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SOIL TEMPERATURE AND WATER EVAPORATION OF SMALL STEEL AND PLASTIC LYSIMETERS REPLACED DAILY

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Soil water evaporation (E) measured by small, weighable lysimeters is affected by their size, construction materials, and replacement frequency. Steel and plastic are commonly used materials, but they have different thermal characteristics. Our objective was to investigate how wall material affects E and soil temperature of small lysimeters filled daily with undisturbed soil. Research was conducted during 5 days in August 1995 at Bushland, Texas, where the soil is a Pullman silty clay loam (fine, mixed, thermic Torrertic Paleustoll, 30% clay, 53% silt). Plastic and steel lysimeters 76 mm long, with inside diameters of 82 and 86 mm, respectively, were filled each morning by pressing them into undisturbed soil, and E was determined by mass change. Soil temperatures inside additional steel and plastic lysimeters were measured by thermocouples. No significant differences in E due to wall material were measured. For lysimeters of both wall materials, daily E ranged from 2 to 5 mm, daytime and nighttime E averaged 2.7 mm and 0.5 mm, respectively, and total cumulative E was 15.5 mm. Evaporation from small lysimeters was within 5% of E from a nearby large, precision, weighing lysimeter. Steel lysimeters were warmer at night near the surface, with significant differences from 0.5 to 0.9 °C, and warmer during the day at the bottom, with significant differences from 0.5 to 2.8 °C. Plastic lysimeters had greater vertical soil temperature differences than steel lysimeters. Significant differences inside plastic lysimeters ranged from about 2.0 to 3.5 °C greater than those of steel lysimeters during the daytime, and 0.5 to 1.0 °C greater during the nighttime. Measured temperature differences were consistent with greater thermal conductivity and enhanced heat transfer in steel sidewalls compared with plastic. Wall material affected temperature distribution, but not evaporation, of small lysimeters that were replaced daily. (Soil Science 2000;165:890–895)

Key words: Soil temperature, soil water evaporation, lysimeter.

WEIGHABLE lysimeters of various sizes are commonly used to measure soil water evaporation (E) by mass balance (Howell et al., 1991). Small lysimeters measured E effectively in diverse situations ranging from bare soil to soil beneath plant canopies (Todd et al., 1996; Evett et al., 1995; Daamen et al., 1993; Wallace et al., 1993; Ham et al., 1990). Boast and Robertson (1982) showed the importance of adequate lysimeter length so that isolated soil columns behave as if "infinitely long." They found that microlysimeters should be at least 70 mm long and should be used no more than 2 days before refilling. Klocke et al. (1990) compared E under a corn canopy from lysimeters 150 mm in diameter and 200 mm long that were replaced weekly with E measured by lysimeters 76 mm in diameter and 60 mm long that were replaced daily. Soil water evaporation rates averaged 0.2 mm d^{-1} more for the larger lysimeters than for the more frequently replaced, smaller lysimeters. This difference was attributed to wetter soil in the larger lysimeters because of no drainage or root extraction. Temperature inside the lysimeters was not measured.

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Evett et al. (1995) investigated the effect of construction material on soil water evaporation and temperatures within lysimeters. They used steel and plastic cylinders that were 100, 200, and 300 mm long, capped on the bottom with 6-mm-thick plastic. Lysimeters were filled once, placed in the field, and weighed daily for 9 days. Eight day cumulative evaporation from steel 200-mm-long lysimeters was significantly less compared with that from plastic lysimeters. It was inferred from temperature distributions within lysimeters that steel walls, with their higher thermal conductivity, conducted more energy downward and away from the evaporating surface than plastic-walled lysimeters. Daytime surface temperatures were cooler and nighttime surface temperatures warmer in steel lysimeters compared with plastic (both 300 mm long). They recommended that sidewall materials have low thermal conductivity to reduce heat transfer and that bottom capping materials have high thermal conductivity to reduce heat buildup at the lysimeter bottom. They speculated that their lysimeters may have overestimated E because the lack of daily replacement eliminated any opportunity for drainage after wetting.

Construction material is clearly a major consideration in lysimetry for E measurement. Although more laborious, daily replacement of lysimeters more closely matches the soil water content within lysimeters with that in the field, compared with longer replacement intervals. Lysimeters replaced daily can be as short as 70 mm (Boast and Robertson, 1982), with consequent reduction in total mass and increase in the achievable precision of E measurement. The objective of this research was to compare and evaluate E and soil temperature distributions of small steel and plastic lysimeters filled with undisturbed soil that were replaced daily. We tested the hypothesis that lysimeter wall material has no effect on E or soil temperature distribution within 76-mm-long lysimeters when they are replaced daily.

MATERIALS AND METHODS

Research was conducted in 1995 from day of year (DOY) 234 to 238 (22–26 August) at Bushland, TX (35° 11′ N, 102° 2′ W, elevation 1169 m), where the soil is a Pullman silty clay loam (fine, mixed, thermic Torrertic Paleustoll, 30% clay, 53% silt). The study area was in the center of the north half of a field 450 m long from north to south and 225 m long from east to west. The soil surface of the field following tillage was bare and smooth.

Steel lysimeters were made from 76-mm-long galvanized conduit with an 86-mm inside diameter and a 1.6-mm wall thickness. Plastic lysimeters were made from 76-mm-long, white, polyvinyl chloride plastic pipe with an 82-mm inside diameter and a wall thickness of 3.4 mm. Each morning, eight lysimeters of each wall material were filled with undisturbed soil at randomly selected locations in the study area by manually pressing them into the field soil. Lysimeters were pulled from the surrounding soil and bottoms were sealed with polyvinyl chloride plastic caps 2 mm thick that were fitted with rubber band gaskets between the cap and lysimeter wall that sealed the bottom and securely retained the soil.

A location for the lysimeters was established with 16 holes that were each lined with 1-mm-thick sheet metal. The sheet metal rings retained the surrounding soil and prevented the holes from collapsing when the lysimeters were removed. Bottom caps were in direct contact with the soil. Surfaces of the lysimeters were level with the surrounding soil surface when placed in the holes. Lysimeters were weighed with a portable battery-powered electronic balance (BD1201, Mettler Instrument Corp., Hightstown, NJ[a]) that was carried to the lysimeter location. Mass was measured to the nearest 0.1 g, which corresponded to a possible precision of 0.02 mm depth equivalent of E. Lysimeters were usually weighed every 2 hours after filling in the morning (between 8 a.m. and 9:30 a.m.) until 7 p.m. or 8 p.m. Final weighing was on the following morning at 7 a.m. Evaporation was also measured by a large (3 m × 3 m × 2.4 m deep), precision, weighing lysimeter, described by Marek et al. (1988) located 17 m south of the small lysimeter area. A data logger (CR7, Campbell Scientific, Logan UT) sampled lysimeter load cells every 6 s and calculated 15-min means that were later processed as half-hour means.

Soil temperature inside small lysimeters was measured by sixteen thermocouples made of 0.51-mm-diameter, solid, copper-constantan wire, with 2 mm of junction soldered and insulated with several coats of liquid vinyl. Every morning, two steel and two plastic lysimeters were filled in the same manner as the weighed lysimeters. Thermocouples were inserted horizontally through holes drilled in the sidewall of each lysimeter. Four thermocouples were installed in each lysimeter, two near the surface at a

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[a] The mention of trade or manufacturer names is for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

TABLE 1

Daily conditions: wind, speed, relative humidity, and saturation deficit are 24-h means, and θ_v is the mean volumetric soil content within small steel lysimeters

DOY	Solar radiation	Wind speed	Air temperature min.	Air temperature mean	Air temperature max.	Relative humidity	Saturation deficit	θ_v
	MJ m^{-2}	m s^{-1}	°C	°C	°C	%	kPa	m^3 m^{-3}
234	18.7	3.5	19.5	25.3	32.3	62	1.40	0.39
235	23.8	4.6	18.8	25.2	32.1	59	1.49	0.28
236	24.0	5.2	18.4	25.3	32.4	53	1.72	0.23
237	23.5	5.4	18.1	26.2	34.1	47	2.03	0.20
238	22.8	3.9	18.9	26.5	33.9	54	1.86	0.18

depth of 2 mm, at the center and near the sidewall, and two near the bottom at a depth of 70 mm, also at the center and near the sidewall. Thermocouples were connected to a multiplexer (AM416, Campbell Scientific, Logan, UT) and were sampled every 5 seconds by a data logger (CR21X, Campbell Scientific, Logan, UT) and 30-min means were calculated.

A mast located at the large weighing lysimeter held a net radiometer (Q*5.5, Radiation and Energy Balance Systems, Seattle, WA), cup anemometer (014A, Met One, Grants Pass, OR), and temperature-humidity probe (HT225R, Rotronics, Huntington, NY). Aerial sensors were mounted at 2 m above the soil surface, except for the net radiometer, which was at 1-m height. Soil heat flux within the large weighing lysimeter was measured with four heat flux transducers (HFT-1, Radiation and Energy Balance Systems, Seattle, WA) buried at 50 mm. Surface soil heat flux was calculated by correcting the heat flux at 50 mm for heat storage above the transducers, determined by change in soil temperature of the soil volume above the heat flux transducers and volumetric soil water content. Soil temperature above the transducers was measured with four pairs of copper-constantan thermocouples (304SS, Omega Engineering, Stamford, CT). Each pair had one thermocouple at 10 mm depth and one at 40 mm depth, wired in parallel to average the soil temperature. These instruments were connected to the same data logger as the large weighing lysimeter.

A 25-mm irrigation was applied to the field by a lateral move sprinkler system after sunset on DOY 233. The following days were generally hot, dry, and windy (Table 1). Daily mean soil water content of the lysimeters was estimated from the volume and mean mass of steel lysimeters and the known bulk density of the soil.

Differences in E between steel and plastic lysimeters were tested with unpaired *t* tests with variances assumed equal and eight observations for each comparison. Differences in near-surface or bottom soil temperatures between steel and plastic lysimeters were tested with unpaired *t* tests with variances assumed equal and four observations for each comparison. Differences were considered significant at $P \leq 0.05$.

RESULTS AND DISCUSSIONS

Soil Water Evaporation

Only two of 24 2-h measurements of E during the daytime were significantly different (data not shown). These measurements were pooled, daytime E averaged 2.7 mm from both steel and plastic lysimeters, and no significant differences were measured (Table 2). Daytime E was greatest, averaging 4.3 mm, on DOY 234 and 235 when the soil surface was visibly wet. Evaporation averaging 1.6 mm, decreased on the following days when the soil surface was dry. Comparison of nighttime E showed no significant differences

TABLE 2

Daytime and nighttime evaporation (E) from steel and plastic lysimeters

DOY	Steel lysimeters Mean E	Steel lysimeters SD	Plastic lysimeters Mean E	Plastic lysimeters SD	*t*-test $P > t$†
	mm	mm	mm	mm	
Daytime					
234	4.21	0.67	4.46	0.51	0.41
235	4.35	1.21	4.03	1.13	0.60
236	1.57	0.15	1.67	0.29	0.41
237	2.22	0.26	2.21	0.52	0.96
238	1.09	0.22	1.13	0.12	0.71
Nighttime					
234	0.70	0.13	0.59	0.09	0.07
235	0.66	0.24	0.61	0.14	0.59
236	0.39	0.10	0.44	0.04	0.21
237	0.30	0.05	0.38	0.12	0.11

†Applies to comparison of mean E of steel and plastic lysimeters within a row.

and averaged 0.5 mm from both steel and plastic lysimeters. Nighttime E was 13% of total daily E, except on DOY 236 when the nighttime percentage of total daily E increased to 20%. No effect of lysimeter wall material on cumulative E was measured, and small lysimeter E was within 5% of E measured by the large weighing lysimeter (Fig. 1). Total cumulative E was 15.5 mm for the small steel and plastic lysimeters and 14.8 mm for the large weighing lysimeter.

Temperature Distribution Inside Small Lysimeters

Near-surface soil temperature differences between steel and plastic lysimeters were not significant during the daytime (Table 3), although from early to midafternoon, near-surface temperatures in steel lysimeters tended to be about 0.5 °C cooler on DOY 234, 235, and 236, about 0.25 °C warmer on DOY 237, and about 1.5 °C warmer on DOY 238 (Fig. 2A). Cooler temperatures occurred when the soil surface was wet, and the trend toward warmer midday temperatures near the surface of steel lysimeters developed as the soil dried, evaporation decreased, and near-surface temperature increased. Steel lysimeters had warmer bottom temperatures during the daytime (Table 3); significant differences ranged from 0.5 to 2.8 °C (Fig. 1).

Nighttime near-surface temperatures averaged from 0.5 to 0.9 °C warmer in steel lysimeters on DOY 235, 236, and 237 compared with plastic lysimeters (Table 3). Significant differences in nighttime near-surface temperature were especially common during the nights of DOY 235 and 236, when soil temperatures near the surface of steel lysimeters ranged from 0.5 to 1.5 °C warmer than those in plastic lysimeters (Fig. 2A). Nighttime bottom temperature differences between steel and plastic lysimeters were, on average, <0.5 °C and were not significantly different (Table 3, Fig. 2B), although nighttime bottom temperatures of steel lysimeters tended to be about 0.4 °C cooler on DOY 234 and 0.5 °C warmer on DOY 235.

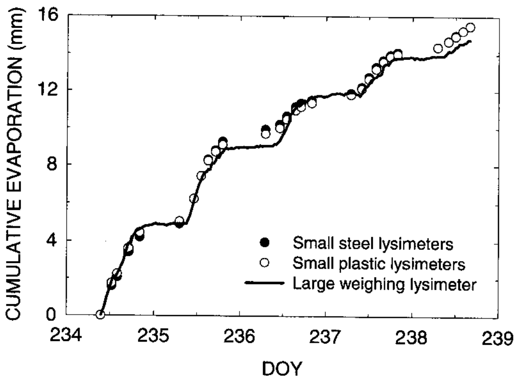

Fig. 1. Cumulative soil water evaporation, measured by small steel and plastic lysimeters, and the large weighing lysimeter.

Vertical temperature differences were calculated for each of the four pairs of thermocouples within the steel or plastic lysimeters. Vertical soil temperature differences were consistent with the direction and magnitude of soil heat flux measured in the large weighing lysimeter (Fig. 3.), with negative vertical temperature differences and negative soil heat flux (away from the surface) during the daytime and positive values (toward the surface) during the nighttime. Plastic lysimeters tended to have greater vertical temperature differences than steel lysimeters. Significant differences in vertical temperature difference were measured during the daytime of DOY 235 and 236, when the vertical temperature differences of plastic lysimeters ranged from about 2.0 to 3.5 °C greater than those of steel lysimeters (Fig. 4). During the nighttime of DOY 235, 236, and 237, the vertical temperature difference of plastic lysimeters ranged from about 0.5 to 1.0 °C greater than those of steel lysimeters (Fig. 4).

TABLE 3

Mean daytime and nighttime soil temperature of steel and plastic lysimeters near the surface and at the bottom of lysimeters

DOY	Steel lysimeters		Plastic lysimeters		*t*-test
	Mean Temp	SD	Mean Temp	SD	$P > t$[†]
			°C		
Daytime, near-surface					
234	26.7	0.6	27.0	0.4	0.58
235	32.8	1.3	32.4	0.8	0.69
236	33.8	0.7	34.0	0.9	0.69
237	33.8	1.0	33.6	1.6	0.85
238	39.2	1.9	37.8	2.7	0.42
Daytime, bottom					
234	27.2	0.2	26.9	0.1	0.06
235	29.7	0.6	27.9	0.4	<0.01
236	31.1	0.2	29.1	0.4	<0.01
237	30.6	0.2	29.2	0.4	<0.01
238	32.1	0.1	30.0	0.3	<0.01
Nighttime, near-surface					
234	18.6	0.5	18.3	0.2	0.23
235	19.7	0.2	18.8	0.2	<0.01
236	20.0	0.1	19.1	0.2	<0.01
237	21.3	0.3	20.8	0.2	0.04
Nighttime, bottom					
234	20.4	0.3	20.8	0.1	0.07
235	21.5	0.4	21.0	0.2	0.08
236	22.0	0.1	21.9	0.1	0.57
237	23.2	0.2	23.4	0.1	0.14

[†] Applies to comparison of mean temperature of steel and plastic lysimeters within a row.

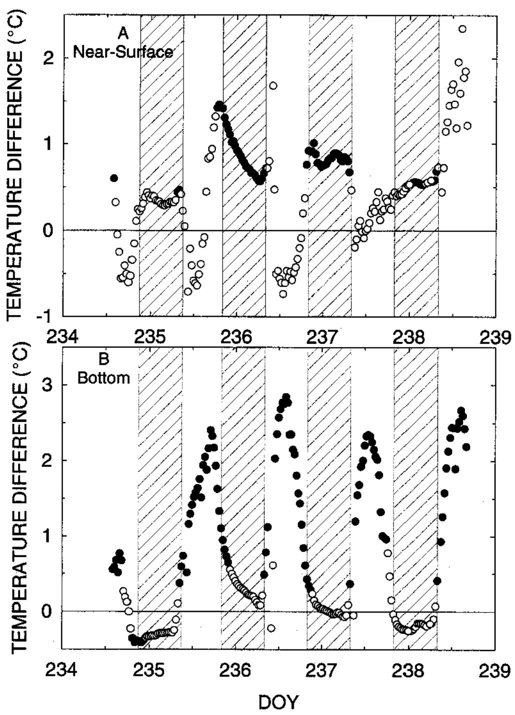

Fig. 2. Differences in soil temperature between small steel and plastic lysimeters near the surface (A) and at the bottom (B) of lysimeters. Differences greater than zero indicate warmer temperatures in steel lysimeters. Closed circles indicate that the difference was significant at the $P \leq 0.05$ level.

Greater vertical gradients in plastic lysimeters implied greater soil heat flux than in steel lysimeters. However, this may not be the case. Assuming that the water content and thermal conductivity of the soil in steel and plastic lysimeters were the same, there should be no difference in temperature and in soil heat flux. One explanation for the presence of greater vertical soil temperature gradients in plastic lysimeters was that steel lysimeters redistributed heat more readily than plastic lysimeters. The path for this increased redistribution was probably the steel sidewall with its greater thermal conductivity. Thermal conductivities are 45.8 W m^{-1} K^{-1} for mild steel (Kreith, 1958) and 0.092 W m^{-1} K^{-1} for polyvinyl chloride plastic (Jones, 1992). The bottom caps acted as a barrier to further heat transfer, and temperature increased so that steel lysimeters were warmer on the bottom than were plastic lysimeters during the daytime, as was seen in Fig. 2B. This enhanced redistribution of heat by the steel sidewalls also explains the tendency for cooler surface temperatures in steel lysimeters during afternoons (Fig. 2A). At night, the process was reversed and the heat in the bottom of steel lysimeters was transferred up the steel sidewalls more quickly, compared with the plastic lysimeters, which resulted in warmer nighttime surface temperatures in steel lysimeters (Fig. 2A).

CONCLUSIONS

No difference in E between small steel and plastic lysimeters was measured, and E from the small lysimeters agreed well with E from a large, precision, weighing lysimeter. Daily E rates from the small lysimeters ranged from 2 to 5 mm d^{-1}. Total E during the study was 15.5 mm for the small steel and plastic lysimeters and 14.8 mm for the large weighing lysimeter.

Near-surface soil temperature was similar in steel and plastic lysimeters during the day, although

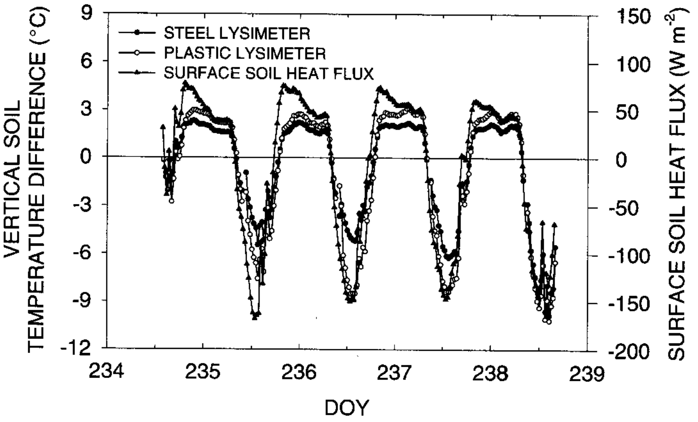

Fig. 3. Mean vertical temperature differences within steel and plastic lysimeters and surface soil heat flux measured in the large weighing lysimeter. Discontinuities occurred during the mornings when thermocouples were installed in new lysimeters. Temperature differences were calculated as the bottom temperature minus the near-surface temperature so that positive values imply positive soil heat flux (to the surface).

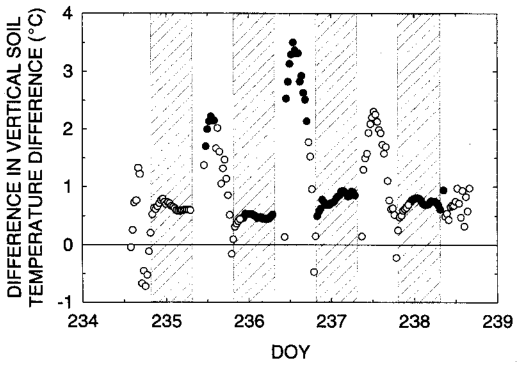

Fig. 4. Difference in vertical temperature differences between steel and plastic lysimeters. A positive difference indicates a larger vertical temperature difference in plastic lysimeters. Closed circles indicate that the difference was significant at the $P \leq 0.05$ level.

steel lysimeters tended to be cooler when the soil surface was wet and warmer when the soil surface was dry. Steel lysimeters were 0.5 to 2.8 °C warmer at the bottom during the day and 0.5 to 0.9 °C warmer near the surface at night compared with plastic lysimeters. Nighttime bottom temperatures were not significantly different. Temperature differences probably developed because heat was transferred more readily by the highly conductive steel sidewalls than by plastic sidewalls. Heat was also distributed more evenly in steel lysimeters so that vertical temperature differences were less in steel lysimeters compared with plastic lysimeters.

There was no effect of wall material on evaporation from small steel or plastic lysimeters that were replaced daily. However, there were differences in temperature distribution between steel and plastic lysimeters. Differences in temperature did not result in measurable differences in soil water evaporation when small lysimeters were replaced daily.

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