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Development of a CFD crop submodel for simulating microclimate and transpiration of ornamental plants grown in a greenhouse under water restriction

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ABSTRACT

Predictive models of soil-plant-atmosphere water transfers may be helpful to better manage water inputs to plants in greenhouses. In particular, Computational Fluid Dynamics appears to be a powerful tool to describe the greenhouse microclimate and plant behavior. Up until now, most models for potted plants grown in greenhouses were established for well-watered conditions. In this context, the aim of this work is to develop a specific submodel to simulate the distributed transpiration and microclimate during plants grown in pots inside greenhouses under water restriction conditions. A 2D transient CFD (Computational Fluid Dynamics) model was implemented and user-defined functions were adapted to take account of the crop interactions with the climate inside the greenhouse. The crop was considered as a porous medium and specific source terms for transpiration and sensible heat transfers were added. A specific submodel was also implemented to calculate the substrate water content based on the water balance between irrigation and transpiration. Particular care was paid to the modeling of stomatal resistance. In order to obtain the input data and to validate the CFD simulations, an experiment was conducted over 16 weeks inside a greenhouse equipped with New Guinea impatiens ornamental plants grown in containers on shelves. Both well-watered and restriction conditions were analyzed. The results of the CFD simulations showed the ability of the model to correctly predict transpiration, air and leaf temperatures as well as air humidity inside the greenhouse for both water regimes. Different irrigation scenarios were then tested, progressively reducing the water supply by providing a lesser amount of water than the growing media water capacity. The simulations made it possible to assess the model response to different irrigation regimes on plant transpiration, usual growing media water potential and climate distribution inside the greenhouse. The tests also showed that the water supply could be reduced by 20% without significantly impacting the transpiration rate and, therefore, potential plant growth. The CFD model could thus be useful to test different irrigation scenarios and better manage water inputs.

1. Introduction

Global change combined with an increase in the water demand enhances the occurrence of water scarcity events, making it necessary to develop strategies to better manage water resources. Since agriculture is the largest consumer of water worldwide, it is urgent to find a way to economize water by adapting inputs to plant needs. This is true in greenhouses, in particular, where reducing water consumption by increasing water efficiency is relevant not only for environmental reasons but for economic reasons to ensure that the horticultural sector can continue being competitive.

In this context, the main idea is to reduce water inputs to plants without significantly impacting the transpiration rate. Understanding of transpiration evolution is helpful to better understand plant water requirements, to adapt irrigation control and, therefore, to provide the best growing conditions. The transpiration process depends on plant metabolism, substrate water availability and climate transpiration demand. The rate of transpiration is controlled by the opening and closing of stomata, which are depicted by the so-called stomatal resistance. Water restriction reduces the substrate water content and may therefore impact transpiration and photosynthesis by inducing stomatal closure. Indeed, reducing irrigation would affect the stomata opening that, itself, impacts CO_2 absorption during photosynthesis and, consequently, plant growth. A compromise must therefore be found between transpiration and photosynthesis to cope with the contradiction between (i) a lower

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Nomenclature

C_D	drag coefficient
C_F	non-linear momentum loss coefficient
C_p	specific heat of air, J kg^{-1} K^{-1}
CTR	cumulated transpiration ratio
$D_{ref,j}$	gap between the considered irrigation case j and the reference case
H	plant height, m
I_λ	monochromatic luminance, W m^{-3} sr^{-1}
$I_{\lambda,T}$	monochromatic luminance of a black body at temperature T, W m^{-3} sr^{-1}
Kc	extinction coefficient for solar radiation
k	turbulent kinetic energy, m^2 s^{-2}
LAD	leaf area density, m^2 m^{-3}
M	molecular weight of species, kg mol^{-1}
N	dimensionless parameter
n	refractive index
P	pressure, Pa
q_s	radiative flux over the whole wavelength spectrum, W m^{-2}
Q_s	sensible heat flux density, W m^{-3}
R_a	leaf aerodynamic resistance, s m^{-1}
R	universal gas constant, J Mol^{-1} K^{-1}
R_{atm}	short wavelength radiation W m^{-2}
rg	reduced global radiation
Rg_0	above-canopy global radiation, W m^{-2}
Rg	global radiation
rh	reduced relative air humidity
RH	relative air humidity, %
$RMSE$	root mean square error
Rn	net radiation, W m^{-2}
$r_{s,\min}$	minimal leaf stomatal resistance, s m^{-1}
R_s	leaf stomatal resistance, s m^{-1}
$\vec{s}$	position vector
s_s	total area of shelves, m^2
S_Φ	source term
ts	time step interval, s
T	temperature, K
Tr_d	latent heat flux density, W m^{-3}
U, V	components of the velocity vector, m s^{-1}
VPD	vapor pressure deficit, Pa
y	variable

α	parameter, kPa^{-1}
$\acute{\alpha}_\lambda$	absorption coefficient
γ	psychrometric constant, Pa K^{-1}
Δ	slope of the saturated water vapor pressure curve, Pa K^{-1}
ε	dissipation rate, m^2 s^{-3}
θ	volumetric water content, v/v
λ	water latent heat of vaporization, kJ kg^{-1}
Γ	diffusion coefficient, kg m^{-1} s^{-1}
μ	dynamic viscosity, kg m^{-1} s^{-1}
ρ	density, kg m^{-3}
σ	Stefan Boltzmann constant ($5.67 \cdot 10^{-8}$ W m^{-2} K^{-4})
$\sigma_{\lambda,d}$	scattering coefficient
τ	reduced temperature
φ	diffusion phase function
Φ	concentration of transported quantity
Ψ	peat matric potential, kPa
$\vec{\acute{\Omega}}$	scattering direction vector
$\vec{\Omega}$	unit vector along the direction of propagation of radiation
$\acute{\Omega}$	solid angle, sr
ω	mass fraction

Subscripts

a	air
abs	absorbed
atm	atmospheric
avg	volume-weighted average
c	well-watered
w_g	ground
l	leaf
PAR	Photosynthetically Active Radiation
r	water restriction
res	residual
sat	saturation
sky	for the sky
w	water

transpiration rate for an optimal management of water resources, and (ii) the expected vegetative development resulting from photosynthetic activity (Monteith, 1977).

The physiological mechanisms associated with irrigation may be assessed through a representative model of the response of plants to different irrigation regimes. Up until now, the question of an optimal control of irrigation for ornamental crops grown in greenhouses has not been investigated to the same extent as it has been for open field crops, and plant-climate models adapted to the greenhouse are not numerous. In order to predict the transpiration rate, the most commonly used method is that suggested by Penman and Monteith (Monteith and Unsworth, 1990), which is based on a heat balance that depends on the plant environment (solar radiation, air temperature and air humidity). The Penman-Monteith model has been applied to ornamental crops — begonia, cyclamen, gardenia, gloxinia, hibiscus, impatiens, pelargonium, poinsettia, schefflera (Baille et al., 1994a, 1994b), geranium (Montero et al., 2001) — as well as to New Guinea impatiens (Morille et al., 2013; Cannavo et al., 2016). This approach is sometimes referred to as the 'big leaf' model since it considers the crop as a uniform medium and assumes that transfers take place along the vertical direction only, which implies an averaging of the variables in the horizontal plane (Fatnassi et al., 2004). Consequently, this one-dimensional method does not give access to the horizontal temperature distribution and heterogeneity of crop transpiration that could occur inside a greenhouse due to heterogeneous ventilation or radiation. Assessing this heterogeneity would make it possible to fit water inputs to plant needs and thus economize water.

Computational Fluid Dynamics (CFD) is a powerful tool that makes it possible to predict the distribution of the climatic variables inside a greenhouse. This numerical device also makes it possible to test different scenarios without need of experimental approach. Modeling the microclimate and transpiration rate distribution in the greenhouse has been extensively investigated in the past through CFD tools. Boulard and Wang (2002) were the first to implement a crop model as part of a general approach to the distributed climate for a lettuce production greenhouse. Bartzanas et al. (2004) and Majdoubi et al. (2009, 2016) considered a tomato crop; Fatnassi et al. (2006) a multi-span rose greenhouse, and Chen et al. (2015) begonia plants. To simulate stomatal resistance, almost all of these works used the Jarvis (1976) model, which

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