The effects of trees on urban heat mitigation

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INTRODUCTION

Nature-based solutions appear to be an interesting option to mitigate urban heat and enhance thermal comfort. However, the effect of green infrastructures on the urban micro-climate are not properly characterized.

The objective of this study is to **estimate the cooling effect of a single tree** on a public place with numerical simulations, and to **discriminate the effects due to soil shading and evapotranspiration**.

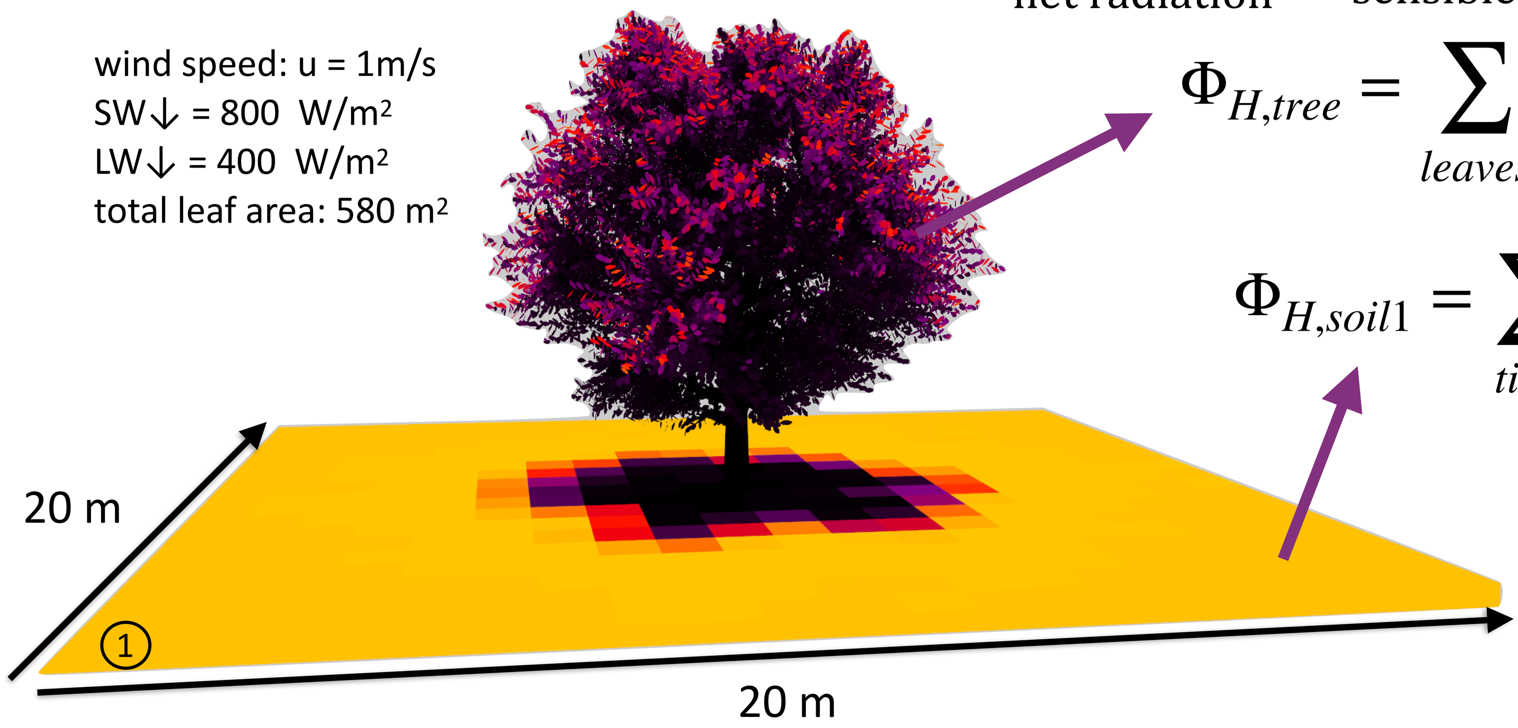
METHODS

The tree is modeled via the C++ application programming interface **Helios** [1]. Several plug-ins available in Helios allow to model:

- the 3D geometry of a tree;
- radiative transfers between the sky, the tree and the soil;
- latent and sensible fluxes emitted by the elements, based on an **energy balance approach**:

$$\underbrace{SW_{abs} + LW_{abs} - \epsilon\sigma T^4}_{\text{net radiation}} = \underbrace{h(T - T_a)}_{\text{sensible heat flux } \phi_H} + \underbrace{LE(T)}_{\text{latent heat flux } \phi_E}$$

SW_{abs}	absorbed short-wave radiation	W.m-2
LW_{abs}	absorbed long-wave radiation	W.m-2
ϵ	surface emissivity	-
σ	Stefan-Boltzmann constant	W.m-2.K-4
T	surface temperature	K
h	convective heat transfer coefficient	W.m-2.K-1
T_a	air temperature	K
L	specific latent heat of water	J.kg-1
E	evapotranspiration rate	kg.m-2.s



$$\Phi_{H,tree} = \sum_{leaves} \phi_{H,leaf} A_{leaf}$$

$$\Phi_{H,soil1} = \sum_{tiles} \phi_{H,tile} S_{tile}$$

$$\Phi_{H,soil2}$$

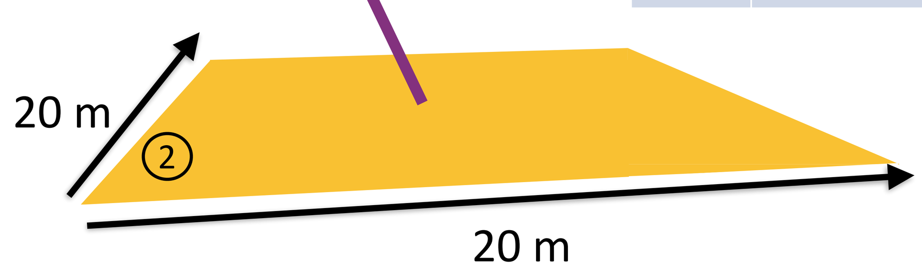


Fig. 1: Walnut tree from Helios library

$$\underbrace{\Phi_{H1} - \Phi_{H2}}_{\text{total cooling}} = \Phi^{nowater}_{H,tree} + \underbrace{(\Phi_{H,tree} - \Phi^{nowater}_{H,tree})}_{\Delta\Phi_{H,evap} \leq 0} + \underbrace{(\Phi_{H,soil1} - \Phi_{H,soil2})}_{\Delta\Phi_{H,shade} \leq 0}$$

The total cooling is the **sum of three terms**: the first one is the sensible heat flux released by the tree in the absence of transpiration, the second one is the contribution of evapotranspiration and the last one is the contribution of shade.

RESULTS & DISCUSSION

To determine the part played by each effect to the total cooling, three simulations are compared: (a) with a transpiring tree (mean E = 45 kg/h), (b) with transpiration prevented (E = 0 kg/h) and (c) without the tree.

Table 1 : Comparison of heat fluxes of the leaves for simulations (a) and (b)

	$\Phi_{H,tree}$(kW)	$\Phi_{H,tree}$(kW)	Mean ϕ_H(W/m²)	Mean ϕ_E(W/m²)
Leaves	-2.7	29	-4.7	50.6
Leaves w/o ET	11.3	0	20	0

Table 2 : Comparison of heat fluxes of the soil for simulations (b) and (c)

	$\Phi_{H,tree}$(kW)	SW_{abs}(kW)	Mean ϕ_H(W/m²)	Mean SW_{abs}(W/m²)
Soil 1	66.8	219	167	548
Soil 2	78.4	256	196	640

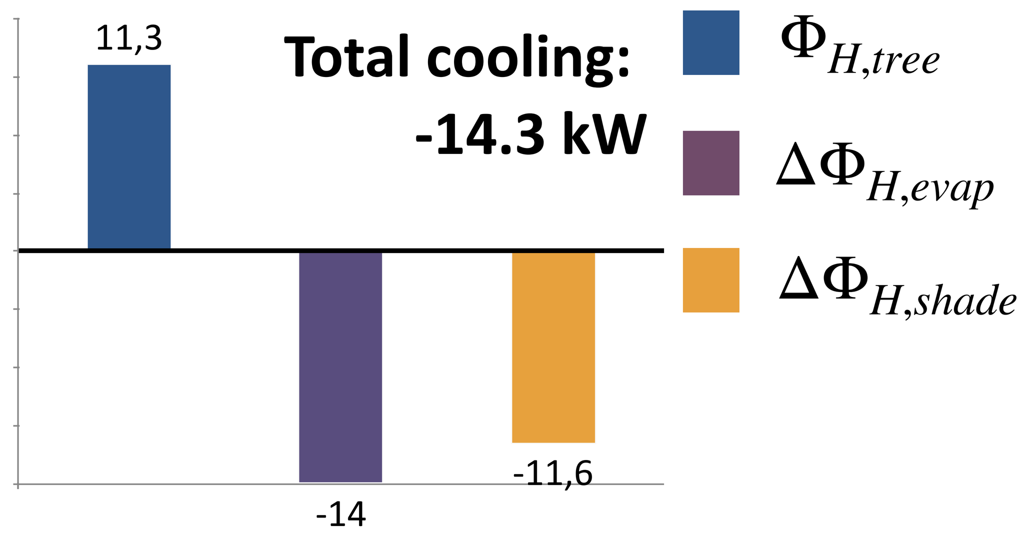


Fig. 2: Contributions of evapotranspiration and shading to the cooling effect of a tree for sim. (a)

When ϕ_E goes from 0 to 50 W/m² for the leaf, benefits on ϕ_H are divided by two (only a diminution of 25 W/m²). It is due to the decrease of leaf temperature, resulting in less emitted radiation:

$$R_{abs} = \underset{(-25)}{\epsilon\sigma T_S^4} + \underset{(-25)}{\phi_H} + \underset{(+50)}{\phi_E}$$

One can derive, analytically, that they are divided by $1 + 4\epsilon\sigma T_e^3/h_{leaf}$ with $T_e = \left(\frac{LW}{\epsilon\sigma}\right)^{1/4}$ the temperature associated with long-wave radiation.

Similarly, when *soil1* receives in average 90 W/m² less than *soil2*, ϕ_H decreases by $90/(1 + \frac{4\epsilon\sigma T_e^3}{h_{soil}})$

CONCLUSION & PERSPECTIVES

This decomposition of total cooling in three terms permits to better understand how a tree thermally impacts its vicinity. In this example, the contributions to the cooling have the same order of magnitude. Hence, the three effects need to be considered for modeling the thermal role of vegetation in cities. Such approaches can be used to model outdoor thermal comfort (including radiation, air temperature, wind velocity and humidity) or integrated in upscaled models to study urban heat island effects.

[1] Bailey, Brian N. "Helios: A Scalable 3D Plant and Environmental Biophysical Modeling Framework." *Frontiers in plant science* 10 (2019).