Long term impact of climate on tree-growth patterns in Paris street trees and its consequences on tree cooling potential: A dendroclimatic approach

David, Ambre[1] - Boura, Anaïs[2] – Rankovic, Aleksandar[1] – Kraepiel, Yvan[1] - Lata, Jean-Christophe[1] - Barot, Sébastien[1]- Abbadie, Luc[1] - Ngao, Jérôme[3]

1 *Institute of Ecology and Environmental Sciences of Paris - iEESParis, 46 rue d'Ulm, 75230 Paris Cedex 5, France, ambre.david@gmail.com, aleks.rankovic@gmail.com, lata@biologie.ens.fr, sebastien.barot@ird.fr, abbadie@biologie.ens.fr*

2 *Research Center of Paleobiodiversity and Paleoenvironments, 57 rue Cuvier, 75231 Paris Cedex 5, France, anais.boura@upmc.fr*

3 *French National Institute for Agricultural Research, 5 chemin de Beaulieu 63039 Clermont-Ferrand Cedex 2, France, jerome.ngao@clermont.inra.fr*

dated: 15 June 2015

1. Introduction

Water availability is widely recognized as being an essential factor for tree survival, growth and for maximizing their ability in mitigating urban heat islands (UHI) through evapotranspiration. In urban areas, where the ground surface is highly impervious and the trees are not regularly irrigated, the reduction of precipitation infiltration into soils may increase water stress for trees (Whitlow et al., 1992; Clark and Kjelgren, 1990). It is also generally predicted that trees in urban sites have higher water losses than trees in natural forests due to increased evapotranspiration demand (McCarthy and Pataki, 2010) and that their average lifespan is shorter (Sæbø et al. 2003). Tree lifetime is constrained by physiological processes. When trees are old or when their physiological functioning are limited, trees stop growing and use their stored reserves. When these reserves are drained, trees decline and die (Downer, 2011). There is currently insufficient data to generalize the physiological responses of trees to the complex urban environment, where both climatic and management factors are entangled. Especially, little information is available on the effect of water stress on tree health, and its consequence on ecosystem services such as UHI mitigation. Furthermore, on-going climatic changes make it all the more necessary to anticipate the potential trajectories of urban trees, in terms of (i) risk assessment of tree survival, and (ii) their potential ability for cooling services.
In this context, a retrospective approach of the long-term relations of trees to urban climate can thus provide a way to both enhance our understanding of current urban tree hydric state and gain insights on future levels of water stress levels under new climates. It is well known that there is a close relationship between tree growth and climate. Indeed, the size and the state of tree-rings are affected by the yearly sequences of favourable and unfavourable climates (Fritts, 1976). In turn, climate phenomena can be identified and reconstructed through ring-width sequences (Hughes, 2002). Thus, dendrochronology can be used as informative tool to understand the long-term influence of past climate on urban trees growth. Consequently, understanding the past trajectory of tree growth under past climates can provide insights on their answer to future climate projections. Since tree cooling potential is tightly linked to water availability, negative feedback of water stress to tree cooling potential can be expected.
The aim of this study is to (i) reconstruct the past growth dynamics of trees in urban environments using dendrochronology methods and principles and (ii) compare the past growth of trees grown in contrasted environments (namely: streets, park and arboretum). These results can help determining urban environmental factors that impact urban trees growth and health the most. They can also be used as preliminary arguments to predict the impact of climate changes on tree growth and the potential tree cooling effects in the city of Paris.

2. Material and Methods

2.1. Tree samples

The study focused on the silver linden (*Tilia tomentosa* Moench), one of the predominant species planted in the streets of Paris. In order to assess the impact of urban environment on growth, trees were sampled in three different living environments. In Paris, 75 street trees and 15 park trees were sampled in several locations (Fig.1), and represent urban sites in this study. In addition, 5 trees were sampled in the National Arboretum of Chèvreloup (Rocquencourt, Versailles, MNHN) and represent trees growing in a non-urban environment. These 100 urban and non-urban trees were selected according to 3 classes of DBH (Diameter at Breast Height, 1.30 m). Class 1 included trees with DBH between 6 to 15 cm (young trees), Class 2 with DBH between 32 to 43 cm (young adults), and Class 3 with DBH between 56 to 74 cm (adults). The age of each tree was determined by using wood core samples (one for each tree). The collected tree rings allowed documenting a 100-year chronosequence. This sampling design enabled a comparative approach of trees of different ages, which was used to disentangle the impact of chronic stress, tree age and climate history. The health status of each tree was visually assessed according to a visual tree assessment (VTA) protocol (Mattheck and Breloer, 1994).

Fig. 1 Site distribution of sampled trees in Paris city

2.2. Tree growth and dendrometric characteristics

Tree cores were collected in March (street trees) and September 2014 (park and arboretum trees) with a Pressler borer (Zimmer SA). In July 2014, total tree height and crown height were measured with an electronic clinometer (Haglöf EC II). The DBH and canopy spread in four direction were measured using a measuring tape. Projected surface and crown volume were estimated using the ellipsoid formula for an area and a volume respectively. Biomass in tree trunks was estimated according to the method described by Rahman et al. (2014).

2.3. Tree-ring measurements and statistical analyses

The number of tree-rings and ring-width were measured using a Lintab measurement table (Rinntech). Tree rings were measured with a resolution of 1:100 mm. Every wood anomaly, such as false-rings, was recorded. Each individual ring-width chronology was cross-dated by *skeleton plotting* (Maxwell et al. 2011) involving the visual inspection of core samples and the visual comparison between individual chronology and the chosen *master chronology*, according to *marker years* corresponding to *marker rings* (Fritts, 1976; Maxwell et al., 2011). The raw tree-rings width series were then standardised, in a first step, by fitting a negative exponential or a non-ascending straight lines function in order to remove age-related and slow environmental process growth trends (*e.g.* low frequency signal at multi-decennial scale). In a second step, the standardised data was fitted by a cubic spline corresponding to third degree polynomials, to eliminate the middle frequency signal affecting tree growth and corresponding to environmental and management process at the decennial scale. Growth indices given by these two steps of standardization were then used for statistical analysis. Raw tree-rings and growth indices were calculated with the DENDRO package (Lebourgeois et al., 2012) using R 3.2.0. Data were subjected to ANOVA and Tukey post-hoc tests when normally distributed, and to Kruskall-Wallis and Wilcoxon-Mann-Whitney tests otherwise. Frequencies were analysed with a X^2 test using R. Differences between groups were considered significant at p <0.05.

3. Results

3.1. Tree growth and dendrometric characteristics

Class 2 and Class 3 of trees living in parks and in the arboretum have the closest age, around 50 years-old, which correspond to the age observed in street trees from Class 2 (Fig. 2). Trees from Class 3 in streets are older than trees from the other sites with an average age of 80 years (Fig. 2A). Wilcoxon-Mann-Whitney tests indicate that there is a significant difference of tree-ring width between urban and non-urban trees (Street *vs.* Park: W=177, *p-value* < 0.05; Street *vs.* Arboretum: W=28, *p-value < 0.05*). Moreover, a decreasing trend following DBH classes is observed for mean tree-ring width for street trees, while an opposite trend is observed for park trees. The mean tree-ring width of arboretum trees tops all classes of urban trees.

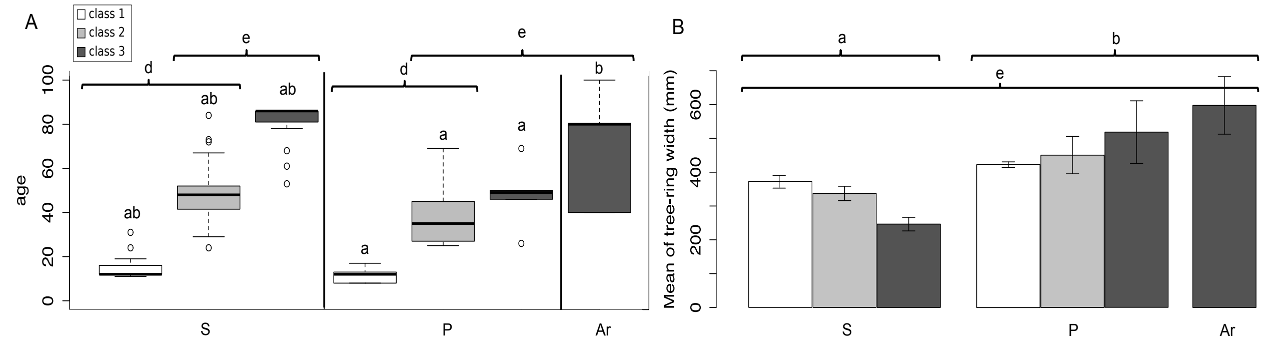

Fig. 2 Tree age (A) and mean of tree-rings width (B) of urban and non-urban trees
Different letters (a,b,c) and (d,e,f) represent significant differences between sites and class respectively. Error bars show standard errors (SD/√(n)). S designates street trees, P is for park trees and Ar is for arboretum trees.

3.2. Descriptive statistics on growth index

Descriptive statistics on standardized data show that there is no significant difference in mean sensitivity (Msb), synchronism coefficient (SR) and first order autocorrelation between site types (Fig. 3). However, statistical tests on mean sensitivity and coefficient of synchronism show significant differences according to tree life stage (Fig. 3A and 3B, 3A: Kruskall-Wallis, X^2 = 51,86, *p-value* < *0.05*; 3B: Kruskall-Wallis, X^2 = 15, *p-value* < *0.05*). However, we observe a highest mean sensitivity for trees living in streets (MSb = 0.45) and parks (MSb = 0.40) and a lower synchronism coefficient (Street: SR = 0.29; Park: SR = 0.33) compared to arboretum trees (MSb = 0.28, SR = 0.38). These results are very clear for the youngest trees in Class 1. The first order autocorrelation increase with DBH and consequently with age (Kruskall-Wallis, X^2 = 24.9028, *p-value* < *0.05*) (Fig. 3C).

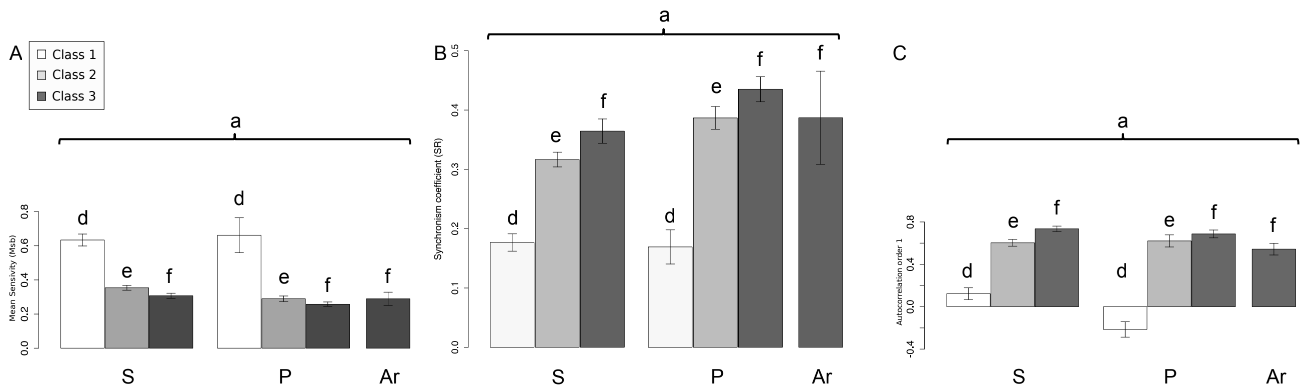

Fig. 3 Mean sensitivity (A), synchronism coefficient (B) and first order autocorrelation (C) of urban and non-urban trees. Different letters (a,b,c) and (d,e,f) represent significant differences between sites and class respectively. Error bars show standard errors (SD/√(n)). S designates street trees, P is for park trees and Ar is for arboretum trees.

3.3. False-rings

Street trees are the most affected by wood anomalies with 70% of trees showing false-ring on cores. This value was higher compared to other sites, with 53% of park trees and 40% of arboretum trees showing false-rings. A X^2 test showed significant differences between the frequencies of each group.

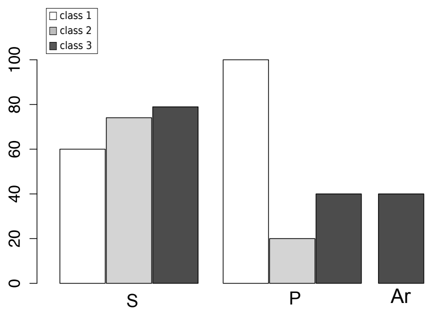

Fig. 4 Frequency of trees with false-ring
S designates street trees, P is for park trees and Ar is for arboretum trees.

4. Discussion

4.1. Tree growth and dendrometric characteristics

Street trees in Paris appear to have a lower growth rate compared to trees living in Paris parks and the arboretum. Indeed, for an equivalent DBH of around 65 cm, Paris street trees are on average 30 years older than trees in parks. This result is confirmed by the lowest mean tree-ring width observed on street tree cores. Several anthropogenic pressures may explain this pattern, such as pruning or the important amount of impervious surfaces that surround street trees. Concerning the physiological functioning of street trees, this limited growth might be explained by lower photosynthetic carbon assimilation due to water stress. Indeed, growth, especially of latewood, is related to soil water deficit (Hinckley et al., 1976). Water deficit is associated with stomata closure and, thus, to the reduction of carbon uptake through photosynthesis. Indeed, results not shown here on biomass (and thus carbon storage) per year show significant differences with tree age and type of site, with the lowest value for trees planted in streets. Dendrochronological studies of beech and oak trees have shown that ring width was positively correlated with rainfall in July and August (Fonti et al., 2010) and negatively correlated with high temperatures in summer (Lebourgeois et al., 2006). To further investigate this issue we will compare these dendrometric data with climatic data. Preliminary results on correlations between tree-rings width and climate variables tend to indicate that precipitations are the limiting factor for the growth of trees planted in street.

4.2. Descriptive statistics on growth index

Mean sensitivity and synchronism coefficient are both important descriptive statistics in dendrochronology. They describe the strength and the level of homogeneity of tree responses to environmental variability linked for example to climate or water availability (Fritts, 1976). Trees in urban area seem to be more sensitive to environmental factors but with a more heterogeneous response within the population. A high mean sensitivity associated with a low synchronism should indicate that trees living in streets, especially the youngest, have a growth much more influenced by local factors acting selectively on individuals (Lebourgeois et al., 2012). Indeed, previous study showed that young trees are more sensitives to environmental factors (Fichtler et al., 2004). This may be due to low quantity of carbohydrates reserves because of their young age, making them more vulnerable to unfavorable climatic conditions (White et al., 2014). The lower value of synchronism for urban trees (0.33) expresses the level of reliability of the cross-dating process. It highlights the important difficulties during the synchronization of individual tree-ring series mostly due to the huge amount of false-rings or other anomalies observed on core samples. Cross-dating could be improved with a second core in order to compare individual tree-ring series and eliminate false or missing rings. However, a low synchronism coefficient does not necessarily imply that climatic signal of our sample is not relevant and the number of trees sampled in Paris Region could increase our chronology quality (Grissino-Mayer, 2001).

First order autocorrelation conveys the degree of correlation between current and previous year growth and is associated with the use of previous photoassimilates for current year's tree ring formation. Thus, growth of older trees in the current year is limited by the growth of the previous year through the accumulated reserves of carbohydrates (Breda & Granier, 1996) but no difference was observed between site types. We could have expected the highest first order autocorrelation value for young adults and adult trees in streets. It seems to indicate that the stress undergone by trees in streets influences directly the amount of carbon fixed by trees, as shown by a lower tree ring width. But this stress does not impact directly the amount of carbohydrates reserves. Indeed, trees growing under conditions of high environmental stress such as severe water stress (Breda et al. 2006, Gruber et al. 2012) or defoliation (Hoch 2005, Palacio et al. 2008) showed high levels of stored non-structural carbohydrates (NSCs) associated with, or despite, reduced growth (Simar et al., 2013). However, recent studies showed significant NSC pools that remain unused by trees. This may reflect a condition intermediate to the 'source' and 'sink' limitations (Bhupinderpal et al. 2003, Hoch 2005). A comparison of intraseasonal variations of growth and reserve could help to better understand these results.

4.3. False-rings as water stress indicator

The frequency of trees with false-rings is significantly higher for trees living in streets than in parks and the arboretum, especially for the oldest. This higher value is probably the expression of important cumulative stress in street tree history. According to Bouriaud et al. (2005), false-rings are mainly associated with drought during the growing season. Thus, this suggests that the limiting factor for the growth of street trees is water availability.

5. Conclusion

Regarding our previous results, it seems that one of the main factors limiting the growth of street trees is water, through precipitations and water availability. However, a retrospective study between growth related to climate data could help to better understand the physiological process highlighted by our study. Nevertheless, the limited growth of trees planted in streets suggests a limited photosynthesis process and consequently a lower capacity of evapotranspiration because of the closure of stomata during water stress. This may strongly limit the cooling potential of street trees during UHI phenomena, as well as their survival in the city.

Acknowledgments

This project was funded and supported by the CDC Biodiversity and ANR Ecoville (grant n° ANR-14-CE22-0021). We are grateful to the National Museum of Natural History, Mrs François Hachette and Mr Philippe Raynaud for allowing sampling campaings in the National Arboretum of Chèvreloup. We are very grateful to Coralie Charlot for her important work and Alexa Dufraisse (French National Centre for Scientific Research) for allowing us to use a Lintab measurement table. We are also especially grateful to the Mairie de Paris, especially Mrs Patricia Orsini, Mrs Beatrice Rizzo and Mr Christophe Simonetti for authorizing us to work on Paris street and park trees and for their priceless help during this study.

References

Bouriaud O., Leban J.M., Bert D., Deleuze C., 2005: Intraannual variations in climate influence growth and wood density of Norway spruce. *Tree Physiology.* **25(6)** 651–660

Breda N., Granier A., 1996: Intra- and interannual variations of transpiration, leaf area index and radial growth of sessile oak stand (*Quercus petraea*). *Annals Sciences Forestry*. **53** 521-536

Breda N., Huc R., Granier A., Dreyer E., 2006 : Temperate forest trees and stands under severe drought: a review of ecophysiological responses, adaptation processes and long-term consequences. *Ann For Sci* **63** 625–644

Clark J. R., Kjelgren R., 1990: Water as a limiting factor in the development of urban trees. *Journal of Arboriculture.* **16** 203–208

Bhupinderpal S., Nordgren A., Lofvenius M. O., Hogberg M. N., Mellander P. E., Hogberg P., 2003 : Tree root and soil heterotrophic respiration as revealed by girdling of boreal Scots pine forest: extending observaions beyond the first year. *Plant Cell Environment.* **26** 1287–1296

Downer J., 2011: Why trees die? *Landscape notes. University of California Cooperative Extension*. **23(3)** 1-6

Fichtler E., Trouet V., Beeckman H., Coppin P., Worbes M., 2004: Climatic signals in tree rings of *Burkea africana* and *Pterocarpus angolensis* from semiarid forests in Namibia, *Trees*. **18** 442–451

Fonti P., Von Arx G., García-González I., Eilmann B., Sass-Klaassen U., Gärtner H., 2010: Studying global change through investigation of the plastic responses of xylem anatomy in tree rings. *New Phytologist*. **185(1)** 42-53.

Fritts H., 1976: Tree rings and climate. *The Blackburn press* pp 567

Grissino-Mayer H. D., 2001 : Evaluating crossdating accuracy: A manual and tutorial for the computer program COFECHA. *Tree-Ring Research* **57(2)** 205-221

Gruber A., Pirkebner D., Florian C., Oberhuber W., 2012 : No evidence for depletion of carbohydrate pools in Scots pine (*Pinus sylvestris* L.) under drought stress. *Plant Biology.* **14** 142–148

Hoch G, 2005 : Fruit-bearing branchlets are carbon autonomous in mature broad-leaved temperate forest trees. *Plant Cell Environment.* **28** 651–659

Hinckley T. M., Thompson D. R., McGinness, N. P., Hinckley, A. R., 1976: Stem growth and phenology of a dominant white oak. *Proceedings of the 1st Central Hardwood Forest Conference Carbondale Ill Edited by JS Fralish GT Weaver and RC Schlesinger Southern Illinois University Carbondale.* **101** 187-202

Hughes M. K., 2002: Dendrochronology in climatology - the state of the art. *Dendrochronologia* **20(1-2)** 95-116

Lebourgeois F., 2006: Sensibilité au climat des Chênes sessile et pédonculé dans le réseau RENECOFOR. Comparaison avec les hêtraies*. Revue Forestière Française*. **LVII** 29-44

LeBourgeois F., Mérian P., 2012: Principes et méthodes de la dendrochronologie.

Mattheck C., Breloer H., 1994: Fiel guild for Visual Tree Assessment (VTA). *Arboricultural Journal: the International Journal of Urban Forestry.* **18(1)** 1-23

Maxwell R. S., Wixom J. A., Hessl A. E., 2011: A comparison of two techniques for measuring and crossdating tree rings. *Dendrochronologia*. **29** 237-243

McCarthy H. R., Pataki D. E., 2010: Drivers of variability in water use of native and non-native urban trees in the greater Los Angeles area. *Urban Ecosystems.* **13(4)** 393-414

Palacio S., Hester A. J., Maestro M., Millard P., 2008 : Browsed *Betula pubescens* trees are not carbon-limited. *Functionnal Ecol*ogy. **22** 808–815.$

Rahman M. A., Armson D., Ennos A. R., 2014: A comparison of the growth and cooling effectiveness of five commonly planted urban tree species. *Urban Ecosystems.* **18** 371-389

Sæbø A., Benedikzt, Randrup TB (2003) Selection of trees for urban forestry in the Nordic countries. *Urban Forestry and Urban Greening*. **2** 101–114

Simard S., Giovannelli A., Treydte K., Traversi M.L., King G. M., Frank D. and Fonti P., 2013 : Intra-annual dynamics of non structural carbohydrates in the cambium of mature conifer trees reflects radial growth demands. *Tree Physiology.* **33** 913-923

White P. B., Soulé P., van de Gevel S., 2014: Impacts of human disturbance on the temporal stability of climate–growth relationships in a red spruce forest, southern Appalachian Mountains, USA. *Dendrochronologia*. **32** 71–77

Whitlow T. H., Bassuk N. L., Reichert D. L.,1992: A 3-year study of water relations of urban street trees. *Journal of Applied Ecology.* **29** 436-450