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Evaporative cooling of a ventilated greenhouse rose crop

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Abstract

Greenhouse crops may suffer from excessive heat load in warm weather. A procedure is developed to evaluate latent heat cooling by means of crop transpiration and free water evaporation from a wet pad and fan system. The procedure uses concurrent external climatic factors as input data. It treats construction characteristics (dimensions and radiometric properties of the roof cover), plant foliage (leaf area, stomatal conductance) and ventilation rate as parameters to calculate heat transport coefficients. Measurements in a greenhouse rose crop (*Rosa indica* L cv 'Mercedes Long') show that the numerical solution of the energy balance equation predicts accurately crop transpiration, foliage temperature, air temperature and humidity inside the greenhouse. With ventilation rates of 30 volume changes per hour and external air humidity below 50%, transpiration of a plant well supplied with water, cools the foliage and the air in the greenhouse below external temperature even when solar radiation is at its maximum value. Cooling obtained with an evaporative wet pad at the air inlet lowers vapour pressure deficit in the greenhouse and decreases transpiration rate. Still, total latent heat dissipation added to pad evaporation and crop transpiration is higher than that obtained by crop transpiration without the wet pad. The combined solution of the energy balance of the air passing through the evaporative pad and of the crop predicts accurately transpiration of the rose crop and internal temperature and humidity. The evaporative pad cools the air considerably; but the lowering of transpiring leaf temperature is only minor. Evaporation from the pad decreases when external humidity increases. Crop transpiration rate when the wet pad operates is nearly independent of external humidity and ventilation rate.

Keywords: Climate control; Transpiration; Energy balance; Temperature; Humidity; Radiation; *Rosa indica* L

1. Introduction

Year round cultivation inside greenhouses in regions with warm summer climates has created the need to investigate cooling procedures. Whitewashing the roof of the greenhouse is the most common means for diminishing heat load, but has a long-term negative effect on the productivity of vegetable, fruit and flower crops. Shading also lowers the ability of plants to cool themselves by transpiration (Boulard et al., 1991).

Transpiration has been recognised as having a dominant role in the dissipation of heat and climate control of greenhouses (Stanghellini, 1987). Models calculating the transpiration of greenhouse crops resolve simplified energy balance equations linearised using the slope of the exponential dependence of saturated water vapour pressure upon temperature (Monteith, 1965; Penman, 1948). The inputs for these calculations are the humidity and air temperature inside the greenhouse, estimates of the absorbed radiant energy, and, in some cases, ventilation rate (Baille et al., 1994; Boulard and Jemaa, 1993; Jolliet and Bailey, 1992; Stanghellini and Meurs, 1992). However, internal temperature and humidity depend on transpiration in the

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List of Symbols

c_p	specific heat of air at constant pressure ($\approx$1005 J kg^{-1} °C^{-1})
$e(T)$	saturated water vapour pressure at temperature T (kPa)
e_i	water vapour pressure in the greenhouse (kPa)
e_o	water vapour pressure outside (kPa)
e_p	water vapour pressure leaving the wet pad (kPa)
E	latent heat flux density from the crop (W m^{-2}) or crop transpiration rate (mm h^{-1})
E_p	latent heat flux density from the wet pad (W m^{-2}) or wet pad evaporation rate (mm h^{-1})
F	leaf area index
f	average horizontal projection area per unit leaf area in the direction of an incident ray
g_c	leaf (stomatal) conductance of water vapour (m s^{-1})
g_cM	leaf (stomatal) conductance of water vapour (mol m^{-2} s^{-1})
$g_\mathrm{cM\text{-}MAX}$	asymptotic leaf (stomatal) conductance of water vapour (mol m^{-2} s^{-1})
H	sensible heat flux density (W m^{-2})
ℓ	leaf diameter (m)
L	latent heat of vaporisation of water (J kg^{-1})
$L_\mathrm{F}(T_\mathrm{o})$	group of terrestrial radiation terms dependent on T_o (W m^{-2})
$L_\mathrm{I}(T_\mathrm{c})$	group of terrestrial radiation terms dependent on T_c (W m^{-2})
L_n	terrestrial radiation balance of the foliage (W m^{-2})
p	fraction of isotropic hemispherical radiation intercepted by the crop foliage
P	photon response of stomata (μmol m^{-2} s^{-1})
p_o	atmospheric pressure (kPa)
$p_{\zeta,\varphi}$	probability of ray interception by a foliage element
q	factor defined in Eq. (4)
r_a	total convective resistance (s m^{-1})
r_b	boundary layer resistance of a leaflet (s m^{-1})
r_c	leaf epidermis resistance to water vapour diffusion (s m^{-1})
r_H	combined convective and conductive resistance (s m^{-1})
R_n	net radiation of the foliage (W m^{-2})
r_s	crop foliage resistance to water vapour diffusion (s m^{-1})
r_U	heat insulation resistance of the greenhouse cover (s m^{-1})
r_X	ventilation resistance (s m^{-1})
S_1	downward solar radiation flux density reaching the top of the crop foliage (W m^{-2})
S_n	solar radiation flux density absorbed by the foliage (W m^{-2})
S_o	solar radiation outside (0–1000 W m^{-2})
S_p	photosynthetic photon flux density (μmol m^{-2} s^{-1})
T_c	crop canopy surface temperature (°C)
T_i	temperature of the air in the greenhouse (°C)
T_o	outside air temperature (°C)
T_p	temperature of the air leaving the wet pad (°C)
T_w	temperature of the wet bulb thermometer (°C)
v_w	volume airflow at temperature T_w entering the greenhouse (m^3 h^{-1})
v_X	total volume airflow entering the greenhouse (m^3 h^{-1})
V	airflow speed in the greenhouse (m s^{-1})
w	factor defined in Eq. (4)
X	number of volume changes per hour by ventilation (h^{-1})
Y	distance between entry vent and exhaust fan (m)
Z	mean height of the greenhouse (m)
γ	psychrometric constant $\approx$0.0667 kPa K^{-1}
ε_R	emission coefficient for terrestrial radiation of the roof cover (IR polyethylene $\approx$0.55)
ε_S	atmospheric emission coefficient ($\approx$0.88)
ζ	zenith angle of an incident ray (radian)
η	efficiency of the evaporative pad
σ	Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4})
ρ	air density (kg m^{-1})
ρ_c	solar reflection coefficient of the foliage ($\approx$0.25)
ρ_R	reflection coefficient for terrestrial radiation of the roof cover, $1 - \rho_\mathrm{R} = \tau_\mathrm{R} + \varepsilon_\mathrm{R}$