

MODEL OF WATER AND NUTRIENTS SUPPLY TO PLANTS IN A SPACE GREENHOUSE

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Abstract

Particulate media are currently used as artificial soils (substrates) in the root growth modules of space greenhouses. The water necessary for plant vegetation is supplied into the substrate and, flowing through it, reaches the roots. One of the methods of supplying nutrients to plants is their being stored in advance in the pores of the particles. Wetting the substrate, the water penetrates the particle pores and the mineral nutrients dissolve. Diffusing inside the pores, the nutrients reach the solution outside the particles and become accessible to the plant roots.

In the proposed model consisting of two sub-models, the root module is considered as a system of lumped parameters. The first sub-model is based on the material balance of the water in the substrate and takes into account the effects of irrigation, transpiration and evaporation. The dependence of the water losses at transpiration and evaporation on the "meteorological" conditions in the space greenhouse and on the grown plants parameters is described by a system of algebraic equations. The second sub-model, based on the first one, describes, in terms of the concentration of the respective nutrient component, its extraction from the substrate grains and consumption by the plant roots.

The model gives a possibility to simulate various conditions of irrigation and nutrition during the plant vegetation.

1. INTRODUCTION

In the variants of space greenhouses developed at present [1-3], the plant root module has three basic functions:

- 1) it serves as a mechanical basis for plant roots fixing and a medium in which they grow;
- 2) in it, by means of a system of devices, water and air necessary for plant vegetation are supplied (irrigation and aeration);
- 3) it contains the nutrients necessary for plants (stored in advance in the pores of the particles) and, by the water at irrigation, makes them accessible to the plant roots (mineral supply).

For many reasons arising from the specific conditions and requirements onboard [1-3], artificial soils (substrates) are preferred to natural ones. The substrates are discrete

loose-packed media consisting of fine-porous mineral particles of narrow-fraction composition [1-2]. Due to the structure of their porous space, the granules possess an immense internal specific surface which permits the mineral nutrients to be deposited in advance as a thin solid film on the pore walls. Another case is when the solid salts fill an essential part of the porous space. When such a medium is wetted, the water penetrates the particle pores and the mineral nutrients dissolve yielding a high-concentrated solution. Diffusing in the solution inside the pores, the nutrients reach the extra-particle solution where they are accessible to the plant roots.

Under microgravity conditions, the transport processes related to the second and third of the enumerated basic functions of the root module have complex character [1-6]. That is why, it seems reasonable to pass over the delicate problem of water motion through the substrate granulated medium under the capillary forces [4,6] and to consider the water and nutrients material balances only. In this way, the root module will be regarded as a system of lumped parameters and the model will take into account only the time evolution of the system completely ignoring the space distribution of the parameters. A preliminary version of this model has been reported in [7].

2. WATER BALANCE

According to the adopted lumped parameter conception of modeling the water supply to the plants, the root module can be considered as a compartment of volume $V [cm^3]$ filled with granulated medium, water, air and plant roots. Let $\theta [-]$ be the "soil" water content, i.e. the water volume inside the particle pores and in the inter-pellet space per unit medium volume. Then, the water mass balance of the root module can be written as follows:

$$(1) \quad \frac{d}{dt}(\rho_w V \theta) = \dot{I}r - \dot{T}r - \dot{E}v.$$

Here, $t [hour]$ is time, $\rho_w = 0.998 g.cm^{-3}$ is the specific density of water, and $\dot{I}r [g.hour^{-1}]$, $\dot{T}r [g.hour^{-1}]$, $\dot{E}v [g.hour^{-1}]$ are irrigation rate, transpiration rate and evaporation rate, respectively.

The irrigation rate is a function of time, $\dot{I}r = \dot{I}r(t)$, which describes the water incomings during the observation period of the plant vegetation. Various scenarios of root module irrigation can be simulated by suitable definition of this function.

The transpiration rate gives the amount of water which is extracted per unit time by the plant roots from the "soil", transported through the plants to their leaves and evaporated into the ambient atmosphere. It can be expressed by the transpiration rate per unit leaf area, $E_L [g.s^{-1}.cm^{-2}]$, and the full leaf area of the plants in the greenhouse. Under assumption that there are $N_p [-]$ identical plants each one having leaf surface area $S_L [cm^2]$, the transpiration rate becomes

$$(2) \quad \dot{T}r = 3.6 \times 10^3 N_p S_L E_L$$

where the numerical factor converts hours into seconds. A model of E_L determination is represented in **Sect. 2.1 - 2.4**.

The evaporation rate term takes into account that on the root module surface may exist n areas of different evaporation intensity (e.g., impermeable to water vapor, blown in different way, contacting environments of different temperature and humidity):

$$(3) \quad \dot{E}v = \sum_{i=1}^n S_i^E E_i^E.$$

Here $S_i^E [cm^2]$ and $E_i^E [g.hour^{-1}.cm^{-2}]$ are the surface area and evaporation rate per unit area of the respective parcel. It is well known [8-10] that E_i^E depends on the “wind” velocity $u [cm.s^{-1}]$ and the jump ($e_s - e$) of the water vapour pressure on the evaporating surface, $e_s [mbar]$, and in the air, $e [mbar]$. It seems that the most appropriate are the empirical formulas having the following form [10]: $E_i^E = A^* \rho_w (1+72u_i)(e_{s,i} - e_i)$. For an evaporating water surface the empirical constant A^* has a value $A^* = 31.2 - 36 cm.hour^{-1}.mbar^{-1}$. At the evaporating surfaces the water vapour is practically saturated. So, to the vapour partial pressures $e_{s,i}$ the Clausius-Clapeyron equation can be applied: $e_{s,i} = A_e \exp(-B/T_{s,i})$. Here $T_{s,i} [K]$ is the absolute temperature of the respective area and the constants are: $A_e = 17.8185 \times 10^8 mbar$, $B = 5.321 \times 10^3 K$. Similarly, the vapour partial pressure in the air above the considered areas can be represented through the air absolute temperatures, $T_{A,i} [K]$, and the relative humidity, $h_{A,i} [-]$: $e_i = A \exp(-B/T_{A,i}) h_{A,i}$. In this way, the evaporation intensity becomes:

$$(4) \quad \dot{E}v = A^* A \rho_w \sum_{i=1}^n S_i^E (1+72u_i) [\exp(-B/T_{s,i}) - \exp(-B/T_{A,i}) h_{A,i}].$$

2.1. TRANSPIRATION RATE PER UNIT LEAF AREA $E_L [g.s^{-1}.cm^{-2}]$

The water mass flux that the plant loses at transpiration can be approximately expressed on the basis of a linear flux-potential concept similar to Ohm’s law in the field of electricity. According to it, the transpiration rate per unit leaf area, E_L , is proportional to the difference $\Delta q = q_L - q_A$ between the absolute humidity of the vapour in the leaf and the air, $q_L, q_A [g.cm^{-3}]$, respectively [11,12]. The coefficient of proportionality can be expressed by the overall leaf-to-air resistance, $r_s + r_a$:

$$(5) \quad E_L = \frac{1}{r_s + r_a} (q_L - q_A),$$

where $r_s [s.cm^{-1}]$ is the stomatal resistance to water vapour and $r_a [s.cm^{-1}]$ is the leaf boundary layer diffusion resistance. Taking into account the Clausius-Clapeyron equation giving the saturation air humidity as a function of the absolute temperature, $T_A [K]$, the absolute air humidity, q_A , can be expressed by the relative one, $h_A [-]$:

$q_A = \frac{A}{T_A} \exp(-B/T_A) h_A$. Here, the new constant A is: $A = 3.76 \times 10^5 g.K.cm^{-3}$. A similar representation for the humidity on the evaporating surfaces of mesophyll cells is given by $q_L = \frac{A}{T_L} \exp(-B/T_L) h_L$, where $T_L [K]$ and $h_L [-]$ are the leaf absolute temperature and

relative humidity, respectively. After introducing the temperature difference between the leaf and the ambient air, $\Delta T = T_L - T_A$, the representation $T_L = T_A + \Delta T$ and the fact that $\Delta T / T_A \ll 1$ lead to the following approximate expression:

$q_L \approx \frac{A}{T_A} \exp(-B/T_A) \left(1 - \frac{\Delta T}{T_A}\right) \exp(B\Delta T/T_A^2) h_L$. In order h_L to be excluded, the following representation of the leaf water potential, ψ_L [bar], is used [11-13]:

$$(6) \quad \psi_L = \rho_W R_W T_L \ln h_L \quad \text{or} \quad h_L = \exp(\psi_L / (\rho_W R_W T_L)),$$

where $R_W = 4.6151 \times 10^{-1} J \cdot g^{-1} \cdot K^{-1}$ is the water vapour gas constant. With respect to $|\psi_L / (\rho_W R_W T_L)| \ll 1$, the last formula yields $h_L \approx 1 + \frac{\psi_L}{\rho_W R_W T_L} \approx 1 + \frac{\psi_L}{\rho_W R_W T_A}$. Thus, introducing these representations into (5) and keeping only the zero and first order terms, the transpiration rate per unit leaf area is obtained in the form:

$$(7) \quad E_L = \frac{A \exp(-B/T_A)}{T_A (r_a + r_s)} \left[\left(1 + \frac{\psi_L}{\rho_W R_W T_A} - \frac{\Delta T}{T_A} \right) \exp\left(B \frac{\Delta T}{T_A^2} \right) - h_A \right].$$

The leaf boundary layer resistance to water vapour, r_a , can be represented as $r_a = 1.1 r_{aH}$ where $r_{aH} [s \cdot cm^{-1}]$ is the respective resistance coefficient at convective heat transfer between the leaf and the air (for details see **Sect. 2.2**).

2.2. STOMATAL RESISTANCE TO WATER VAPOUR $r_s [s \cdot cm^{-1}]$

The stomatal resistance, r_s , can be described by the empirical formula proposed by Ross [12]. It takes into account the dependence of r_s on the intensity of the **Photosynthetically Active Radiation** (PhAR), $I_\Phi [W \cdot cm^{-2}]$, and the actual leaf water potential, ψ_L , as well as on the plant morph-physiological characteristics:

$$(8) \quad r_s = r_{s0} \left(1 + \frac{\gamma_\Phi}{I_\Phi} \right) \frac{\psi_m - \zeta \psi_L}{\psi_m - \psi_L} \exp(\delta (r_s + r_a) E_L).$$

Here, the introduced parameters are:

- $r_{s0} [s \cdot cm^{-1}]$ - the minimal stomatal resistance to water vapour (resistance at fully open stomata) - its value is specific for a plant species;
- $\gamma_\Phi [W \cdot cm^{-2}]$ - parameter characterizing the dependence of stomatal resistance on PhAR intensity, I_Φ ;
- $\psi_m [bar]$ - critical level of the leaf water potential at which the stomata close;
- $\zeta [-]$ - parameter characterizing the stomata reaction to changes in the leaf water potential;
- $\delta [cm^3 \cdot g^{-1}]$ - coefficient characterizing the dependence of the stomatal resistance on the air humidity jump, because (according to (5)) it is, in fact, a coefficient in front of the difference $\Delta q = q_L - q_A$.

2.3. LEAF THERMAL BALANCE

In order to determine the leaf temperature, T_L , or the temperature drop, $\Delta T = T_L - T_A$, the leaf thermal balance is used [14,15,12]:

$$(9) \quad \underbrace{\kappa_Q I_Q}_I + \underbrace{(a_1 + b_1 \sqrt{e}) \sigma T_A^4 - \delta_L [\sigma T_A^4 + 4\sigma T_A^3 \Delta T]}_{II} + \underbrace{\frac{2\rho_A c_{pA}}{a_H} \sqrt{\frac{u}{b_L}} \Delta T}_{IV} - \underbrace{\Lambda E_L}_V = 0.$$

It takes into account the respective incoming and outgoing energy fluxes:

- I - the total radiation absorbed by the leaf: $I_Q [W.cm^{-2}]$ - the intensity of the total “solar” radiation, $\kappa_Q [-]$ - leaf absorption coefficient for this radiation (assumed value $\kappa_Q = 0.5$);
- II - the atmospheric counter-radiation according to the empirical formula of Brunt [15,14]: $\sigma = 5.67 \times 10^{-12} W.cm^{-2}.K^{-4}$ - Stefan - Boltzmann constant, $e [mbar]$ - the water vapour pressure in the air, a_1, b_1 - empirical constants (assumed values: $a_1 = 0.53$, $b_1 = 0.065 mbar^{-1/2}$, [12]);
- III - the linearized leaf radiation $\delta_L \sigma T_L^4$: $\delta_L [-]$ - leaf adsorption coefficient (assumed value, $\delta_L = 1$ - perfect black body);
- IV - the rate of convective heat exchange between both leaf sides and the air with a structural representation $2 \frac{\rho_A c_{pA} (T_L - T_A)}{r_{aH}}$ where $\rho_A = 1.19 \times 10^{-3} g.cm^{-3}$ is the air density, $c_{pA} = 1.014 W.s.g^{-1}.K^{-1}$ is its specific heat capacity. The heat resistance coefficient per one leaf side, $r_{aH} [s.cm^{-1}]$, is parameterized by the “wind” velocity $u [cm.s^{-1}]$ and the characteristic length of the leaf $b_L [cm]$: $r_{aH} = a_H \sqrt{b_L/u}$. The empirical constant a_H depends on the turbulence intensity as well as on the leaf shape and orientation – for a “mean” leaf at “averaged” conditions, $a_H \approx 0.9 s^{1/2}.cm^{-1}$ [12];
- V - the rate of energy loss for vaporization at transpiration: $\Lambda [W.s.g^{-1}]$ is the latent heat of water vaporization (according to [15,12], $\Lambda = 3243 - 2.72 T_L \approx 3243 - 2.72 T_A$).

2.4. WATER TRANSPORT IN THE SOIL AND IN A PLANT

In order to relate the transpiration rate per unit leaf area to the “soil” conditions in the root module, the linear flux-potential concept used at transpiration rate determination will be applied again [12,8]. For this purpose a model plant is considered. According to the concept, the rate of the water flow through this plant, $Q_{WP} [g.s^{-1}]$, can be expressed as

$$(10) \quad Q_{WP} = \frac{10^{-6}}{r_p} (\psi_R - \psi_L),$$

where ψ_R [bar] is the root water potential and r_p [s.cm⁻¹] is the resistance to water flow inside the plant. The multiplier 10⁻⁶ is a conversion factor because 1bar=10⁶ g.cm⁻¹.s⁻². Assuming a steady-state transport process in the “soil”, this flow rate, the evaporation rate for the whole plant, $S_L E_L$ and the root water uptake for the whole plant, Q_{WR} [g.s⁻¹], must be equal each other:

$$(11) \quad Q_{WR} = \frac{10^{-6}}{r_p} (\psi_R - \psi_L) = S_L E_L .$$

Aiming at determination of Q_{WR} , the Darcy law [16,12] for water transport through an unsaturated medium of water matrix potential ψ [bar] is used. Considering a cylindrical root portion of unit length and of radius r [cm], it is assumed that this medium surrounds the root symmetrically up to a distance d [cm] from its axis which can be identified as the half-distance to the axis of the closest other root. Then, the Darcy law for the radial direction can be written as

$$(12) \quad v = -10^{-6} k_s \frac{d\psi}{dy}$$

where v [cm.s⁻¹] is the linear seepage velocity, y [cm] is the radial coordinate, and the hydraulic conductivity of the medium, $k_s(\psi)$ [cm³.s.g⁻¹], is assumed to be approximated as $k_s(\psi) = 10^{6b} a (-\psi)^{-b}$ [12]. The parameters a [cm^{3-b}.s^{1-2b}.g^{-1+b}] and b [-] specify the substrate hydraulic conductivity. At steady-state conditions, the water flux through each cylindrical surface coaxial with the root axis will not depend on the radius y : $2\pi y v = \text{const} = v_R$, where v_R [cm².s⁻¹] is the water volume flux per unit root length, $v_R = v|_{y=r} 2\pi r$. Then, (12) leads to an integrable equation which yields:

$$(13) \quad v_R \int_r^d \frac{dy}{y} = 2\pi a 10^{6(b-1)} \int_{\psi_R}^{\psi_S} (-\psi)^{-b} d(-\psi)$$

where ψ_S [bar] is the water potential at the outer edge of the “soil” cylinder, i.e. the substrate medium water potential. Performing this integration and taking into account that Q_{WR} can be expressed by the whole plant root area S_R [cm²],

$Q_{WR} = \rho_W v_R [\text{root length}] = \rho_W v_R \frac{S_R}{2\pi r}$, one obtains

$$(14) \quad Q_{WR} = \frac{10^{6(b-1)} \rho_W S_R a}{r (1-b) \ln(d/r)} [(-\psi_S)^{1-b} - (-\psi_R)^{1-b}] .$$

Finally, both relations in (11) allow Q_{WR} and ψ_R to be excluded from this equality:

$$(15) \quad (-\psi_S)^{1-b} = 10^{-6(b-1)} \left[[10^{-6} (-\psi_L) - r_p S_L E_L]^{1-b} + \frac{r (1-b) \ln(d/r)}{\rho_W a} \frac{S_L E_L}{S_R} \right] .$$

The “soil” water potential of an unsaturated medium, ψ_s , is closely related to its water content, θ [8,16,12]. Here, it is assumed that this relation can be approximated by a simple two-parametrical formula [12]: $\psi_s = a_\psi \theta^{-b_\psi}$. The parameters a_ψ [bar] and b_ψ [-] specify the hydraulic properties of the respective soil, and in the case under consideration, those of the particulate substrate medium.

The formulas given in **Sect. 2.1 – 2.4** make it possible to determine θ from the balance equation (1).

3. NUTRIENT BALANCE

The second sub-model describes the balance of nutrients in the root module. Assuming that the involved nutrient species do not interact each other neither chemically, nor physically, the nutrient solution can be considered as a mixture. This enables the respective balance equation for such a species to be formulated independently of the others. If c [$g.cm^{-3}$] is the mass per unit solution volume of any nutrient component, its balance equation for the root module compartment can be written in the form:

$$(16) \quad \frac{d}{dt}(V\theta c) = j_{source} - j_{diff} - j_{conv}.$$

Here, j_{source} [$g.hour^{-1}$], j_{diff} [$g.hour^{-1}$] and j_{conv} [$g.hour^{-1}$] are the nutrient source rate and its consumption rates via diffusion and convection, respectively.

If σ_p [cm^{-1}] is the surface of the particles per unit root module volume and $j[c(t_s)]$ [$g.s^{-1}.cm^{-2}$] is the density of the nutrient flux from the particles, depending on the regarded concentration $c(t_s)$, the nutrient source rate term will be

$$(17) \quad j_{source} = 3.6 \times 10^3 V \sigma_p j[c(t_s)]$$

where t_s [s] is the time in seconds: $t_s = 3.6 \times 10^3 t$. In [17] an analytical representation of this density, $j_R[c(t_s)]$, is derived for the case of diffusive extraction of substance from spherically symmetrical particles of radius R [cm] and porosity m [-]:

$$(18) \quad j_R[c(t_s)] = \alpha \left[(c_i(t_s) - c(t_s)) - \int_0^{t_s} (c_i(\tau) - c(\tau)) e^{-\frac{\gamma}{m}(t_s - \tau)} \frac{df_2^* \left(\frac{t_s - \tau}{m} \right)}{dt_s} d\tau \right].$$

Here, α [$cm.s^{-1}$] ($\alpha > 0$) is a coefficient of mass exchange between the particles and the surrounding nutrient solution and $c_i(t_s)$ [$g.cm^{-3}$] is an effective concentration of the intra-pore solution. This concentration is expressed by the equilibrium constant of the solution saturation with the component under study, c_* [$g.cm^{-3}$], the initial concentration inside the particles, c_0 [$g.cm^{-3}$], and the kinetic coefficient of dissolving, γ [s^{-1}], $\gamma > 0$:

$c_i(t_s) \equiv c_* + (c_0 - c_*) e^{-\frac{\gamma}{m} t_s}$. The kernel function of this integral expression,

$f_2^*(t_s) = 1 - \sum_{n=1}^{\infty} \frac{2Bi e^{-\frac{D\mu_n^2}{R^2} t_s}}{Bi(Bi-1) + \mu_n^2}$, depends on the diffusion coefficient at the specific conditions of the particle porous space (dispersion coefficient) $D[cm^2.s^{-1}]$ and the dimensionless Biot number, $Bi \equiv \alpha R/D$. The characteristic numbers $\mu_n[-]$ are roots of the equation $tg \mu = -\frac{1}{Bi-1} \mu$. The behavior of this kernel function is described in [17].

To express the dependence of the rate of nutrient consumption by plants via diffusion, \dot{J}_{diff} , on the solution concentration past the roots, c , a Michaelis-Menten-like formula will be used [18]:

$$(19) \quad \dot{J}_{diff} = 3.6 \times 10^3 V \sigma_R M \frac{c}{K_M + c}.$$

Here, $\sigma_R[cm^{-1}]$ is the surface of the roots per unit root module volume, $M[g.s^{-1}.cm^{-2}]$ is the maximal density of the root uptake and $K_M[g.cm^{-3}]$ is the Michaelis constant.

Obviously, the rate of convective consumption of the nutrients by the plant roots depends directly on the rate of water consumption by the plants, i.e. on the transpired water volume, $\dot{T}r/\rho_w$:

$$(20) \quad \dot{J}_{conv} = (\dot{T}r/\rho_w)c.$$

In this way, in addition to the water content function, $\theta(t)$, common for both balance equations, the nutrient balance is related with the water one by the transpiration rate, $\dot{T}r(t)$, too. That is why the nutrition sub-model is based on the water balance sub-model.

4. APPLICATION OF THE MODEL

The application of the proposed model requires the following groups of parameters to be available:

- **root module parameters:** $V[cm^3]$, $S_i^E[cm^2]$;
- **substrate parameters:** $\sigma_p[cm^{-1}]$, $R[cm]$, $m[-]$;
 $a_\psi[bar]$, $b_\psi[-]$, $a[cm^{3-b}.s^{1-2b}.g^{-1+b}]$, $b[-]$;
- **space cabin parameters:** $u[cm.s^{-1}]$, $T_A[K]$, $h_A[-]$, $e[mbar]$,
 $I_Q[W.cm^{-2}]$, $I_\Phi[W.cm^{-2}]$,
 $T_{s,i}[K]$, $u_i[cm.s^{-1}]$, $T_{A,i}[K]$, $h_{A,i}[-]$;
- **nutrients parameters:** $c_0[g.cm^{-3}]$, $c_*[g.cm^{-3}]$, $\gamma[s^{-1}]$, $D[cm^2.s^{-1}]$, $\alpha[cm.s^{-1}]$,
 $M[g.s^{-1}.cm^{-2}]$, $K_M[g.cm^{-3}]$;
- **plant parameters:** $N_P[-]$, $r_P[s.cm^{-1}]$,
 $\sigma_R[cm^{-1}]$, $S_R[cm^2]$, $r[cm]$, $d[cm]$,
 $S_L[cm^2]$, $b_L[cm]$, $r_{s0}[s.cm^{-1}]$, $\gamma_\Phi[W.cm^{-2}]$, $\psi_m[bar]$,
 $\zeta[-]$, $\delta[cm^3.g^{-1}]$.

Realistic data for these parameters allow, by use of the water balance equation and the system of algebraic equations given in **Sect. 2**, to determine the leaf transpiration parameters, E_L, ψ_L, T_L, r_s , and to predict the water content of the substrate, $\theta(t)$. Then, from the balance equations described in **Sect. 3** the concentration of the respective nutrient substances can be calculated.

In this way, the model might be useful as a tool of simulation of plant growth conditions in a space greenhouse including various irrigation and nutrient regimes.

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