Modelling soil-plant-atmosphere water transfer in greenhouse cultivation, under water restriction: how does plant growth affects transpiration and soil hydrodynamic properties?

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Abstract

In greenhouses, optimized plant crop management is crucial for environmental reasons and for maintaining the competitiveness of the horticultural sector. In this context, reducing water consumption by increasing water efficiency is of high interest but requires predictive models of soil-plant-atmosphere water transfer. Such models have mainly been developed for open field conditions and very few models exist under greenhouse and plant in container contexts. The objective of this study is to develop a specific model predicting soil-plant water transport for plants in constrained conditions.

In this prospect, “New Guinea” Impatiens were cultivated in containers inside a greenhouse during fifteen weeks under both water-comfort and water-restricted irrigation management. Plant transpiration and water status in peat were recorded every 10 minutes whereas measurements of peat saturated hydraulic conductivity (Ks) and water retention were performed every 30 days.
Simulations of water-restricted plant transpiration were conducted using HYDRUS 1D with input data inferred from measurements. These data include the water-comfort plant transpiration, the hydraulic conductivity, the van Genuchten retention curve of peat and root water uptake parameters assuming that plant growth was negligible during water restriction.

Experimental results show that the water matric potential reached a minimal value of -58 kPa during water restrictions. Results also reveal that peat water retention increased along time with root growth due to peat macroporosity decrease and microporosity increase.
Simulations show that HYDRUS reproduces accurately the water-restricted plant transpiration for a given week and therefore gives promising results. However, even if formalisms have been validated, it appears that parameters are not steady during plant growth, suggesting the actual limit of soil-plant water balance models. Thus, peat hydraulic properties and root water uptake changes need to be modeled.
Future works is needed to increase the simulation of the growth-dependent water-restricted plant transpiration and to take into account the spatial root distribution. Moreover, in order to get a complete growing media-plant-greenhouse climate model, the challenge is now to couple the soil-plant model with a plant-climate model under water restriction taking account accurately of the stomatal resistance.

Keywords: transpiration, water restriction, peat, container, greenhouse, soil water retention

1. Introduction

In greenhouses, optimized plant crop management is crucial for environmental reasons as well as competitiveness of the horticultural sector. In this context, reducing water consumption by increasing water efficiency is of high interest but requires predictive models of soil-plant-atmosphere water transfer. However, such models were initially developed for open field conditions (Damour et al., 2010) and very few models exist for plant cultivated in container under greenhouse conditions (Casaroli, et al., 2010).

Soil-plant-atmosphere models developed for open field conditions generally consider that soil hydrodynamic properties such as water retention and hydraulic conductivity are constant along crop growth. However, root growth affect soil physical properties, particularly porosity distribution (Allaire-Leung et al., 1999). Such phenomenon is amplified when crops are cultivated in container, where root content can reach 10% of the total volume (Raviv and Lieth, 2008). Several models exist to depict the root water uptake, using constant properties and a reduction function to take into account the matric potential of water in the growing media. . Among these models, linear (Feddes, et al., 1988) or curvilinear shapes (Van Genuchten, 1985) have been proposed. However, they were established in soils without volume limitation, and their capacity adaptation to growing media in container is not obvious. Then, the question is to know whether including crop growth, and consequently soil-plant properties changes, would improve water balance models.

The objective of the present study is to develop a specific model predicting water uptake for plants with roots in constrained conditions. Such model must be able to predict accurately plant transpiration under water restriction. In this prospect, field surveys were carried out inside a greenhouse, with Impatiens plants grown in containers filled in with peat substrate with the aim to establish the parameters of the model and to proceed to the validation stage.

2. Materials and methods

2.1 Experimental set-up

Experiments were conducted inside a 100-m^2 (10 m×10 m) compartment with shade screen of a glasshouse oriented north-south and located in Angers (47°28′ North, 0°33′ East and 39 m altitude) in north-western France. Experiments were carried out during 16 weeks from 28th March to 20th July 2013 with Impatiens (*Novae-guinea*, cv.'Sonic Scarlet') as plant model. Young Impatiens (3-4 leaves) were potted in 0.74 l containers (8.7 cm height) filled in with fine peat (5-20 mm particle size) with the same peat bulk density (ie 0.1 g dw cm^{-3}). Plants were equally distributed over four shelves, representing a total area of 18 m^2, and with an initial density of 28 plants per m^2.

During the experiment, plant density was decreased to favour plant growth (final density of 15 plants per m^2). Plants were watered by flooding the shelves with a complete nutrient solution. Flowers were regularly removed.

2.2 Climate measurements

Climate parameters cited hereafter were measured for both water-comfort and water-restricted conditions (Fig. 1).

The above canopy global radiation was measured by a radiometer (CNR1, Kipp&Zonen, Delft, The Netherlands, ±10 W/m^2).

The temperature (T_a, ±0.1 ◦C) and relative humidity (RH, ±2% HR) of the within and above canopy air were measured by shielded and ventilated sensors (Vaisala HMP45C, Campbell Scientific Ltd., Antony, France). The relative air humidity was used together with the air temperature to compute the vapor pressure deficit.

All of the above-mentioned parameters were measured every 3 s and averaged online over 10 min periods with a data logger system (CR5000, Campbell Scientific Ltd., Antony, France).

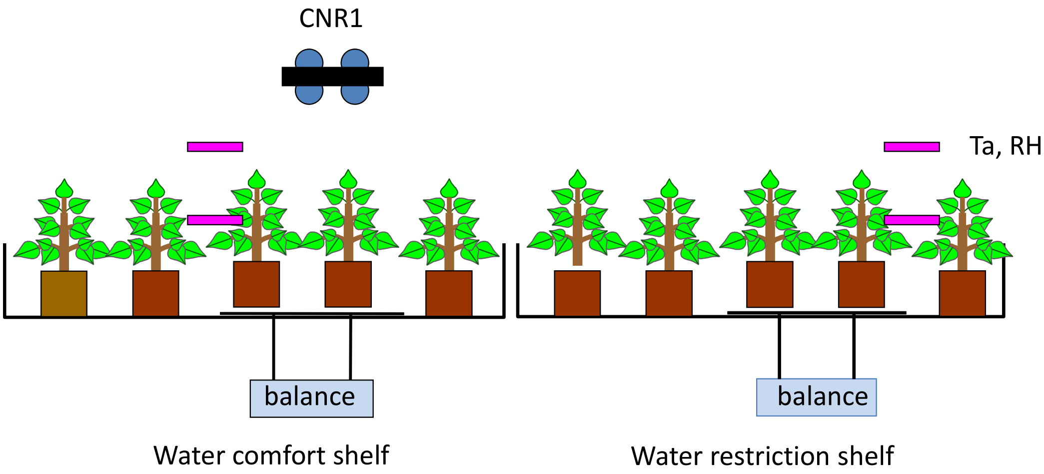


Figure 1: Sketch of the experimental device

2.3 Growing media properties

Peat matric potential (ψ, kPa) was measured with microtensiometers (capillary of 2 mm-dia) every 10 minutes with the same data logger system. They were horizontally placed in pairs at 2 cm from the base of the container. Six containers were instrumented among which 3 were placed in the water-comfort shelf and the 3 others in the water-restricted shelf. Finally, there were 6 replicates per shelf.
Peat hydrodynamic parameters were also measured at weeks 9 and 15. First, peat water retention curve was determined with (1) matric potential measured every ten minutes by microtensiometers installed in containers submitted to water restriction, and (2) peat volumetric water content calculated every ten minutes using container mass variations. Secondly, the peat saturated hydraulic conductivity (*Ks*) was measured using a mini-disc infiltrometer (Decagon Devices, Inc.; Pullman, WA, USA). The samples were previously saturated in water for 48 h. Measurements were triplicated and carried out in a Mariotte chamber with a 2 cm suction force corresponding to an effective suction at the soil surface of −1 cm.

Impacts of water restriction on the peat-plant system were studied at two stages of plant growth: 9 and 15 weeks after plantation (i.e. 3rd June and 15th July, respectively). For this purpose, the irrigation of one shelf (shelf n°2) was stopped until plants evidenced water stress visual signs and microtensiometers switched off. For the plants on the three other shelves, water-comfort conditions were applied with water potential in peat kept higher than -2 kPa. Water-comfort and water-restricted crop transpirations (T, kg m^{-2} h^{-1}) were measured by two scales (Melter-Toledo, Greifensee, Switzerland, ±0.1 g) located approximately at the center of the shelves (Fig. 1). As demonstrated by previous studies, the substrate evaporation was negligible (Morille et al., 2013)

2.4 Modelling methodology

Water flow was simulated using the HYDRUS 1D software (Simunek et al., 2005) describing water movement in one-dimensional transport domains in variably-saturated porous media, using the equation of Richards (1931). It requires two nonlinear functions: the soil water retention curve ($\theta(\psi)$, eq. [1]) and the reduction transpiration curve ($T_r/T_c(\psi)$, eq.[2]) modeled using (van Genuchten, 1980) and (Van Genuchten, 1985) models, respectively:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1+(\alpha.\psi)^n]^m} \qquad [1]$$

where ψ is the soil water suction (kPa), θ is the soil volumetric water content (m^3 m^{-3}), θ_s is the soil saturated volumetric water content (m^3 m^{-3}) corresponding to the total porosity presented above, θ_r is the soil residual volumetric water content (m^3 m^{-3}) and α (kPa^{-1}), n (dimensionless) and m=1−1/n (dimensionless) are fitting parameters.

$$\frac{T_r}{T_c} = \frac{1}{1+\left(\frac{\psi}{\psi_{50}}\right)^p} \qquad [2]$$

where T_r and T_c are water-restricted and water comfort transpirations, respectively, ψ_{50} is the matric potential corresponding to a T_r/T_c ratio of 50%, and p is a fitting parameter. Van Genuchten model parameters were determined by minimizing errors between observed and measured data at weeks 9 and 15.

HYDRUS simulations of the transpiration under water restriction were conducted. The equivalent growing media thickness introduced in the model was determined by considering the volume of growing media in the containers covering 1 m^2 of shelf. At weeks 9 and 15 there were 19 and 15 containers per m^2, respectively; representing 14.1 and 10.5 mm of growing media per m^2, respectively. A seepage face (-0.1 cm) was set as the bottom limit condition. HYDRUS input parameters were the measured T_c, Ks value, and the coefficients provided by the Van Genuchten models. They were used at weeks 9 and 15. In both cases, initial condition corresponded to a matric potential of 0 over 3.2 and 2.4 mm of the bottom of the growing media at weeks 9 and 15, respectively (ie the 2 first centimeters of the bottom of the containers after water irrigation at 6 am).
Transpiration is expressed in mm h^{-1}, corresponding to liters of water transpired per m^2 of shelf and per hour.

3. Results & Discussions

3.1 Water balance modelling at week 9

Measured transpiration and peat matric potential at week 9 are presented in Fig. 2. Measurements were conducted during three days, until plants displayed water stress visual signs and microtensiometers switched off. The lowest matric potential value reached was 58.5 kPa. Transpiration evolution was correlated with night/day cycles with minimal and maximal transpirations at around 2 am and 2 pm, respectively. Under water comfort conditions, transpiration (T_c) reached a maximal value of 0.26 mm h^{-1} at Day 3, and peat matric potential ranged between -0.8 and -0.2 kPa. Microclimate during this period presented a minimal and maximal air temperature of 17 and 30°C, a minimum and maximum global radiation of 0 and 127 W m^{-2}, and a minimum and maximum vapor pressure deficit of 0.4 and 2.9 kPa.

Transpiration values under water comfort and water restriction were similar until Day 3 at 10 am. During this period, the matric potential remained higher than -25 kPa. However, transpiration values became significantly different from 10 am on day 3, the maximal transpiration values were then 0.26 and 0.17 mm h^{-1} under water comfort and water restriction, respectively. This difference was explained by the important matric potential decay, from -25 to -58.5 kPa. After 9 weeks of plant growth, water stress was considered for matrix potential lower than -25kPa. It is well known that water stress conditions favor transpiration reduction through stomata closure, hence a photosynthetic activity reduction (Lenzi et al., 2009).

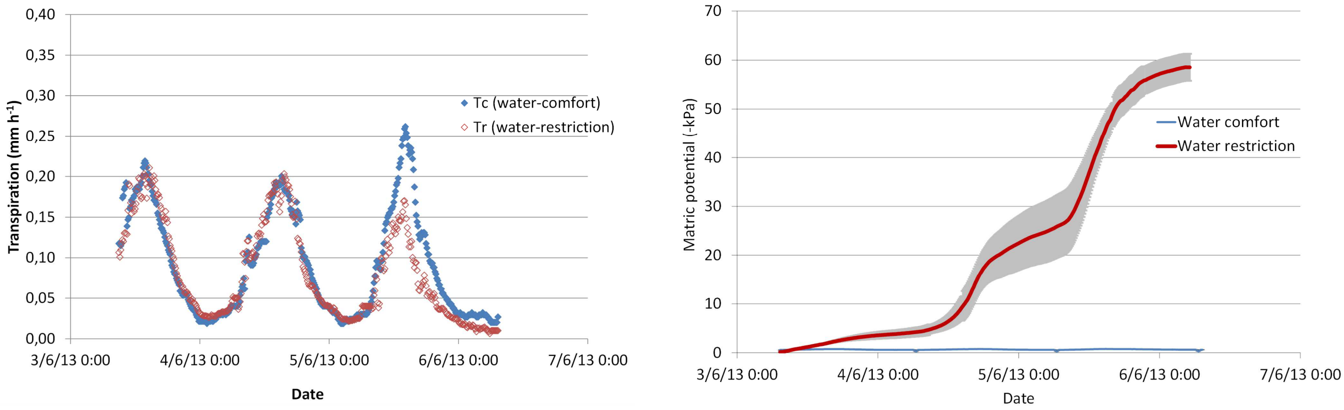


Figure 2: Plant transpiration and peat matric potential 9 weeks after plantation. On the left: transpiration under water comfort (Tc) and under water restriction (Tr). On the right: peat matric potential under water comfort and under water restriction. Grey zone represents standard errors (6 replicates)

Van Genuchten parameters for the water retention and root water uptake models at week 9 are presented in Table 1. Model calibration performance was satisfactory regarding RMSE values.

Table 1: Van Genuchten model parameters presented in eq.[1] & [2], established for the peat water retention and the reduction transpiration function at week 9

Water retention model (eq. [1])					**Reduction transpiration function (eq. [2])**		
θ_s	θ_r	α	n	RMSE	ψ_{50}	p	RMSE
0.892	0.100	0.644	1.314	0.018	-54.618	2.872	0.080

These parameters were used to simulate plant transpiration under water-restriction (T_r) with HYDRUS (Fig. 3). The measured peat saturated hydraulic conductivity was 4000 mm h^{-1}. HYDRUS provided good agreement of the simulated transpirations with the measured ones, particularly on day 3, when T_c and T_r were different (Fig.2). The corresponding RMSE was 0.02 mm h^{-1}.

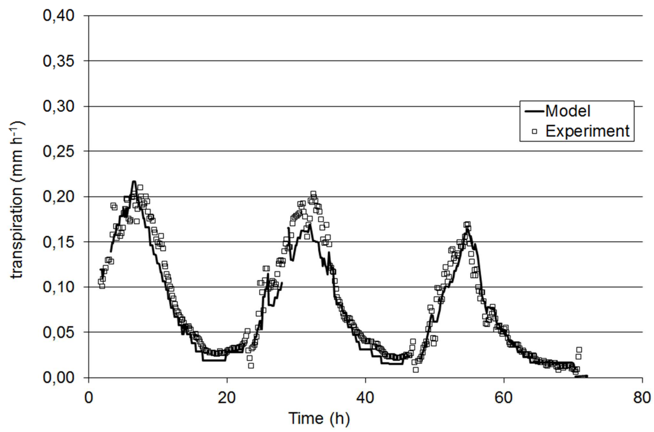


Figure 3: Measured and modelled plant transpiration under water-restricted conditions 9 weeks after plantation

3.2 Ability of the model to simulate water balance at another crop stage

Measured plant transpiration and peat matric potential at week 15 are shown in Fig. 4. Important differences can be observed compared to week 9. First, plant water stress was observed one day earlier (day 2). Secondly, T_c maximal value was 1.4 times higher (0.36 mm h^{-}

[1] on day 1). Finally, on day 2, T_r became inferior to T_c, when peat matric potential was lower than -18 kPa (instead of -25 kPa at week 9).
Microclimate during this period presented a minimal and maximal air temperature of 21 and 35°C; a minimum and maximum global radiation of 0 and 104 W m^{-2}; and a minimum and maximum vapor pressure deficit of 0.5 and 4 kPa. The increases of the air temperature and VPD, compared to week 9, together with the plant growth explain the higher plant transpiration at week 15.

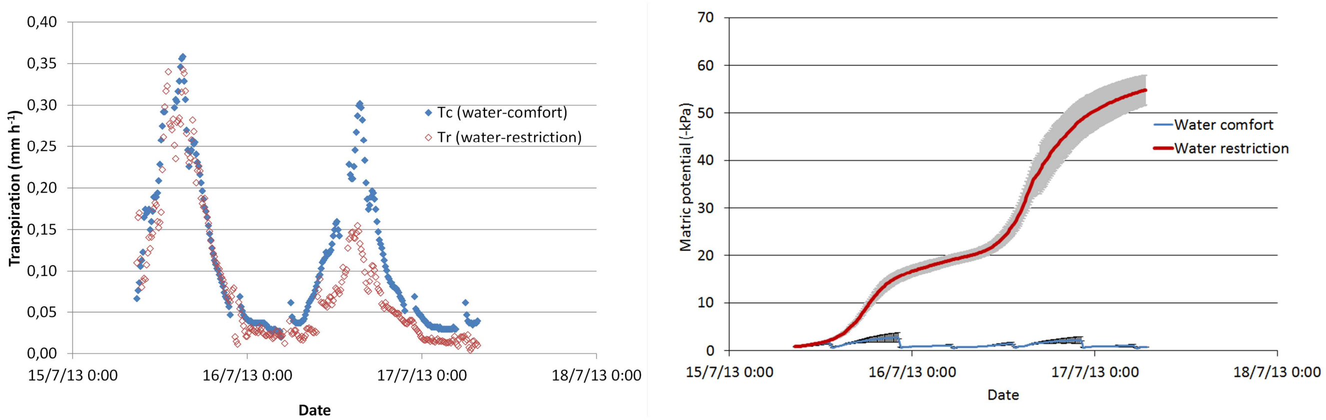


Figure 4: Plant transpiration and peat matric potential 15 weeks after plantation. On the left: transpiration under water comfort (Tc) and under water restriction (Tr). On the right: peat matric potential under water comfort and under water restriction. Grey zone represents standard errors (6 replicates)

We ran HYDRUS simulations on week 15 with parameters established from week 9 and values of T_c measured at week 15. Results are presented in Fig. 4. If HYDRUS provided satisfactorily results during the first day, it overestimated T_r on day 2 (RMSE of 0.04 mm h^{-1}).

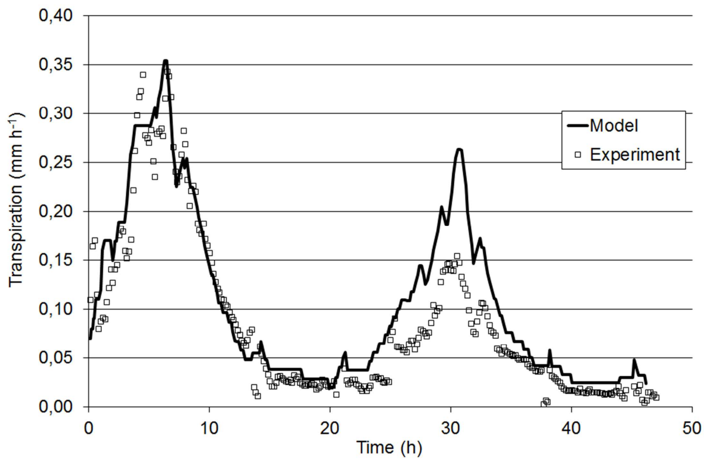
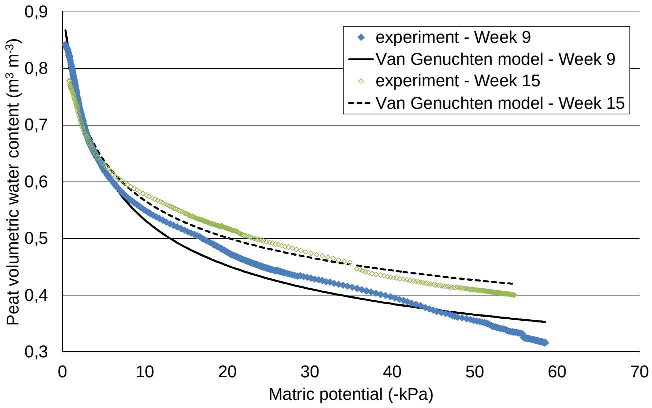


Figure 5: Measured and modelled plant transpiration under water-restricted conditions 15 weeks after plantation, by using the same hydrodynamic and reduction transpiration parameters as week 9

Such differences can be explained by peat hydrodynamic and root water uptake pattern changes between week 9 and week 15. In Fig. 6, peat water retention and root water uptake curves are presented for weeks 9 and 15.
It can be observed that first, peat water retention curve changed: water retention tended to increase with plant growth. Such an evolution is due to root growth impact on peat porosity changes, reducing macroporosity, hence an increase of microporosity and water retention (Cannavo and Michel, 2013). In our experiment, root volume content increased from 4.4 to 9% of the total substrate volume. The main consequence was a decrease in the peat water reservoir (calculated from peat water content differences between -10 and -50 kPa) from 7 to 4 mm that accelerated water stress conditions.
Secondly, T_r /T_c ratio decreased faster, from a matric potential of -18 kPa, showing that plant growth also affected root water extraction. Therefore, Van Genuchten parameters changed between weeks 9 and 15.



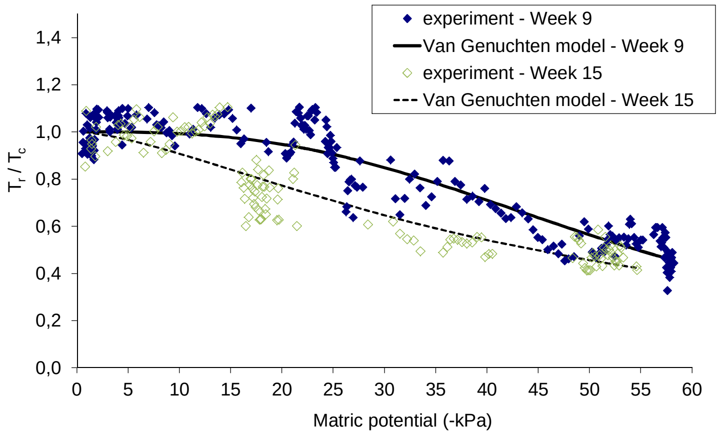


Figure 6: Comparison of peat water retention and reduction transpiration at weeks 9 & 15. Left: Measured and modelled water retention. Right: Measured and modelled reduction transpiration.

New parameters for week 15 are presented in Table 2. Some differences appeared, particularly the matric potential corresponding to a T_r /T_c ratio of 0.5 which was 10 kPa lower at week 9 than at week 15 (Table 1). The peat saturated hydraulic conductivity did not change and was 400 cm h^{-1}.

Table 2: Van Genuchten model parameters presented in eq.[1] & [2], established for the peat water retention and the reduction transpiration at week 15

Water retention model (eq. [1])					**Reduction transpiration function (eq. [2])**		
θ_s	θ_r	α	n	RMSE	ψ_{50}	p	RMSE
0,869	0.100	0.837	1.229	0.032	-44.501	1.525	0.109

Finally, HYDRUS was run with actualised Van Genuchten parameters obtained from week 15 (Fig. 7). Simulation of T_r was better, with a similar RMSE as the initial model on week 9 (0.02 mm h^{-1}), even if HYDRUS slightly underestimated transpiration on day 1. It means that to predict accurately water balance in container cropping systems, it is necessary to take into account growing media hydrodynamic properties and root water uptake changes due to root growth and important root density. Moreover, the aerial biomass growth has to be taken into account since foliar area greatly influences transpiration.

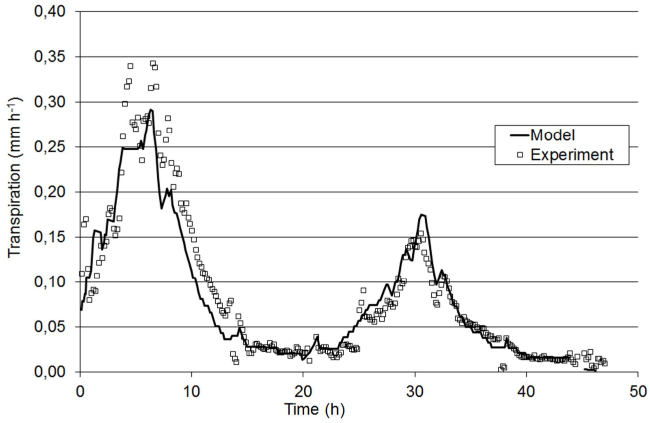


Figure 7: Measured and modelled plant transpiration under water-restricted conditions 15 weeks after plantation, by using peat hydrodynamic properties and reduction transpiration parameters measured at this stage

4. Conclusions

The study of Impatiens growth in containers with water restriction led to the following conclusions:

- Transpiration was strongly affected by climate, plant biomass and peat physical properties
- Transpiration modelling suggested that peat hydrodynamic properties and root water uptake changes have to be taken into consideration to accurately predict transpiration under water restriction during plant growth and particularly during root growth.

Future works need to integrate into the model the heterogeneous spatial distribution of root in the container that may have impacts on water availability heterogeneity and therefore on root water uptake. Furthermore, to get a soil-plant-atmosphere model dedicated to limited volume of growing media and confined climate, water-restricted transpiration prediction needs to focus on the stomatal resistance that determines transpiration.

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