The results of this study can deepen our understanding of the cooling benefits of urban trees and help mitigate heat stress from the urban planning perspective.

2. Data and methods

2.1 Data selection and processing

The fractional tree cover (FTC) was obtained from the Copernicus Global Land Service (CGLS) dataset (2019). Based on over 20, 000 random samples, Buchhorn et al. (2020) reported that the CGLS dataset had an overall accuracy of better than 80% for all land-cover types and a global average absolute error of 9% for the FTC (Buchhorn *et al* 2020). The surface water was derived from the Global Surface Water (GSW) data produced by the Joint Research Centre (JRC) (Pekel *et al* 2016), which provides annual maximum surface water extents. Surface elevation information was obtained from Global 30 Arc-Second Elevation (GTOPO30) dataset.

The growing popularity of Citizen Weather Stations (CWS) in urban areas in recent years has facilitated the crowdsourcing of intensive meteorological observations.

Venter et al. (2021) obtained hourly T_a data for July 2019 from all available CWS provided by Netatmo in Europe (Chakraborty *et al* 2022b). The CWS T_a data underwent additional cleaning processing to remove stations with poor data quality or significant missing data (Venter *et al* 2021). This led to the final selection of 75,293 CWS stations, distributed across 931 European urban clusters. The boundaries of urban clusters were derived from the Global Human Settlement Layer (GHSL) dataset using the clustering method proposed by Venter et al. (2021).

Daily T_s data for the European urban clusters during July 2019 were collected from the MODIS products (MOD11A1 and MYD11A1). These T_s data were preprocessed into clear-sky pixels with an average T_s error less than or equal to 3 K. MODIS satellites collected data every day around 1:30, 10:30, 13:30, and 22:30 local time to provide daytime and nighttime T_s observations. To obtain the hour-by-hour T_s values, the MODIS transit time from local solar time was converted to UTC local time by subtracting the longitude of the MODIS grid and dividing by 15, according to the MODIS user guide (Wan 2006). The time zones of each urban cluster were then accounted for and combined with daylight saving time to offset the UTC of each city. This resulted in T_s readings with specific hourly timestamps that could be synchronized with the hourly CWS dataset (Chakraborty *et al* 2022b, Venter *et al* 2021).

The T_s pixels were paired with the treated CWS T_a stations based on coordinates and time (Venter *et al* 2021). Subsequently, we calculated the median values of T_s and T_a at each station for the study period separately. We chose the median rather than the mean to avoid the effects of extreme temperatures. Then, we extracted information

about tree cover fraction, elevation, and the presence of surface water for each station. In each urban clusters, we removed stations covered by surface water or influenced by topographic relief (out of the range of mean elevation ± 100 meters) (Cao *et al* 2016, Li *et al* 2022). In addition, we removed urban clusters with too few stations (< 20) to ensure the stability of the regression model for calculating the CE of urban trees. The above processes reduced the number of available stations to 40,364. Ultimately, a total of 392 urban clusters were included in this study. It should be emphasized that the MOD11A1 T_s had data gaps during nighttime due to cloud contamination and quality degradation, resulting in an insufficient number of observations (< 20) in some urban clusters. Therefore, we calculated the CE corresponding to the MOD11A1 nighttime T_s (~22:30) only for the 232 urban clusters.

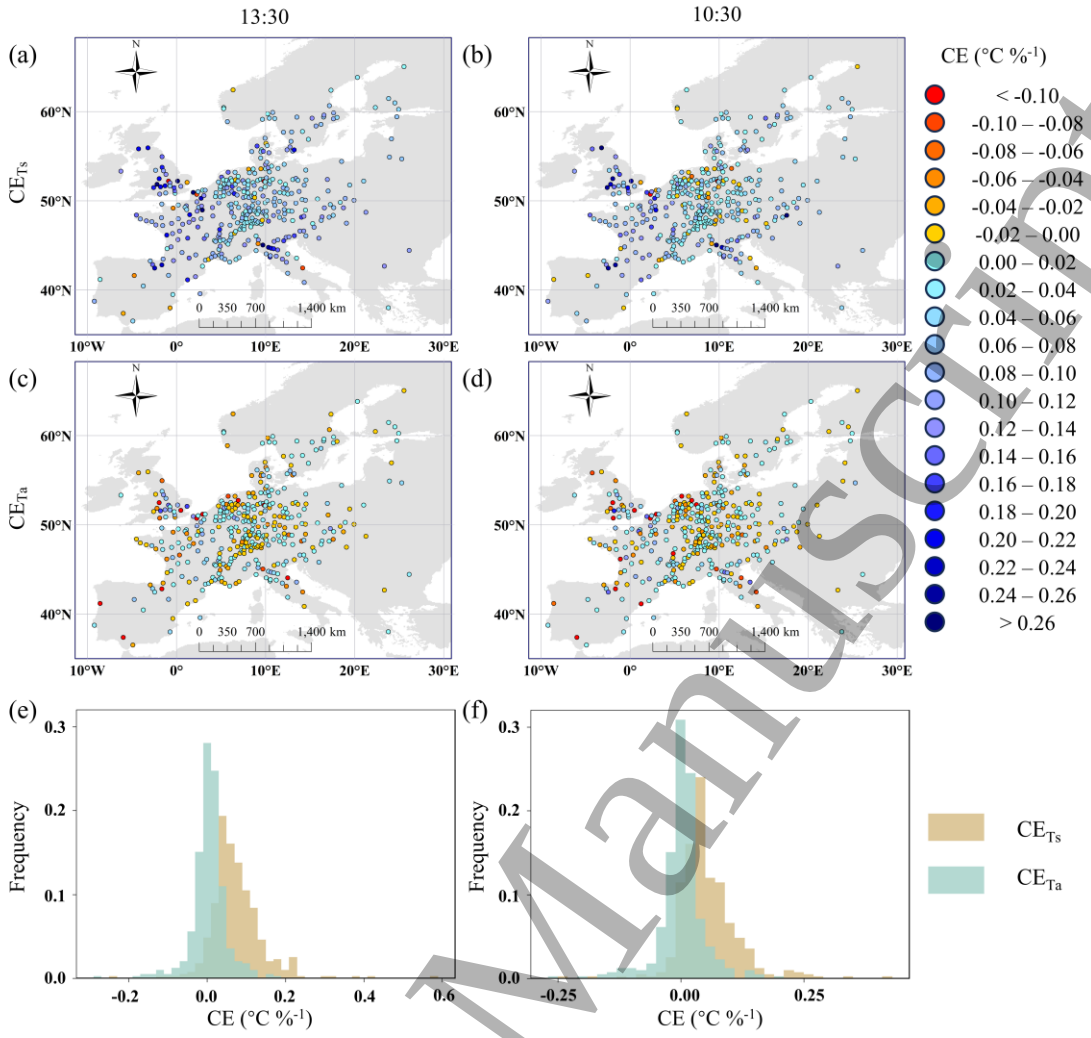

Figure 1. Spatial patterns and frequency distributions of daytime urban trees' cooling efficiency (CE) across European urban clusters. CE_{Ts} and CE_{Ta} represent the CE estimated by surface temperature and the CE estimated by air temperature, respectively. The observational times are ~13:30 for AQUA and ~10:30 for TERRA, respectively. The air temperature corresponds to overpassing time of the overlaying MODIS pixels.

2.2 Calculation of urban trees' CE

In this study, we employed a univariate linear regression model to calculate the CE_{Ts} and CE_{Ta} for each urban cluster. In this model, we considered FTC as the

independent variable, and either T_s or T_a as the dependent variable. We computed the regression coefficients and used the opposite of these coefficients as the urban trees' CE , denoted as $CE_{Ts} = -\triangle T_s/\triangle FTC$ and $CE_{Ta} = -\triangle T_a/\triangle FTC$. CE_{Ts} and CE_{Ta} represent the reduction in T_s and T_a, respectively, for each 1% increase in the percentage of urban trees, and measure the CE of urban trees with respect to T_s and T_a (Cheng *et al* 2022, Wang *et al* 2019, Wang *et al* 2020, Yang *et al* 2022). If CE_{Ts} is higher than CE_{Ta}, it suggests a higher estimated CE of urban trees based on T_s compared to T_a, and vice versa.

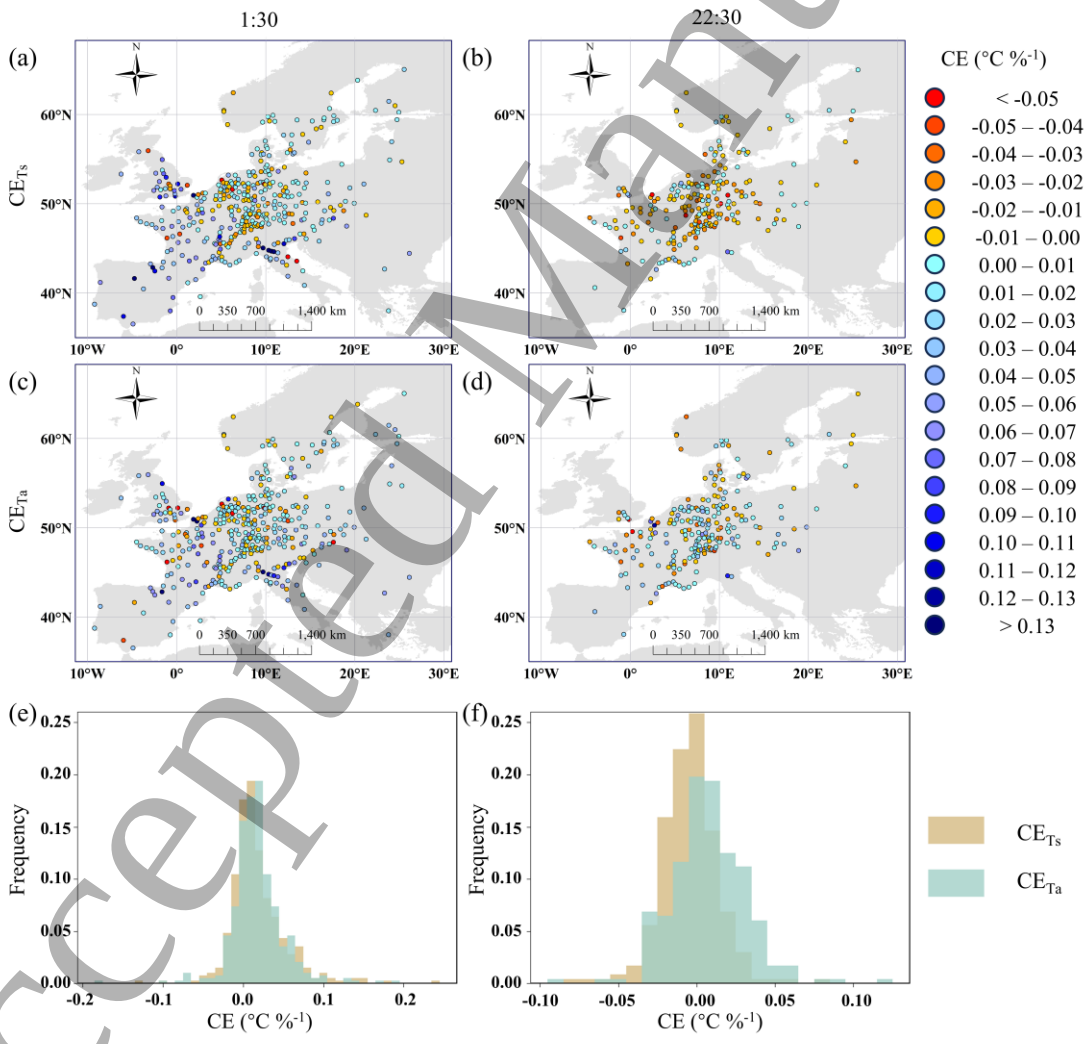

Figure 2. Spatial patterns and frequency distributions of nighttime urban trees' cooling

efficiency (CE) across European urban clusters. CE_{Ts} and CE_{Ta} represent the CE estimated by surface temperature and the CE estimated by air temperature, respectively. The observational times are ~1:30 for AQUA and ~22:30 for TERRA, respectively. The air temperature corresponds to overpassing time of the overlaying MODIS pixels.

3. Results

During the daytime, both CE_{Ts} and CE_{Ta} show positive values in most urban clusters, indicating the prevailing cooling effect exerted by urban trees on local temperatures. Statistically, over 90% urban clusters exhibit positive daytime CE_{Ts}, whereas the corresponding percentage for daytime CE_{Ta} stands at approximately 60%. Besides, higher values of CE_{Ts} and CE_{Ta} are mostly concentrated in western Europe and south-central Europe. On average for all urban clusters, CE_{Ts} reaches 0.075 [0.069, 0.082] °C $\%^{-1}$ (95 % confidence intervals in parentheses, hereafter) and 0.055 [0.049, 0.061] °C $\%^{-1}$ at local times ~13:30 and ~10:30, respectively. These mean values of CE_{Ts} are significantly ($p < 0.001$, t-test) higher than corresponding averages of CE_{Ta}, which are 0.006 [0.001, 0.010] °C $\%^{-1}$ and 0.003 [-0.001, 0.008] °C $\%^{-1}$, respectively (Figure 3). These results indicate that the daytime urban trees' CE quantified by T_s differs from that estimated by T_a, which is further supported by the weak correlation between CE_{Ts} and CE_{Ta} across all urban clusters (Figure 4).

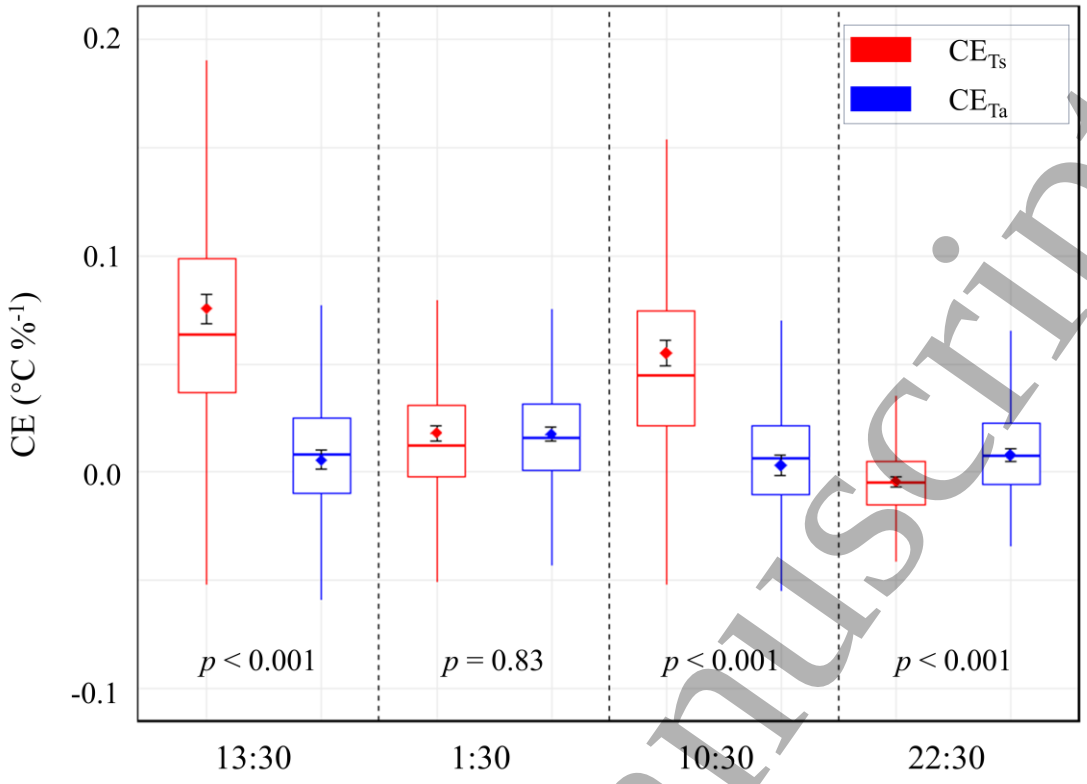

Figure 3. Comparisons of the urban trees' cooling efficiency estimated by surface temperature (CE_{Ts}) with that estimated by air temperature (CE_{Ta}). The *p*-value represents the significance of t-tests between CE_{Ts} and CE_{Ta}. If the *p*-value is less than 0.05, it indicates a statistically significant difference between CE_{Ts} and CE_{Ta}. The lines and dots in the boxes represent median and mean values of trees' cooling efficiency, respectively. The error bars indicate 95% confidence intervals. The observational times are ~13:30 and~1:30 for AQUA, and ~10:30 and ~22:30 for TERRA. The air temperature corresponding to overlaying MODIS pixels are used for daytime and nighttime overpasses.

At night, CE_{Ta} is found to be positive in over 70% urban clusters, while CE_{Ts} does not exhibit a fixed positive or negative tendency. In addition, higher values of CE_{Ts} and CE_{Ta} are concentrated in western Europe and south-central Europe. On average for all

urban clusters, CE_{Ts} reaches 0.018 [0.015, 0.022] °C $\%^{-1}$ and -0.004 [-0.007, -0.002] °C $\%^{-1}$ at local times ~13:30 and ~10:30, respectively. The mean values of these CE_{Ts} did not differ significantly from the corresponding averages for CE_{Ta}, which are 0.018 [0.014, 0.021] °C $\%^{-1}$ and 0.008 [0.005, 0.011] °C $\%^{-1}$, respectively (Figure 3). These results indicate that the nighttime urban tree' CE quantified with T_s has a higher similarity to that estimated by T_a compared to the daytime results. This finding is further supported by the observation that the distribution of CE_{Ts} and CE_{Ta} aligns more closely with the 1:1 line during nighttime than during daytime (Figure 4).

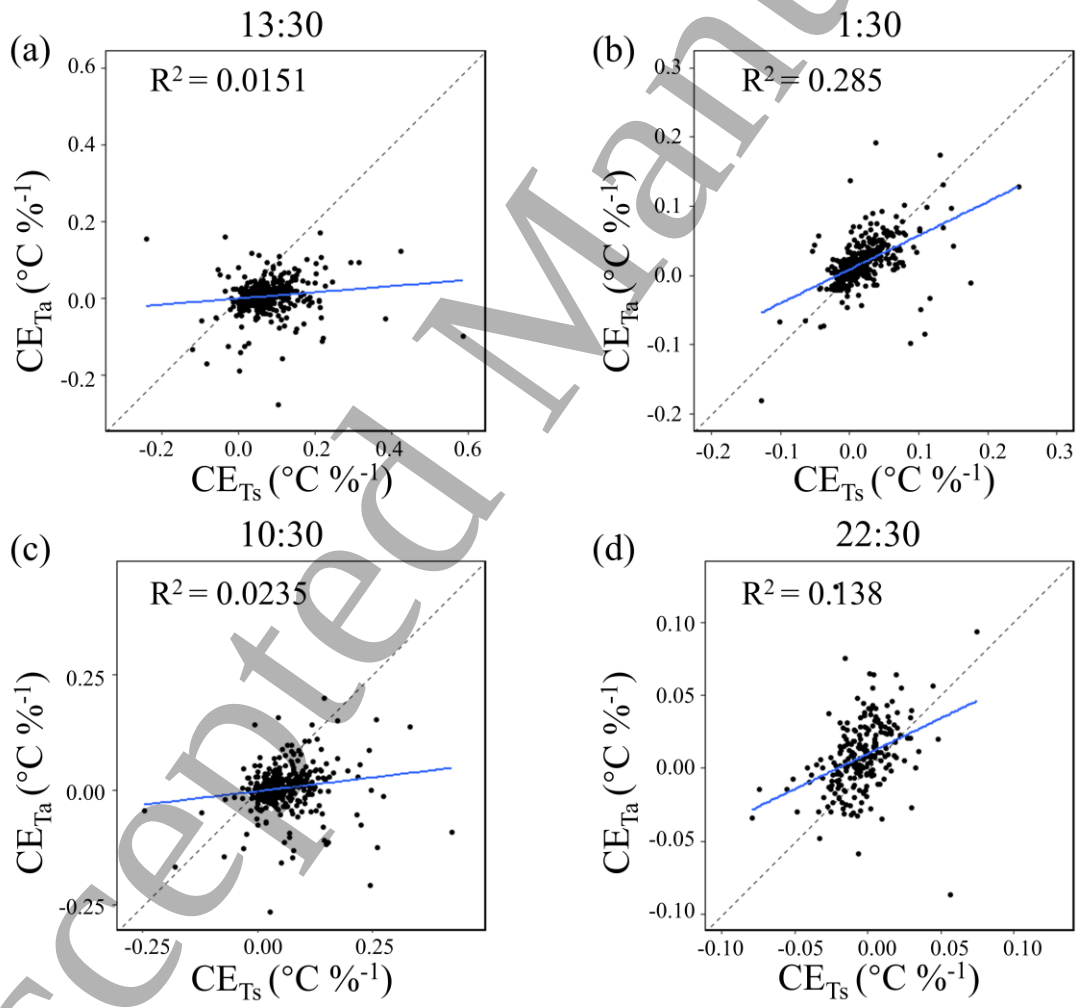

Figure 4. Correlations between the urban trees' cooling efficiency estimated by surface temperature (CE_{Ts}) and that estimated by air temperature (CE_{Ta}). The observational

times are ~13:30 and~1:30 for AQUA, and ~10:30 and ~22:30 for TERRA. The air temperature corresponding to overlaying MODIS pixels are used for daytime and nighttime overpasses.

To provide a more intuitive representation of the difference between CE_{Ts} and CE_{Ta}, we selected six prototypical urban clusters (Berlin, Paris, Reims Budapest, Bratislava, and Wien) with different climates, tree species, and city sizes for closer examination (Figure 5). It can be seen that both daytime T_s and T_a show almost a consistent decreasing trend with increasing FTC (i.e. fractional tree cover), suggesting that trees can play a role in reducing urban localized temperatures. However, T_s typically exhibits a greater range of spatial variability relative to T_a, and the extent of temperature change triggered by an equivalent percentage increase in FTC is more pronounced for T_s compared to T_a. This discrepancy in the response of T_s and T_a to increased FTC ultimately leads to the observed difference between CE_{Ts} and CE_{Ta}.

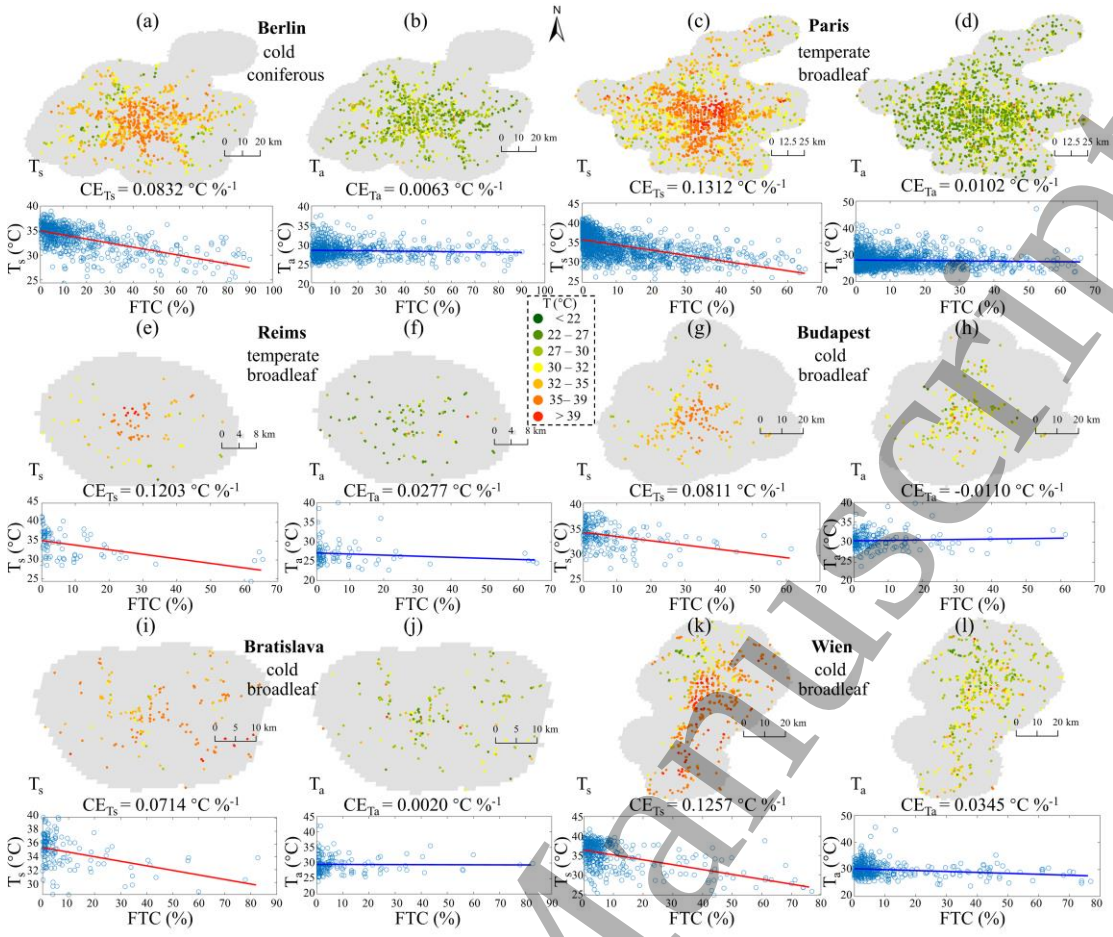

Figure 5. Changes of surface temperature (T_s) and air temperature (T_a) along fractional tree cover (FTC) gradients, taking Berlin, Paris, Reims Budapest, Bratislava, and Wien as examples. These urban clusters are situated in various climate zones, including temperate and cold zones, and feature different dominant tree species, such as coniferous and broadleaf trees.

4.Discussion

4.1 Spatiotemporal difference in the urban trees' CE estimated by T_s and T_a

The findings suggest a noticeable CE of urban trees during the daytime, and the impact of trees on reducing T_s is found to be substantially more than that on T_a. Tree release water vapor through small pores called stomata in their leaves, also known as

transpiration (Pirasteh-Anosheh *et al* 2016). As this water evaporates, it absorbs heat from the surroundings, lowering the temperature of the surface, which in turn impacts the near surface (Gunawardena *et al* 2017). Evapotranspiration occurs in the immediate vicinity of the ground, where trees draw up water from the soil and release water vapor through stomata in their leaves (Berry *et al* 2010). This close proximity to the surface means that the CE is more directly felt at ground level (Armson *et al* 2012). While water vapor released through evapotranspiration does influence T_a, the impact is somewhat diluted as it mixes with the larger volume of the atmosphere (Gunawardena *et al* 2017). Therefore, the CE for T_a is not as concentrated as it is at the surface. Second, trees provide shade by blocking sunlight from reaching the ground, which reduces the amount of solar radiation absorbed by the Earth's surface, leading to a substantial CE (Coutts *et al* 2016). On the other hand, T_a is influenced by a variety of factors, including the absorption of solar radiation by the atmosphere, conduction, convection, and radiation (Raman *et al* 2014). While shading by trees can have some influence on the T_a by reducing the amount of solar radiation reaching the ground, the atmosphere itself is less directly affected by shading compared to the surface (Rahman *et al* 2017). Therefore, the shade provided by trees has a more direct impact on the T_s than on the T_a. Third, trees play a pivotal role in creating microclimates by regulating soil moisture in their immediate surroundings (Pramova *et al* 2012). Adequate soil moisture contributes to a cooler surface, and the impact of soil moisture regulation is particularly significant at the surface level, where trees interact with the ground (Lagergren and Lindroth 2002). In summary, the creation of microclimates by trees involves a

combination of factors, including the evapotranspiration process, soil moisture control, and shade provision. While these factors also influence T_a, their immediate and more pronounced effects are often observed at the surface level where the vegetation interacts intimately with the ground.

However, the CE of urban trees on nighttime temperatures is very limited in most cities. During the night, in the absence of sunlight for photosynthesis, trees generally close their stomata (Domec *et al* 2012). As a consequence of stomatal closure, metabolic activities in the leaves, including transpiration, slow down or cease (Dawson *et al* 2007). This reduction in transpiration leads to a notable decrease in the CE facilitated by this process (Zheng *et al* 2021). In addition, trees, especially deciduous ones, typically have a lower albedo, which results in more energy absorption during the day (Hami *et al* 2019). The additional absorbed energy is then released at night, thereby offsetting the cooling benefits that trees typically provide (Li *et al* 2015, Peng *et al* 2014). Furthermore, in urban environments, tall and dense trees can influence the dissipation of heat from various structures. The obstruction of airflow may contribute to heat retention in certain areas, especially during calm nights (Cleugh 1998, Zhao *et al* 2023b). The factors mentioned above, to some extent, offer a plausible explanation for the reduced CE of trees at night. This also underscores the complex interplay of various factors in shaping the overall thermal behavior of urban environments influenced by tree cover.

We have identified notable variations in the CE of urban trees across different cities. Firstly, the daytime CE is found to be higher in western Europe compared to central

Europe (Figure 1). This difference may be attributed to variations in tree species. Western Europe is dominated by oaks from broadleaf forests (https://inventaire-forestier.ign.fr/spip.php?rubrique86), while central Europe is dominated by spruce and pine from coniferous forests (Holzwarth *et al* 2020). Characteristics of urban trees, such as leaf structure, color, size, and density, directly influence their effects on the surrounding environment and the observed CE (Liu *et al* 2019, Wang *et al* 2021). Secondly, a relatively higher CE is also observed in south-central Europe, characterized by a hotter and drier environment. This may be attributed to the nonlinear response of urban trees' activity to meteorological conditions, which generally manifests itself as an increase in evapotranspiration rates with increasing temperature and decreasing humidity (Wang *et al* 2019, Wang *et al* 2020, Yang *et al* 2022). Besides, the role of urban trees in moderating temperature is also influenced by their spatial configurations, with densely and continuously distributed trees tending to provide more cooling benefits (Fan *et al* 2019, Zhou *et al* 2017). This may provide a plausible explanation for the significantly higher CE in some well-greened cities, such as Ludenscheid and Sodertalje (Figure 1).

4.2 Significance and implications.

This study finds that the estimated daytime CE of urban trees, based on T_a, is largely lower than that based on T_s, which is in line with field-level estimates for general afforestation (Novick and Katul 2020) and multi-city estimates based on vegetation index (Chakraborty *et al* 2022c). Many recent multi-city studies have primarily utilized

T_s instead of T_a to assess the cooling efficiency of trees in mitigating hot environments (Chakraborty *et al* 2022a, Cheng *et al* 2022, Chinchilla *et al* 2021, Schwaab *et al* 2021, Wang *et al* 2019, Wang *et al* 2020, Zhao *et al* 2023a, Zhou *et al* 2021). However, T_a is more closely related to temperatures perceived by humans than T_s. Hence, the current T_s-based CE might inflate the cooling effectiveness of tree planting concerning public health outcomes. This could potentially foster an excessively optimistic perspective regarding the cooling advantages associated with urban trees (Chakraborty *et al* 2022c, Venter *et al* 2021, Wang *et al* 2023a). It should be noted that increased fractional tree cover seems to be associated with a more efficient cooling of temperatures in western and south-central Europe. Therefore, emphasizing the increase of tree cover in these regions could be crucial for mitigating the adverse effects of high temperatures on human well-being. However, overall, it appears that the increase in tree cover in most parts of Europe is not significantly associated with a reduction in T_a. Particularly at night, there is even evidence of a warming effect of tree cover in some cities. Consequently, relying solely on increasing tree cover may not be sufficient for alleviating urban heat stress, and a more comprehensive approach may be necessary. Policymakers should contemplate implementing additional measures to effectively address the escalating urban heat island effect. Feasible practical measures may involve enhancing surface albedo through the adoption of lighter roofing and paving materials, along with reducing human-generated heat emissions through promoting energy-saving lifestyles (Hayes *et al* 2022).

While we focus on urban vegetation impacts on T_a and T_s in the present study, there

are other aspects of heat exposure within cities that should be kept in mind. Of note, urban trees can also increase humidity through transpiration (Meili *et al* 2020), which, in turn, can increase moist heat stress, all else remaining equal (Chakraborty *et al* 2022c, Ho *et al* 2016). While T_s should not directly be used as a proxy for heat stress, T_s has been successfully used as input to data-driven models to estimate urban T_a (Venter et al 2020, Zhang et al 2022a) and even humidity (Wang *et al* 2023b). Trees can also provide shading, which during midday, can have a dominant impact on reducing heat loading (Middel *et al* 2021). However, T_a is only indirectly related to shading and satellites cannot sufficiently resolve shading from trees since they are primarily observing the top of the tree canopy. A recent study (Li *et al* 2023) over Philadelphia, USA estimated mean radiant temperature (T_{mrt}), a metric for thermal discomfort that also accounts for radiant heat, and found that satellite-derived T_s showed medium to strong associations with T_{mrt}. A future direction may be to examine quantitative differences and similarities between the CE for T_s and T_{mrt}.

4.3 Limitations and future studies

The present study has certain limitations that should be kept in mind. First, it's important to note that the study area is limited to Europe, and therefore our findings cannot be generalized to other climate zones globally. Second, this study only considers data from the summer month of July, overlooking seasonal variations in vegetation activity, which are temperature-dependent. It is crucial to conduct in-depth investigations into the similarities and differences in CE quantified T_s and T_a in other

seasons to capture the full spectrum of potential variations. Third, there is a discrepancy in the spatial continuity and scale between satellite T_s observations and in situ T_a measurements, and a more detailed analysis considering variations at different spatial scales could provide additional insights. Fourthly, there are sampling biases in the CWS data which are difficult to correct for. The most prominent bias is that CWS are typically placed in residential areas, rather than in commercial districts, which tend to experience higher temperatures (as indicated by T_s) (Chakraborty *et al* 2022c, Hulley *et al* 2019). This means that when utilizing CWS data, we might systematically overlook non-residential areas where pedestrians could still face higher-than-expected heat stress. To ensure the accurate utilization of CWS in urban research, it is essential to improve the metadata for the sensor locations. Furthermore, there is a pressing need for more robust quality control measures. To address the aforementioned limitations, future investigations should incorporate large-scale, multi-seasonal and multi-scale analyses from multiple data sources, to support more robust constrains on the physiologically-relevant cooling efficiency of urban trees.

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76RL01830.

Data availability

The data that support the findings of this study are openly available. The CWS air temperature measurements and corresponding MODIS land surface temperature observations are available at https://github.com/TC25/Europe_CWS. The CGLS fractional tree cover data can be downloaded from https://zenodo.org/records/3939050. The JCR global surface water data can be accessed from https://global-surface-water.appspot.com/download. The Global 30 Arc-Second Elevation data is available from https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-global-30-arc-second-elevation-gtopo30.

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