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Design, Construction, and Field Evaluation of a Lysimeter System for Determining Turfgrass Water Use

Benjamin Wherley[1], Thomas Sinclair[1*], Michael Dukes[2], and Grady Miller[3]

[1] *University of Florida, Agronomy, IFAS Building 350, P.O. Box 110965, 2005 SW 23 Street, Gainesville, FL 32611-0965*

[2] *University of Florida, Agricultural and Biological Engineering, 107 Frazier Rogers Hall, P.O. Box 110570 , Gainesville, FL 32611*

[3] *North Carolina State University, Crop Science, Campus Box 7620 , Raleigh, NC 27695*

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Lysimeters are often used in turfgrass and plant water-use studies; however, no detailed description exists for a lysimeter system of moderate volume allowing for rapid, direct measurement of evapotranspiration on a number of replicates. A lysimeter was developed using 250-mm diameter and 330-mm long polyvinyl chloride piping resulting in a lysimeter volume of 15.5 L. These lysimeters were installed in the field by constructing a plastic soil-retention sleeve that was placed in the soil. The sleeve was matched to the lysimeter diameter so that there was only a 6-mm air gap between the lysimeter and the sleeve. After turf had filled in around lysimeter edges, there was no detectable difference in measured soil temperatures between lysimeters and surrounding plots at the 15-cm depth; however, volumetric soil moisture content of lysimeters was ~3% higher than that of surrounding soil. The lysimeter was weighed in the field by positioning a tripod hoist over the lysimeter. A load cell was installed in the hoist cable assembly so that when the lysimeter was lifted free of the soil-retention sleeve the weight of the lysimeter could be recorded. The system was shown to provide highly reproducible weight measurement data based on paired *t*-test analysis of repeated weighing data.

Population growth and water concerns are creating an increased need to better understand water use by all plants, including turfgrasses. Lysimeters, which are often used in water-use studies, are containers of soil representing the field environment used to determine the evapotranspiration (ET) of a growing crop or evaporation from bare soil (Aboukhaled et al., 1982). ET can be estimated using lysimeters, which allow for direct calculation of mass changes due to plant water loss and soil evaporation (Young et al., 1997). A wide range of lysimeters have been documented in the literature, however there is currently no standard for lysimeter design in turfgrass studies, and consequently, a wide variety of styles and sizes have been used (Bremer, 2003). Lysimeters may be round, square or rectangular, constructed from concrete, steel, fiberglass or plastic, and range in size from 0.05 m to 2 m in diameter and from 0.4 to 2-m deep (Winton and Weber, 1996).

With regard to turfgrass ET studies, lysimeter volumes ranging from as small as 1.5 L (DaCosta and Huang, 2006) to as large as 20,000 L (Young et al., 1996) have been used. Although a smaller lysimeter volume allows for greater ease of handling, replication, and ease of repeated measurements, numerous studies involving a range of species have shown decreased growth and/or water use can occur when plants are grown in too limiting soil volume (Peterson et al., 1984; Robbins and Pharr, 1988; Townend and Dickinson, 1995; Ray and Sinclair, 1998). Conversely, while very large lysimeter volumes allow for maximal rooting, units cannot be easily weighed and ET is usually estimated indirectly from water balance techniques (Biran et al., 1981; Kneebone and Pepper, 1984; Devitt et al., 1992). Furthermore, the number of replicates that can be easily measured is drastically reduced in studies utilizing large lysimeters (Devitt et al., 1992; Young et al., 1996).

Consequently, a vast number of turfgrass researchers have settled on lysimeters ranging in volume from 6 to 12 L (Aronson et al., 1987; Beard et al., 1992; Feldhake et al., 1983, 1984; Johns et al., 1983; Kim and Beard, 1988; Qian et al., 1996; Rogowski and Jacoby, 1977; Salaiz et al., 1991), because units of this size can be repeatedly lifted from the soil. While not always explicitly detailed, weighing events in these studies typically entail manually lifting units up out of the ground and onto portable scales, or even transporting units to a central location for weighing (Feldhake et al., 1983).

The objective of this research was to design and construct an inexpensive lysimeter/weighing system that would be an improvement over past approaches with regard to rooting volume, construction, and weighing technique. We believe the system described here is an improvement over the existing versions reported in the literature because 1) the lysimeters provide greater rooting volume than what has generally been provided in past studies; 2) the relatively low cost of materials allows a significant number of replicates to be installed in the field; and 3) the lysimeters can be easily and rapidly weighed by one person in the field (48 measurements in under 3 h) using a portable tripod and load cell that eliminates the difficulties associated with manually lifting and transporting units to a central location for weighing. It was also of interest to determine whether these lysimeters would produce an environment representative of the soil in ambient plots with respect to soil temperature and volumetric water content.

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*Corresponding author; email: trsinc@ufl.edu; phone: (352) 392-6180

Materials and Methods

Various materials were considered in designing a lysimeter that would meet our research goals. However, due to the frequent removal from the ground and the need to fabricate a sleeve to maintain a vertical soil wall around the lysimeter, a smooth-sided lysimeter was needed, and polyvinyl chloride (PVC) pipe was chosen.

Final cost for the lysimeter and sleeve design was considered during the prototype stage. Due to the number of lysimeters needed and minimum sizes of available stock materials, many of the stock materials (PVC pipe, foam board, buckets, metal rods, etc) were purchased as a large unit size or in bulk quantities. Based on the final lysimeter design and materials cost at the time of purchase, the cost per lysimeter was approximately $21. A breakdown of materials and cost for the lysimeter, outside sleeve, and weighing apparatus are presented in Table 1.

Lysimeter construction

Lysimeters were constructed of PVC pipe and foam board. Schedule 40 PVC of 254-mm (10 inches) inside diameter was purchased in standard 6.1 m (20 ft) lengths. The pipe was cut with either a hand-held circular saw with a high-tooth-count blade or with an industrial band saw with gates to hold the PVC square (preferred method). The pipe was cut to 330 mm (13 inches) lengths to allow adequate room to insert steel rods to support the bottom plate such that the resulting interior depth was 305 mm (12 inches) (Fig. 1).

To make the lysimeter bottom, 6-mm-thick, rigid PVC foam board was cut using a router or jigsaw after careful measurement using the inside edge of the lysimeter. A router is ideal, as after a template is made with the jigsaw, additional bottoms can be produced rapidly using a router with a flute bit with bearing. Four 17.5 mm (11/16 in) drain holes were drilled in each foam board bottom. These were laid out equally from the center point. The 12.7 mm (1/2 in)-14 NPT (National Pipe Thread) tap was used to thread these holes to accept 12.7 mm (1/2 in) PVC plugs. Four 12.7 mm (1/2 in) plugs were installed.

Table 1. Components and approximate cost of materials used in construction of a single lysimeter, outside sleeve, and cost of items for weighing apparatus.

Components	Quantity	Cost
Lysimeter materials		$21
10-inch I.D.[z] × 13-inch-long PVC pipe	1	
10-inch diameter × 6-mm rigid PVC foam board	1	
½-inch PVC threaded plugs	4	
¼-inch × 10¾-inch steel round stock	1	
¼-inch × 2¼-inch steel round stock	6	
4-mm × 9-inch utility cord	3	
Caulk tube (silicon based)	1	
10-inch-diameter round landscape fabric (DuPont geotextile)	1	
Outside sleeve		$5
5-gal bucket (7 needed to make 6 sleeves)	1	
1/8-inch pop rivets	8	
Weighing apparatus		
Game hoist tripod (Cabela's Inc., Sidney, NE)	1	$135
Load cell (Central Carolina Scale, Sanford, NC)	1	$625
Carabineers	3	$20

[z] I.D. = inner diameter; PVC = polyvinyl chloride.

The foam board bottom was placed into the PVC pipe, resting on steel rod supports (Fig. 1). The steel rods were inserted in the wall of the pipe. Eight 6.4-mm (1/4 inch) holes, centered 16 mm (5/8 inch) above the bottom edge, were drilled around the bottom edge of PVC tube. Two of these holes were drilled directly across from one another. A 6.4 × 273 mm (1/4 × 10 ¾ inch) steel rod was placed into these two opposing holes. The remaining six holes were spaced evenly, three on each side of the steel rod that divided the diameter of the pipe in half. The 6.4 x 57 mm (1/4 × 2¼ inches) steel rod pieces were placed in these six holes, such that they were flush with the outside surface of the PVC pipe. Once the foam board was placed in the PVC pipe the interior seam was sealed with silicone based caulk. A single layer of landscape fabric was cut to fit the inside diameter of PVC pipe and placed inside the lysimeter to prevent soil from exiting the drainage holes in the foam board bottom.

Three 6.4-mm (1/4 inch) holes centered 9.5 mm (3/8 inch) below the top edge were drilled around the top edge of PVC tube, evenly spaced around the diameter of the tube (Fig. 1). Braided reinforced nylon cord (4-mm diameter) was threaded through each hole with an overhand knot tied on the inside and a bowline knot tied on the outside of the lysimeter to allow it to be hooked to a carabiner. The carabiner served as the attachment point for lifting the lysimeters out of the ground. After subsequent field testing, some cord attachments in the lysimeters were removed. In place of the rope, steel hooks were made for attaching to the lysimeter via the drilled holes. These hooks were made from the bucket handles that were removed from the 18.9 L (5 gal) buckets used for the outer sleeves. The 'hooked' end works well for attaching to the holes on the lysimeter. These handles were cut at the straight end and curved with pliers to form a closed end.

Outer sleeve construction

The outer sleeve was constructed using a typical 18.9 L (5 gal) paint bucket with the bottom cut out. The bucket was modified, as the original inside diameter is less than the outside diameter of the lysimeter. Expansion of the bucket was accomplished by pulling the handle out of the bucket and slicing the bucket from top to bottom using a circular saw. Using a router with a flute bit with bearing, the bottoms were cut out of the buckets (a PVC handsaw can also be used).

An additional 140 mm (5½ inch) wide vertical bucket slice was required to expand the diameter of the outer sleeve bucket. This piece was riveted onto the outside of the outer sleeve bucket

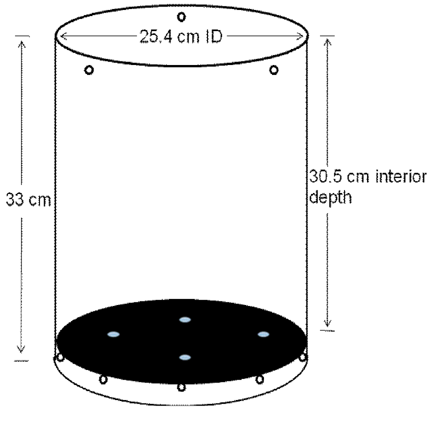

Fig. 1. Diagram of lysimeter cylinder without the exterior sleeve.

to create an inside diameter that allowed for a 6-mm (1/4 inch) gap between the lysimeter and outer sleeve. The inside diameter of the outer bucket was between 279 and 283 mm (11 and 11 1/8 inches). This measurement should be taken on the bottom of the bucket, which will ultimately be the top when the sleeve is put in the ground. Before riveting the slice onto the outer sleeve bucket, the protruding rings from the slice added to the bucket were removed using a PVC handsaw. Using spring clamps, the slice was clamped onto the outer sleeve bucket, taking care to achieve the proper inside diameter measurement. Four holes were drilled through both layers on both sides before installing 3.2 mm (1/8 inch) pop rivets. The bottom portion of the paint bucket becomes the top of the outer sleeve.

Field installation

Depending on soil type, a two-man auger or tractor-mounted auger may be used to prepare a hole for the lysimeter plus outer sleeve. For our testing, sod placed in the lysimeters was removed from the exact spot for the lysimeter before the hole was augured. A piece of 25-cm (10 inches) PVC cut to a length of 15 cm (6 inches) was used to extract the sod, so that it fit in the lysimeter. A beveled edge was ground on this piece of PVC using a hand grinder to allow for easier insertion. Using a piece of wood and a mallet, the PVC was driven into the ground to cut the sod. The soil below the extracted sod was removed to form a hole to insert the lysimeter sleeve. The auger hole was approximately 30 cm (12 inches) in diameter and about 38-cm (15 inches) deep (depth of the outer sleeve's length). This depth allowed for a base of rock (8- to 25-mm diameter) under the lysimeter facilitating water percolation below the lyimeter. Once the hole was dug, the outer sleeve was installed with the protruding rings on the bottom. Any gaps in the soil were backfilled around the sleeve with native soil from the site. Rock (8 to 16-mm diameter) was placed at the bottom inside the lysimeter on top of the geotextile fabric to facilitating drainage from the lysimeter. The lysimeters were filled with desired soil a few centimeters at a time and lightly tamped. After filling, the sod removed from the site was added as the top layer in the lysimeter at the appropriate level. The lysimeter was inserted into the sleeve and its height was adjusted by adding or removing gravel at the bottom of the hole so that it was flush with the surrounding turfgrass. If settling in the hole was experienced later on, it was easily corrected by adding gravel.

Lifting and weighing lysimeters

A commercially produced deer hoist (Cabela's Inc, Sidney, NE) was purchased to serve as a tripod to aid in removing the lysimeters during weighing events (Fig. 2). The hoist comes fitted with a crank and cable to raise and lower the lysimeter. A battery-powered load cell (CAS S-Beam, NTEP CoC 96-073A1, Central Carolina Scale, Sanford NC) connecting the hoist cable to the lysimeter was used to weigh the lysimeters. The load cell had a resolution of 5 g, which resulted in a resolution of 0.1 mm water loss for these lysimeters. The S-shaped load cell was attached to the lysimeter via a 3-point rope hitch. The load cell was also connected to a battery-powered digital indicator (Salter 200 SL, Central Carolina Scale). When a lysimeter was to be weighed, the hoist with the load cell was centered over the lysimeter. Three carabiners attached to the hitch allowed for quick connect-disconnects to the lysimeter. A shield to deflect wind was fitted around the hoist legs to minimize wind interference but the shield was generally unnecessary.

Results and Discussion

Uniformity of soil conditions: Lysimeters vs. ambient soil

One of the objectives of this project was to design a system that produced a minimal air gap between the lysimeters and plastic sleeves which lined surrounding soil, thus reducing the potential for variation in temperatures between lysimeters and ambient soils. In readings obtained 3 weeks after installation as well as more recently, soil temperatures (at the 15-cm depth) did not significantly differ between lysimeters and ambient soil (Table 2). Two factors likely contributed to this. First, care was taken to ensure that holes into which lysimeters were installed were only large enough for outer sleeves to fit into, minimizing the amount of bare soil between the lysimeter and surrounding

Fig. 2. Photograph of tripod placement, hoist, load cell, harness, lysimeter, and output display.

Table 2. Soil temperatures (°C) at 15-cm depth within lysimeters and ambient soil from immediate plots for three dates during the 2008 season. There were no significant differences within species × sampling date based on ANOVA at $\alpha = 0.05$ (n=12).

		3 Apr.	9 Apr.	18 July
Species a	Lysimeter	23.0	21.9	30.3
	Ambient	23.2	22.1	30.3
Species b	Lysimeter	22.0	21.2	29.7
	Ambient	22.0	21.1	29.7
Species c	Lysimeter	21.7	21.0	29.2
	Ambient	21.6	21.0	29.1
Species d	Lysimeter	22.0	21.5	29.6
	Ambient	21.9	21.7	29.5
Combined	Lysimeter	22.2	21.4	29.7
	Ambient	22.2	21.5	29.6

turf immediately following installation. Furthermore, the design, which utilizes a sleeve that has an inner diameter similar to the outer diameter of the lysimeter, left only a 6-mm (1/4 inch) air gap between the lysimeter wall and outer sleeve, further minimizing the likelihood of preferential warming or cooling.

Volumetric water content (VWC) of soil was also monitored in lysimeters and ambient plots using time domain reflectrometry (Field Scout TDR 300, Spectrum Technologies, Plainfield, IL). Readings, obtained from the 0- to 20-cm depth 24 h following rainfall or irrigation, revealed significant differences in VWC between lysimeters and ambient soil. On average, VWC of lysimeter soils was approximately 0.03 $m^3 \cdot m^{-3}$ higher than ambient soils (Table 3). This has actually been beneficial in the current project because well-watered treatments are required and drainage holes are sealed.

Table 3. Water content ($m^3 \cdot m^{-3}$ soil) of lysimeters and ambient soil from immediate plots for four turfgrass species over three dates during the 2008 season. Measurements were obtained for the 0–25 cm depth using a time domain reflectometry probe.

		3 Apr.	9 Apr.	18 July
Species a	Lysimeter	0.11	0.12*[z]	0.15*
	Ambient	0.09	0.10	0.11
Species b	Lysimeter	0.12*	0.14	0.14*
	Ambient	0.09	0.10	0.11
Species c	Lysimeter	0.13*	0.14*	0.16*
	Ambient	0.10	0.10	0.12
Species d	Lysimeter	0.10*	0.11*	0.14*
	Ambient	0.08	0.08	0.11
Combined	Lysimeter	0.11*	0.13*	0.15*
	Ambient	0.09	0.09	0.11

[z] Asterisks denote significant differences within species × sampling date based on ANOVA at $\alpha = 0.05$ (n=12).

Repeatability of lysimeter weight measurements

There was concern that due to the large total mass of the lysimeters combined with the experimental error from using the load cell, that measurement sensitivity would not be sufficient to produce reproducible results. To test the system a study was performed at North Carolina State University Turfgrass Field Research Laboratory, Raleigh, NC, to analyze the reproducibility of the system for measuring lysimeter weights. Eighteen field-installed lysimeters containing dormant bermudagrass (*Cynodon dactylon* × *C. transvaalensis* Burtt-Davy) established atop clay loam soil were weighed using the load cell attached to the tripod hoist. Drainage holes in the bottoms of lysimeters had been plugged during the study. Sixty minutes was required to weigh the 18 lysimeters (once). The lysimeters were then immediately weighed again in the same order. The weights (in kg) were recorded and subjected to analysis of group means and paired *t* tests (SAS 9.2, Cary, NC). The mean lysimeter weights were 30,539 ± 224 (SE) g for the first weighing and 30,540 ± 223 (SE) g for the second (Table 4). Total range in lysimeter weight was 28,990 to 32,170 g. The greatest weight difference noted between the first and second weighing was 25 g, most likely due to some attached mud on the bottom of the lysimeter that was knocked off when re-inserting the lysimeter. Otherwise, the mean difference between the two weighings was 5.8 ± 0.8 (SE) g, corresponding to the sensitivity of the load cell. Based on analysis of data, no significant difference could be detected between the first and second weighing ($P > 0.998$), demonstrating the high precision and reproducibility of system and load cell for taking weight measurements.

Table 4. Summary of *t* test results analyzing the reproducibility of weight measurements made using the load cell and tripod hoist system (n = 18). Values are means ± standard error.

	Wt 1	Wt 2	Difference (1–2)	*P* value
	grams			
Minimum	28,990	28,995		
Maximum	32,170	32,165		
Mean	30,539 ± 224	30,540 ± 223	0.83 ± 1.3	0.998

Conclusions

These lysimeters have been successfully used for over a year in turfgrass water use studies on both sand and clay soil types. This system is an improvement over the versions previously reported in the literature because of 1) the increased rooting volume offered relative to past studies, 2) the relatively low cost of materials, allowing a large number of replicates to be installed in the field, and 3) the ease and speed at which portable measurements can be made by a single person in the field. Furthermore, our results demonstrated that the environment produced by the lysimeter is reflective of surrounding soil with regard to temperature. Volumetric water content of lysimeters was slightly higher than surrounding soil. However, this may be advantageous in studies requiring well-watered conditions. This lysimeter system will be of significant benefit to those conducting future studies involving water use.

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