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Modelling zinc uptake and radial transport in roots

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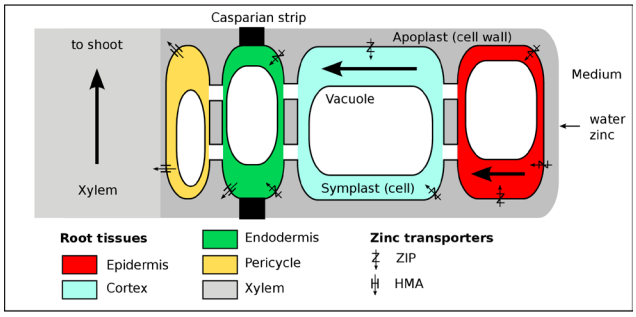
Highlights: Modelling of zinc radial transport in roots was undertaken to understand the experimentally observed pattern of zinc accumulation near the central cylinder of the root. The model confirms the hypothesis that low abundance of the efflux transporter HMA4 produces this radial gradient in zinc concentration, but surprisingly, transpiration was found also to be a key parameter.

Keywords: zinc, radial transport, regulation, diffusion, root

Zinc is an essential micronutrient in green plants, yet toxic at high concentrations. Only specialized hyperaccumulator plants can tolerate high zinc doses and are therefore of special interest for their potential application in phytoremediation and crop development (Clemens et al., 2002). Zinc ions are taken up from the soil along with water and are transported radially towards the root's vascular bundle in two parallel pathways: the cell wall (apoplast) and the cytoplasm (symplast). Cross-membrane transport into and out of the cytoplasm is mediated by ZIP and HMA transporter proteins, respectively (Fig. 1). Experimental results show a pattern of zinc accumulation close to the centre of the root, which disappears at high levels of HMA (Hanikenne et al., 2008). Using a computational model, we study the roles of ZIP regulation, HMA level and water flow velocity in creation of this radial pattern.

A comprehensive one-dimensional dynamical model of radial zinc transport is developed to conduct simulations (Claus et al., 2012). This model accounts for the structure of the root consisting of symplast and apoplast and includes effects of water flow, diffusion, and cross-membrane transport via transporters. It also incorporates the radial geometry and varying porosity of root tissues, as well as regulation of ZIP transporters. We use existing biological data to estimate parameters and analyze the properties of the model in numerical simulations.



Apoplast:

$$\partial_t(\Psi\, rZ) + \partial_r\big((D/r)\,\Psi\, rZ - \Psi\, D\,\partial_r(rZ)\big) = r\,Q_{apo}$$

Symplast:

$$\partial_t(\Phi\, rZ) + \partial_r\big((v + D/r)\,\Phi\, rZ - \Phi\, D\,\partial_r(rZ)\big) = r\,Q_{sym}$$

Ψ, Φ	volume fraction in apoplast/symplast
r	radial coordinate
Z	zinc concentration
D	diffusion coefficient
v	water flow velocity
$Q_{apo,sym}$	membrane fluxes into apoplast, symplast

Fig. 1. Schematic description of zinc transport in roots from the medium towards the xylem. Arrows indicate the direction of transport. Equations on the right describe the radial transport of zinc in symplastic and apoplastic compartments (see Claus et al., 2012 for details).

In the steady state, the model reproduces the zinc gradient found in experiments as well as its loss at increased levels of HMA. Surprisingly, water flow velocity is found to be also a key parameter for producing this gradient. Simulations in time and space show short adaptation times to changes in external conditions. Since a slow ZIP regulation lead in these scenarios to high-amplitude oscillations, our results suggest that the time scales of regulation and transport need to be similar in the order of seconds to minutes.

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