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The role of lysimeters in the development of our understanding of soil water and nutrient dynamics in ecosystems

M. J. Goss[1] & W. Ehlers[2]

[1]*University of Guelph, Kemptville Campus, Kemptville, ON KOG 1J0, Canada, and* [2]*Georg-August University, Department of Crop Sciences, Institute of Agronomy, Von-Siebold-Strasse 8, 37075 Göttingen, Germany*

Abstract

This paper considers the development of lysimeters and their role in the evolution of our understanding of the dynamics of water and plant nutrients in ecosystems. Lysimeters are delineated volumes of soil. They can be divided into those filled with repacked soil, and those enclosing an undisturbed monolith. The original repacked lysimeter was developed to investigate the concept that all life stems from water, and is considered to be the first quantitative experiment in history. It focussed on the growth of a willow tree and how much of the increment was derived from the soil solids. From this start some 360 years ago lysimeters quickly contributed to the quantification of the transpiration stream and the differentiation of water loss by evaporation from the soil from loss via the leaves of plants. Chronologically, further development began about 210 years ago with the exploration of whether precipitation could account for all the water moving from the land to the oceans, and was the origin of springs. In part, this required a careful quantification of soil evaporation, runoff and deep drainage. This in turn led to the quantification of the soil water balance. As a result, we are able to predict indices, such as crop water use efficiency, drainage and irrigation requirements, contributions to stream flow, groundwater recharge and nutrient loss by leaching. Recognition that the quantification of drainage and leaching required soils of natural structure and profile integrity resulted in the building of the first monolith lysimeter and the development of 'pan' or 'Ebermayer' lysimeters. Improved technology allowed a better understanding of the role of soil in the regional water balance through the development of small diameter lysimeters that could be transported to a central location subject to the same climatic variables. In contrast, other technological changes allowed the impact of typical soil management operations carried out using regular machinery to be applied on field-scale lysimeters. The contribution of the different types of lysimeter to the development of our understanding of soil use and management is considered.

Keywords: Lysimeters, soil structure, water balance, water use efficiency, evapotranspiration, nutrient dynamics

Introduction

There have been two distinct but interweaving strands in the use of lysimeters, stemming back over almost four centuries to the time of the natural philosophers. The first strand is the development of our understanding of plant physiology and soil constraints to crop development. The second strand is the understanding of field and regional hydrology. Johannes Baptista van Helmont (1579–1644) is often credited with conducting the first quantitative experiment in history (van Helmont, 1648), in which he grew a willow tree (*Salix sp.* L.) in an earthen pot enclosed with a perforated lead lid for a period of 5 years. He went on to show that although the willow removed water from the soil, there was little or no removal of soil solids. In this experiment, van Helmont demonstrated empirically what Nicolaus of Cusa had described in a theoretical treatment in 1450. Both were focussed on the idea of the ancient Greeks that all life stemmed from water. In 1724, Stephen Hales took these experiments one stage further to distinguish between the weight of water lost from the soil during the growth of a sunflower plant (*Helianthus annuus*, L.) and the mass transpired (Hales, 1727). In contrast, de la Hire (in 1688) and Dalton (in 1796) filled

Correspondence: M. J. Goss. E-mail: mgoss@uoguelph.ca

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boxes with soil to establish the components of the hydrologic cycle (de la Hire, 1703; Dalton, 1802) and identify the links between rainfall, groundwater, springs and river flow. Both strands of research initially came together in the development of our understanding of evaporation from soil and from plant leaves, and the uptake of water by crops, the transpiration stream and the concept of water-use efficiency (Ehlers & Goss, 2003). Subsequently, interest has also focussed on the plant nutrients that enter the soil with precipitation and in organic or inorganic fertilizer, are formed by weathering of soil minerals or the activity of microbes, and can be lost in drainage water.

All the early experiments were carried out using soil that was packed into a vessel and then planted (or not) with woody or herbaceous species. Salisbury & Ross (1992) described this experimental set-up as a lysimeter approach. This paper charts the development of lysimeters and their role in the evolution of our understanding of the dynamics of water and nutrients in ecosystems.

Philippe de la Hire (1640–1718)

In the last quarter of the 17th century in France, the source of the water feeding rivers and streams became a contentious issue. Attempts were made to compare the weight of water reaching the land in rain and snow with the amount flowing away in rivers and streams (Dooge, 1974). To investigate this question de la Hire (1703) began an experiment in 1688, in which he constructed three cylindrical lysimeters with a surface area of 0.37 m^2, the first being about 2.44 m deep, the second 0.2 m deep, and the third 0.4 m deep. Each had a pipe set in the bottom, and was filled with a mix of sand and garden soil. The lysimeters were then set in the earth with the surface exposed to the weather. Even after 15 years *in situ*, de la Hire had not observed any water draining from the pipe of the deepest lysimeter, but although it took some 8 months exposure to rain and snow before the shallowest lysimeter began to drain, it then released some water after most rainfall events. Similar results were obtained with the 0.4 m lysimeter. However, when the latter was planted with herbaceous plants, there was no drainage and the rain was insufficient to prevent them from wilting.

Based on these experiments de la Hire, who is generally recognized as the instigator of the use of lysimeters for hydrological studies, concluded that rainfall was insufficient to contribute to the flows from natural springs. He also considered that plants squandered water under the influence of the sun and wind.

John Dalton (1766–1844)

Dalton's contribution was to clearly define the principal components of the hydrologic cycle and to quantify them. In the 100 years between the work of de la Hire and Dalton, there had been no resolution of the origin of springs, but the work of both Edmond Halley (1656–1742) and Stephen Hales (1677–1761) had established the importance of evaporation as a component of a distinct cycle, which linked snow, rain, rivers and oceans. Hales had also made an estimate of the addition of water to bare soil from dew. Halley had even provided an account of evaporation from an open pan of water as a measure of the maximum rate of evaporation from the land. Seasonal variability in evaporation had been recorded by Halley, who also attempted an estimate of the water balance for the Mediterranean basin. Nevertheless, Halley did not fully accept that precipitation was the sole source of water feeding rivers (Dooge, 1974). Rainfall records were increasingly available when Dalton began his investigations in the 1790s, and he understood the yearly as well as seasonal variability in precipitation. By that time, the flows of major rivers were also being measured routinely. The critical component was the evaporative return from the land to the atmosphere. It was to clarify this component that Dalton and his friend Thomas Hoyle built their lysimeter, starting in 1795. It consisted of a cylindrical vessel 0.25 m in diameter by 0.91 m deep. Two pipes led from the lysimeter: one 2.5 cm from the top and the other from near the base that was sealed with a metal plate. The tubes allowed drainage water to be collected in glass bottles. The base of the vessel was covered with a mix of sand and gravel and then the whole lysimeter was filled with fresh soil. The vessel was then placed in a hole dug in the ground and soil packed around it, except where access was needed to collect drainage water. The soil in the lysimeter was then saturated with water. In the early stages the level of the soil in the lysimeter was above the position of the upper drainage pipe, but thereafter natural consolidation meant that the pipe was too far above the soil surface to provide extensive data on surface runoff. For the first year the soil was kept bare but for the second 2 years it was covered with grass. The difference between the rainfall measured in an adjacent gauge and the drainage collected was assumed to be an estimate of the evaporative loss. Dalton recognized that by assuming that there was no change in water storage over the year, evaporation would be under-estimated in summer but over-estimated in autumn. In each year the rainfall exceeded the estimated evaporation from the lysimeter, and drainage ranged from 175 to 278 mm per annum. There was no clear difference in the estimate of evaporation from the lysimeter with a bare soil surface or one covered in grass (Dalton, 1802).

Based on Dalton's analysis we can write the equation for a regional water balance as:

$$\mathrm{r} + \mathrm{d} = \mathrm{Q} + \mathrm{E} + \Delta\mathrm{S} + \mathrm{B} \qquad (1)$$

where r is rain, d is dew, Q is river discharge, E is the evaporation, ΔS is the change in water stored, and B is the error in estimation; for Dalton's calculation this amounted to approximately −178 mm (7 inches) for the area of England

and Wales. Dalton (1802) suggested that his estimate of evaporation was the main source of error. In addition, drainage from the lysimeter was under-estimated because under fast flow conditions the collection bottles were seen to overflow, so the full weight of water leaving the lysimeter was not determined. He identified a number of contributions to the error in the evaporation value. Evaporation in Manchester, where the lysimeter was located, was greater than in other parts of the country because there was more rain. The lack of surface runoff during much of the experiment helped maintain the soil surface wetter than normal and that in turn would result in increased evaporation. This led Dalton to state: ‘Upon the whole then I think that we can finally conclude that the rain and dew of this country are equivalent to the quantity of water carried off by evaporation and by the rivers’. Dalton finally concluded that ‘The origin of springs may still therefore be attributed to rain, till some more decisive experiments appear to the contrary’ (Dalton, 1802).

Although not directly related to his lysimeter measurements, Dalton went on to develop an expression to describe the rate of evaporation, *E*, as a function of the temperature of the water and the vapour pressure of the atmosphere:

$$\mathrm{E} = \mathrm{c}(e^{*} - e) \tag{2}$$

where c is a factor depending on wind speed, e^* is the saturated vapour pressure at the temperature of the water and e is vapour pressure of the air over the period of observation.

John Lawes (1814–1900)

The first lysimeters built to retain the natural structure and profile of the soil were constructed at Rothamsted, England (1870). Lawes undertook their construction to determine the quantity and chemical quality of the deep drainage component of the water balance. Each of these ‘monolith’ lysimeters had a surface area equivalent to one thousandth of an acre (4 m^2), the first being 20 inches (0.51 m) deep, the second was 1.02 m and the third 1.53 m deep (Lawes *et al.*, 1881a). The soil was first isolated on the four vertical faces and then undermined and supported on perforated cast-iron plates strengthened with iron girders to allow the drainage water to be collected via a funnel, initially in glass vessels and subsequently by channelling it through a tipping-bucket arrangement. These drain-gauges were kept free of vegetation and the vertical isolation prevented runoff, such that

$$\mathrm{P} = \Delta\mathrm{S} + \mathrm{D} + \mathrm{E} \tag{3}$$

was close to zero on a long term annual basis where P is precipitation, D is drainage, E is the evaporation, and ΔS is the change in soil water content.

The drainage from the drain gauges ranged from 42.1% (deepest lysimeter) to 47.4% (1.02 m deep lysimeter) of the annual precipitation over the first 10 years from 1871 to 1880, with that from the shallow (0.5 m) lysimeter being similar to that of the deepest (Lawes *et al.*, 1881a). That means that evaporation from the bare soil was about 57% of rainfall. Later, Russell (1907) showed that the annual evaporation from the deepest of the lysimeters averaged 53% of rainfall over the first 35 years. Keen (1936) reported that the average value of drainage from the deepest lysimeter was close to 50%. Differences between the lysimeters changed over time with more evaporation taking place from the two shallower lysimeters after an initial period when it was less than that from the deepest one, which Russell (1907) argued was because of increasing continuity of porosity over time.

Keen (1936) described how information from the Rothamsted lysimeters (drain gauges) had contributed to an understanding of the movement of water through soil, the equilibration between infiltrating water and the water originally present, and the depth limitations for evaporation from different soil layers.

Further developments in construction and measurements

The first monolith lysimeters introduced into USA were constructed by Sturtevant starting in 1875 (Sturtevant, 1882). In 1888, Sanborn constructed three monolith lysimeters in Missouri. Each of them had a surface area of one hundredth of an acre (40.5 m^2) and was 1.2 m deep. Water was collected from the soil at the base of the lysimeters using tile drains connected to sealed pipes that discharged into barrels. Drainage was measured on the basis of the weight of water collected in a barrel over a period of time (Sanborn, 1889).

Improvements in technology allowed more exact assessment of changes in the water content of the lysimeter soil by weight. The first weighing lysimeter was constructed in Germany (von Seelhorst, 1902). The soil was packed in bins mounted on wheels and ran on rails that passed over a sensitive balance. Water could drain from the bottom of the bins via a pipe.

All these lysimeter constructions prevented surface runoff, although Ebermayer, working in Bavaria, Germany, suggested a different approach to lysimeter construction that was successfully implemented by Russian scientists (Kohnke *et al.*, 1940). Essentially, an area of land was undermined and a thin funnel-shaped pan inserted, which allowed drainage water arriving at that location to be collected. Surface runoff from the land could be collected in a separate system. Such lysimeters had no lateral boundary walls to encourage preferential vertical channelling of precipitation. The Ebermayer lysimeter installation at the New Jersey Agricultural Experimental Station (Joffe, 1929) collected water from below five horizons (two in the A, two in the B and one in the C horizon) and was the first major construction of this type in USA (Figure 1). This was the start of the use of pan lysimeters, which have been widely adopted for water quality studies (Soileau & Hauck, 1987).

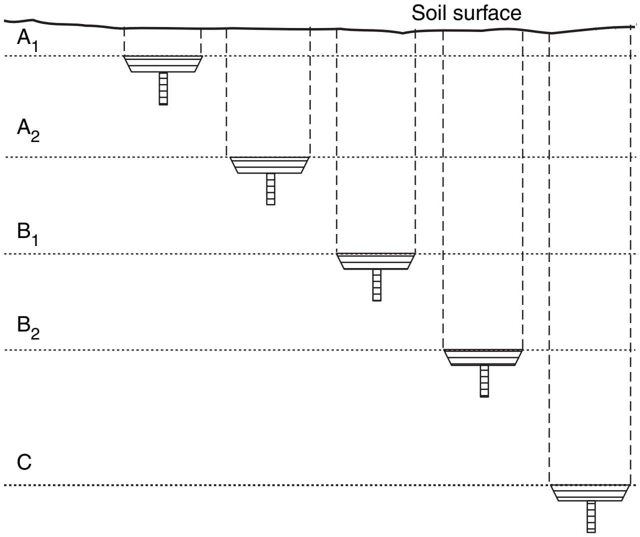

Figure 1 Diagramatic representation of the Ebermayer lysimeter installation established at the New Jersey Agricultural Experimental station. Based on Joffe, 1929. Each lysimeter consisted of a flat funnel 0.3 m in diameter and approximately 0.05 m in depth. The top of the funnel was closed with a perforated plate. The funnel was filled with quartz pebbles. The lysimeters were installed from a trench. They were forced along tunnels established at the interface between successive soil horizons (indicated by horizontal broken lines) and wedged upwards against the bottom of the overlying soil layer. The water entering each funnel is assumed to enter from the cylinder of soil extending from the perforated plate to the soil surface (vertical broken lines). A tube led from the funnel to a sample-collecting vessel.

Hydrologic studies

The lysimeter facilities at the North Appalachian Experimental Watershed, Coshocton, Ohio were built in 1937 and incorporated many of the essential features for studying the components of the soil water balance (Garstka, 1937; Riesbol & Sherman, 1938). Three batteries of lysimeters were constructed on three soils at different locations within the watershed. Each battery consisted of three lysimeters. A fourth unit was constructed at two of the locations to give a total of 11 lysimeters. Each of the lysimeters (Figure 2) had a surface area of 8.09 m^2 (4.26 m × 1.9 m) and was 2.4 m in depth. The lysimeters maintained the natural slope of the land (average slope on the lysimeters ranged from 6% to 23%) and at the lower end had equipment to collect surface runoff. Percolate sieves formed the base plate of the lysimeter and allowed collection of drainage water. Baffles inserted through the side walls prevented preferential flow at the lateral boundaries. One lysimeter at each of the three locations was set on a sensitive, self-recording weighing machine that cycled every 10 min. The area around each lysimeter formed a border area, but a 38 cm boundary zone could not be vegetated. At two sites the parent material was shale but the third site was sandstone. The plough layer in all lysimeters was a silt loam, but below that the B horizons varied from loam to silt loam or clay depending on the parent material. The lysimeters were cropped with maize (*Zea mays*, L.) in rotation with wheat (*Triticum aestivum*, L.) and pasture species, or only with pasture species.

Importantly, the role of condensation from the atmosphere in contributing to total water availability was highlighted together with the capturing of precipitation from small rainstorms of <1.5 mm that was not identified in rain gauges (Harrold & Dreibelbis, 1951, 1958). Subsequent investigations identified that the level of water addition through condensation was over-estimated because of grease seal used between the lysimeter wall and the retaining wall (Harrold & Dreibelbis, 1964). The full equation for the water balance, including dew, becomes:

$$\mathrm{P} + \mathrm{C} = \mathrm{R} + \Delta\mathrm{S} + \mathrm{D} + \mathrm{E} + \mathrm{I} + \mathrm{T} \tag{4}$$

where P is the total precipitation, C is dew and other condensation from the atmosphere, R is the part that runs off without entering the soil, ΔS is the change in water stored in the soil, D is the water draining out of the soil or is subject to deep seepage, E is the direct evaporation from the soil surface, I is the part of the precipitation intercepted and held on the stems and leaves of the plants, and T is that part of the precipitation that returns to the atmosphere through transpiration of the plants. These last three in combination (E, I, T, commonly just ET, evapotranspiration) comprised 80 to 90% of the water input through P and C (Harrold & Dreibelbis, 1951, 1958, 1967). The studies at Coshocton also showed the markedly later time of maximum soil water extraction under maize compared with wheat and pasture species (Harrold & Dreibelbis, 1951, 1958).

Results for the water balance from the Coshocton lysimeters were compared with those of an adjacent small watershed, and were found to be closely similar (Harrold & Dreibelbis, 1967). Most of the studies in North America used loamy or sandy soils, but there was considerable interest in clay soils in England and the Netherlands. The use of lysimeters of smaller surface area allowed the collection of soil monoliths that could be transported to a central facility, where the weather variables are the same, thereby permitting greater insight into how the water balance changes over time in different soils.

At Letcombe Laboratory, Oxfordshire, UK, a lysimeter installation was established in 1973 that allowed a comparison of monoliths from a coarse textured soil and a clay soil (Belford, 1979). The monoliths had a surface area of approximately 0.5 m^2 (0.79 m diameter) and a depth of 1.35 m. The hydrology of the clay monoliths was made similar to that of the field from where the soil was collected, by including a subsoil drain in the lysimeters at the same depth as the mole drains in the field. Under these conditions, aeration of the soil in the clay lysimeters was shown to match that in the

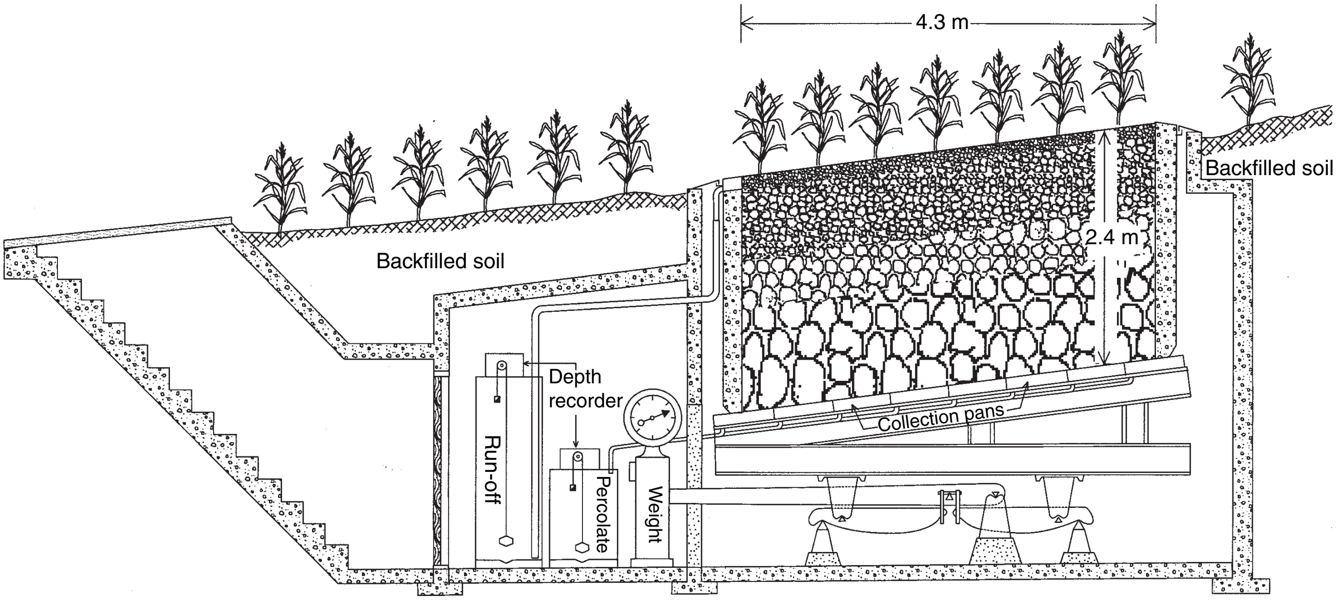

Figure 2 Weighing lysimeter construction used at the North Appalachian Experimental Watershed, Coshocton, Ohio. Construction of the facility with 11 lysimeters in all was carried out in 1937. Note the natural slope of the land was maintained in the containment of the monolith lysimeter. Run-off from the soil surface and deep drainage (Percolate) were collected separately. (Diagram courtesy of Dr Martin Shipitalo, USDA. ARS, North Appalachian Experimental Watershed, Coshocton, OH, USA).

field (Belford, 1979). Water content of the soils was determined using neutron scatter. Drainage water was collected from the bottom of the lysimeters through a steel base that contained either gravel (clay soil) or fine sand for support. Ceramic tension candles could be inserted into the supporting sand to provide appropriate potential gradients in free-draining coarse-textured soil. Water table height in the clay soil could be maintained by setting the position of an outlet tube from the steel base. An important finding from these studies was that for autumn-sown crops, providing sufficient drainage to prevent the water table from encroaching into the top 0.5 m of soil for extended periods was sufficient to ensure optimum yields (Belford, 1981). Importantly, the impact of waterlogging in the cool winter months was much less than in the warmer parts of the year because the rate at which the oxygen levels in the soil declined was temperature dependant (Cannell *et al*., 1985).

All the lysimeter installations described above have the limitation that agronomic activities associated with soil management (tillage), sowing, crop protection, harvesting, residue management or manure management are limited to hand operations. Also, the depth of root development could be restricted artificially by constraints to the size of the lysimeters. In 1978, a large-scale field lysimeter installation was established in a deep clay soil at a field site of Letcombe Laboratory near Faringdon, Oxfordshire, UK (Cannell *et al*., 1984). The facility, operated jointly with the Field Drainage Unit of the Ministry of Agriculture, Fisheries and Food, consisted of 20 hydrologically isolated plots (lysimeters), each 0.25 ha in area. The plots were arranged in a field of more or less uniform 2% slope, such that lateral movement between lysimeters was constrained by heavy-duty polythene curtains inserted to a depth of 1.3 m (Figure 3). Movement down the slope from lysimeter to lysimeter was prevented by gravel-filled trenches with a perforated collection drain at 1 m. Drainage water was collected from within half the plots using mole drains, which were drawn downslope at a depth of 0.6 m and discharged into a pipe drain system. These pipe drains were set at 0.9 m depth and had a fill of gravel to a depth of 0.5 m. The remaining plots had only the pipe drain at 0.9 m for the collection of deep drainage. The mole channels were drawn into the gravel fill. Surface runoff down slope was intercepted by plastic guttering sunk just below the soil surface at the lower end of a lysimeter. Water flowing downslope in the Ap horizon over the interface with the B horizon (interflow) was intercepted in a further perforated pipe drain set at 0.35 m depth and located in a plastic-lined trench with gravel to 0.2 m (Figure 3).

Surface runoff, interflow, and drainage were delivered to automatically recording v-notch weirs through sealed pipes and were sampled for nutrient analysis. Water content was determined regularly using neutron scatter. Soil water potential profiles were determined to a depth of 2 m using banks of tensiometers (Howse & Goss, 1982). A bank of piezometers allowed the depth of the water table to be determined together with the saturated hydraulic conductivity (Goss & Youngs, 1983; Youngs & Goss, 1988).

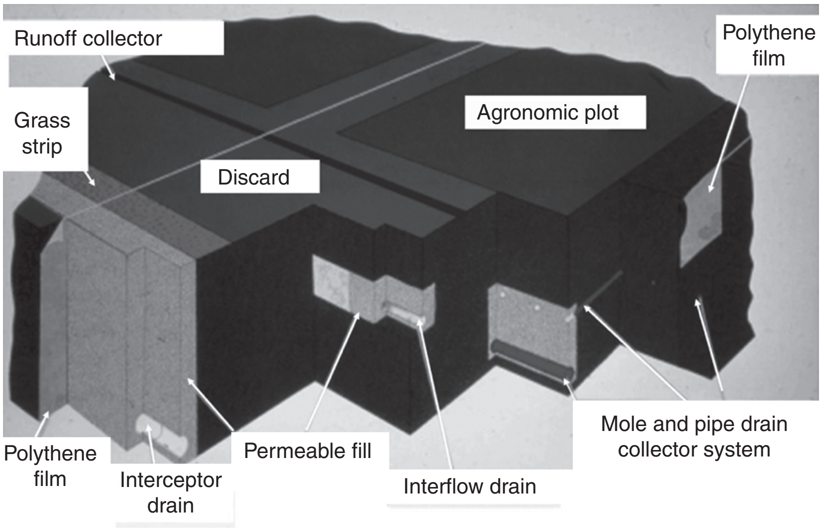

Figure 3 Field lysimeters construction at Letcombe Laboratory, Oxford, UK in 1988. The Polythene film ‘curtains’ were aligned perpendicular to the slope to prevent lateral flow of water between adjacent lysimeters. The interceptor drain with its gravel backfill prevented surface water and percolation, because of precipitation falling downslope of the collector systems, from passing from one lysimeter to the next one down the slope. Water from the mole and pipe drain collectors, the interflow drain collectors and the surface runoff collectors were transferred in closed pipes to ‘Vnotch’ weirs for flow rate determination. Automated samplers drew aliquots of the drainage into bottles that were transferred to the laboratory for nutrient analysis.

In calculating the water balance for each lysimeter, soil evaporation, interception on the plant canopy and transpiration from the leaves were combined as evapotranspiration. The budget based on the components measured was given by:

$$P = R + D + F_i + \Delta S + ET \qquad (5)$$

where P is total precipitation, R is surface runoff, D is deep drainage, F_i is interflow, ΔS is change in soil storage, and ET is evapotranspiration.

Surface runoff from the lysimeters varied between 2% and 6% of total precipitation, compared with 3-7% in interflow from November to March. Some 66% of the precipitation was intercepted by the mole and pipe-drain system in the same period (Table 1). In the spring and summer, a greater volume of water was extracted by wheat crops from lysimeters where the mole drains removed water from the top 0.5 m during the autumn and winter months (Goss *et al.*, 1984).

Evaporation and transpiration

Early lysimeter studies did not attempt to differentiate between evaporation from the soil and the water moving from the soil to the atmosphere via the plant transpiration stream. Quantifying the volume of water required by a growing plant in reaching a mature reproductive weight is important in determining our ability to grow crops in an arid environment. The first systematic investigation of the water requirements of maize took place at the Agricultural Experimental Station of Nebraska (Montgomery & Kiesselbach, 1912). Water use by different crops was studied by Briggs and Shantz at Akron, Colorado, USA, between 1911 and 1913 (Briggs & Shantz, 1914). Essentially the experimental approach used in the two studies was the same. Lysimeters consisted of large cans containing soil, and were fitted with a tight-fitting cover, which had sealed openings for the stems of plants. Drainage and direct evaporation from the soil surface being precluded, transpiration was the main pathway

Table 1 Average values for the components of the soil water balance in the Letcombe Laboratory field lysimeters for the first 2 years (1978-80: based on Harris *et al.* (1984) and Goss *et al.* (1984)

				Evapotranspiration (mm)	
Season	Precipitation (mm)	Surface runoff and interflow (mm)	Deep drainage (mm)	From Equation (5)	Potential (Penman)
Winter (November –March)	290	20	191	79	93
Spring–Fall (April–October)	410	0	0	410	483

of water removal. The water used by the plants was determined by weighing the lysimeters.

These studies showed that water use varied on a daily as well as on an annual basis, but there was a clear connection with variation in the intensity of solar radiation (Briggs & Shantz, 1914), air temperature, humidity and wind velocity (Montgomery & Kiesselbach, 1912). Optimum dry-matter production was associated with plants maintained in moist soil, where water requirement per unit of dry weight produced (WR) was least. However, WR did not vary greatly for plants growing in conditions of deficiency or sufficiency. Water use was linked to leaf area rather than to plant dry weight, and also to the loss of water from a free water surface (Montgomery & Kiesselbach, 1912; Briggs & Shantz, 1914).

Briggs & Shantz (1913) reviewed one experiment of Montgomery & Kiesselbach (1912), where WR was determined for maize grown under very humid or dry conditions, and deduced that the water use per unit of dry matter produced depended on the saturation deficit of the atmosphere (Table 2). Results from a comparison of the Rothamsted lysimeters with the water balance under cropped land (Keen, 1936), together with work in the Coshocton lysimeters (Harrold & Dreibelbis, 1967) established that in many situations total evapotranspiration was dependent on plant rooting depth.

de Wit (1958) published a comprehensive literature investigation of transpiration and crop yield. The linkage between WR and open pan evaporation in the experiments reported by Briggs & Shantz (1913) was further explored. The error in estimating WR was relatively large, encouraging de Wit to consider the components of WR. The dry matter production was therefore considered in terms of the transpiration as a proportion of open pan evaporation.

The resulting linear regression has the form:

$$\mathrm{P} = \mathrm{m_c} T/E_o \tag{6}$$

where P is dry matter produced to harvest, T is the mass of water transpired, E_0 is the open pan evaporation over the same period, and $\mathrm{m_c}$ is a constant that varies only with crop species. de Wit suggested that this relationship held until the value of T approached a maximum value determined by the growing conditions.

Table 2 Water requirement of maize (*Zea mays* L.) and the relative significance of comparisons with ‘open-pan’ evaporation and mean saturation deficit: based on Montgomery & Kiesselbach (1912), Briggs & Shantz (1913) and Tanner & Sinclair (1983)

	Humid atmosphere	Dry atmosphere	Ratio humid: dry
Water requirement - WR - ($\mathrm{gH_2O/g}$ dm)	214	340	0.63
Open pan evaporation - E_0-(mm)	94	168	0.56
WR/E_0	2.3	3.7	0.62
Saturation deficit-SD- of atmosphere (kPa)	1.9	3.1	0.61
WR/SD	112	109	1.03

WR, weight produced; E_0, open pan evaporation.

In humid conditions with no water limitations the equation reduced to:

$$\mathrm{P} = \mathrm{n}T \tag{7}$$

where n is a constant for a plant species.

The link between WR and saturation deficit noted by Briggs & Shantz (1913) was considered by Arkley (1963). Using the saturation deficit as a weighting parameter for T produced a family of curves segregated by mean temperature. However, when the transpiration efficiency (P/T), the inverse ratio of WR, was considered data coalesced about a single line given by:

$$\mathrm{P}/T = \alpha[e^*/(e^* - e)] \tag{8}$$

where α is a constant, e^* is the saturation vapour pressure at the mean temperature of the atmosphere, and e is the actual vapour pressure.

Working from a process-based approach, Bierhuizen & Slatyer (1965) concluded that the equation most appropriate for describing the relationship between transpiration efficiency and saturation deficit was:

$$\mathrm{P}/T = \mathrm{k}/(e^* - e). \tag{9}$$

For more details see Ehlers & Goss (2003).

Evaporative water loss from most lysimeters is a combination of transpiration from the plants and evaporation from the soil surface. The use of covers with sealed collars that fit around plants after establishment has allowed transpiration to be determined directly. Short mini-lysimeters were developed by Boast & Robertson (1982) that can be used to determine soil evaporation under the plant canopy (Klocke *et al.*, 1990). Evapotranspiration can be obtained from measuring total water loss in the absence of drainage, and subtracting a separately determined value of soil evaporation allows the transpiration loss to be calculated. A plot of dry matter production against evapotranspiration also permits the estimation of cumulative soil evaporation in the presence of plants from the intercept on the horizontal axis (Hanks & Rasmussen, 1982) (see Figure 4 for example). Ritchie (1983) suggested that the evapotranspiration intercept indicates soil evaporation during the early part of the growing season, when the leaf area index is < 1. The slope of the regression of dry matter on cumulative evapotranspiration is the transpiration efficiency, being 0.00893 kg/L $\mathrm{H_2O}$ for the forage maize shown in Figure 4 (Mundel, 1992). The reciprocal of this relationship is the transpiration ratio, and for this forage corn crop it is 112 L $\mathrm{H_2O}$/kg dry matter. On the field scale lysimeters of Letcombe Laboratory, Goss *et al.* (1984) reported water use efficiencies for winter wheat of 0.0052 kg/L $\mathrm{H_2O}$.

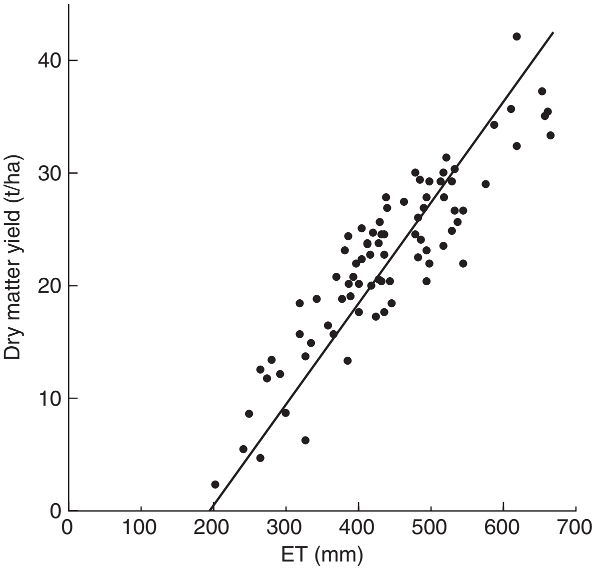

Figure 4 Relationship between cumulative evapotranspiration (ET) and dry matter yield of forage maize (*Zea mays*, L.) grown on lysimeters in north-east Germany (based on Mundel, 1992). The intercept on the ET axis (194 mm) is considered to indicate the cumulative soil evaporation.

The lysimeters at Coshocton, Ohio, provided information on the water use efficiency of different crops in terms of the weight of dry matter produced per unit of water used in evapotranspiration. An important conclusion was that the depth of rooting was important for the magnitude of the evapotranspiration loss and hence also for the amount of water available to be lost in drainage.

Lysimeters have been used extensively to determine crop coefficients of water use, particularly the evapotranspiration relative to a reference crop, or a valid model of a reference crop, or to a standard device for measuring evaporation, such as an open pan of water (Pruitt, 1991; Wright, 1991). In all cases, a key issue is how well the growth and water dynamics associated with the crop in the lysimeter installation accord with that of a crop in the field (Allen *et al.*, 1991). In semiarid conditions the major soil factors that affect this are the surface wetness of the soil and the available water remaining in the profile confined in the lysimeter (Wright, 1991), especially if the confined soil only drains if a water table exists at the base (Allen *et al.*, 1991).

Nutrient dynamics and water quality

Early investigations into the mass of plant nutrients removed in drainage water involved the use of filled lysimeters studies in the laboratory (Way, 1850). Lawes *et al.* (1881b) recognized that the profile integrity was important for the infiltration of precipitation and the mobilizing of nutrients from the soil and the exchange of those present in rainfall. This early work helped lay the foundation of cation exchange properties of clays and soil organic matter.

In analyzing results of the chemical composition of the water draining from the Rothamsted drain gauges, Lawes *et al.* (1881b) divided the drainage year into the period from October to March (winter) and April to September (summer). Drainage was 62% of rainfall over winter but only 27% in summer. The greatest removal of plant nutrients was associated with the period of greatest flow. Over the period May 1877–April 1881, the average content of nitrate in the leachate from the 1.02 m deep lysimeter was 22 kg/ha in winter and 14.1 kg/ha in the remainder of the year. At Rothamsted, and at Coshocton the nitrate leached was accompanied mainly by calcium (Lawes *et al.*, 1881b; Harrold & Dreibelbis, 1967). At Craibstone near Aberdeen, Scotland, Hendrick (1921) built three lysimeters similar in construction to those at Rothamsted. Each lysimeter was 1 m in depth and had a surface area of 4 m^2. The soil, of glacial origin, was acidic and contained no free calcium carbonate. Although the main cation leaching with nitrate at both Craibstone and at Coshocton (Ohio) was calcium, significant losses of potassium, magnesium and sodium were identified (Hendrick, 1930; Harrold & Dreibelbis, 1967).

In the field-scale clay soil lysimeters of Letcombe Laboratory, the weight of nitrate-N leached was directly related to the volume of drainage water (Goss *et al.*, 1998). Similar results were reported by Kolenbrander (1981). However, the exact relationship depended on a number of factors. The mass of N in the soil is critical, and this depends on how much has been added as fertilizer or is mineralized from organic matter (Goss *et al.*, 1993; Juergens-Gschwind, 1989), and what has been removed in uptake by the crop (Juergens-Gschwind, 1989; Goss *et al.*, 1993, 1998). Consequently more N is leached from uncropped soil than under a crop (Joachim, 1928; Hendrick, 1930; Kolenbrander, 1981; Juergens-Gschwind, 1989; Goss *et al.*, 1998). Some crops leave more N in the roots and in above-ground harvest residues than others, so that more N is available for leaching from under residues of winter oil-seed rape (*Brassica napus*, L.) than from under those of winter wheat (Goss *et al.*, 1998). Perennial grasses grow for more months of the year than do most small-grained cereals. As a result they take up N from the soil for a greater proportion of the period when N is being mineralized. In addition, perennial grasses use more water than annual crops, which also tends to reduce the amount of N leached (Juergens-Gschwind, 1989). This increased water use by perennial crops relative to annual crops has been called 'enhanced evapotranspiration' (Juergens-Gschwind, 1989), although the explanation is that perennials have a greater leaf area index at the start of the growing season and a longer green-leaf-area duration. The mass of N leached tends to be least for grass, especially unfertilized grass, than from other crops (Hendrick, 1930; Harrold & Dreibelbis, 1967; Goss *et al*., 1998). The final factor is the structure of the soil (Soileau & Hauck, 1987; Juergens-Gschwind, 1989). This can be the reason for greater N loss by leaching from ploughed land than from soil under no-till (e.g. Goss *et al*., 1993). The greater preponderance of vertical pores and channels in untilled land compared with ploughed soil allowed water to bypass much of the soil and thereby not mix with the water in the soil matrix. Tillage impacts could largely be explained on the basis of the reduction in preferential flow. In the autumn and winter months, nitrate in the soil came mainly from the mineralization of soil organic matter. The bypass or preferential flow in the no-till soil would conserve N in the finer pores of the matrix, whereas in the ploughed land the infiltrating water tended to drive nitrate-rich water from the pores of the matrix downwards by piston displacement. More than 100 years earlier Lawes *et al*. (1881b) had recognized the role of earthworm and root channels in moderating the concentration of nitrate in drainage water. It is important to note that in the spring the effect of macropore flow can be the reverse of that in the autumn. If nitrogen fertilizer is surface-applied in spring or summer, the preferential channels in the no-till soil can allow nitrate-rich water to permeate rapidly to depths below the rooting zone (Tyler & Thomas, 1977; Goss *et al*., 1993). This phenomenon is particularly evident when intense rainfall causes water to pond at the surface.

Conclusions

From their inception lysimeters have allowed the role of the plant in the local hydrological balance to be investigated and established. At the same time, the lysimeter has been a powerful tool in developing a greater understanding of the components of the soil water balance and to allow a detailed quantitative assessment. This has allowed key crop parameters to be developed that can improve the effectiveness of water use under semi arid climates. The ability to integrate information obtained at different levels of investigation, both in terms of scale and intensity, has resulted in more holistic understanding of soil water dynamics. Lysimeters have allowed the quality of water draining from agricultural land to be determined, and, as exemplified by information from plant nutrient studies, the role of management practices to be evaluated. Leaching loss of nitrate has been shown to vary greatly under different crops, but was much less under perennial grasses with little or no fertilizer than under intensively managed arable crops or from bare soil.

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