Original article

Effects of severe pruning on the microclimate amelioration capacity and on the physiology of two urban tree species

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ABSTRACT

With the constant increase of the world human population, considering the rise of temperature and the frequency of heat waves predictable by climate change, a mitigation of the negative effects on human health in urban context becomes crucial.

The green component of a city has a high potential on climate regulation and it becomes a key factor for the planification and sustainability of the urban environment. Incorrect pruning, especially if made by topping cut and associated whit big cuts, can significantly affect total leaf area of trees, their growth pattern as well as their microclimate amelioration capacity.

The purpose of this study is to evaluate the effect of topping practice on the microclimate and on the physiology of trees. In 2004, 90 uniform diameter trees of *Acer platanoides* L. (Ap) and *Tilia x europaea* L. (Te) of the same age were planted in an experimental plot. After twelve years, when they reach 18 cm of average diameter, half of these trees were submitted to a topping operation, following a randomized block configuration, by removing 85 % of the crown to simulate a bad techniques which are alas common in city green management. The evaluation of human comfort was done using two biometeorological indices calculated from humidity and temperature, measured with a sensor under the canopy while the growth of trees was monitored with biometric measurements. Leaf gas exchanges were assessed during the two growing seasons after topping (2017–2018) with an infrared gas analyser and by measuring CO_2 assimilation as the function of internal $[CO_2]$, A/Ci curves were drawn. From photosynthesis and transpiration values per unit leaf area, total CO_2 assimilation and latent heat dissipation through transpiration have been scaled to the whole plant using Big Leaf model.

This study shows how topping significantly impacts the capacity of trees to ameliorate the microclimate. Biometeorological indices showed higher values below topped trees, especially in the hottest months. Despite a temporary increase of transpiration, the energy dissipated by topped trees was significantly lower, due to the smaller total leaf area. Topped trees showed an average value of latent heat dissipated by the hole tree 73,5 % lower in Te and 81,1 % in Ap. Topped trees showed different growth patterns, with higher investment in crown growth at the cost of stem enlargement. This strong crown growth reaction is due principally to adventitious watersprouts and root suckers, with higher average leaf area compared to unpruned trees. In the two years after topping, both species showed some level of compensatory photosynthesis, as well as higher stomatal conductance, chlorophyll content and mesophyll conductance to CO_2. Even considering this temporary photosynthetic increase, due to the large amount of surface removed, topping caused a loss in the total CO_2 assimilation.

These results show how a correct management is necessary to assure an effective and efficient microclimate improvement. The maintenance of apical control and apical dominance are key issues to preserve a healthy tree structure, as well as the long-term efficiency of the photosynthetic apparatus.

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1. Introduction

The urban heat island (UHI, i.e., the rise in urban temperatures compared to the surrounding rural environment) is a well-known phenomenon that can exhibit both spatial and temporal variations due to meteorological characteristics and the structural configuration of urban areas (Santamouris et al., 2001). UHI is typically associated with a positive urban thermal balance, linked to changes in the absorption and reflection of solar radiation, as well as the concentration of anthropogenic heat sources (Santamouris, 2014). UHI can pose significant risks to human health and ecosystems. For example, during the 2003 heatwave, heat-related deaths in Europe exceeded 70,000, while in 2022, the death toll surpassed 60,000 (Robine et al., 2008; Ballester et al., 2022). This effect is expected to intensify globally due to climate change (Guo et al., 2018).

In addition to temperature, air humidity and wind speed can also impact human thermal comfort, health, and well-being (Takács et al., 2016). The flux densities of short- and long-wave radiation from the environment, which influence the human energy balance, can also affect thermal comfort, though individuals' sensitivity (or susceptibility) to outdoor thermal environments may vary (Stathopoulos et al., 2004). Human thermal comfort can be assessed using a variety of theoretical and empirical indices, which require input parameters such as solar radiation, humidity, and air temperature. Two commonly used indices are the Apparent Temperature Index (ATI) and the HUMIDEX index. As reported by Brandani et al. (2016), the ATI considers several factors that influence an individual's perception of weather, including temperature, humidity, wind speed, and the rate at which the human body dissipates heat (Steadman, 1994). By incorporating these elements, the ATI offers a comprehensive and reliable assessment of the impact of temperature on human comfort and health. The HUMIDEX is a temperature-humidity index first introduced in Masterton and Richardson (1979). It provides valuable information about how hot and uncomfortable weather feels to individuals by considering two key meteorological parameters: air temperature and relative humidity.

Urban green areas are an effective nature-based solution to mitigate the intensity of UHI, improve human thermal comfort, and provide multiple ecosystem services (Takebayashi and Moriyama, 2007; Takacs et al., 2016). Trees, because of their higher crown dimensions and total leaf area compared to shrubs and grass, play a key role in the provision of such benefits (Shashua-Bar et al., 2009). Climate amelioration by urban trees is mainly linked to air temperature reduction, which is achieved through transpiration and shading. Tree crowns reduce air temperature by shielding direct solar radiation, i.e., limiting the absorption of short-wave radiation and consequently reducing long-wave emission from the ground to the surrounding environment (Rahman et al., 2021). The shading capacity of individual trees depends on plant and canopy height and crown radius, which determine the size of the shaded area, as well as canopy density and Plant Area Index (PAI), which influence the density of the shade (Rahman et al., 2015; McPherson et al., 2018). Moreover, through the process of transpiration, advected heat is absorbed, allowing energy to be partitioned more as latent rather than sensible heat flux (Rahman et al., 2017).

Transpiration is determined by two major resistances: aerodynamic and stomatal resistance, which set the transpiration rate per unit of leaf area, and by crown radius and leaf area index, which determine the transpiring area (Allan et al., 1998; Luo et al., 2018). Aerodynamic resistance is primarily influenced by environmental factors, such as air humidity and windspeed. Stomatal resistance is finely modulated by the plant in response to genetic, environmental, and cultural stimuli (Pace et al., 2021).

Some research has been conducted to evaluate, through empirical and process-based approaches, the potential of different species to cool the environment through shading and transpiration (Rahman et al., 2015; McPherson et al., 2018). Such information may be crucial to support the "right tree in the right place" concept (Ferrini et al., 2017).

However, to maximize the provision of the desired benefits, proper management should not be overlooked.

Pruning is a major management practice that affects tree crown size and/or density, and thus the tree's capacity to improve the microclimate and provide other ecosystem services (Ferrini et al., 2017). Consistently, routinely pruned street trees assimilated 20–70 % less CO_2 compared to even-aged, unpruned park trees due to their smaller crown radius, rather than changes in photosynthetic rate per unit of leaf area (Fini et al., 2023). Both pruning intensity (e.g., percentage of branch biomass or buds removed) and pruning method (e.g., types of pruning cuts adopted) can affect the delivery of ecosystem services, as well as the tree's recovery from pruning.

It can be easily hypothesized that, in the short term, higher pruning intensities are associated with larger reductions in leaf area and Leaf Area Index (LAI), resulting in greater declines in the provision of ecosystem services, including cooling (Armson et al., 2013; Moser et al., 2015). However, in the medium term (a 1–3-year period), trees can respond to pruning through growth and physiological adjustments to restore leaf area and carbon gain (Fini et al., 2015). Compensatory growth can occur in pruned trees through sustained primary growth of shoots and watersprouts, which often occurs at the expense of stem secondary growth (Neilsen and Pinkard, 2003). Compensatory photosynthesis, i.e., a temporary increase in net photosynthesis proportional to the amount of leaf area removed after pruning, compared to the pre-pruning period, is another common tree response to high-intensity pruning (Medhurst et al., 2006; Gilman and Grabosky, 2009). Compensatory photosynthesis is mainly due to changes in the source-sink ratio, resulting in a higher leaf nitrogen pool, increased carboxylation efficiency, and enhanced electron transport in leaves retained after pruning compared to leaves on unpruned trees, rather than changes in hydraulic factors (e.g., changes in root-shoot ratio, higher hydraulic conductivity) (Turnbull et al., 2007; Fini et al., 2015). Thus, cooling may be more sensitive to pruning intensity than CO_2 assimilation.

Pruning methods can also affect tree responses to pruning and the subsequent delivery of ecosystem services. Three main types of pruning cuts are commonly used worldwide to prune shade trees (Gilman, 2012): removal cut, reduction cut and topping (internodal) cut. The latter type of cut is strongly discouraged in scientific literature and pruning standards, because if widely and indiscriminately applied to first and second order branches can harm tree structure by suppressing both apical dominance (i.e., the inhibition of lateral bud sprouting by the apex in an individual branch) and apical control (i.e., the influence of apical growing axis on elongation and orientation of lateral shoots within an individual branch) (Cline, 1997; Fini et al., 2015; EAS, 2023). As a result, both tree architecture and tolerance to abiotic stress may be harmed in the medium term (Fini et al., 2015).

Nonetheless, intense pruning, achieved through topping cuts, is still carried out on urban trees in several Countries, despite the vast literature that underline the negative effects associated with it (Campanella et al., 2009; Vogt et al., 2015; Badrulhisham and Othman, 2016; Muscas et al., 2024).

Proper planning and management of urban trees should be targeted to obtain large, healthy, long-lived tress with a structure capable of maximizing benefits to the community and minimizing hazard. There is, however, a lack of knowledge of the effect of common management practices, such as pruning, on micro-climate (Yang et al. 2013). Using empiric and process-based models which have been recently developed to evaluate cooling potential of different species (Rötzer et al., 2019, Pace et al., 2021), we aimed here to assess the effects of intense pruning conducted through topping on the microclimatic amelioration capacity of established adult trees of two urban tree species, as well as on their growth patterns and physiological behaviour.

Specifically, we aimed at: (1) quantifying the decrease in cooling through shading and transpiration due to topping and its impact on human thermal comfort; (2) evaluating plant morpho-physiological

responses to topping, to assess whether topped plants can recover ecosystem services provisioning within a normal pruning cycle.

2. Materials and methods

2.1. Environmental conditions and experimental trees

In early spring 2004, 52 *Tilia* x *europaea* L. and 52 *Acer platanoides* L. (10–12 cm circumference at 1.3 m) were planted in an experimental plot at Fondazione Minoprio (Vertemate con Minoprio, Como, Italy; 45°43' 41'' N, 9°04' 55'' E). These two species have been selected for their widespread use in urban settings, for their different development sequence (Millet, 2012) and for their different bud arrangement. Trees were planted in a well-drained loamy sand (51 % w/w sand, 40 % silt, 9 % clay) with pH = 6.5. The planting design was a quincunx with 6 m planting distance within the row and 3.5 m between the rows. Trees were only irrigated in the first year after transplant to mitigate post-planting stress, then never watered again. The experimental site is characterized by a warm temperate climate (Cfb, according to Köppen and Geiger classification), with mean annual rainfall and temperature, calculated over the last 30 years before the beginning of the experiment, of 1106 mm and 13.3 °C, respectively. Daily air temperature, wind speed, solar radiation and rainfall were recorded throughout the experimental period using a local weather station owned by the authors (Vantage Pro 2, Davis, San Francisco, CA, U.S.) (Fig. 1).

2.2. Pruning treatment and experimental set-up

Trees of *Acer platanoides* L. (Ap) and *Tilia x europaea* (Te), were allowed to establish and grow undisturbed for twelve years. Then, when they showed a DBH of 18.9 cm ± 0.49 in Ap and 17 cm ± 0.83 in Te, half of the trees (i.e., 26 for each species) were subjected to a severe pruning treatment (pruned), while the remaining half of the trees was left unpruned (control). Pruning was carried out on pruned trees during winter (February 2017) by topping structural first- and second-order branches to remove about 85 % of dormant buds, to mimic what is still done in municipalities in different parts of the world (Campanella et al., 2009; Muscas et al., 2024). The pruning cuts were made between consecutive branches using bypass hand pruners and chainsaw. This type of pruning cut is an internodal cut which completely removes the apical part of the branch without leaving a lateral shoot with sufficient size to become the new leader (Fini et al., 2015). Twenty-four trees located at the edge of the experimental area were excluded from the

experiment to eliminate the variability linked to the edge effect. The experimental design was a randomized complete block design with 4 blocks and 5 plants per species and treatment in each block (20 plant in each block; 80 plants in total).

2.3. Micro-climatical parameters

Six HOBO-pro series RH/Temp sensors (Onset Computer Corp., Bourne, Massachusetts) were mounted on a wooden post at a height of 150 cm from the ground. Four of these sensors were positioned directly in the experimental field (two under topped trees and two under the unpruned control trees). The last two sensors were placed at 15 m horizontally from the field, in a grass area. Measurements were collected during the growing season (May – September) of the two years after pruning (2017 and 2018). Air temperature and humidity were recorded every minute and data were used to calculate two biometeorological indexes. The surface temperature of the soil was measured directly on the ground, on a sunny day during the second year after pruning, using a FLIR duo R ™ thermal camera.

2.4. Biometric measurements and Leaf Area Index

All biometric parameters were measured immediately after the topping treatment and 12 and 24 months after pruning (MAP). Stem circumference was measured at a height of 1.3 m on each plant using a measuring tape. Stem diameter (DBH) was then calculated from the circumference. Tree height (H_{tot}) and first branch height (H_b) were measured using a handmade graduated pole (10 cm accuracy), with each value derived from the average of two independent measurements made by two different operators. Crown Projection Area (CPA) was calculated from the quadratic mean of the canopy radius as: CPA = radius^2 * π. The canopy radius was measured on each plant using a measuring tape, according to the vertical sightseeing method (Pretzsch et al., 2015). The total volume of the crown (V_{crown}) was obtained using the ellipsoid equation V_{crown}= 4/3πabc; where: a and b are the half-axes measured in perpendicular directions and c is half the height of the living crown (difference between the tree height and the first branch height).

Leaf area index (LAI, $m^2\,m^{-2}$), i.e. half of the total leaf area per unit of horizontal ground area, was calculated as LAI = (1-WAI/PAI)*PAI, where PAI is Plant Area Index ($m^2\,m^{-2}$) and WAI is the Woody Area Index ($m^2\,m^{-2}$). PAI, the fraction of ground shaded by the vertical projection of all canopy elements, including leaves and branches
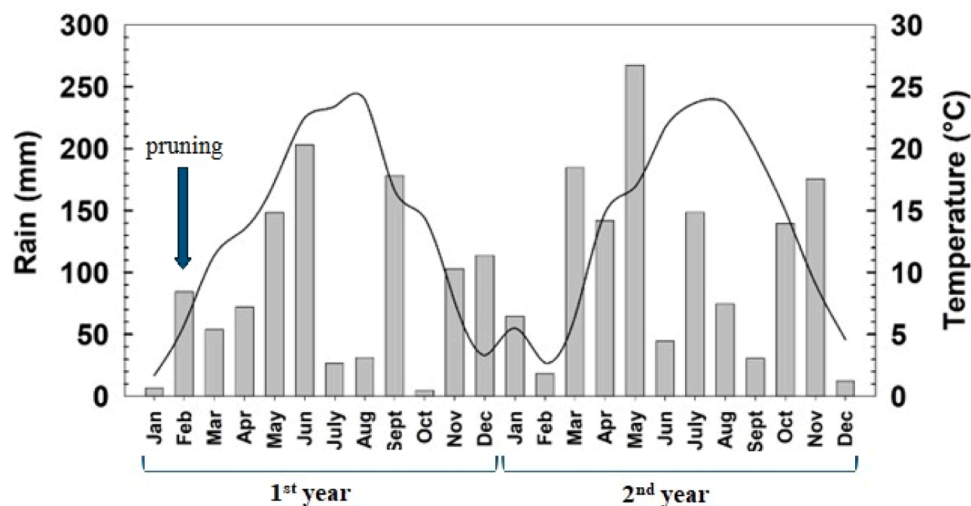

Fig. 1. Monthly average of temperature (line) and rainfall (bars) in the experimental site (Vertemate con Minoprio, CO Italy) during the experimental period (2017–2018).

(Sanusi, 2017), was measured using a ceptometer (AccuPAR model LP-80 PAR/LAI, Decagon Devices, WA) during the leaf-on period. The ceptometer was calibrated using an external PAR sensor, equipped within the instrument. Woody Area Index (WAI), i.e. the fraction of ground shaded by the vertical projection of tree branches (Sjöman, 2016), was measured using the same ceptometer after full leaf drop during winter 2018 (22 MAP). PAI and WAI measurements were taken on sunny days between 12.00 and 14.30 on 76 trees (19 trees per species and treatment). This subset was created to avoid measuring trees that were hardly accessible for a proper canopy transmittance measurement, particularly during winter when WAI was measured. To account for the light conditions, fractional beam (direct light on the total) is measured by the instrument and values during measurement were always higher than 0.83. Measurements were conducted by performing 4 independent measurements of above- and below- canopy irradiance, in four different representative areas of the shaded surface.

The Total Leaf Area (TLA) was obtained by multiplying the CPA by LAI. The Relative Growth Rate of stem diameter (RGR$_{DBH}$), total volume of the crown (RGR$_{Vcrown}$), crown projection area (RGR$_{CPA}$) and Total Leaf Area (RGR$_{TLA}$) were calculated as [ln(Xt1) − ln(Xt0)]*(t1− t0)−1; where: X is DBH or V$_{crown}$ or CPA or TLA at times 0 and 1, and t1− t0 is time (in days) between measurements (Newbery et al., 2011). The Leaf Area Density (LAD, m^2 m^{-3}) was calculated as a proxy for crown density as LAD = TLA/ V$_{crown}$ (Franceschi et al., 2022).

Shoot elongation was measured 12 and 24 MAP. In the unpruned control, the apical shoots of the first order lateral branches were measured, while on topped trees measurements were carried out on new sprouts that originated after the pruning from the cut. In each randomized block, two plant per species and treatments were selected, for each one 10 shoots/sprouts were measured (320 shoots measured in each date).

2.5. Leaf gas exchange and PSII photochemistry

Four, seven (June and September of the first year after pruning, respectively), sixteen, seventeen and nineteen (June, July and September of the second year, respectively) months after pruning, leaf gas exchange was measured on 3 fully expanded leaves per species, pruning treatment, and block (48 leaves per sampling date) using an infrared gas analyser (Ciras 2, PP-System, Amesbury, MA, U.S.). Measurements were conducted in sunny days between 9.30 and 12.30. To standardize the leaf typology, the first fully expanded leaf exposed to full sunlight during the measurement and attached to the apical shoot of primary branches, located in the upper half of the crown to minimize the effect of shading from neighbouring plants. In pruned trees, which did not preserve an apical shoot after topping, the first fully expanded sun leaf was sampled on the watersprout with the largest diameter among those released after pruning. To access the canopy, a fruit picking device (Rosatello Columbia mini, Lagnasco, CN, Italy) was used. Measurements were carried out at ambient temperature, providing the leaves in the cuvette with saturating irradiance (1300 μmol m^{-2}s^{-1}, provided using the integrated CFM light unit) and an external CO$_2$ concentration (C$_a$) of 400 ppm. Relative humidity was set in the cuvette as 70–80 % of the external RH to avoid condensation. Measured parameters were net CO$_2$ assimilation (A, μmol CO$_2$ m^{-2} s^{-1}), stomatal conductance to water vapour (g$_{sw}$, mmol m^{-2} s^{-1}), transpiration (E, mmol H$_2$O m^{-2} s^{-1}), and CO$_2$ concentration in the substomatal chamber (C$_i$, ppm). Instantaneous water uses efficiency (WUE) was calculated as the ratio between A and E. Stomatal conductance to CO$_2$ (g$_{sc}$) was calculated from g$_{sw}$ as: g$_{sc}$ = g$_{sw}$/ 1.6. Leaf temperature (T$_{leaf}$) was measured using the temperature probe integrated into the Ciras cuvette. In this experiment we used a standard 2.5 cm^2 Parkinson PLC6 cuvette, coupled with a chlorophyll fluorescence module (CFM; PP-System), which provides modulated chlorophyll fluorescence measurements. Simultaneous fluorescence and gas exchange measurements allowed the estimation of mesophyll conductance to CO$_2$ diffusion (g$_m$, mmol m^{-2} s^{-1}) using the variable J method (Fini

et al., 2016). Finally, the CO$_2$ concentration in the chloroplasts (C$_c$) was calculated as: C$_c$=C$_i$ – (A/g$_m$) (Long and Bernacchi (2003)). During the second growing season (19 months after pruning), CO$_2$ assimilation was measured as a function of internal CO$_2$ concentration (A/Ci curves). Curves were drawn decreasing stepwise C$_a$ from 400 ppm to 50 ppm, then C$_a$ was raised back to 400 and, finally, C$_a$ was increased stepwise to 1800 ppm. When drawing the curve, leaves were left to acclimate until steady-state when exposed to 400 ppm CO$_2$. For other CO$_2$ concentration levels, the leaf was acclimated for 5–10 minutes as needed to reach stable A and Ci. The apparent maximum rate of carboxylation by Rubisco (V$_{c, max}$) and the apparent maximum electron transport rate contributing to ribulose 1.5-BP regeneration (J$_{max}$) were calculated from A/Ci curves as described by Sharkey et al. (2007) (more details in Appendix 1).

2.6. Leaf greenness index and average leaf area traits

Immediately after leaf gas exchange measurement, leaf greenness index, a parameter highly correlated with the total leaf chlorophyll content (Percival et al., 2008), was measured on the same leaves used for gas exchange, using a SPAD-meter (SPAD 502. Minolta, Osaka, Japan).

Six and nineteen months after the topping treatment, 48 fully expanded sun leaves (12 per species and treatment) were collected from the medial portion of the apical shoot of three primary branches and immediately scanned using an A3 scanner. An image analysis software (Image Tool v1.3, University of Texas, San Antonio, TX, U.S.) was used to measure the average leaf area.

2.7. Estimate of ecosystem services and disservices

2.7.1. Human thermal Comfort

The ATI and the HUMIDEX were calculated as follows:

$$ATI = \quad T_{air} + 0.348e - 0.7 \times V_{10} + 0.7\frac{Q_g}{(V_{10} + 10)} - 4.25 \qquad (1)$$

$$HUMIDEX = \quad T_{air} + \left[\frac{5}{9} \quad \times (e - 10)\right] \qquad (2)$$

where T$_{air}$ (°C) is the measured air temperature, V$_{10}$ is the wind speed measured at 10 m height (m s^{-1}), e is the water vapor pressure (hPa), and Q$_g$ is the heat-flow rate per unit area of body surface due to net extra radiation (Steadman, 1994). Q$_g$ was computed using the Stefan-Boltzmann law, which states that the radiative heat flux depends on the fourth power of the temperature difference between the body and its surroundings:

$$Q_g = \sigma\varepsilon\left(T_b^4 - T_e^4\right)$$

Where σ is the Stefan-Boltzmann constant (5.67 * 10^{-8} Wm^{-2}K^{-4}), ε is the emissivity of the body surface, T$_b$ is the temperature of the body surface (K), T$_e$ is the temperature of the environment (K). T$_e$ was calculated as follow: T$_e$ = T$_{air}$ + 273.15

The emissivity of human skin was assumed to be 0.97. T$_b$ was estimated as the weighted average of the skin temperature (T$_{skin}$; K) and core temperature (T$_{core}$; K):

$$T_b = 0.9 * T_{skin} + 0.1 * T_{core}$$

The body's core temperature was assumed to be 37 °C (310.15 K). T$_{skin}$ was approximated assuming that as the air temperature increases, the skin temperature adjusts slightly higher, but remains close to its physiological baseline:

$$T_{skin} = \left(33 + \frac{T_{air} - 20}{2}\right) + 273.15$$

The e was calculated as follow:

$$e = 6.112 \times \left(10^{\frac{7.5 \times T_{air}}{237.7 + T_{air}}}\right) \times \frac{RH}{100} \qquad (3)$$

where RH is the relative humidity (%). Both indexes were calculated under pruned crowns, under unpruned crowns and over the grass field, from the data of the respective sensors.

2.7.2. Shading

For the quantification of the shielding effect of vegetation against direct solar radiation, the area of shadow projected to the ground by each individual tree (A_{shade}, m^2) was calculated as: $A_{shade} = \cot(\delta) * (H_{tot} - H_b) * D_{crown}$ where: δ is the zenith angle of the sun (for illustrative purposes, the date of June 21st was selected to model A_{shade} as function of δ), D_{crown} is the crown diameter and ($H_{tot} - H_b$) is the height of the living crown (Rotzer et al., 2019, modified).

The capacity of a shade to effectively intercept the solar radiation is linked to the shape, dimension and density of the shade itself. To summarize these characteristics, the Shade Index (Franceschi et al., 2022) was calculated as:

$$ShadeIndex = LAD * A_{shade} \qquad (4)$$

Where: A_{shade} (m^2) is the shade area and LAD is the Leaf Area Density (m^2 m^{-3}), calculated as the ratio between Total Leaf Area (TLA, m^2) and Crown Volume (V_{crown}, m^3).

To assess the topping effect on the amount of energy that is intercepted by the crown, a process-based model was used. In this model, a surface net energy balance between inside and outside the shaded ground, at steady state, was performed. The energy reduction by shading (SER) was then calculated as:

$$SER = (q_{a,out} - q_{a,in}) + (q_{s,out} - q_{s,in}) - (q_{c,out} - q_{c,in}) - (q_{r,out} - q_{r,in}) \qquad (5)$$

Where q_a is the absorbed energy from global solar radiation, q_c is the convection energy, q_s and q_r are respectively the absorbed and emitted IR (for more detailed information see annex 1). The values of energy reduction by shading scaled to the whole crown (SER_{tree}) were obtained multiplying the model output, SER, with the shade area (A_{shade}).

2.7.3. Latent heat dissipation

The quantification of the latent heat dissipated through transpiration was based on one-step Penman-Monteith approach. The latent heat flux due to transpiration λT_c (W m^{-2}) was calculated daily, according to Rana et al. (2019).

$$\lambda Tc = \frac{\Delta Q + \rho_a C_p \frac{VPD}{R_a}}{\Delta + \gamma \left(1 + \frac{R_s}{R_a}\right)} \qquad (6)$$

Where: Q is the available energy in W m^{-2}; ρ_a is the mean air density at constant pressure; C_p is the specific heat of air; Δ represents the slope of the saturation vapour pressure-temperature relationship; R_a is the aerodynamic resistance and R_s is the surface resistance (more information in the Annex 1).

The values of latent heat flow per ground square meter (LH_{CPA}, W m^{-2}) were then converted into latent heat flow per tree (LH_{tree} W tree^{-1}) multiplying for the CPA (m^2 tree^{-1}) of the year when the g_{sw} measurements were done. More information about the models used for the quantification of both latent heat dissipation and shading effects can be found into Appendix 1.

2.7.4. CO_2 assimilation

The hourly CO_2 assimilation per unit crown projection area was calculate according to the Big Leaf model as (Sellers, 1997): A_{cpaBL} (g m^{-2} soil h^{-1}) = A (g m^{-2} leaf s^{-1}) * (1-e^(-k/LAI))/k * 3600 (s h^{-1}), where A is the average net CO_2 assimilation measured at saturating light

in the two growing seasons after topping, e is the irrational Nepero number, LAI is Leaf area index, k is the extinction coefficient for both solar radiation and nitrogen gradients in a canopy (assumed to be 0.5), and 3600 is the number of seconds within one hour.

2.8. Statistics

Data were analysed using a linear mixed models for repeated measures. In the model "species", "pruning treatment" and "months after pruning" were considered fixed factors. In order to reflect the hierarchical structure of the data, as random factors "subject" nested within "block" (subject repeated at different measurement points) were used. Triple interaction was tested, as well as the interactions between fixed factors. The structure of the correlation was chosen based on the best fitting. For balanced data that were not equally spaced in time, a homogeneous ante-dependence correlation structure (AD1) was used. In contrast, for data that had an unbalanced experimental design heterogeneous auto-regressive correlation structure (AR1h) was employed. The assumption of the normality and homoscedasticity were verified by visual inspection of the diagnostic plots. Homogeneous subsets were identified using Tukey's and Sidak's post-hoc tests. Data were analysed using SPSS software (SPSS v.29, IBM, NY, U.S.).

3. Results

3.1. Effect on Crown Dimension and Growth response to pruning

At the beginning of the trial, trees within each species showed a similar stem diameter ($p = 0.744$). Stem DBH relative growth rate (RGR_{DBH}) was significantly reduced by topping in both species (-56.5 % and - 91.3 % compared to control in *T. x europaea* and *A. platanoides* respectively, $p < 0.01$), although in Te differences between topped and control trees were significant only during the second growing season after topping (Table 1).

Total Leaf Area (TLA) was significantly lower in topped, compared to unpruned trees of both species at pruning (-98.2 % and −96.4 % in Te and Ap, respectively) after the first (-88.9 % and −85.6 % in Te and Ap, respectively) and second (-80.7 % and −78.1 % in Te and Ap, respectively) growing seasons after pruning. The relative increase of total leaf area was significantly higher for trees which had been topped (on average 34 cm^2 m^{-2} day^{-1}), compared to those left unpruned (on average 4.85 cm^2 m^{-2} day^{-1}, Table 1), both between 0 and 12 MAP and 12–24 MAP ($RGR_{TLA\ 0-12}$, $RGR_{TLA\ 12-24}$). Crown Projection Area (CPA) and Volume of the Crown (V_{crown}) were significantly affected by pruning treatment ($p<0.001$ and $p<0.00$ for CPA and V_{crown}, respectively) in every measurement (Table 1).

CPA was reduced, because of pruning, by 97.9 % and 95.1 %, at 0 MAP and by 87.4 % and 80.3 %, at 12 MAP in Te and Ap respectively, compared to unpruned trees. Moreover, V_{crown} was reduced by 99 % and 97 % at 0 MAP and by 73 % and 74.5 % at 12 MAP in topped Te and Ap, respectively.

At 24 MAP, the CPA of topped Te and Ap were still 77.2 % and 68.3 % lower compared to unpruned trees while a significant pruning x species interaction was found in the crown volume: unpruned Te had higher Vcrown than unpruned Ap, whereas Vcrown did not differ between topped Ap and Te (Table 1).

Leaf Area Index (LAI) was significantly affected by topping treatment and species (Table 1). The topping treatment decreased the LAI by 13.8 % trees in Te and by 25.9 % in Ap. On average, Te showed higher LAI values than Ap (4.98 and 3.65, respectively).

The Leaf Area Density (LAD) showed a significant interaction between species and pruning at every MAP (Table 1). In Te pruning led to significantly higher values of LAD in each measurement. Topped Te showed a crown 227.9 %, 161.6 % and 131.9 % denser compared unpruned tress, at 0, 12 and 24 MAP (Fig. 3 C), respectively. In contrast, in Ap the differences were smaller and never significant and at 24 MAP the

Table 1

Effect of topping on: Relative Grow Rate of stem diameter (RGR$_{DBH}$, cm m^{-1} day^{-1}), Relative Grow Rate of total leaf area (RGR$_{TLA}$, cm^2 m^{-2} day^{-1}), Relative Grow Rate of crown projected area (RGR$_{CPA}$, cm^2 m^{-2} day^{-1}), Relative Grow Rate of crown volume (RGR$_{Vcrown}$, dm^3 m^{-3} day^{-1}), total leaf area (TLA, m^2), crown projection area (CPA, m^2), crown volume (V$_{crown}$, m^3), Leaf Area Density (LAD, m^2 m^{-3}), shoot length and Leaf Area Index (LAI). MAP stands for month after pruning. In case of significative effect of both factors, but not significative interaction, small letters on the line refer to significant differences between treatment while big letters on the line refer to significant differences between species.

	MAP	Tilia				Acer				significance (*p*-value)			
		Unpruned		Topped		Unpruned		Topped		treatment	species	TxS	TxSxMAP
RGR$_{DBH}$	0–12	0.021	a	0.012	ab	0.017	a	0.002	b	< 0.001	0.019	0.266	< 0.001
	12–24	0.02	a	0.006	b	0.018	a	0.001	b	< 0.001	0.073	0.462	
RGR$_{TLA}$	0–12	3.13	b	75.96	a	5.41	b	66.43	a	< 0.001	0.566	0.35	< 0.001
	12–24	7425	b	34.51	a	2.34	b	34.45	a	< 0.001	0.304	0.903	
RGR$_{CPA}$	0–12	3.13	b	75.96	a	5.41	b	66.43	a	< 0.001	0.566	0.35	< 0.001
	12–24	6003	b	29.46	a	3.84	b	26.72	a	< 0.001	0.304	0.903	
RGR$_{Vcrown}$	0–12	0.436	b	9.17	a	0.74	b	8447	a	< 0.001	0.782	0.496	< 0.001
	12–24	0.711	b	3.64	a	0.60	b	3912	a	< 0.001	0.745	0.441	
TLA	0	162.58	a	2.94	c	93.85	b	3.4	c	< 0.001	< 0.001	< 0.001	
	12	172.99	a	19.15	c	103.96	b	14.96	c	< 0.001	< 0.001	< 0.001	0.003
	24	194.43	a	37.51	c	111.99	b	24.49	c	< 0.001	< 0.001	< 0.001	
CPA	0	31.44	a	0.66	c	24.25	b	1.18	c	< 0.001	0.053	0.026	
	12	33.46	a	4.29	b	26.86	a	5.21	b	< 0.001	0.134	0049	0.03
	24	37.61	a,A	8.4	b,A	28.94	a,B	8.53	b,B	< 0.001	0045	0039	
Vcrown	0	171.24	a	1.27	c	118.79	b	2.72	c	< 0.001	0.011	0.007	
	12	186.64	a	14.55	b	136.80	a	18.52	b	< 0.001	0.039	0.016	0.281
	24	214.83	a	33.09	c	153.06	b	37.52	c	< 0.001	0.021	0.008	
LAD	0	0.96	b	3.17	a	0.82	b	1.25	b	< 0.001	< 0.001	0.002	
	12	0.94	b	2.47	a	0.78	b	0.88	b	0.002	< 0.001	0.006	< 0.001
	24	0.92	b	2.14	a	0.75	b	0.66	b	0.009	< 0.001	0.004	
Shoot length	12	20	c	104.15	b	29.6	c	131.59	a	< 0.001	< 0.001	< 0.001	< 0.001
	24	18.05	c	82.63	b	29.79	c	138.23	a	< 0.001	< 0.001	< 0.001	
LAI	16	5.14	a,A	4.43	b,A	3.84	a,B	2.84	b,B	< 0.001	< 0.001	0.636	

LAD of topped trees was even smaller than the unpruned control.

Shoot elongation was significantly affected by pruning treatments and species, and a significant pruning x species interaction was found (Table 1). Shoot elongation was similar in unpruned Te and Ap. Conversely, during both years after pruning, topped Ap displayed longer shoot elongation compared to topped Te. Overall, during the two growing seasons after pruning, topped Ap displayed 344 % and 364 % higher shoot elongation compared to unpruned plants, while topped Te displayed 421 % and 358 % longer shoots compared to the unpruned control.

3.2. Shading, latent heat dissipation and overall effects on thermal comfort

3.2.1. Biometeorological Index

The average ATI values under the pruned trees and on the grass field were significantly higher than the corresponding ATI values estimated under unpruned trees (Control) between 8:00 and 16:00 h in May and September, and between 8:00 and 17:00 h from June to August (Fig. 2). The average ATI values in surfaces under pruned trees were not significantly different from that calculated for grass field throughout the day in May, August and September, while ATI values in surfaces under pruned trees were significantly higher than that in grass field between 13:00 and 15:00 h in June and between 13:00 and 14:00 h in July.

The seasonal average ATI values (between May, June, July, August and September) in grass field (26.4 °C) and surfaces under pruned trees (26.8 °C) were higher than in control (25.7 °C). The average HUMIDEX values follow the same trend, with higher values in grass field (23.6 °C) and in surfaces under pruned trees (24 °C) than in control (23 °C), only in June, July, August and September. Only HUMIDEX values in May differ between grass field and surfaces under pruned trees, with decreasing values from pruned to grass to control (17.4 °C, 17.1 °C, and 16.3 °C).

3.2.2. Shading

The shaded area was significantly smaller in topped trees (*p*<0.01) in both years (Fig. 3 A, B). Immediately after pruning, topping decreased the ground area shaded (A$_{shade}$) of Te and Ap canopies by 95.1 % and 89.4 %, compared to control. On 12 and 24 MAP, topped Te still projected 81.5 % and 72.7 % smaller shaded area compared to unpruned Te. Similarly, the shaded area cast by topped Ap canopies was still 70.7 % and 55.8 % lower than in unpruned trees on 12 and 24 MAP, respectively. The soil surface temperature below the crown was significantly affected by pruning only in Ap (*p*<0.01). The soil under the crown of topped Ap was 5.21 °C higher than under unpruned trees (data not shown).

Topping enhanced the Leaf Area Density (LAD) only in Te, at every MAP, while this effect was not significative in Ap (Fig. 3 C, D).The shade index, a parameter that considers both dimensions and density of the crown (Fig. 3E, F), was significantly lower in topped trees compared to the control, in both species, regardless of the moment of the day or the MAP. At pruning (0 MAP), the shade index of topped trees of both species was 86 % lower than in control trees. The shade index of topped Te and Ap remained significantly lower both at 12 MAP (71.4 % and 68 %, respectively) and at 24 MAP (62.9 % and 60.1 %, respectively).

The surface energy balance between the unshaded area and the area shaded by the canopy, i.e. the energy reduction by crown shading per square meter of shaded area (SER), differed significantly between topped and unpruned trees of both species. SER was 10.5 % and 19.5 % lower, respectively in topped Te and in topped Ap. However, the energy reduction by shading from the whole tree (SER$_{tree}$, Fig. 3 G, H) was significantly lower in both species. Indeed, SER$_{tree}$ was reduced by 95.5 % and 91.8 % at 0 MAP, by 83.4 % and 76.4 % at 12 MAP and by 75.6 % and 64.4 % at 24 MAP in topped Te and Ap, respectively, compared to unpruned control.

3.2.3. Latent heat dissipation

Transpiration per unit of leaf area (E) was significantly (*p* < 0.001) higher in topped than in control Te in all sampling dates, except on 4 MAP (Fig. 4 A, B). Topped Ap showed significantly higher E than control trees on 7 and 16 MAP.

The latent heat dissipated per unit crown-projection-area (LH$_{cpa}$ through transpiration wasn't statistically affected by pruning in Te, except on 17 and 19 MAP, when topped Te displayed 29.8 % and 56 %
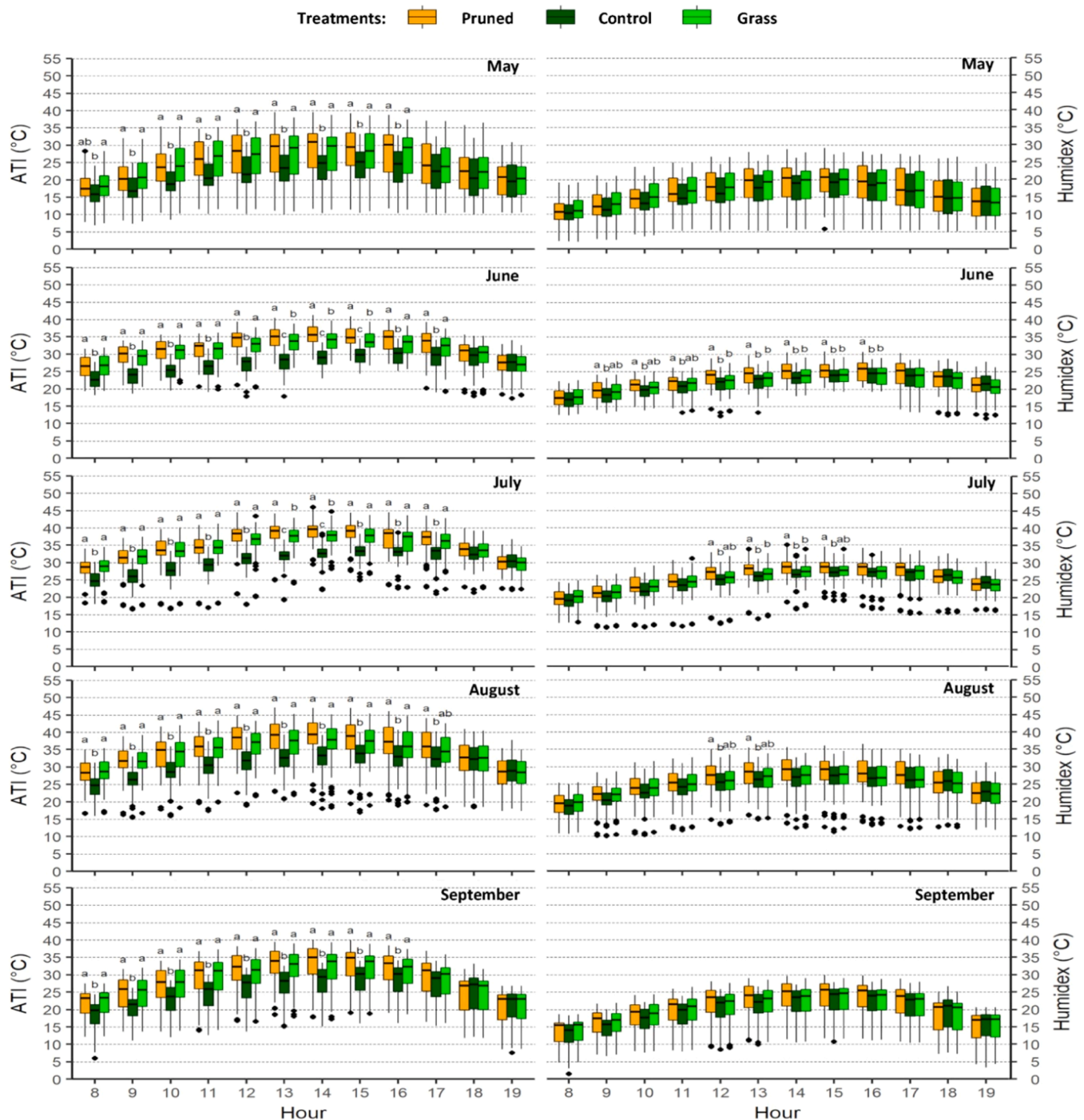
Fig. 2. Hourly apparent temperature index (ATI, °C) and HUMIDEX (°C) in different months of the first year after pruning (2017) and for the three treatment: Pruned (Orange boxplot), unpruned control (dark green box-plot), and grass (light green box-plot). Different letters indicate significant differences ($p<0.05$) between treatment at the same hour, according to the Tukey post-hoc test.

higher LH_{cpa} than control trees. In Ap, the effect of topping was significant only at 16 and 17 MAP, when topped Ap showed 12.9 % and 18.4 % lower LH_{cpa} than control trees (Fig. 4 C, D).

On the other hand, considering the strong reduction in crown dimensions due to topping, the Latent Heat dissipated by the whole tree (LH_{tree}) was significantly lower in topped, compared to control trees, in all measurement days and in both species (on average, −78,2 % and −74 % in Te and Ap, respectively) (Fig. 4E, F). The effect of topping on net CO_2 assimilation at the whole plant level (A_{treeBL}) was significant in every measurement in both species. In unpruned Te and Ap, A_{treeBL} was

respectively 4 and 5.3 times higher than in topped trees (data not shown).

3.3. Leaf characteristics and gas exchange

Topping significantly affected the size of leaves developed after pruning was carried out ($p<0.01$). Leaves developed on topped trees were 111.6 % (Te) and 36.5 % (Ap) larger than those of unpruned control (Fig. 5 A).

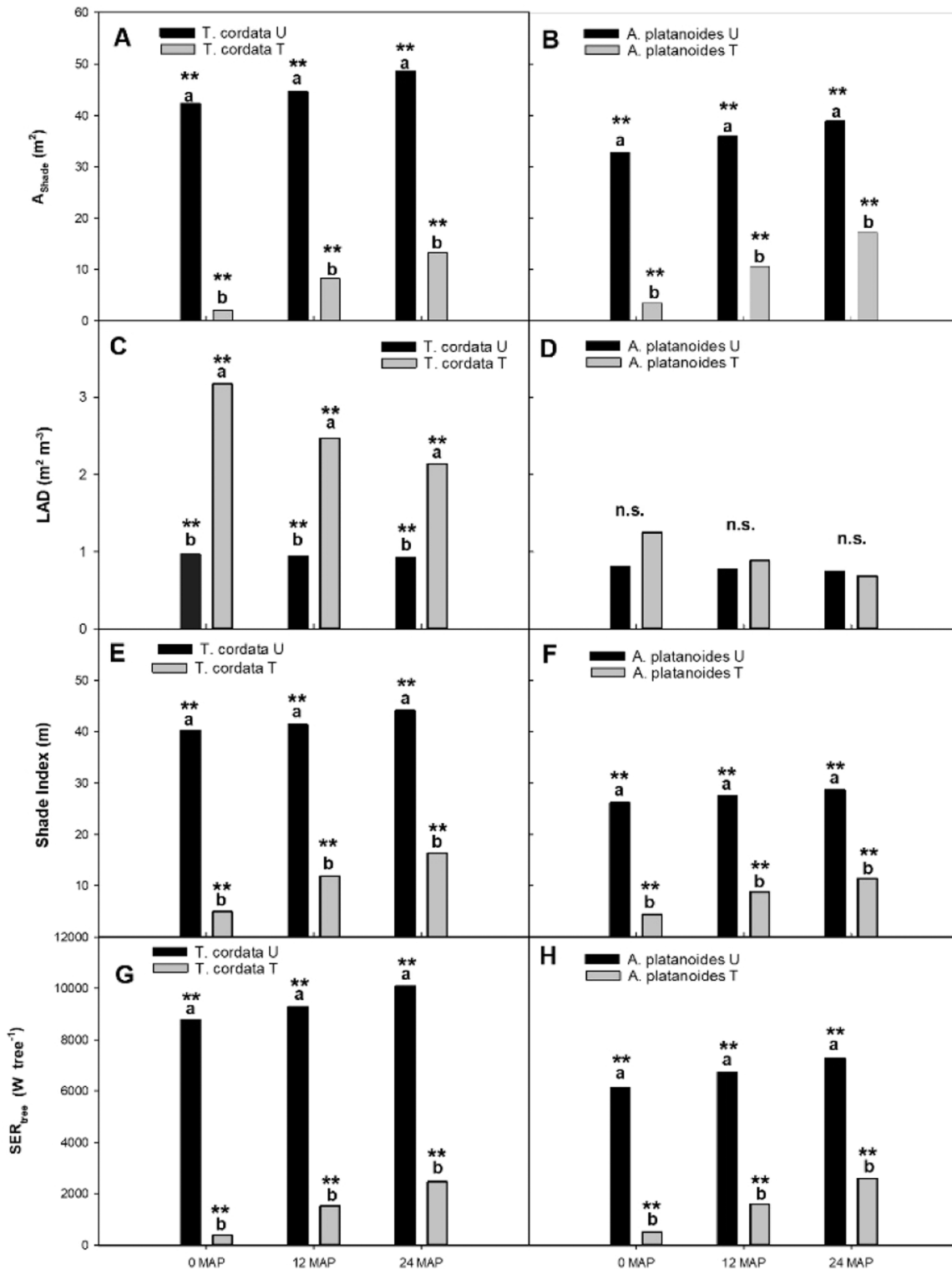Leaf greenness index was significantly affected by pruning only at (7

Fig. 3. Topping effect on: Shade area in squared meter (A_{shade}, A and B) Lead area density (LAD, C and D), Shade index (E and F); Energy reduction by shading per tree (SER_{tree}, G and H); MAP stands for month after pruning **= $p<0.01$; *= $p<0.05$ and n.s.= non-significant. Different letter means significant differences between treatment.

MAP) ($p < 0.01$) and only in Ap. On 7 MAP, pruned Ap had 14.2 % higher leaf greenness index than unpruned control (Fig. 5B). No significant difference in leaf greenness index was found in the second growing season after pruning.

Water Use Efficiency (WUE = A/E) was not statistically affected by pruning treatment in Ap, except on 19 MAP when topped trees displayed

31 % lower WUE than control (Fig. 6A, B). In Te, WUE was generally lower in topped plants, compared to control, except for 4 MAP when the opposite was observed. Topping increased net CO_2 assimilation (A) in only 1 of the 5 sampling dates conducted during the 19 months after pruning treatments were imposed (Fig. 6C, D). Seven MAP, A of topped Ap was 53.8 % higher compared to unpruned trees (Fig. 6C). Topped Te
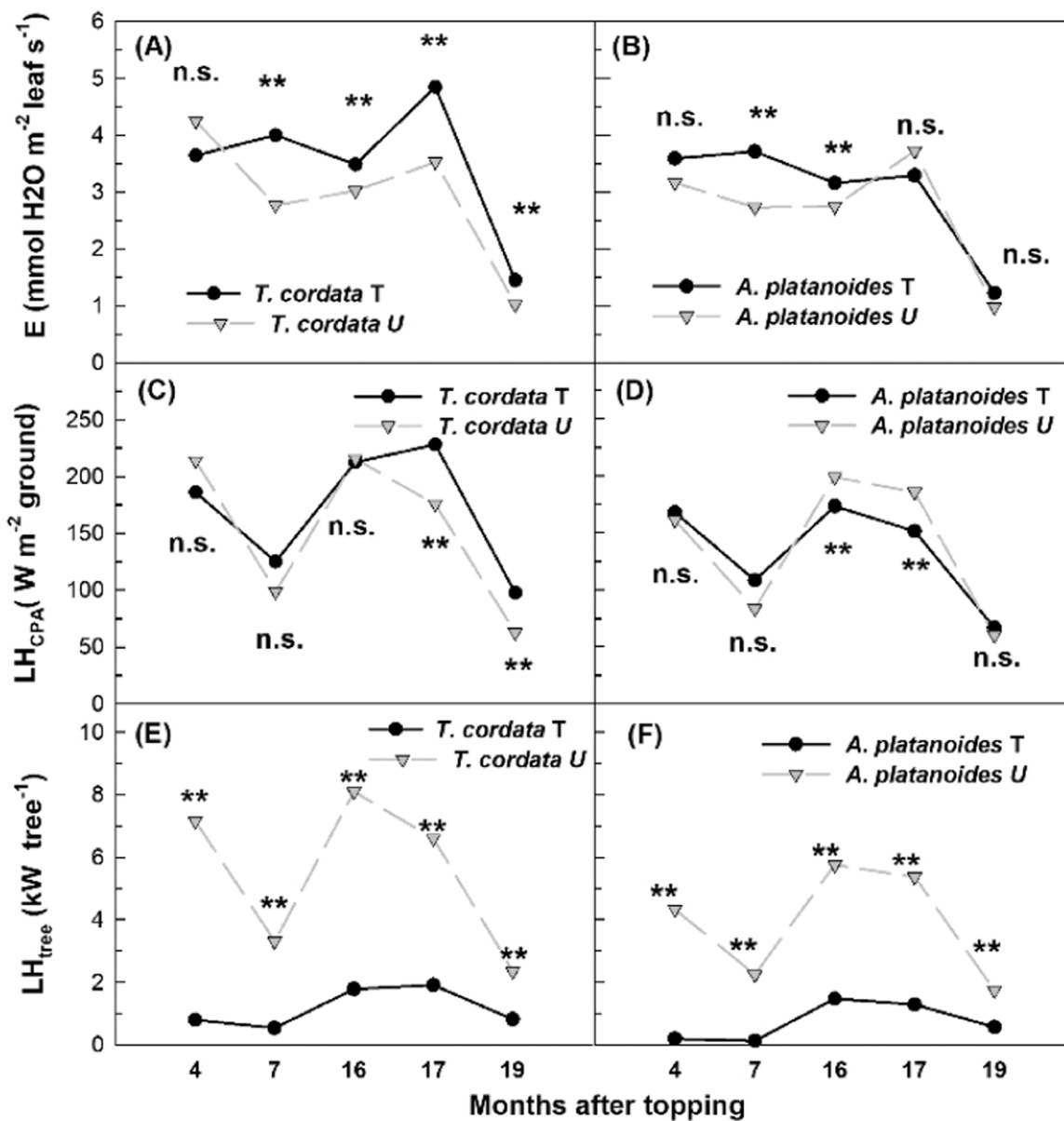
Fig. 4. Topping effect on: transpiration at saturating light per leaf area unit in Te and Ap (E, A and B); The total latent heat dissipated per ground unit obtained with the Penman-Monteith equation (LH$_{cpa}$, C and D); The latent heat dissipated at the whole tree level (LH$_{tree}$) (E and F). ** = $p<0.01$; * = $p<0.05$ and n.s.= non-significant.
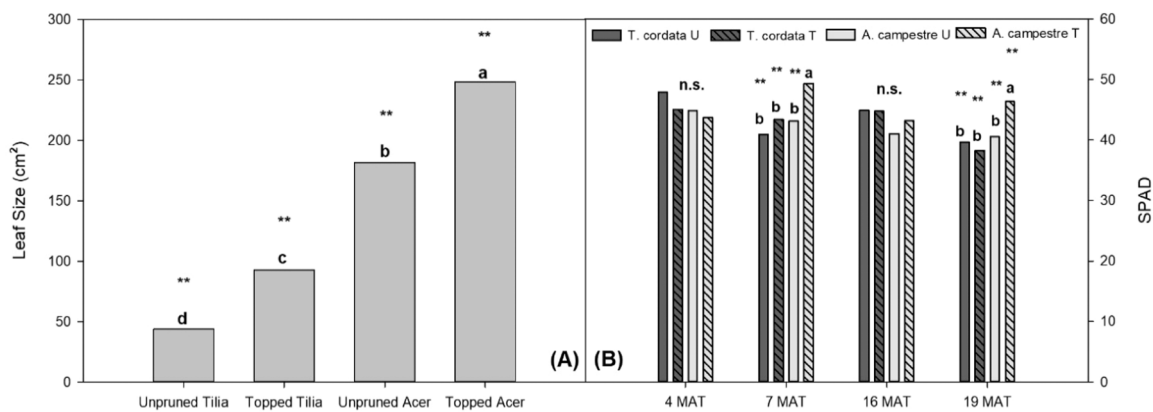

Fig. 5. Topping effect on: (A) Average leaf size; (B) Leaf greenness index. MAP = months after pruning, U = unpruned, T = topped. ** = $p<0.01$; * = $p<0.05$ and n.s.= non-significant.
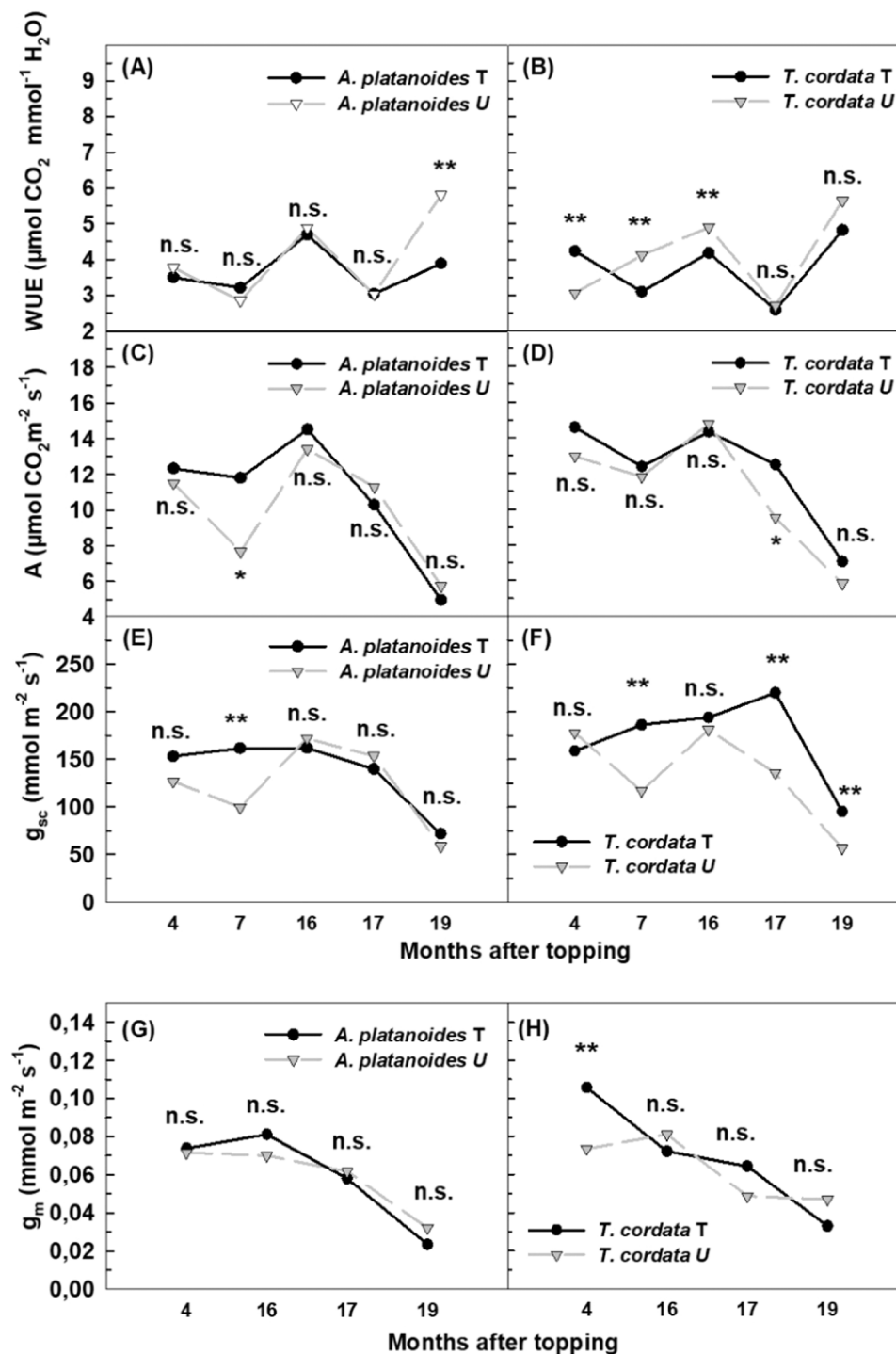
Fig. 6. Effects of topping on: Water use efficiency (WUE) (A and B); total CO_2 assimilation (A) (C and D); stomatal conductance (g_s) (E and F) at 4,7,16,17,19 month after topping of respectively Ap and Te; mesophyll conductance to CO_2 diffusion (G and H) **= $p < 0.01$; *= $p < 0.05$; n.s.= non-significant; U=unpruned control and T=topped.

displayed 31.1 % higher A compared to control trees on 17 MAP (Fig. 6D). Stomatal conductance to CO_2 (g_{sc}) displayed a similar trend as A in Ap: 7 MAP topped maples displayed 62.8 % higher g_{sc} compared to control trees (Fig. 6E). Topped Te displayed 38.3 % higher g_{sc} than control trees in 3 of the 5 measurements dates (7, 17, and 19 MAP) (Fig. 6F). Similarly, pruning induced larger changes in mesophyll conductance to CO_2 diffusion (g_m) in Te than in Ap (Fig. 6G, H). In Te, topping increased g_m by 30.4 % compared to unpruned control early after pruning (4 MAP), although differences were no longer significant

in later measurements.

Intercellular CO_2 concentration (C_i) was affected by pruning differently according to species and time after pruning (Table 2). In Te, topping led to an early drop in C_i during the spring after pruning was imposed (4 MAP) while at the end of the the summer (7 and 19 MAP) topped Te showed higher Ci than control. In Ap, pruning induced no change in Ci during the first growing season. Thereafter, Ci declined in topped trees compared to control during spring (16 MAP), then increased by the end of the summer (19 MAP). On the other hand, the

Table 2
Effect of topping on the CO_2 concentration in the substomatal chamber (C_i), the CO_2 concentration in the chloroplasts (C_c), the apparent maximum rate of carboxylation by Rubisco (Vc, max) and the apparent maximum electron transport rate contributing to ribulose 1.5-BP regeneration (J_{max}). MAP stands for month after pruning. In case of significative effect of both factors, but not significative interaction, small letters on the line refer to significant differences between treatment while big letters on the line refer to significant differences between species.

	MAP	Tilia				Acer				significance (p-value)			TxSxMAP
		Unpruned		Topped		Unpruned		Topped		treatment	species	TxS	
C_i	4	291.3	a	248.1	b	255.6	ab	266.7	ab	0.005	< 0.001	< 0.001	
	7	228.7	b	265.2	a	257.7	a	256.8	a	< 0.001	< 0.001	< 0.001	
	16	248.7	ab	239	a	259.7	a	263.4	b	< 0.001	< 0.001	< 0.001	< 0.001
	17	262.5	ab	277	a	260.7	b	257.6	b	< 0.001	0.015	< 0.001	
	19	254.4	b	268.8	a	251.5	b	288.6	a	< 0.001	< 0.001	< 0.001	
C_c	4	71.8	b	102.7	a	73.3	b	84.1	b	< 0.001	< 0.001	< 0.001	
	16	56	b	56.2	b	65.4	a	57.8	a	0.036	0.114	0.11	0.185
	17	67	c	76.7	b	78.2	a	73.2	ac	0.012	0.198	< 0.001	
	19	37.2	a,A	36.0	b,A	33.6	a,B	31.9	b,B	< 0.001	< 0.001	0.069	
Vc,max	16	91.6	a	99.1	a	77	b	90.7	a	0.065	0.169	< 0.001	
Jmax	16	147.5	ab	141.3	ab	129.9	b	159.2	a	0.325	0.402	< 0.001	

CO_2 concentration in the chloroplast (C_c) in topped Te was significantly larger than unpruned Te only at 4 and 17 MAP (Table 2). The apparent carboxilation efficency by Rubisco ($V_{c,max}$) and the apparent contribuition of electron transport to Ribulose regeneration (J_{max}) were significantly higher in topped Ap compared with unpruned control in the second growing season after pruning (Table 2).

4. Discussion

The impact of urban vegetation on local climate is deeply linked to the total surface of the leaves and their physiological activity (Rahman et al., 2015). Understanding the consequences of pruning on human comfort is essential for landscape management and for designing urban green spaces that optimize thermal comfort and overall environmental well-being. The results of this experiment clearly show that topping can significantly lower a tree's cooling capacity in the short-run and can trigger structural and physiological inefficiencies (Fini et al., 2015; Suchocka et al., 2021) in trees that prevent or delay the recovery of ecosystem services provisioning in the years after the pruning event.

4.1. Thermal comfort under unpruned trees, topped trees, and on grass field

Both the ATI and the HUMIDEX indexes consistently indicated, as hypothesized, that thermal comfort was worse under topped trees than under unpruned trees for most of the day, during spring and summer. Differences in the duration and in the intensity of the periods of discomfort between the two indexes can be due to windspeed being considered only by the ATI index equation (Eq. 1) (Ho et al., 2016). On the contrary windspeed is not considered in Humidex equation (Eq. 2). It was, instead, surprising to observe that the presence of topped trees failed to improve thermal comfort, compared to the grass area. Such an effect may be cause by two main reasons. Firstly, the presence of topped trees may affect wind profile and reduce windspeed, compared to lawn, thus increasing humidity-related discomfort. Secondly, shading and autumn leaf drop by topped trees yielded a sparse distribution of turf under the trees, which may lead to lower evapotranspirational cooling by the grass cover, thus resulting in higher surface and air temperature (Lin et al., 2007; Konarska et al. 2014).

4.2. Effect of topping on shading and latent heat dissipation

Results of this research confirmed that topping caused a drastic reduction in the projected shade area, mostly due to decreases in crown radius and plant height in topped compared to unpruned trees. Shade density was less consistently affected by pruning. Leaf Area Index (LAI), Total Leaf Area (TLA) and Crown Volume (V_{crown}) were generally lower in topped trees of both species than in control. Nonetheless, in Te, TLA was reduced less than proportionally compared to V_{crown}, which led to an increase in Leaf Area Density (LAD), a major determinant of shade density, in topped Te compared to the control (Franceschi et al., 2022). This effect was not observed in Ap, which was characterized by longer shoot growth after topping, thus resulting in a faster increase in V_{crown} after topping compared to Te. Although topping reduced shade index (which considers both shade area and shade density) in both species (-85.5 %, −69.7 % and −61.5 %, on a daily basis, at 0, 12 and 24 MAP, respectively), differences between topped and unpruned trees were higher in early morning and late afternoon and lower during the central hours of the day. The lower differences in shade index between topped and unpruned trees during the central hours of the day can be explained by the shaded area being smallest when the sun is close to the zenith, thus minimizing differences in shaded area between treatments.

The range of values of the energy reduction by shading per unit crown-projection area (SER W m^{-2}) obtained in this work are in line with those reported by previous literature (Pace et al., 2021). Pruning reduced SER in both species, with larger reductions observed in Ap than in Te (data not shown). This indicates that the increases in LAD observed in Te, but not in Ap, after topping could partially offset the pruning-induced reduction in LAI. Energy reduction through shading by the whole tree (SER$_{tree}$, W tree^{-1}) was affected to a greater extent than SER by pruning, indicating that the crown size is more sensitive to topping compared to crown density, consistently with previous estimates (Fini et al., 2023)

Transpirational cooling, the other driver of microclimate amelioration by trees, is affected, under given environmental conditions, by morpho-physiological tree attributes such as transpiring leaf area and stomatal conductance (Rana et al., 2019). Consistently to previous research (Fini et al., 2015) we show here that pruned trees can partially compensate for the decline in total leaf area with transient increases in leaf gas exchange per unit leaf area (Turnbull, 2007). Net photosynthetic rate is usually more prone to such compensatory increase than stomatal conductance (g_{sw}) (Fini et al., 2015). Nonetheless, at high pruning severity such as that applied in this research, which deeply affects the ratio between transpiring leaf area and absorbing root surface, the compensatory increase may become relevant (13–45 % higher in topped compared to control trees) even for g_{sw}. A rise in stomatal conductance and transpiration per unit leaf area is normally associated with an increase in the capacity of leaves to dissipate latent heat (Rahman et al., 2015). However, when latent heat dissipation was upscaled from single leaf to the canopy, the reduction in Leaf Area Index (LAI) and crown radius experienced by pruned trees may offset their higher latent heat dissipation per unit leaf area due to the compensatory increase in g_{sw}. The two species selected for this research nicely illustrate this idea: pruned Te developed dense clusters of vegetation, so that, during the

second growing season after topping, the LAI of topped Te was only 13.8 % lower than the LAI of unpruned trees, while transpiration increased by 23.3 % because of pruning. Thus, Thus, latent heat dissipated per unit crown projection area (LH$_{cpa}$) was 28.1 % higher in topped than control trees during the second year after pruning. Conversely, LAI of topped Ap was still 26 % lower than in control trees two years after pruning, and the compensatory increase in g$_{sw}$ failed to compensate for the LAI reduction. Thus, LH$_{cpa}$ was 6.9 % lower in pruned than in control Ap during the second growing season after pruning. Nonetheless, when also crown radius is also taken into account, and latent heat dissipation by the whole tree (LH$_{tree}$) is considered, topped plants of Te and Ap showed, on average, over the entire experiment a 78.2 % and 74 % lower LH$_{tree}$ compared to unpruned trees.

4.3. Topping effects on tree growth and physiology

Tree response to pruning involves a series of physiological and structural adjustments that affect the recovery of the delivery of ecosystem services over time (Fini et al., 2023). It was shown that pruning with excessive intensity can promote functional traits that favour fast growth of new vegetation, rather than stress tolerance (Fini et al., 2015).

At the leaf level, our results confirm that high intensity pruning induces a transient increase in net photosynthetic rate, the so-called "compensatory photosynthesis" (Turnbull et al., 2007). This increase is mainly achieved through a higher activity of Rubisco and Calvin cycle enzymes (Turnbull et al., 2007), as corroborated by the higher efficiency of carboxylation and higher contribution of the electron transport chain to ribulose regeneration observed in this research in topped compared to control Ap plants. Higher leaf chlorophyll content and, in Te, a transient increase in mesophyll conductance may have also contributed to the temporary increase in net photosynthetic rate in topped trees. Leaf morphological characteristics were also affected by high intensity pruning. To compensate for the missing leaf area, the area of newly developed leaves was 111 % (Te) and 36 % (Ap) larger in topped than in unpruned trees. This finding is consistent with previous reports, which also noted that the increase in leaf area after high intensity pruning is often associated with a decline in leaf mass per area, a trait which is positively correlated with stress tolerance (Poorter and Bongers, 2006; Fini et al., 2015). Further, a larger leaf size can increase the photosynthetic surface of individual branches but can also lead to leaf over-heating, because of lower heat dissipation by conduction-convection (Nobel, 2009). This idea is confirmed in our research which showed that the average leaf temperature increased by 3.7 % and 3.4 % in topped Ap and Te, respectively, compared to control, with larger differences observed in the summer measurement.

Although topped trees compensated for the missing leaf area by increasing photosynthesis per unit leaf area, when net photosynthetic rate was upscaled to the whole tree to assess the overall carbon gain, CO$_2$ uptake by topped trees was 75 % (Te) and 81 % (Ap) lower than that of unpruned trees. The lower availability of freshly assimilated carbon may make topped trees more dependent on stored starch reserves for growing and defending in the years after pruning, although the effects of pruning on non-structural-carbohydrate pool of trees have not been elucidated yet (Day et al., 2011; Ramirez et al., 2018).

Shoot elongation aimed at restoring canopy spread was a priority for topped trees of both species, which developed 344–420 % longer shoots compared to control, in the 12 months after pruning. To sustain shoot primary growth despite lower availability of freshly assimilated carbon, resources must be drained from other growth processes, such as stem secondary growth (Fini et al., 2015) or defence metabolisms (Suchocka et al., 2021).

The duration of this shift in resource allocation between primary and secondary growth may be a tool to quantify tree species capacity to recover after topping. During the second growing season after pruning shoot elongation started declining in topped Te (-20 %) but not in

topped Ap (+5 %), suggesting a faster recovery in the former species. Nonetheless, full recovery of physiology may occur when trees have regained the pre-pruning whole-plant carbon uptake, which requires the recovery of crown projection area. Both the tree species used in this research failed to recover crown projection area and crown volume to the size of the unpruned control within 2 years.

5. Limitation

This work evaluates the effect of pruning on the capacity of trees to improve the surrounding microclimate. A first limitation of this research is that we only pruned trees once, so we cannot draw conclusions on the effects of repeated pruning cycles on ecosystem services delivery. A second limitation is that the research lasted for two-growing seasons, which is less than a typical pruning cycle of trees in an urban environment. Longer studies are needed to assess whether topped trees may fully recover their cooling capacity within a pruning cycle. Moreover, only two species were tested in this work. Thus, more studies on other tree urban species are needed to generalize the results. A fourth limitation is that, although we allowed trees to establish for 12 years after planting, they were still relatively young at the beginning of the research. Thus, their response and capacity to recover from topping may differ compared to late mature and senescent trees.

6. Conclusion

In conclusion, the intense pruning treatment carried out through topping reduced the capacity of trees to provide shade and to dissipate latent heat through transpiration. Trees respond to severe pruning through morphological and physiological adjustments that may increase photosynthesis and transpiration at the leaf level. Despite this, the crown size may be chronically constrained if pruning is routinely carried out, resulting in higher thermal discomfort for the population. These findings could have major implications for urban forestry, guiding policy makers and stakeholders in urban tree management. Due to climate change, cities are more and more exposed to the deleterious consequences of the urban heat island effect, which may be mitigated through science-based management of urban vegetation. We provide here new evidence about the negative effects of an incorrect tree pruning technique such as topping on microclimate. Such evidence may discourage countries and municipalities that still widely apply topping to urban trees to switch to other management strategies to increase tree contribution to urban heat island mitigation. Indeed, the capacity to recover from pruning, as well as pruning response, are strongly affected by species. More information on pruning tolerance and on time needed to recover ecosystem services provisioning after pruning is needed, also taking into account potential disservices (e.g. higher likelihood of failure due to poor structure and decay) which may arise from improper pruning.

CRediT authorship contribution statement

Francesco Ferrini: Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Alessio Fini:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sebastien Comin:** Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Denise Corsini:** Writing – review & editing, Investigation. **Irene Vigevani:** Writing – review & editing, Investigation, Formal analysis. **Piero Frangi:** Resources, Investigation. **Marco Napoli:** Writing – original draft, Methodology, Investigation, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The author is an Editorial Board Member/Editor-in-Chief/Associate Editor/Guest Editor for *[Journal name]* and was not involved in the editorial review or the decision to publish this article.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2024.128583.

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