A MODEL TO SIMULATE ENERGY AND MASS EXCHANGE IN AGRICULTURAL SCREENHOUSES

Mario B. Siqueira, mariosiqueira@unb.br
Departamento de Engenharia Mecânica, Universidade de Brasília, Brasília, Brazil

Abstract. *A model to simulate the microclimate screenhoused plantation is proposed. The model solves numerically transport equation for momentum, temperature and water vapor mixing ratio using a 2nd order closure for momentum. A radiation transfer model is incorporated to capture the modulation of the screen in the radiation exchange between the vegetation and the atomosphere. Screen is assumed as a non-isotropic drag element to account for its effect on the flow field and consequently on the turbulent transport. Results seem qualitatively reasonable and shows a reduced loss of irrigated water to the atmosphere, saving water, an important feature for regions with scarce water resources. Experimental data are still needed to properly parameterize and validate the model.*

Keywords*: screenhouse, microclimate, energy exchange, mass exchange*

1. INTRODUCTION

Screenhouses are used in agriculture to attain a number of objectives such as limit the chance of contamination by insects excluding them from the crop environment, shading for supra-optimal solar radiation condition, create favorable thermal climate for the crop, and avoid birds and bats to access the fruits (Tanny *et al.*, 2006). Clearly the presence of a screen also affects the exchange of radiation, energy and mass between the crop and environment. Recently, this fact has called the attention of growers in arid region, because its use might actually provide an opportunity to save water. Modeling the exchange process within the screenhouse would be a valuable instrument in designing screens and screenhouse configurations that would optimize water use efficiency maximizing the production while minimizing water use. The work here describes a model to simulate the microclimate inside in the screenhouse to evaluate the effects of screen on the exchange of heat and mass.

2. MATERIALS AND METHODS

In order to model energy and mass exchange in a screenhoused plantation, momentum and sensible- and latent-heat transport equations must be solved. In the model developed here, the screenhouse was taken as infinitely long and wide. By doing so, all longitudinal (in reference to mean wind direction) and transversal gradients can be assumed negligible making the problem one-dimensional, in which the vertical direction is the only one to be considered in the equations. This assumption would be appropriate for extensive agricultural plantation in which transition effects from the edges is quickly lost relative to the dimensions of screenhouse. This would be the case of the ones used in Israel for instances, in which some of them could be as much as 600m long. A turbulence closure model is required to solve the equations. A 2nd order closure model was used to model development here.

2.1. Momentum transport model

The one-dimensional, neutrally stratified, time- and horizontally-averaged conservation equation for streamwise (x) momentum in a canopy flow is given by (Wilson, 1988; Katul and Chang, 1999):

$$\frac{\partial \overline{u}}{\partial t} = -\frac{\partial \overline{u'w'}}{\partial z} - C_d a \overline{u}\left|\overline{u}\right|; \tag{1}$$

where u and w are the streamwise and vertical components of the velocity respectively, $a(z)$ is the leaf area density, and C_d is the drag coefficient for the leaves, the overbar denote time averaging operator and prime represents excursions of the mean. The second term on the right-hand side of Eq. 1 represents the momentum sink in a conventional parameterization for plant-flow interaction.

The canopy turbulence model adopted here follows the Wilson (1988) for canopy flows, in which turbulent kinetic energy (TKE) is split in two band frequencies, “turbulent shear kinetic energy” (SKE, low frequency) and “wake kinetic energy” (WKE, high frequency energy). The WKE promoted by canopy was included to account the bypass of the usual turbulence energy cascade due to intervention of drag elements. The conversion of SKE (SKE is denoted here as k) to WKE is modeled as an additional dissipation term in k equation. No transport equation for WKE is needed because its feedback to SKE is minimal (Wilson, 1988). The budget equation for the tangential stress and low-frequency band (SKE band) normal stress is given by:

$$\frac{\partial \overline{u_i' u_j'}}{\partial t} = P_{ij} + R_{ij} + T_{ij} - \varepsilon_{ij} \tag{2}$$

where subscript refers to orthogonal coordinates, P is the production term, R is the redistribution term, T is the transport term and ε is the dissipation term. P, R and T used here are described in Wilson (1988) where model constants are also presented. Equation (2) is solved for the three velocity component variances and for $\overline{u'w'}$. Following Wilson (1988), the dissipation is decomposed in two contributions:

$$\varepsilon_{ij} = \frac{2}{3}\varepsilon\delta_{ij} + \left(2C_d\, a\,\overline{u}\,\overline{u_i' u_j'}\delta_{ij} + 2C_d\, a\,\overline{u}\,\overline{u_i' u_j'}\delta_{i1}\delta_{j1}\right) \tag{3}$$

with no summation implied over repeated indices. Here ε is viscous dissipation and the term in parenthesis represents the short-curt energy cascade SKE to MKE transformation. Contrary to Wilson (1988), an actual transport equation for ε was used because Wilson's (1988) ε parameterization may not hold for screenhoused plantation. This equation is given by (Launder, 1996; Pope, 2000; Katul *et al.*, 2004):

$$\frac{\partial \varepsilon}{\partial t} = \frac{\partial}{\partial z}\left(c_{\varepsilon 3}\frac{k}{\varepsilon}\overline{w'^2}\frac{\partial \varepsilon}{\partial z}\right) + c_{\varepsilon 1}\frac{\varepsilon}{k}\frac{P_{ii}}{2} - c_{\varepsilon 2}\frac{\varepsilon^2}{k} \tag{4}$$

where $c_{\varepsilon 3}$, $c_{\varepsilon 1}$ and $c_{\varepsilon 2}$ are model constants given in Katul, Mahrt *et al.* (2004).

Similar to the vegetation canopy, the screen effects on the flow field were modeled as drag acting on the flow. However, because of its geometry, isotropy could not be assumed since it has different projected areas in different directions. In order to overcome this problem the product of screen drag and area, as they always appear as a product in the model equations, was set as a tensor with different values for each direction.

2.2. Scalar transport model

Similarly to momentum, the one-dimensional, neutrally stratified, time- and horizontally-averaged conservation equation for a scalar quantity in a canopy flow is given by:

$$\frac{\partial \overline{c}}{\partial t} = -\frac{\partial \overline{w'c'}}{\partial z} + S \tag{5}$$

where c is a generic scalar (temperature or water vapor mixing ratio) and S is a source/sink of c in the canopy volume, given by:

$$S = 2\,a\,G\left(c_L - \overline{c}\right) \tag{6}$$

c_L in Eq. (6) is the scalar value at leaf and G is the leaf conductance. G is estimated with a resistance model comprised of a leaf boundary-layer resistance (inverse of conductance), function of local flow velocity, and a stomatal resistance, which is obtained from a physiological model (Campbell and Norman, 1998), arranged in series.

For the scalar flux, a model budget equation could be written as (Meyers and Paw U, 1987):

$$\frac{\partial \overline{w'c'}}{\partial t} = -\overline{w'^2}\frac{\partial \overline{c}}{\partial z} - \frac{\partial}{\partial z}\left(c_s\frac{k}{\varepsilon}\left(\overline{w'^2}\frac{\partial \overline{w'c'}}{\partial z}\right)\right) - c_{\theta 3}\frac{\varepsilon}{k}\overline{w'c'} + c_{\varepsilon\theta}\frac{\varepsilon}{k}\overline{w'c'} \tag{7}$$

where c_s, $c_{\theta 3}$ and $c_{\varepsilon\theta}$ are model constants, which numerical values can be found in Meyers and Paw U (1987).

To model the microclimate inside the screenhouse, temperature (surrogate for internal energy) and water-vapor mixing-ratio transport equations must be solved as scalars. In the case of temperature, only boundary-layer resistance is considered in the estimation of G, because the source of internal energy to canopy air is the heat exchange between the leaf surface and canopy air around it. Additionally, since screen is considered in the model as a drag element, it becomes a heat source as well, requiring calculation of boundary layer resistance, also function of flow velocity at the screen height. Furthermore soil surface temperature is required as a boundary condition for the temperature equation and also for radiation exchange estimation. A one-dimensional soil heat equation was incorporated in the model to compute soil temperature profile.

2.3. Radiation transfer model

A canopy shortwave radiation (SW) attenuation model (Leuning *et al.*, 1995) was used to simulate SW exchange between vegetation and atmosphere. The model splits incoming solar SW (SW_{sun}) into direct bean and diffuse radiation due to the fact that canopy attenuation is different for each of these components. For longwave thermal radiation (LW) exchange in the canopy, a similar attenuation model as described in Campbell and Norman (1998) was implemented, but computing LW independently for the upward and downward radiation and including the emission from the canopy elements.

The screen modulation on incoming radiation is described by the following equations:

$$SW_b = SW_{sun,b}\left(1-\phi\right) \tag{8}$$

$$SW_d = SW_{sun,d}\ (1-\phi)+\left[SW_{sun,b}\left(1-\rho_{sc,SW}\right)\tau_{SW,b}+SW_{sun,d}\tau_{SW,d}\right]\phi \tag{9}$$

$$LW = LW_{sky}\ (1-\phi)+LW_{sky}\phi\ \tau_{LW}+\phi e\sigma_{SB}T_{sc}{}^4 \tag{10}$$

where SW_b, SW_d, LW are direct bean solar radiation, diffuse solar radiation and longwave radiation respectively reaching canopy top, subscript sun and sky refers incoming solar and atmosphere radiation (reaching the screen) respectively, σ_{SB} is Stefan-Boltzmann constant, ϕ is the screen solidity, τ_{SW} and τ_{LW} are screen transmissivity to SW and LW radiation respectively, $\rho_{sc,SW}$ is screen reflectivity to SW, e is screen emissivity and T_{sc} is the screen temperature.

2.3. Screen energy balance

Since screen temperature is used to compute the heat source to surrounding air (as a drag element) and to estimate its own LW emission, an energy budget for the screen is required:

$$\begin{aligned} c_{sc}\frac{dT_{sc}}{dt} &= \left[SW_{sun,b}\left(1-\rho_{sc,SW}-\tau_{SW,b}\right)+SW_{sun,d}\left(1-\rho_{sc,SW}-\tau_{SW,d}\right)\right]\phi+ \\ &+\left(LW_{sky}+LW_{can}\right)\left(1-\rho_{sc,LW}-\tau_{LW}\right)\phi-2\phi\sigma_{SB}T_{sc}{}^4-S_T \end{aligned} \tag{11}$$

where c_{sc} is the specific of the screen material, LW_{can} is the LW outgoing from the canopy volume and S_T is the turbulent heat flux from the screen accounted as a heat source to the air.

3. RESULTS AND DISCUSSION

In order to understand the modulation of the screen on the energy and mass exchange in irrigated plantations, the model partial differential equations described above were solved using finite-volume approach for two banana plantations: one open and one screenhoused. The choice of banana is due to the fact that it is a common practice to have it planted in irrigated screenhouses in arid regions such as Israel. The screen radiative properties, derived from a short laboratory experiment measuring radiation fluxes above and below an actual screen, are given in Tab. 1. Because SW transmissivity is a function of zenith angle their relationship, fit from the data, is provided in Fig. 1. The numerical simulations were performed for a total of 10-day time-span with repeated daily meteorological forcing (upper boundary conditions) given in Fig. 2. The results discussed here represent the last day of the simulations, where the first the first 9 days were taken as spin-up to make sure the daily cycle is in steady state.

Table 1: Radiative properties of the screen derived from a short experiment, in which SW and LW radiation were measured above and below the screen.

Parameter	symbol	Value
solidity	ϕ	0.3
transmissivity to diffuse SW(1)	$\tau_{SW,d}$	0.45
reflectivity to SW	$\rho_{sc,SW}$	0.2
transmissivity to LW	$\tau_{LW,d}$	0.45
reflectivity to LW	$\rho_{sc,LW}$	0.05
emissivity	e	0.45

(1) note that the transmissivity to bean SW is a function of zenith angle ψ (see Fig. 1)

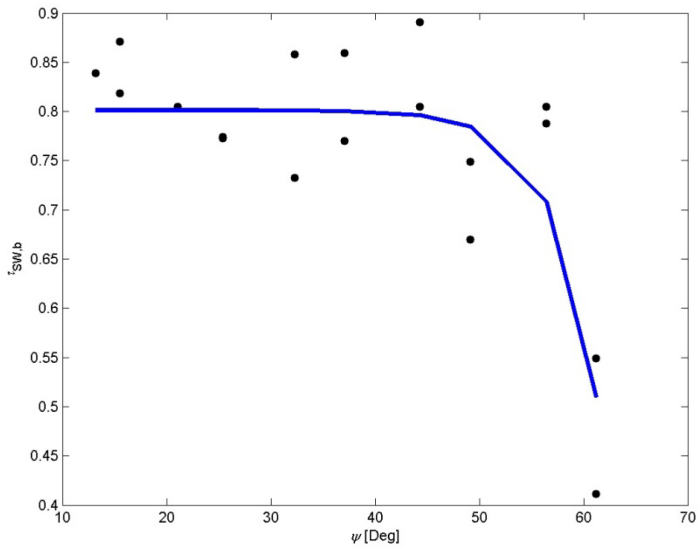

Figure 1. Screen transmissivity to direct incoming solar shortwave radiation ($\tau_{SW,b}$) as a function of zenith angle (ψ)

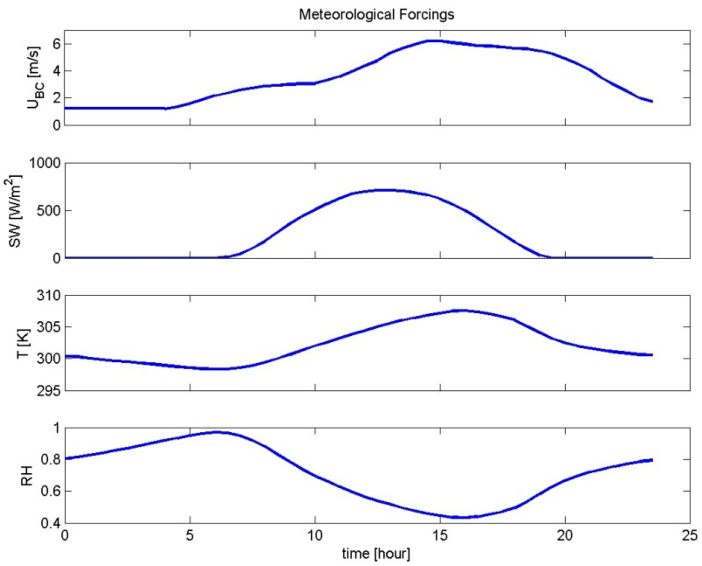

Figure 2. Meteorological forcing used in the simulation. The variables represent upper boundary condition (BC) located at 20m high. U_{BC} is streamwise velocity (same as $\bar{u}$) at upper BC

The flow fields for both cases were simulated a priori since all buoyancy effects were neglected (neutral stability) making temperature and velocity statistics decoupled. Additionally, for the sake of comparison between the two simulations, the velocity at the upper boundary was made the same for the two cases, instead of the usual scaling variable friction velocity. The reason for this choice is due to the fact that the differences in surface roughness caused by the presence of the screen. As expected, the velocity profile, shown in Fig. 3, is reduced in the space between the screen and the top of the vegetation. Interestingly, it recovers rapidly above the screen. This is not entirely surprising, given that the screen overall effect translate into an elevated and less rough surface. In fact, the simulated friction velocity for screenhoused case to maintain same velocity at the upper boundary is 0.73 of the open plantation one (shown in Fig. 2). The velocity-component standard deviation and turbulent shear stress profiles are depicted in Fig. 4. They show similar attenuation inside the canopy but diverge in the space between canopy height and the screen. Above the screen the velocity statistics recover the roughness sub-layer behavior. It should be emphasized that these plots are normalized by friction velocity, which are not the same for the two different simulations.

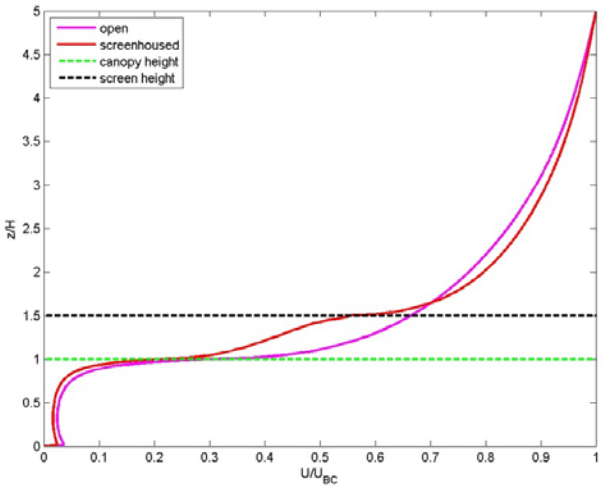

Figure 3. Streamwise velocity profile normalized by the velocity at the upper BC

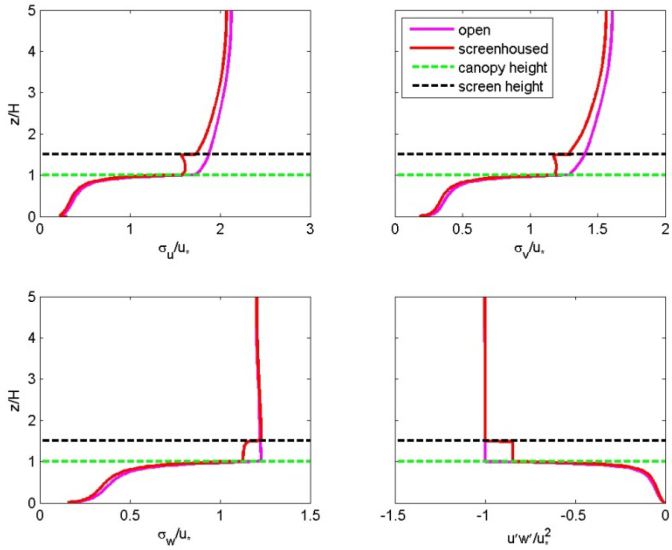

Figure 4. Velocity component standard deviation (e.g. $\sigma_u = \sqrt{u'^2}$) and shear stress profiles normalized by friction velocity u_*

The consequences of the presence of the screen in terms of the overall energy exchange are demonstrated in Fig. 5, in which modeled sensible- and latent-heat flux time series above the canopy are presented. The two sensible-heat flux time series pertinent to the screenhoused plantation are above and below the screen. The difference between the two is the turbulent heat exchange between the screen and the air in its vicinity. Because the energy balance is imbedded in the formulation and the daily cycle is in steady state after the spin up period, the summation of latent- in sensible-heat fluxes integrated over the day must match the net radiation. So the combined effect of the screen in radiation modulation, mainly the greenhouse effect and the SW radiation reflection, led to reduce both sensible- and latent-heat flux.

The effect of the screen on temperature can be seen in Fig. 6 (left panels), which shows the contour plots of temperature as a function of time and height. The screen promotes a strong increase in temperature during the day inside the screenhouse. This is a consequence of a combination of factors. First, the modulation of the screen on radiation transfer, which allows more incoming SW solar radiation than the outgoing thermal LW emitted by the surface (soil and canopy) and reflects part of the incoming SW. Additionally, turbulent diffusivity is reduced due to the screen drag acting on the flow field, which has marked influence on the velocity statistics as demonstrated above. The latter effect is also clear in the water vapor mixing ratio, which distributions are also given in Fig. 6 (right panels). The water vapor transpired by the vegetation is retained inside the screen house because of the compromised turbulent transport. Since transpiration is a diffusion process, the higher humidity maintained inside the screenhouse led to irrigation water savings, relevant to the arid region.

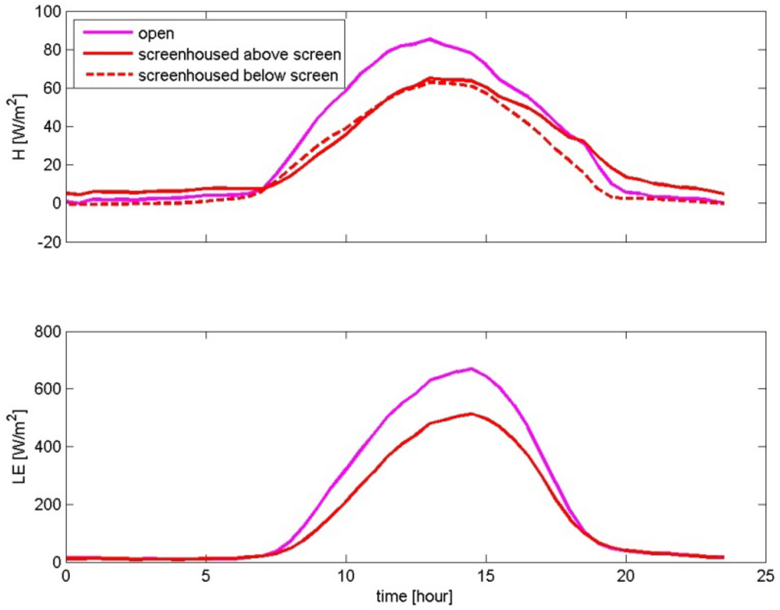

Figure 5. Sensible- (H, upper panel) and latent-heat (LE, lower panel) fluxes at the upper boundary for the two cases, open and screenhoused plantations. The sensible heat in the space between the canopy and the screen is also shown for the screen housed plantation.

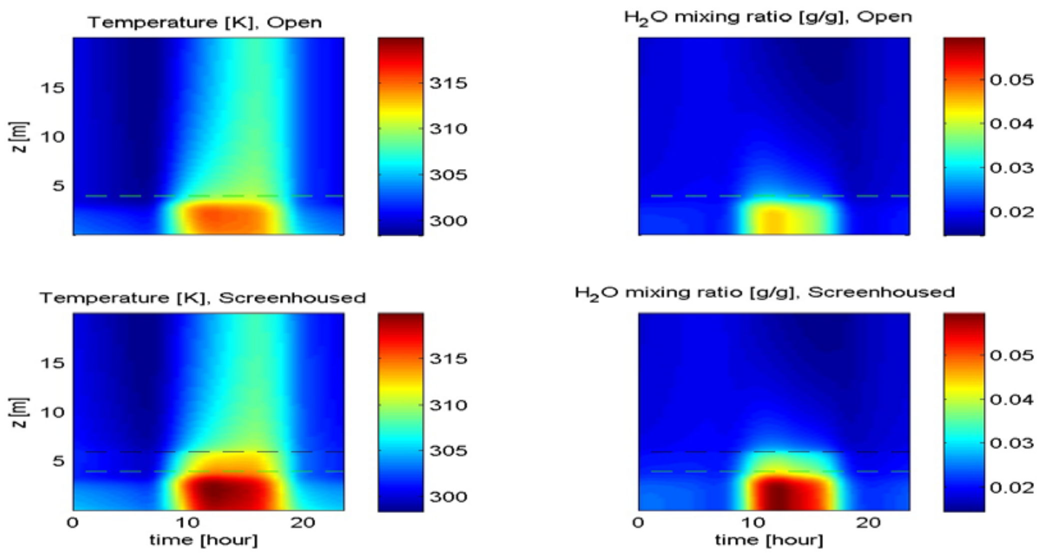

Figure 6. Temperature distribution as a function of time and vertical coordinate for open (upper left panel) and screenhoused (lower left panel) plantations. Dashed lines represent canopy (green) and screen (black) heights. Water-vapor mixing ratio distribution for open (upper right panel) and screenhoused (lower right panel) plantations.

4. Conclusions

The conclusions from the work presented here can be summarized as

- The presence of the screen, modeled as a non-isotropic drag element, reduced the velocity statistics responsible for turbulent transport and the effective roughness of the surface;
- The radiation modulation of the screen decreased the latent- and sensible-heat fluxes.
- Combined effects of the screen in radiation modulation and turbulence characteristics resulted in warmer and more humid ambient inside the screen;
- As a consequence, the screenhoused plantation requires less irrigation to sustain photosynthesis;
- The model proposed here provided reasonable qualitative results. Experimental data are still required to better parameterize and validate the model;

3. ACKNOWLEDGEMENTS

This study was supported in part by Bi-national Agricultural Research and Development (BARD) fund (IS-3861-06).

4. REFERENCES

Campbell, G. S. and Norman, J. M., 1998, "An introduction to environmental biophysics". New York: Spriger-Verlag. 306 p.
Katul, G. G. and Chang, W.-H., 1999, "Principal length scales in second-order closure models for canopy turbulence". Journal of Applied Meteorology, v.38, p.1631-1643.
Katul, G. G., Mahrt, M., Poggi, D. and Sanz, C., 2004, "One- and two-equation models for canopy turbulence". Boundary-Layer Meteorology, v.113, p.81-109.
Launder, B., 1996, "An introduction to single-point closure methodology". In: Lumley, J. (Ed.). Simulating and Modeling of Turbulent Flows. New York: Oxford University Press, p.243-311
Leuning, R., Kelliher, F. M., Purry, D. G. G. D. and Schulze, E.-D., 1995, "Leaf nitrogen, photosynthesis, conductance, and transpiration: scaling from leaves to canopies". Plant, Cell and Environment, v.18, p.1183-1200.
Meyers, T. P. and Paw U, K. T., 1987, "Modeling the plant canopy micrometeorology with higher-order closure principles". Agricultural and Forest Meteorology, v.41, p.143-163.
Pope, S. B., 2000, "Turbulent Flows". New York: Cambridge University Press. 771 p.
Tanny, J., Haijun, L. and Shabtai, C., 2006, "Airflow characteristics, energy balance and eddy covariance measurements in a banana screenhouse". Agricultural and Forest Meteorology, v.139, p.105-118.
Wilson, J. D., 1988, "A second-order closure model for flow through vegetation". Boundary-Layer Meteorology, v.42, p.371-392.

5. RESPONSIBILITY NOTICE

The author is the only responsible for the printed material included in this paper.