Decoding soil-plant-atmosphere processes by extending in-situ monitoring and experimental data with numerical modelling

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Abstract: The soil-plant-atmosphere nexus is a complex and interconnected system that is essential for the functioning of ecosystems. Understanding the dynamics and processes occurring in this system is crucial for addressing issues related to soil degradation, climate change, and food security. The experimental data collection from displacement soil cores or monoliths (soil columns) and in-situ monitoring of the soil processes can be further enhanced by applying models of various complexity to quantify different fluxes. Numerical modelling can be used as a predictive tool for estimation of various transport processes in unsaturated soil within agricultural, environmental and geotechnical applications. The approach of combining numerical simulations with laboratory analytics and extensive field observations has been proven to be very efficient. In homogeneous soil, vadose zone modelling is commonly based on Richards equation for describing water flow, and advection-dispersion equations for solute transport; which usually works quite well in describing physical processes. However, there is still difficulty in estimation and modelling of preferential flow and nonuniform solute transport in structured soils.

The presentation aims at discussing vadose zone processes and modelling capabilities and restraints by presenting various examples of modelling with HYDRUS suite. The examples illustrate the use of various models like single porosity, dual-porosity and dual permeability and their ability to account for various soil structure properties but also properties of other porous materials, like coal, which is a relevant issue in mine rehabilitation.

The modelling was performed on various scales, from column, profile, plot to hillslope using one-dimensional and two-dimensional model domains. In-situ examples and soil column observations include data from soil moisture and matric potential sensors, lysimeter fluxes and outflows and collection of water samples from surface or subsurface runoff instruments. The collected water samples i.e., leachate includes analytical determination of various contaminants like nitrates, pesticides, pharmaceuticals and trace elements. The ability of models to represent solute transport parameters and processes like leaching, sorption and degradation will be presented briefly. The complexity of solute transport processes and the ability of modelling them is additionally enhanced by the difficulty of modelling non-uniform water flow which is the governing process underlying the solute transport in structured soils.

The issue of non-linearity in vadose zone is mainly connected to heterogeneity in soil properties (chemical, physical, biological) which can be difficult to quantify or integrate into numerical models. Modelling capabilities are now on high level, while meanwhile we still have issues of incorporation and proper quantification of soil structure formation or how to link soil hydraulic properties to vegetation metrics like biomass and leaf area index. Modelling preferential flow in structured soils requires further development of sophisticated models that can capture the heterogeneity, complexity, nonlinearity, and scale of the system. In order to properly quantify transport processes in vadose zone we need to implement some of the more complex models into larger scale predictions. More specifically, this accounts for the states of soil properties, including the spatial structure of solids and pores, as well as their dynamics, including soil mass and solute transfer quantification between soil matrix and fracture (pore) domains. The availability of high-quality experimental data is also essential to ensure accurate model calibration.

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