Special Section: Lysimeters in Vadose Zone Research

Lysimeters in Vadose Zone Research

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Lysimeters are methodological experimental tools to study the water and matter fluxes in the vadose zone, as well as the environmental fate of chemicals. Lysimeters are available in various types. The most sophisticated lysimeters are filled monolithically, are equipped with a pressure-controlled lower boundary, and are weighable, allowing the measurement of hydraulic fluxes, i.e., rainfall, drainage, evapotranspiration, dew, and hoar frost with high precision. This special section of *Vadose Zone Journal* reports on current lysimeter research.

Core Ideas

- Lysimeters bridge the gap between laboratory and field experiments.
- Lysimeters allow the measurement of a complete water balance.
- Lysimeters provide a complete mass balance for a representative ecosystem segment.

The technical term *lysimeter* is composed of the Greek *lyo* (to dissolve, to lose) and *metron* (to measure). Lysimeters are methodological experimental tools to study the water and chemical fluxes in the vadose zone, as well as the environmental fate of chemicals. Originally, lysimeter experiments were conducted to investigate the source of springs and rivers and water loss from soil by transpiration from plants (Goss and Ehlers, 2009). Probably the first comprehensive scientific lysimeter experiment was performed in France from 1688 to 1703 by Philippe de la Hire, who investigated whether rainwater can be the source of springs (de la Hire, 1703). He placed lead basins at different depths in the soil and monitored outflow from these basins. He used a system that is now known as zero-tension pan lysimeters. Since then, lysimeters have been an integral part of hydrological and agricultural research, and more recently lysimeters have been used to study environmental processes in the vadose zone, including climate change, carbon sequestration, and gas emissions.

Lysimeters come in many different forms and sizes, ranging from simple buckets filled with soil to several meter-sized containers planted with trees. The most sophisticated lysimeters are filled with undisturbed soil, are equipped with pressure-controlled porous plates at the bottom, allowing the hydraulic pressure to be adjusted to match that of the surrounding soil, and are weighable, allowing the measurement of hydraulic fluxes, i.e., rainfall, drainage, and evapotranspiration, with high precision (Singh et al., 2018). To be most representative of a field soil, lysimeters are usually embedded into the undisturbed soil to avoid artifacts caused by temperature gradients. A schematic of a modern weighing lysimeter is shown in Fig. 1, and an example of the installation and setup of lysimeters in the field is shown in Fig. 2.

Lysimeters provide us with an experimental tool to study environmental processes in soils under controlled but still realistic conditions. They represent an intermediate between laboratory and field conditions (Table 1) and as such are well suited to study complex soil processes. Weighable lysimeters with installed sensors to measure the water content allow us to measure all terms of the water balance:

$$\Delta W = P + I + D - (A + S + B + \mathrm{ET}) + \mathrm{CR} \quad [1]$$

where ΔW is the change in the lysimeter weight, P is precipitation, I is irrigation, D is dew, A is runoff, S is seepage or drainage, B is the change in the biomass, ET is evapotranspiration, and CR is capillary rise. The overall weight change ΔW can be measured with the lysimeter balance, usually with high resolution (<100 g), while runoff (A) and seepage water or drainage (S) can be collected separately in collection vessels and measured by

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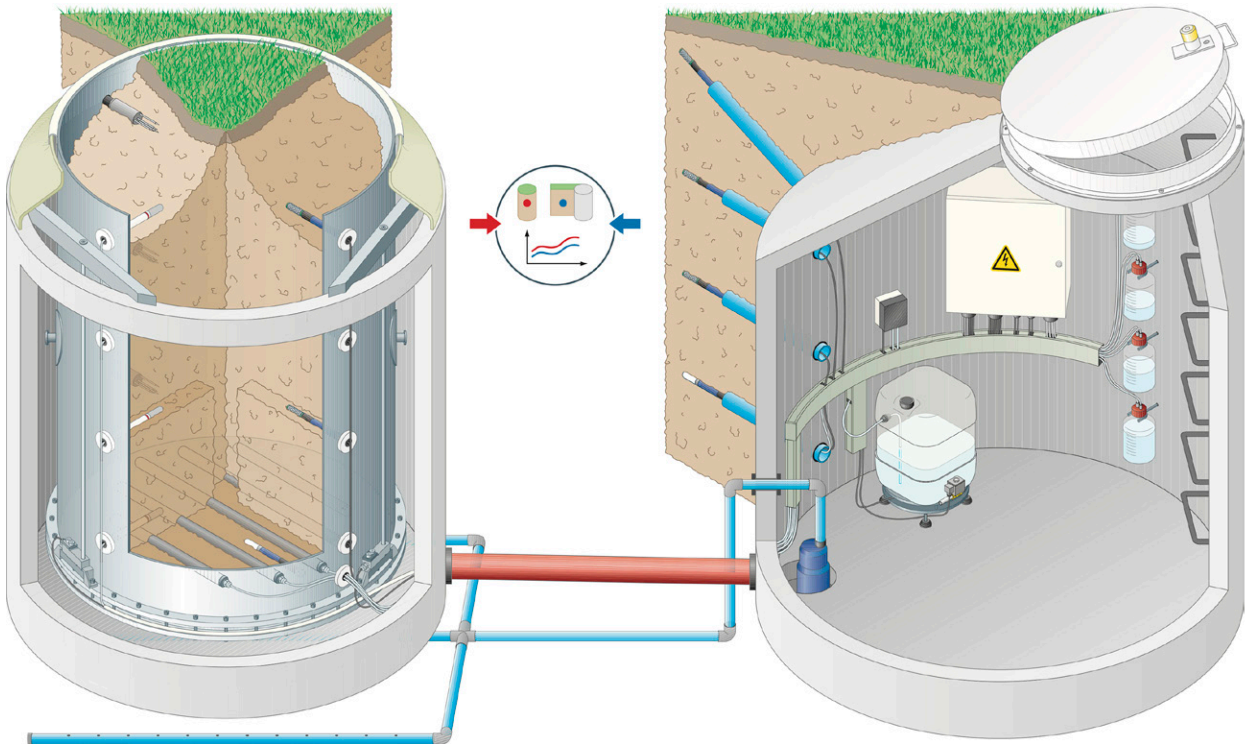

Fig. 1. Schematic of a weighing lysimeter (left) in combination with a service pit (right).

Fig. 2. (a) Coring of an undisturbed lysimeter core, (b) installed lysimeter, (c) instrumentation, and (d) view of a lysimeter setup with underground access.

Table 1. The lysimeter as linkage between laboratory and field experiments.

Laboratory	Lysimeters	Field experiments
	Advantages	
controlled conditions	undisturbed soil	realistic situation
reproducible	agricultural practice	
mass balance	mass balance	
cheap	repetitions	
radioactive isotopes	radioactive isotopes	
	Disadvantages	
artificial	(disturbed drainage)	soil variability
	restricted dimensions	no mass balance
	expensive	limited control of boundary conditions
		expensive

separate balances. The change in lysimeter weight ΔW can be taken as the change in the weight of water inside the lysimeter if no changes in biomass have occurred. Changes in local water contents ($\Delta\theta_i$) inside the lysimeter can be measured by moisture sensors (e.g., time domain reflectometry or tensiometers). The solute mass balance can be measured with a lysimeter as

$$L = C_s \times S \qquad [2]$$

where L is the solute flux (mg m^{-2}), C_s is the solute concentration in the drainage (mg L^{-1}), and S is the amount of seepage water or drainage (L m^{-2} = mm).

Lysimeters are often equipped with sensors to measure water content, temperature, and chemical parameters. Weighing lysimeters, and particularly those with undisturbed soils and with pressure-controlled bottoms, require considerable expertise to setup and to maintain. Commercial systems are now readily available and can be installed almost anywhere. The design and use of lysimeters have been summarized in several review articles (e.g., Cameron et al., 1992, Meissner et al., 2007; von Unold and Fank, 2008; Goss and Ehlers 2009; Evett et al., 2015; Pütz et al., 2016). Data obtained from lysimeter studies provide invaluable information for regulators, particularly for monitoring and assessment of pesticide leaching through soil. Researchers are using lysimeters for process-oriented investigations, and lysimeters have become integral components of agricultural and ecological observatories (Klammler and Fank, 2014; Evett et al., 2015; Pangle et al., 2015; Pütz et al., 2016).

This Special Section

The purpose of this special section is to provide an overview of recent research with lysimeters. The papers are grouped according to the following topics: (i) evaporation and evapotranspiration; (ii) chemical leaching and recharge; and (iii) modeling and process evaluation.

Evaporation and Evapotranspiration

Lysimeters are often used to quantify evaporation and evapotranspiration. Weighing lysimeters are especially suited for that purpose because the water loss from the soil can be measured with high precision, and these lysimeters are often used as reference for evapotranspiration measurements. In a series of papers, evapotranspiration measurements from weighing lysimeters were compared with other methods, i.e., the Penman–Monteith FAO method (Doležal et al., 2018), the eddy covariance method (Teuling, 2018), and free-drainage lysimeters (Ruth et al., 2018). The results indicate that the different methods do not always agree with each other.

Fully instrumented weighing lysimeters, however, are expensive and difficult to install and maintain. As an alternative to weighing lysimeters, Wuest (2018) proposed low-cost lysimeters consisting of buckets, which are buried in the soil and periodically removed and weighed, to estimate the effects of different surface covers and treatments on soil evaporation.

Chemical Leaching and Recharge

Lysimeters allow the quantification of water and chemical flux in the vadose zone. Different types of lysimeters can be used for that purpose, and Singh et al. (2018) describe the various devices and discuss their use and limitations. Lysimeters with a suction-controlled bottom boundary are excellent tools to monitor and quantify nutrient and contaminant fluxes and to detect seasonal leaching patterns (Brye et al., 2018), to detect effects of crop management on water and nitrate fluxes (Ochsner et al., 2018), to quantify leaching of pesticides (Kupfersberger et al., 2018), to determine the degree of preferential flow of the pesticide atrazine (Torrentó et al., this issue), and to quantify recharge (Nocco et al., 2018).

Modeling and Process Evaluation

Lysimeter data are often used to calibrate and test numerical models of water flow and chemical transport. Kupfersberger et al. (2018) used lysimeter data to calibrate a regional pesticide transport model. Graham et al. (2018) used drainage data from lysimeters to estimate soil hydraulic properties and used these data to simulate drainage, soil water content, and evapotranspiration from lysimeters. Wang et al. (2018) used laboratory lysimeters to decipher the role of changing water table elevations, and associated changes in redox potentials in soils and on greenhouse gas emissions (N_2O and CO_2).

While most lysimeter studies are conducted in agricultural or forested areas, Dijkema et al. (2018) used data from a desert lysimeter to simulate water flow in desert soil. Their data and simulations point to the need to better understand vapor phase exchange processes in arid soils. Lastly, Germann and Prasuhn (2018) showed how the viscous flow approach can be used to quantify preferential flow in lysimeters and how to predict the duration of perched water tables that develop in free-drainage lysimeters.

Future Research and Outlook on the Use of Lysimeters

Lysimeters are versatile tools and, as shown in this special section, are used in a variety of experimental scenarios. Lysimeter technology has improved considerably in recent years, allowing us to design and build lysimeter systems that more and more mimic a natural soil. Nonetheless, the technology can be further optimized, particularly with regard to control of boundary conditions and the sampling of undisturbed soil cores for monolithic lysimeters, where, for the latter, there is no validated method that has been extensively tested for its advantages and disadvantages. The dynamics of the water and temperature regime—and the associated water and energy balances—of a lysimeter can only be correctly measured and quantified with a realistic control of the lower boundary condition (Abdou and Flury, 2004; Groh et al., 2016). Further, there is need for the development of filter algorithms to eliminate interference, such as wind effects or other disturbances, and data control algorithms for data quality control and backup. Lysimeters will play an important role for extrapolation studies, mechanistic investigations to identify and quantify soil processes, and especially as an integral part of long-term terrestrial observatories, where lysimeters can help to identify trends in soil and climate change.

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