IMPACT OF A MODERATE WATER STRESS ON THE CLIMATIC SERVICES PROVIDED BY STREET TREES: AN EXPERIMENTAL STUDY INSIDE AN OUTDOOR CANYON STREET SCALE MODEL

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Abstract: With climate change, cities are experiencing more frequent heatwaves which are also enhanced by the urban characteristics. The cast shadows and evapotranspiration provided by street trees appear to be able to mitigate the cities microclimate but might depend on the trees water supply. In this study, the climatic benefits (air temperature reduction, Universal Thermal Climate Index) provided by street trees (*Malus Coccinella*® 'Courtarou') located in a 1/5 scale canyon street model and exposed to a moderate water restriction were monitored during a 10 days sunny and warm period in July 2021. Although the trees experiencing water restriction reduced their transpiration, they maintained a level of benefits close to that of the well-watered trees probably because the radiation interception by their foliage was still important.

Keywords: Water restriction, tree transpiration, human thermal comfort, urban environment

Introduction

The ongoing climate change is accompanied by a multiplication of extreme events such as heatwaves. In cities, overheatings are already enhanced by the urban configuration, the reduction of the amount of vegetation and water surfaces and the nature of the materials, which produce an Urban Heat Island (UHI) effect (Bouyer, 2009) and may cause sanitary issues. Vegetation, especially street trees, may counteract this phenomenon by means of two main benefits: cast shadows and evapotranspiration. However, the water resources of trees won't be guaranteed all along the growing season in the near future given that the quantity and the distribution of rainfalls are expected to be modified. As a consequence, their ability to maintain significant cooling benefits under such conditions needs to be studied.

Since the pioneering work of Oke (2002), many studies related to the UHI quantified the overheating effect in various cities, such as Paris where it can exceed 10 °C (Cantat, 2004), and its characteristics as reviewed by Arnfield (2003). Different promising strategies to mitigate the urban climate based on urban geometry and urban greening (including street trees) were already explored (Jamei et al., 2016). A wide range of air temperature reduction attributable to street trees can be found in the literature (from 0.4 °C to 6 °C) (Mballo et al., 2021). Several studies took place in canyon streets, a common urban configuration which appeared to be adapted to observe the phenomena at stake in the UHI and now tend to be used at a reduced scale to assess experimentally the climatic benefits of vegetation. Mballo et al. (2021), for instance, measured a 2.7 °C air temperature reduction at mid-day under well-watered street trees in a reduced-scale canyon street. Gebert et al. (2019) or Chen et al. (2011) are some of the few authors to have measured the soil water content and established a link between tree transpiration and soil water availability. However, very few studies tried to link the climatic benefits of street trees to their hydric status. In order to enlighten this relationship, the present work proposes to evaluate the microclimate and human thermal comfort under trees grown in a reduced scale canyon street during a controlled moderate water restriction.

1. Materials and methods

The experiments were realized in a 1/5 scale canyon street model built at Institut Agro Rennes-Angers, France (47°28' N, 0°33' W) in 2017-2018. The street (see dimensions in Fig. 1) is bordered by two buildings made of a concrete wall covered with white paint on the street side forming a canyon which aspect ratio (height of the buildings divided by the width of the street) is 1. The street is oriented North-South and its ground is covered with a 0.04 m layer of asphalt. The street is divided into one treeless zone (southern part) and two treed zones (northern part and middle of the street) both containing 5 aligned ornamental apple trees (*Malus Coccinella®* 'Courtarou') which were 4 years old at the time of the experiment. Each tree was planted in a container filled with a 44.5 L volume of a topsoil-compost mixture (from now on referred as "soil") placed in a pit dug along the North-South central axis of the street. The containers were covered with lids and the pits with asphalt panels preventing rainfalls infiltration and evaporation from the soil. The trees were drip-irrigated daily from June 1, 2021 between 20h and 22h UTC with an amount of water allowing to fill the soil up to the water-field capacity. The occasional drainage water was collected manually every day in a tank placed below every container. The matric potential and the soil volumetric water content were monitored in the 3 central containers of each zone with 4 tensiometers (0.15 m and 0.3 m depth, East-West central axis, STCP 850, SDEC, [0:1000 hPa] ± 0.5%) and 2 capacitive probes (0.225 m depth, North-south central axis, ECH20 EC-5, Decagon, [0:100%] ± 0.03 $m^3.m^{-3}$). A daily water balance is realized over the transpiration period (adjusted according to the sunlight duration and the climatic demand) to evaluate tree transpiration which was considered equal to the soil water content variation (Mballo et al., 2021).

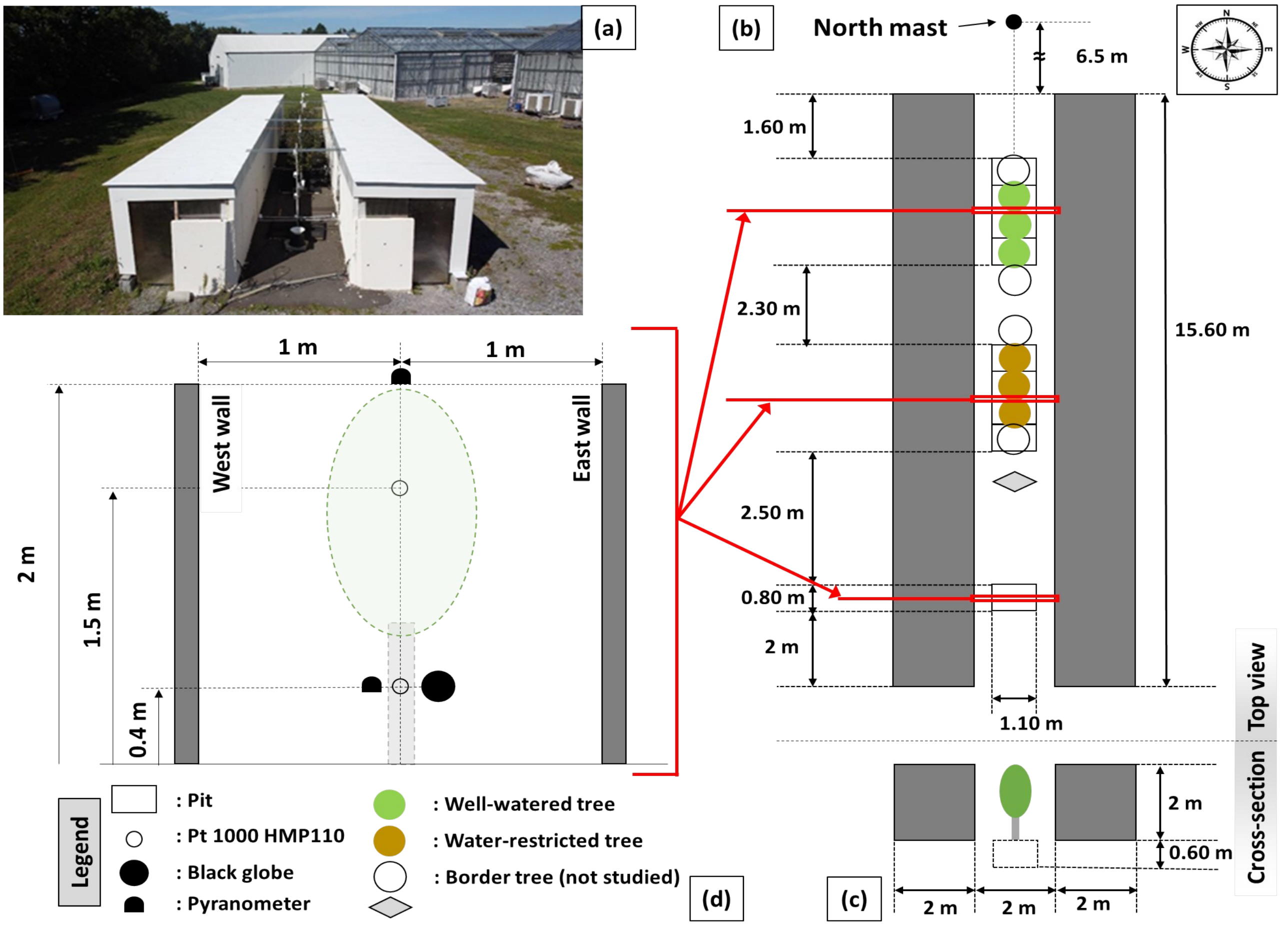

figure 1. South view picture of the street (a). Drawing of the top view (b) and a cross-section (c) of the canyon street. Location of the sensors in the three studied zones (d).

Meteorological sensors were mounted in the center of each zone at three heights above the ground of the street (Fig. 1): 0.4 m (which corresponds to a height of 2 m at full-scale, for the evaluation of human thermal comfort) and 1.5 m and 2 m which are respectively inside and above the tree crowns. Air temperature and relative humidity were measured at 0.4 m and 1.5 m from the ground with platinum and capacitive probes (Pt 1000 HMP, Vaisala, [-40:60] ± 0.2 °C and [0:100] ± 2%). Globe temperature was measured at 0.4 m from the ground using platinum probes enclosed in black painted copper spheres of 15 cm diameter. The above-mentioned measurements were also carried out outside the street on a mast located approximately 6.5 m north from the street. Pyranometers (CNR4, Campbell Scientific Ltd, [0:2000 W/m^2] ± 10%) placed above and under the trees (0.4 m and 2 m from the ground) were used to measure the solar short wave radiation and to calculate a radiation transmission ratio defined as the radiation measured under the trees divided by that measured above them. The wind speed was measured inside the street with a 3D sonic anemometer (CSAT3, Campbell Scientific Ltd, [0:30] ± 0.08 $m.s^{-1}$) mounted at 0.4 m from the ground and outside the street with a LCJ CV-7 2D sonic anemometer ([0.5:148] ± 0.5 $km.h^{-1}$) placed at 2 m from the ground on a mast located 8 m west from the street. The meteorological variables measured on both masts located outside the street were used to evaluate reference evapotranspiration with the Penman-Monteith equation whereas those measured inside the street were used to evaluate the human thermal comfort by calculating the Universal Thermal Climate Index (UTCI) (Bröde et al., 2011).

Previous studies were carried out using the present scale canyon street model with a similar setup leading to the characterization of the microclimate inside the street with well-watered trees (Mballo et al., 2021). In the present study, during a sunny period in July 2021, one treed zone (North area) was kept well-watered (irrigation: 4.8 $L.tree^{-1}.day^{-1}$) while the irrigation of the second one (middle area) was stopped from July 15, 2021. The matric potential and the soil volumetric water content of this zone were then expected to decrease, empty the readily available water content of the soil (determined with the FAO et al. (2006) recommendations) and finally reach the permanent wilting point. At that moment, the irrigation of the water restricted zone was partially turned back on to half of the dose of the well-watered trees. This 2.4 $L.tree^{-1}.day^{-1}$ irrigation was close to the transpiration rates of the well-watered trees and was meant to maintain the available water content above the permanent wilting point and within the non-readily available water storage capacity for a few days. Full irrigation was finally turned back on July 23, 2021, because deteriorated weather conditions were forecast for the next days.

2. Results

The trees access to water can be assessed with the evolution of the soil volumetric water content. Fig. 2 shows as an example the evolution of the average soil volumetric water content for one well-watered tree and one water restricted tree (for each tree an average value was calculated with both capacitive probes of its container). Similar patterns were observed for the other trees which are not shown here for more visibility. After the last irrigation (July 14) the soil volumetric water content of the water restricted trees decreased and they began to experience water stress on July 17 when their readily available water storage capacity was fully emptied. On the same day, their matric potential went beyond the measurement range of the tensiometers (lower limit comprised between -800 and -1000 hPa) whose signal was lost for the rest of the experiment. The permanent wilting point was approached on July 20 and irrigation was partially turned back on the same day. The daily amount of water poured appeared to be sufficient to gradually refill the soil water storage capacity and the field capacity was reached back on July 24. During this whole period, the soil volumetric water content of the well-watered trees remained close to the field capacity.

The daily transpiration of the 3 central trees of each zone, was compared to a reference evapotranspiration as shown on Fig. 3. Before the water restriction, all trees were having similar behaviors but when the reference evapotranspiration doubled between July 14 and 19 (from about 3.5 $L.m^{-2}.day^{-1}$ to 7 $L.m^{-2}.day^{-1}$), the transpiration of the well-watered trees increased by about 70% while that of the water restricted trees collapsed by about 70% during the same period. They reached a minimum transpiration of about 0.5 $L.day^{-1}$ on July 20 that is almost 5 times less than the transpiration of the well-watered trees. As a consequence, the water restricted trees sprayed less water into the air of the street during that period as shown by Fig. 4a which introduces the evolution of the daily average absolute humidity calculated around noon between 11h and 13h UTC inside the tree crowns. A maximum difference between both zones was reached on July 19, the absolute humidity being about 0.5 $g_{water}/kg_{dry\ air}$ lower in the water restricted zone, whereas both zones had shown similar behaviours before the irrigation stop (difference lower than 0.27 $g_{water}/kg_{dry\ air}$). After the irrigation return, the transpiration of the water restricted trees rose back and reached a rate close to that of the well-watered trees on July 24 and the difference of absolute humidity between both zones decreased.

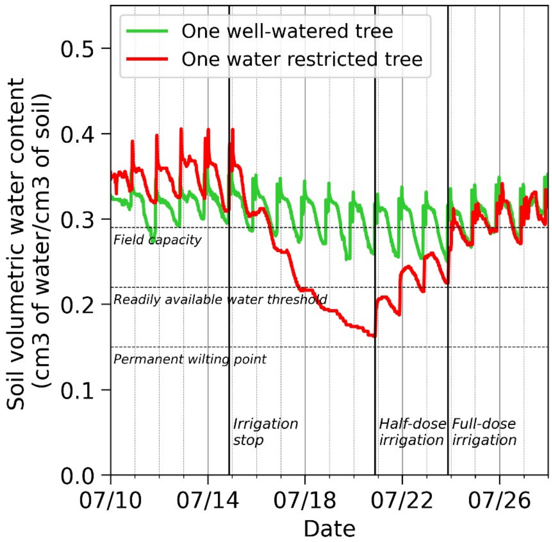

figure 2. Evolution of the mean soil volumetric water content measured for one well-watered tree and one water restricted tree.

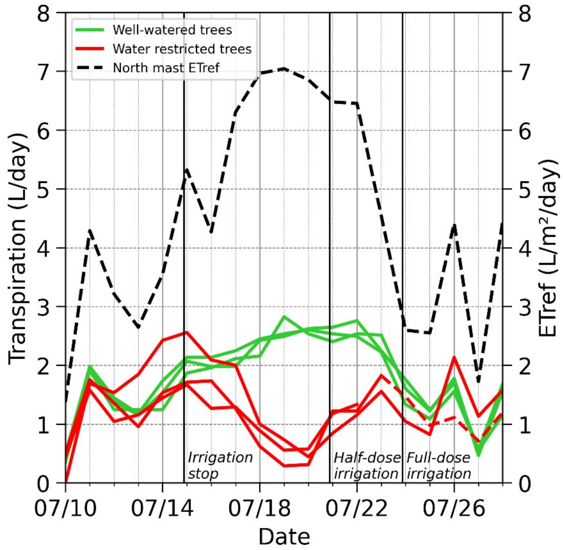

figure 3. Evolution of the daily transpiration estimated for the 3 central trees of each zone and the corresponding local reference evapotranspiration Etref. Red dotted line: only 1 ECH20 EC-5 working, red solid line stopped on July 22: no more ECH20 EC-5 working.

Regarding the cast shadows provided by the trees, second phenomenon involved in the climatic benefits, the daily radiation transmission ratios (averaged around noon) of both vegetated zones remained very close all along the water restriction period (mean difference is 0.03) except on July 20 when a temporary extreme difference (0.11) was observed (Fig. 4b). Thus, both vegetated zones kept providing efficient radiation interception, their ratio being much lower than that of the non-vegetated zone.

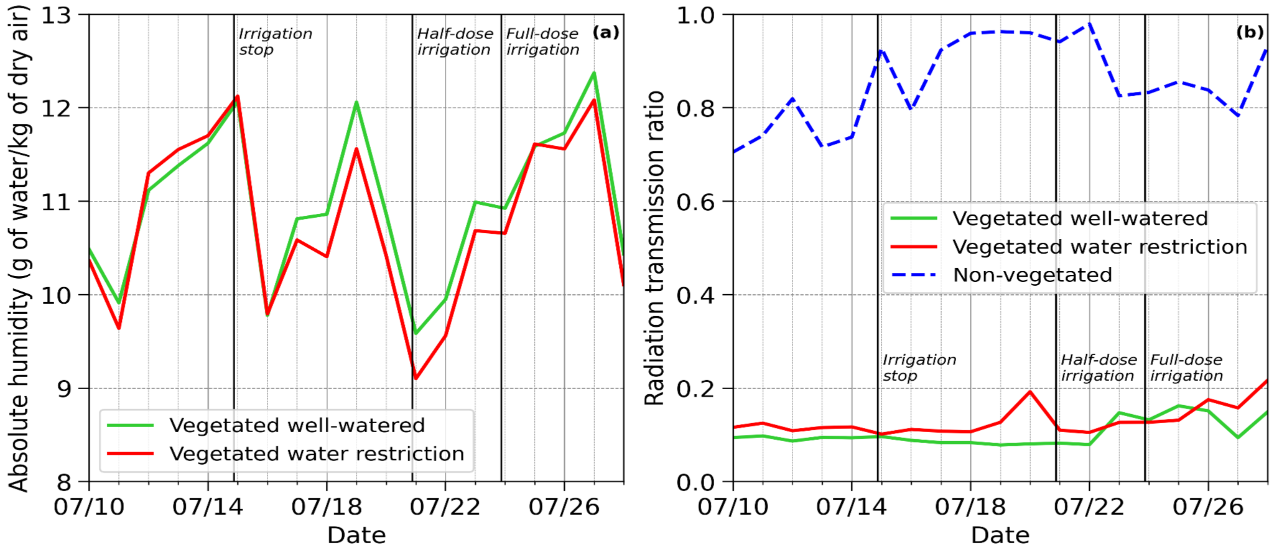

figure 4. a) Evolution of the absolute humidity averaged from 11h to 13h UTC at 1.5 m from the ground, b) evolution of the radiation transmission ratio between 2.1 and 0.4 m from the ground averaged from 11h to 13h UTC.

The daily average air temperature calculated around noon at 0.4 m from the ground (which corresponds approximately to human height at full-scale) highlights the overheating effect of the street (Fig. 5a). The non-vegetated zone is on average 1.4 °C higher than the local environment (North mast located outside the street) and a maximum difference of 2.6 °C was measured on July 15. Before the restriction period, the difference of mean air temperature calculated in both vegetated zones remained lower than 0.2 °C, which corresponds to the measurement accuracy of the platinum probes. Then, from July 17 to July 20, this difference exceeded 0.3 °C during four days and reached a maximum value of 0.4 °C on July 19. Such difference between both vegetated zones is quite low and the cooling effect of the water restricted zone is still noticeable, the daily mean air temperature calculated in this zone being at least 1 °C lower and up to 3.3 °C lower than that calculated in the non-vegetated zone.

The UTCI, calculated at 0.4 m from the ground in each zone as well as at the North mast, and averaged around noon is shown in Fig. 5b. The UTCI appears to be already higher in the water restricted zone than in the well-watered one (+ 0.9 °C in average) before the irrigation stop. From July 15, this difference increases and will remain higher than 1.1 °C for the rest of the analyzed period even after the end of the water restriction. This difference reaches a maximum value of 2.1 °C on July 20 while the soil volumetric water content of the water restricted zone is at its lowest point. Yet, on the same day, the water restricted zone and the well-watered zone provided respectively a 5.7 °C and a 7.8 °C UTCI reduction compared to the non-vegetated zone whose UTCI was 1.3 °C higher than that estimated outside the street. The water restricted zone was maintained in the moderate heat stress category, like the well-watered zone.

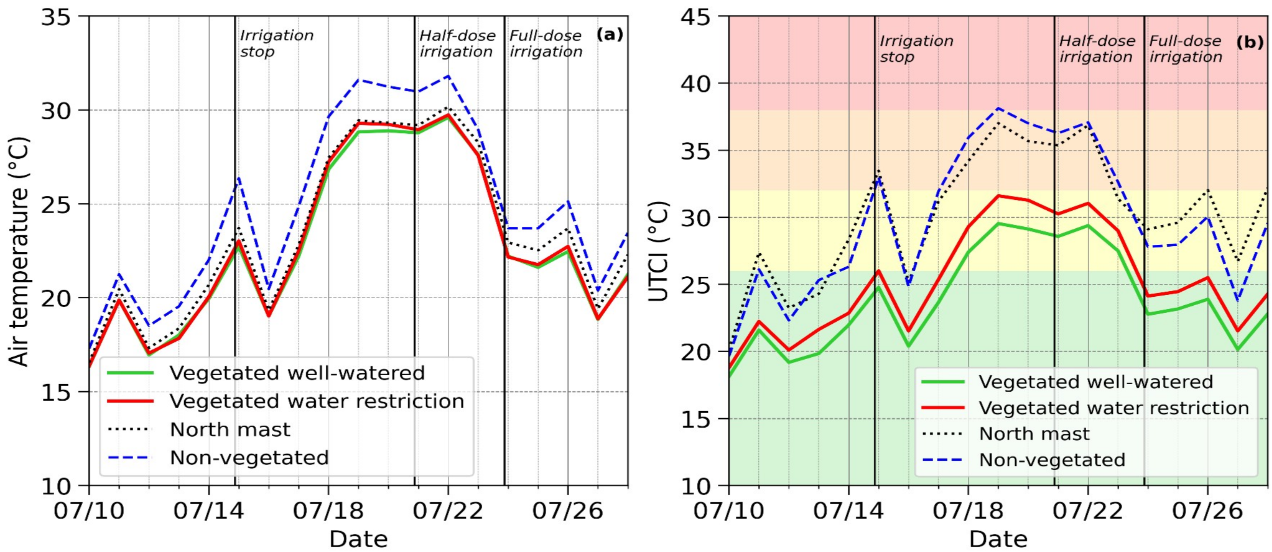

figure 5. a) Evolution of the air temperature averaged from 11h to 13h UTC at 0.4 m from the ground, b) evolution of the UTCI averaged from 11h to 13h UTC at 0.4 m from the ground regarding the different thermal stress categories: no thermal stress (9 to 26 °C UTCI, green), moderate heat stress (26 to 32 °C UTCI, yellow), high heat stress (32 to 38 °C UTCI, orange), very high heat stress (38 to 46 °C UTCI, red) and extreme heat stress (>46 °C UTCI, not shown).

3. Discussion

The water restricted zone kept providing efficient cooling benefits all along the restriction period regarding both the air temperature, which remained close to that of the well-watered trees, and UTCI which was kept in the moderate heat stress category in both vegetated zones. During the studied period, the water restricted trees were maintained under the readily available water threshold for only 5 days (from July 17 to July 21). Thus, among both phenomena involved in the climatic benefits, only tree transpiration was very impacted whereas the water restricted trees kept providing efficient cast shadows. Indeed, the water restricted trees used nearly 57% less water for their transpiration than the well-watered trees while the irrigation was completely stopped (from July 16 to July 20) despite the high reference evapotranspiration of that period (Fig. 3). They sprayed less water into the air of the street lowering the contribution of evapotranspiration to air cooling. On the contrary, no significant evolution of the radiation transmission ratio of the water restricted trees was observed. Although a few weaknesses were visually noticed on the leaves of the water restricted trees from July 20 (some leaves starting to wither or turning yellow and falling), no impact of the water restriction beyond the irrigation return could be observed. The water restriction might have been too short and not intense enough to induce an important foliage loss. Then, the low impact on the climatic benefits observed in the present study is consistent with the conclusions of Mballo et al. (2021) who estimated that shade cover effect was responsible for 74% of the cooling benefits of trees and transpiration for the remaining 26%.

Finally, the impact of the water restriction was higher on the UTCI than on air temperature. The UTCI evaluation, requires the calculation of the mean radiant temperature (Tmrt), which is very sensitive to all short wave and long wave radiation. A noticeable Tmrt difference was observed (not shown) between both vegetated zones during the water restriction but cannot be attributed to short wave radiation as explained previously. Given that transpiration is a mechanism that helps the trees to cool down their leaves, the water restricted trees, by reducing their transpiration, might not have been able to cool down their foliage whose temperature rose, increasing the long wave radiation fluxes. Further analysis will have to be carried out to enlighten the relationship between this mechanism and the impact on the UTCI.

Conclusion

The present work showed that ornamental apple trees grown in a 1/5 scale canyon street, when exposed to a moderate water stress, were able to maintain a level of climatic benefits close to that of well-watered trees. A short-term significant impact was measured on their transpiration but not on their ability to intercept the short wave radiation. In the next step of the project, the effect of a more severe water stress will be investigated to analyze up to what extent the climatic benefits of the trees can be impacted by longer periods of drought.

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