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Advancing Design and Functionality of Lysimeter/Ecotron Systems through Modeling

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Lysimeter systems play a crucial role in understanding the complex interactions within the soil-plant-atmosphere continuum. In the context of climate change, where precise insights into water and nutrient fluxes, energy exchange, and greenhouse gas dynamics are essential, lysimeters equipped with advanced hydraulic and thermal controls are increasingly indispensable. A key innovation in this field is the integration of suction-controlled hydraulic boundary conditions and active temperature regulation, which significantly enhances the capability of lysimeters to mimic natural processes while maintaining experimental control. These functionalities are particularly critical in ecotron experimental platforms, where controlled yet realistic environmental conditions are required for high-resolution and high-quality observations.
Our research focuses on the optimization of lysimeter design and functionality using advanced computational tools. Specifically, we developed a 2D- and a comprehensive 3D-modeling approaches to investigate and refine the technical design of lysimeter systems equipped with underpressure-controlled hydraulic boundary conditions and temperature regulation mechanisms. Two simulation models, HYDRUS and FEFLOW, were systematically tested and compared for their suitability in simulating these complex systems.
We present the results of scenario analyses conducted to evaluate and optimize critical design parameters, including (1) the number and spatial arrangement of suction cups required to achieve precise suction-controlled hydraulic boundary conditions, (2) the number, positioning, and dimensions of heat exchanger pipes for effective temperature regulation and (3) the influence of insulation thickness at the bottom of the lysimeter on thermal efficiency and system stability. Our findings also demonstrate the strengths and limitations of both HYDRUS and FEFLOW in capturing the dynamics of water and energy transport in lysimeters. Our work not only contributes to the technical advancement of lysimeter and ecotron platforms but also supports their broader application in ecosystem research. By integrating robust design methodologies with cutting-edge simulation tools, we provide a framework for enhancing the reliability and functionality of these experimental systems.
In conclusion, this study highlights the potential of modeling and scenario-based optimization in improving the design and operational efficiency of lysimeters with advanced hydraulic and thermal controls. The insights gained from our research are expected to support future applications of lysimeter and ecotron systems in addressing critical questions related to climate change impacts on terrestrial ecosystems.