Uptake of nitrogen by roots

This note reports a further development of the nitrogen uptake model implemented in Daisy (Hansen et al. 1991; Hansen and Abrahamsen 2009). The new development pertains to root uptake kinetics. The simulation of the crop nitrogen demand is unchanged.

Amino acid, ammonium and nitrate can be taken up by plants by active processes (e.g. Miller and Cramer, 2004). In agricultural systems, the relative importance of these nitrogen sources is largely determined by the agricultural practice, e.g. fertilization. In Daisy it is assumed that nitrate is the dominant source. Ammonium is treated like nitrate, though with the modification that the sorption of ammonium is taken into account. The uptake of amino acids is neglected. Furthermore it is assumed that the nitrate uptake is governed by transport to the root surface (mass flow and diffusion) in combination with uptake kinetics at the root surface as described by Michaelis-Menten kinetics. The uptake kinetics of nitrate is governed by a dual-affinity system (Tsay et al. 2007) viz. a high affinity system with a low uptake capacity and a low affinity system with high uptake capacity.

The transport of a solute (ammonium or nitrate) from the bulk soil to the root surfaces is based on a number of assumptions similar to those adopted for water flow (Hansen and Abrahamsen, 2009): 1) each root may exploit an average effective volume of soil which is assumed to be a cylinder around the root; 2) the radius of this cylinder is assumed to correspond to the average half distance between the roots; 3) the solute is transferred to the root surface by both mass flow and diffusion 4) the concentration - distance profile around a root develops in time in a stepwise manner and at each time-step it approximates to a steady state profile (Baldwin *et al.* 1973). Based on these assumptions the solute-flux towards the root surface is estimated:

$$I = \begin{cases} 4\pi D\left(C - C_r\right)\left[\dfrac{\beta^2 \ln \beta^2}{\beta^2 - 1} - 1\right]^{-1} & \alpha = 0 \\ 4\pi D \dfrac{\left(\beta^2 - 1\right)C - \ln\left(\beta^2\right)C_r}{\left(\beta^2 - 1\right) - \ln\left(\beta^2\right)} & \alpha = 2 \\ 2\pi D\alpha \dfrac{\left(\beta^2 - 1\right)\left(1 - \alpha/2\right)C - \left(\beta^{2-\alpha} - 1\right)C_r}{\left(\beta^2 - 1\right)\left(1 - \alpha/2\right) - \left(\beta^{2-\alpha} - 1\right)} & \text{else} \end{cases} \quad (1)$$

$$\alpha = \frac{S_r}{2\pi L D} \quad (2)$$

$$\beta = (r_r^2 \pi L)^{-1/2} \quad (3)$$

where I is the solute uptake per unit length of the root, D is the diffusion coefficient in the soil, C is the bulk concentration in soil solution and C_r is the concentration at root surface, S_r is the water uptake expressed as a volumetric sink term, r_r is the root radius, and L is the root density.

The model is static (assuming steady-state conditions); however applied to a transient system the model works as series of steady-states, i.e. in a quasi-steady-state manner, hence soil nitrogen content changes in time and, therefore also concentrations change in time. As a result also soil nitrogen content is important when applying the model to a transient system, although only in an indirect way.

In the soil, diffusion is influenced by the water content of the soil both in terms of the diffusion cross-section and the tortuous pathway followed by the solute through pores. The bulk soil diffusion coefficient is calculated as:

$$D = \theta D_l f_l \tag{4}$$

where θ is the volumetric soil water content, D_l is the diffusion coefficient in free solution, and f_l is a so-called tortuosity factor, which can be estimated in several ways. In Daisy, the default tortuosity factor is a step-wise linear model:

$$f_l = \begin{cases} f_l^0 & \theta \le \theta_0 \\ f_l^0 + a\left(\theta - \theta_0\right) & \theta > \theta_0 \end{cases} \tag{5}$$

where f_l^0, θ_0 and a are constants. A value of f_l^0 equal to 10^{-6} is selected arbitrarily, while a and θ_0 are parameters characterizing the soil (default values: a=2, θ_0 = soil water content at the permanent wilting point. The diffusion coefficient of nitrate in free solution is around 0.072 $cm^2\ h^{-1}$.

The parameter α reflects the relation between the effectiveness of mass transfer to diffusion; $\alpha = 0$ corresponds to an instance where the mass transfer contribution is zero and diffusion is the only mechanism contributing to transfer; α typically assumes a value in the interval 0 to 0.1. β is characterizing the geometry of the system; large values of β corresponds to sparse root systems and low values correspond to the high root density.

Eq. (1) shows that a linear relation exists between root uptake I and the C_r i.e.:

$$I = a_z + b_z C_r \tag{6}$$

$$a_z = \begin{cases} 4\pi D\left[\dfrac{\beta^2 \ln \beta^2}{\beta^2 - 1} - 1\right]^{-1} C & \alpha = 0 \\ 4\pi D \dfrac{\left(\beta^2 - 1\right)}{\left(\beta^2 - 1\right) - \ln\left(\beta^2\right)} C & \alpha = 2 \\ 2\pi D \dfrac{\alpha\left(\beta^2 - 1\right)\left(1 - \alpha/2\right)}{\left(\beta^2 - 1\right)\left(1 - \alpha/2\right) - \left(\beta^{2-\alpha} - 1\right)} C & \text{else} \end{cases} \tag{7}$$

and

$$b_z = \begin{cases} -4\pi D\left[\dfrac{\beta^2 \ln \beta^2}{\beta^2 - 1} - 1\right]^{-1} & \alpha = 0 \\ -4\pi D \dfrac{\ln\left(\beta^2\right)}{\left(\beta^2 - 1\right) - \ln\left(\beta^2\right)} & \alpha = 2 \\ -2\pi D \dfrac{\alpha\left(\beta^{2-\alpha} - 1\right)}{\left(\beta^2 - 1\right)(1 - \alpha/2) - \left(\beta^{2-\alpha} - 1\right)} & \text{else} \end{cases} \tag{8}$$

The dual-affinity uptake kinetics can be described as:

$$I = \frac{F_1 C_r}{K_1 + C_r} + \frac{F_2 C_r}{K_2 + C_r} \tag{9}$$

where *F* and *K* refer to the max uptake rate and the half-saturation constant, respectively, and the subscripts 1 and 2 refer to the high affinity system and low affinity system, respectively. Equating (6) and (9) yields:

$$a_z + b_z C_r = \frac{F_1 C_r}{K_1 + C_r} + \frac{F_2 C_r}{K_2 + C_r} \tag{10}$$

Characterizing nitrate uptake Tsay et al. (2007) suggests 50 µM (0.7 mg NO^-_3-N/L) and 5 mM (70 mg NO^-_3-N/L) for the half-saturation constant for the high and for the low affinity system, respectively. The max uptake rates are more uncertain. Based on preliminary calibrations of max uptake rates we suggest a value of 25 ng/cm/h and 250 ng/cm/h for the high and for the low affinity system, respectively. Equation (10) can be solved for C_r and *I* can subsequently be calculated using eq. (6) or eq. (9).

References

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