Evaluation of Microlysimeters used in Turfgrass Evapotranspiration Studies with the Dual-Probe Heat-Pulse Technique

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ABSTRACT

Microlysimeters (ML) are commonly used in turfgrass evapotranspiration (ET) studies. No standard exists for ML which has resulted in multiple designs that may affect soil moisture. The effects of ML design on volumetric soil water content (θ_v) were investigated using the dual-probe heat-pulse (DPHP) technique. DPHP sensors were installed at 5, 15, and 25 cm in the ambient soil profile and in 3 designs of ML: 1) 15 cm diam. x 30 cm, mesh base, soil fill (MSL); 2) 15 cm diam. x 30 cm, plexiglass base (one drainage hole), soil fill (PSL); 3) 10 cm diam. x 20 cm, mesh base, soil (intact cores) (MSNL). Sleeves and a 5 cm layer of gravel were placed in MSL and PSL. DPHP estimates of θ_v revealed that soils consistently dried faster in MSL and PSL than in the ambient profile, probably because of higher LAI and biomass in MSL and PSL than in surrounding turf, limitations of roots to extract soil water only from ML, and evaporation through open bases. In MSNL, θ_v was similar to but may have been in hydraulic contact with ambient soils. Correlation was good between θ_v determined by DPHP and by gravimetric methods; DPHP sensors on average (all ML) measured θ_v to within 0.025 $m^3\ m^{-3}$ of gravimetric estimates. ET estimates varied significantly among ML and were strongly correlated to LAI and aboveground biomass (r=0.85). Results suggest that establishment/maintenance of similar LAI and biomass between ML and surrounding turf may be more important than ML design in providing accurate ET estimates, and bases should be sealed during ET measurements to prevent hydraulic contact with soil, drainage, or evaporation through bases.

Key Words: Lysimeters; lysimeter design; ET; soil moisture sensors;

Abbreviations: DPHP, dual-probe heat-pulse; AP, ambient profile; ET, evapotranspiration; LAI, leaf area index; MSL, mesh soil lined microlysimeter; MFCL, mesh fritted clay lined microlysimeter; ML, microlysimeters; MSNL, mesh soil not lined microlysimeter; PSL, plexiglass soil lined microlysimeter; RMSE, root mean square error; WPSL, wide plexiglass soil lined microlysimeter.

In turfgrass, estimating water-use rates (Shearman 1986 and 1989; Aronson et al. 1987) and evaluating the effects of cultural practices on evapotranspiration (ET) (Shearman and Beard 1973; Feldhake et al. 1983 and 1985) are important because of increasing competition for water (Reisner 1993). Evapotranspiration studies in turfgrass are sometimes designed to identify cultivars or species that maintain high quality while using less water (Feldhake et al. 1984; Fry and Butler 1989; Qian and Fry 1997). Microlysimeters (ML) are often used in turfgrass studies to gravimetrically estimate ET rates and to compare ET rates among cultivars or species (Kim and Beard 1988; Bowman and Macaulay 1991; Green et al. 1991; Qian et al. 1996). Using this method, ML are irrigated, allowed time for the free drainage of water to cease, and then weighed wet; ML are then weighed one or more days later and the water loss is attributed to ET. However, no standard design for ML exists and consequently, a wide variety of styles are used in turfgrass ET studies. For example, ML may be fabricated at different sizes (e.g., diam. and depths), from different wall materials (e.g., plastic or steel), with different types of bases (e.g., mesh screen or solid), filled with different materials (e.g., native soil or fritted clay), prepared differently (e.g., planting sod into ML weeks ahead of deployment to allow sod establishment vs. using intact cores from field at beginning of study), or deployed differently in the field (e.g., holes may or may not be lined with sleeves, and bases may or may not be lined with gravel) (Feldhake et al 1983; Kim and Beard 1988; Shearman 1989; Qian et al. 1996; Keeley and Koski 1997). The effects of ML design on soil moisture or on temporal changes in soil moisture remain uncertain (Evett et al. 1995).

Recently, the dual-probe heat-pulse (DPHP) technique has been developed and tested for measuring volumetric soil water content (θ_v) and changes in θ_v over time in the laboratory and in the field (Bristow et al. 1993; Campbell et al. 1991; Tarara and Ham 1997; Bremer et al. 1998, 2001; Bremer and Ham 1999, 2002; Basinger et al. 2003), including under turfgrass (Song et al. 1998). The DPHP sensor is approximately 5.5 cm long x 1.6 cm diam., with the probe spacing around 6 mm, which allows for small-scale spatial measurements of θ_v that can be made in small containers such as ML. The DPHP technique uses a heater and a temperature probe to determine the volumetric heat capacity of the soil, which is highly dependent on its water content; volumetric heat capacity can readily be converted to θ_v. Further details on the theory of the DPHP technique are available from a number of sources (Campbell et al. 1991; Tarara and Ham 1997; Song et al. 1998; Basinger et al. 2003).

The major objectives of this experiment were to evaluate the effect of ML design on soil water content and on temporal changes in soil water content among three types of ML using DPHP sensors inside the ML and in the adjacent (ambient) soil profile. The accuracy of DPHP sensors was tested by comparing measurements of θ_v from DPHP sensors with gravimetric estimates of θ_v; gravimetric measurements of θ_v were obtained periodically by removing ML from the field and weighing individually. Linear regression was performed with water content data from gravimetric methods and DPHP sensors from each ML to compare the relationships among ML types. A smaller part of this study involved the comparison of gravimetric estimates of ET among 5 ML types, 3 of which were equipped with DPHC sensors as mentioned above. Green leaf area index and aboveground biomass were measured to evaluate their impact on estimates of ET.

MATERIALS AND METHODS

The study was conducted from mid July to mid September, 2002 at the Rocky Ford Turfgrass Research Center near Manhattan, Kansas (Rocky Ford; 39.12^{o}N, 96.35^{o}W). The soil at the site was Chase silt loam (fine, montmorillonitic, mesic, Aquic, Arquidolls). Mean air temperature during the study was 26.9^{o}C and average daily maximum and minimum temperatures were 33.4^{o}C and 20.6^{o}C, respectively.

Microlysimeter designs, construction, and deployment

Differences in ML design included 3 sizes (10 cm diam. x 20 cm, 15 cm diam. x 30 cm, and 25 cm diam. x 20 cm), 2 fill materials (native soil and fritted clay), 2 base covers (screen and plexiglass), 2 preparation techniques (pre-sodding in greenhouse 86 d prior to deployment and use of intact soil cores from field), and 2 types of holes (pre-dug with sleeves installed to prevent sides from collapsing and bases lined with gravel, and holes with no sleeves and no gravel bases). Five designs of ML, replicated 3 times each (i.e., 15 experimental units), were fabricated from poly-vinyl chloride (PVC) tubes for this study. Four of the 5 ML types were installed into pre-dug holes where the perimeters were lined with larger PVC tubes (~5 cm larger than their respective ML diameters) to prevent the sides from collapsing, and the bases were lined with approximately 5 cm of gravel. Sleeves were not required in a smaller ML type, nor were the bases lined with gravel (#3 below).

The five designs included: 1) 15 cm diam. x 30 cm, base covered with fine-mesh aluminum screen (~1 mm^2 openings in screen) and reinforced with larger wire mesh (~6.5 mm), and packed with native soil from the field site (MSL; mesh [base], soil [fill], lined [sleeve]); 2) 15 cm diam. x 30 cm, base covered with solid plexi-glass with one hole in center for drainage (13 mm diam.), and packed with native soil from the field site (PSL; plexiglass, soil, lined); 3) 10 cm diam. x 20 cm, base covered with screen described for MSL, filled with intact cores of native soil (MSNL; mesh, soil, not lined); 4) 15 cm diam. x 30 cm, base covered with screen described for MSL, filled with fritted clay (MFCL; mesh, fritted clay, lined); and 5) 25 cm diam. x 20 cm, bottom covered with plexiglass with one hole in center (13 mm diam.) for drainage, and packed with native soil from the site (WPSL; wide, plexiglass, soil, lined).

MSNL ML were pushed directly into the soil and then removed with the soil cores intact. The screen was then placed over the base and the ML returned to the same hole. In MSL, PSL, and WPSL ML, soil was packed to a uniform bulk density that ranged between 1.15 and 1.24 g cm^{-3} among ML; uniform bulk densities in MSL, PSL, and MSNL ML were necessary for later use of the DPHP sensors. Fritted clay (Turface, Profile Products LLC, Buffalo Grove, IL) was mixed with 9.9 g kg^{-1} 13-13-13 controlled release fertilizer (Carl Pool, Gladewater, TX) and poured into MFCL ML, watered, and allowed to settle.

On April 20 (day of year [DOY] 110), 2002, sod (approximately 2.5 cm thick) was collected from an established stand of K-31 tall fescue (*Festuca arundinacea* Schreb.) at Rocky Ford. Sod was cut to the diameter of each respective ML, washed free of soil, and planted into the ML after they had been packed with soil (MSL, PSL, and WPSL) or filled with fritted clay (MFCL) and saturated with water. Microlysimeters were placed in a greenhouse for about 3 months, watered as needed to avoid wilt, fertilized with 5 g N m^{-2} (urea) on May 10 (DOY 130), and clipped weekly at 7.5 cm.

On July 15 (DOY 196), ML were transferred to plots established in the same stand of K-31 tall fescue at Rocky Ford. MSNL ML were also installed in the field as described above on July 15. DPHC sensors were installed into MSL, PSL, and MSNL prior to their deployment to the field. Microlysimeters were saturated with water and the surrounding area irrigated with ~5 cm of water. After allowing 12 to 30 h for drainage, ML were removed from the field, weighed, and immediately returned (ML were not sealed during ET measurements). Microlysimeters were then weighed every 24 to 96 hours during periods without precipitation to obtain gravimetric estimates of ET during the study. Microlysimeters were consistently weighed between 1230 and 1400 h. During one 2-week period (DOY 234 to 248), irrigation was withheld to observe the effects of drydown on soil moisture (with DPHP sensors) and gravimetric estimates of ET among ML. Grass in the ML were mowed weekly along with the surrounding turf at 7.5 cm with a walk-behind rotary mower.

On a number of days, estimates of ET were unrealistically high from MSL and PSL during the study, and were sometimes considerably higher (e.g., 27%) than ET_p for up to 5 days. Because ML were not sealed during ET measurements, some of the water loss attributed to ET may have been from drainage. Later evaluations in the laboratory revealed that in ML filled with soil (silt loam), free drainage continued for at least 24 h after irrigation. Therefore, because of possible drainage during ET measurements, the only gravimetric estimates of ET presented were from the 2-week drydown period when drainage was not a factor; 27 h were allowed for drainage prior to the first ET measurement and no precipitation occurred during that period. Laboratory results suggest that it is advisable to seal the bases of ML to ensure no drainage during ET measurements.

Evaluation of soil water content inside ML with dual-probe heat-pulse technique

Volumetric soil water content (θ_v) and temperature inside MSL, PSL, and MSNL ML and in the ambient profile (AP) were measured automatically using the DPHP technique (Campbell et al. 1991; Tarara and Ham 1997; Song et al. 1998). Sensors were fabricated in the laboratory as described by Basinger et al. (2003). The only exception is that in this study, the heater and temperature probes were not inserted into prefabricated PVC blocks. Rather, the heater and temperature probes were held in place in prefabricated templates so that the probes were held parallel with a spacing of approximately 6 mm. Epoxy (Micro-Mark CR-600, Berkeley Heights, NJ) was then poured into the template so that the connections between the heater and temperature probes and the ribbon cable were completely covered and made waterproof and electrically insulated.

DPHP sensors were installed at 3 depths (5, 15, and 25 cm) in MSL and PSL ML and in AP, and at two depths in the smaller MSNL microlysimeter (5 and 15 cm); all sensors were installed prior to deployment to the field. DPHC sensors were not installed in all ML because of practical limitations in sensor availability and data acquisition capacity and because DPHC sensors may not be appropriate for use in fritted clay, which was used in MFCL.

Measurements of θ_v were logged every 2 to 6 h and soil temperatures every 30 min. All data acquisition and control were accomplished with a micrologger and accessories (CR10x and three AM16/32, Campbell Scientific, Logan, UT). Cables running from DPHP sensors in the ML to the data-acquisition system were equipped with connectors (EN3C6M and EN3L6F, Switchcraft, Chicago, IL) so they could be detached and removed from the field for gravimetric measurements. Values of mean θ_v and soil temperature for whole containers and AP were obtained by averaging measurements from DPHP sensors from all depths within each container ($[\theta_{v\text{-}5cm}+\theta_{v\text{-}15cm}+\theta_{v\text{-}25cm}]/3$). Estimates of θ_v from DPHP sensors were corrected with an empirical calibration equation to correct for slight overestimates of θ_v at low water contents (Basinger et al. 2003). Air temperatures at 2 m were obtained from a nearby weather station at Rocky Ford.

Soil bulk densities and organic matter were measured in the ML and at each depth in AP to provide parameter estimates for calculations of θ_v. Bulk densities of soils inside MSL, PSL, and WPSL ML ranged from 1.15 to 1.24 g cm^{-3}, and organic matter was 2.3%. In AP, bulk densities (determined from volumetric samples 5.4 cm diam. x 3 cm) were 1.35, 1.42, and 1.47 g cm^{-3} and organic matter was 5.4, 4.0, and 2.6% at 5, 15, and 25 cm, respectively.

Green leaf area index and aboveground biomass

Green LAI and aboveground biomass were harvested and measured from each ML and the areas directly above DPHP sensors (0.082 m^2) at the end of the study. Green LAI was measured with an area meter (LI-3100, Li-Cor, Lincoln, NE), and total aboveground biomass was determined gravimetrically after samples had been dried in a forced-air oven for 48 h at 60^{o}C.

Experimental design and data analysis

In the field, 18 locations separated by 1 m were marked for this study. Six treatments, replicated 3 times each, were arranged in a randomized block design. Five treatments included each of the 5 ML designs (MSL, PSL, MFCL, WPSL, and MSNL) and a sixth treatment included DPHP sensors in AP. Thus, measurements of θ_v from DPHP sensors in MSL, PSL, MSNL, and AP, and gravimetric measurements of each of the 5 ML types were replicated 3 times each.

Tests of differences in measurements of θ_v and soil temperatures from DPHP sensors, gravimetric estimates of ET, and LAI and aboveground biomass among ML types and the ambient profile were conducted with the general linear model procedure of SAS (SAS Institute Inc, Cary, NC). Differences between means on a given day or for a given ML were separated by the least significance difference test at the 0.05 level. Although DPHP sensors measured θ_v 4 to 12 times each day, tests of differences were conducted only on θ_v at 1800 h for each day.

Correlations between ET and green LAI and aboveground biomass were conducted with the correlation procedure of SAS.

Reference and potential ET were estimated using daytime data from a weather station at Rocky Ford. The Penman-Monteith equation (FAO-56; FAO 1998), which assumes nonlimiting soil moisture and a canopy resistance of 70 s m^{-1}, was used to estimate reference ET (ET_r). The Penman equation (Penman 1948), which assumes nonlimiting soil moisture and a wet canopy (i.e., no canopy resistance), was used to estimate potential ET (ET_p). Nighttime ET, which was assumed to be 10% of total daily ET (Brutsaert and Sugita 1992), was added to daytime values to obtain cumulative estimates of reference ET. Reference and potential ET provided reference points for comparison with gravimetric estimates of ET among ML.

RESULTS AND DISCUSSION

In the following discussion, soil moistures in AP are presented as 2 averages to allow comparisons between 2 sizes (depths) of whole containers and AP. Average soil moisture in both MSL and PSL are compared to the soil moisture in AP averaged over 3 depths, because MSL and PSL contained DPHP sensors at 5, 15, and 25 cm. Average soil moisture in MSNL is compared to the average of 2 depths in AP because MSNL contained DPHP sensors only at 5 and 15 cm.

Effects of ML design on soil water content

Volumetric soil water content (θ_v) was similar among ML and AP for about 3 days following irrigation on DOY 197 (Fig. 1). However, after 3 days MSL and PSL began to dry faster than AP, and MSL and PSL were significantly lower (~0.13 m^3 m^{-3}) than AP by the end of a 5.5 day drydown period (Fig. 1a). In MSNL, θ_v remained similar to AP for the entire 5.5 day drydown period (Fig. 1b). In MSL and PSL, green LAI and aboveground biomass were significantly greater than in AP or MSNL (Fig. 2), which likely resulted in higher transpiration rates (i.e., faster water depletion) in MSL and PSL. In ML, the amount of extractable water by turfgrass roots is limited to the available reservoir inside the ML, whereas in ambient soils the roots may extract water from lower in the profile. Visual observations revealed that numerous roots had penetrated to and were growing along the base of MSL and PSL by the end of the 86 d preconditioning period in the greenhouse, suggesting well developed root systems in those ML. Thus, soil water in MSL and PSL was likely depleted more rapidly in the 0-30 cm profile compared to ambient soils. In MSNL, root pruning may have occurred during installation of ML and consequently, the root system may not have been as developed as in MSL and PSL. Furthermore, soils in MSNL may have been in hydraulic contact with the ambient soil, which may have affected θ_v inside MSNL compared with MSL and PSL which were separated from ambient soils with a gravel layer.

Following subsequent irrigations on DOY 203 and 204, θ_v increased and no significant differences in θ_v were observed among ML and AP on DOY 205 (Fig. 1). During a second drydown period between DOY 205 and 208, the pattern was similar to the first, with MSL and PSL drying faster than MSNL. Microlysimeters were irrigated with surrounding turf on DOY 203 and 204 (i.e., no additional water was added to ML other than normal irrigation), and irrigation may not have been enough to equilibrate the ML with the surrounding soil. Thus, θ_v was apparently slightly lower following irrigation in MSL and PSL than in AP which may have caused a more rapid drydown from DOY 205-209 compared to the first drydown (Fig. 1a). By DOY 209, θ_v in both MSL and PSL were significantly lower than AP, while θ_v in MSNL remained similar to AP. During both drydown periods, MSL tended to be slightly drier than PSL, and on both occasions became significantly lower than AP one day earlier than PSL.

At each specific depth, soils dried at different rates among ML and the ambient profile (Fig. 3). At the end of both drying periods, significant differences in θ_v were observed at each depth. However, the patterns of drying were different among ML and AP at different depths. For example, θ_v in PSL decreased more rapidly at 5 cm than in MSNL, MSL, or AP during both drydown periods (Fig. 3a). However, at lower depths θ_v decreased more rapidly in MSL than in other ML or AP (Fig 3b-3c). At 25 cm in particular, θ_v consistently declined faster in MSL than in PSL and AP (Fig. 3c); evaporation may have occurred through the screen base of MSL, through the gravel layer, and into the air surrounding MSL (i.e., air in the sleeve). Although differences between PSL and MSL at 25 cm were not significant, visual observations during installation of DPHP sensors confirmed that soils were noticeably drier at 25 cm in MSL than in PSL.

Later in the growing season, measurements of θ_v in the ML were repeated during a 2-week drydown period. During that period (DOY 233 to 248; Figs. 4 and 5), the pattern of differences in θ_v among ML and the ambient soil was similar to that of earlier drydowns (Figs. 1 and 3). For example, θ_v in MSL and PSL declined more rapidly than AP (Fig. 4a) while θ_v in MSNL and AP were similar throughout the drydown (Fig. 4b). In MSL, θ_v was consistently lower than PSL during the drydown. By the end of the drydown, both MSL and PSL were significantly lower than AP. In MSNL, θ_v was nearly identical to AP for the first week of the drydown. However, during the second week θ_v was consistently lower in MSNL than in AP, which indicated the depletion of soil moisture inside the ML.

At 5 cm, θ_v was consistently lower in MSL and PSL although no significant differences were detected during the 2-week drydown (Fig. 5a). At lower depths, θ_v decreased more rapidly in MSL than in other ML or the ambient profile, and was significantly lower than the profile and MSNL by the end of the drydown (Figs. 5b and 5c). As in the initial drydown, the largest differences occurred at 25 cm, where MSL was consistently lowest and AP was consistently highest. The θ_v in PSL also declined more rapidly than AP at lower depths and was significantly lower than AP by the end of the 2-week drydown.

Comparisons of Gravimetric and Dual-Probe Heat-Pulse Measurements of Volumetric Soil Water Content

Measurements of θ_v from DPHP sensors were averaged for each whole container and then compared to gravimetric measurements of θ_v from each respective ML through linear regression. Reasonable agreement was found between gravimetric and DPHP measurements of θ_v, particularly in MSL and PSL (Figs. 6a-6c). In the range of soil moisture between 0.10 to 0.50 $m^3\ m^{-3}$, the root mean square error (RMSE) of the θ_v calculated from DPHP sensors and from gravimetric measurements was 0.033 and the mean discrepancy of measurements in all ML were 0.025 $m^3\ m^{-3}$. These errors are somewhat higher than reported in other studies (Song et al. 1998; Basinger et al. 2003), and are likely related in part to the density of DPHP sensors. For example, Song et al. (1998) determined that one DPHP sensor per 314 cm^3 soil was sufficient to obtain accurate representation of θ_v inside containers. In this study, only one DPHP sensor per 1,767 cm^3 was installed in MSL and PSL. Thus, DPHC measurements of θ_v in the center of the ML may not have represented θ_v in soil nearer the edges of MSL and PSL, which may have contributed to higher error compared to other studies.

Among ML, agreement was greatest in MSL (Fig. 6a; mean discrepancy = 0.014 $m^3 m^{-3}$ and RMSE = 0.016), slightly less in PSL (Fig. 6b; mean discrepancy = 0.02 $m^3 m^{-3}$ and RMSE = 0.023), and least in MSNL (Fig. 6c; mean discrepancy = 0.043 $m^3 m^{-3}$ and RMSE = 0.051). In MSNL, DPHP sensors overestimated θ_v at all moisture contents measured and scatter about the mean was greater (r^2=0.79) compared to MSL and PSL. In MSNL, DPHP estimates of θ_v may have had greater inherent error because of uncertainty in bulk density measurements at different depths. In MSNL, bulk densities of the entire containers were measured at the end of the study, and those values were used to calculate θ_v at both depths. However, because soil in MSNL was intact cores from the ambient soil, the bulk density may have varied by depth as in the ambient profile.

Gravimetric estimates of ET among 5 ML designs

Gravimetric estimates of ET varied significantly among ML designs (Table 1). For example, cumulative ET during the 14-d drydown period was about 2 times greater from MSL and PSL than from MSNL; ET estimates were highest from MSL and PSL and lowest from MSNL. Early in the period when soil moisture was non-limiting, ET from MSL and PSL was about 24% higher than ET_r, and ET from MSNL was 47% lower than ET_r. Because MSNL may have been in hydraulic contact with ambient soils, their estimates of ET may be suspect. For example, Rogowski and Jacoby (1977) reported lower water losses from ML in hydraulic contact with soils compared with ML with sealed bases. Estimates of ET from MFCL and WPSL were similar and both were similar to ET_r when water was non-limiting. Interestingly, estimates of ET from MSL and PSL were similar throughout the drydown despite the differences in θ_v observed at different depths with DPHP sensors (Figs. 1, 3-5).

Green LAI and biomass varied significantly among ML (Fig. 2), and may have been the largest contributor to variability in ET estimates. Green LAI and biomass both were strongly correlated with ET rates among ML when water was non-limiting (DOY 135-138; Pearson correlation coefficient=0.85; $p<0.001$). For example, LAI and aboveground biomass were highest in MSL and PSL (Fig. 2) which corresponded to the highest ET rates of the study (Table 1). Conversely, LAI and biomass were lowest in MSNL and corresponded to the lowest ET rates. Previous studies have revealed strong correlations between clipping dry weights and ET rates in ML (Bowman and Macaulay 1991), although others have reported similar ET rates among ML with significant differences in LAI (Rogowski and Jacoby 1977).

Aboveground biomass was significantly greater than surrounding (ambient) turf in four of the five ML designs (Fig. 2b). Higher biomass probably resulted from the preconditioning period in the greenhouse, which was conducted in the four ML that exhibited greater biomass compared to ambient turf. Visual observations of root growth along the base of ML by the end of the 86-day preconditioning period in the greenhouse suggested a higher root biomass in the four ML designs compared to ambient soils and MSNL; higher root biomass has been positively correlated to higher aboveground biomass in turf (Marcum et al. 1995). Other factors may have contributed to higher aboveground biomass in the four ML. For example, soil temperatures were higher (data not shown) and bulk densities were lower (i.e., higher porosities) in ML compared to ambient soils. However, soil temperatures were also higher and bulk densities lower in MSNL compared to ambient soils, yet aboveground biomass in MSNL was not significantly higher than surrounding turf. Fertilizer additions were similar among ML and surrounding turf and thus, likely did not contribute to differences in aboveground biomass.

In general, ET estimates declined with time during the drydown (Table 1) because of decreasing soil moisture in the ML. Estimates of ET from ML filled with silt loam (i.e., MSL, PSL, WPSL, and MSNL) did not decline for about 8 d despite high ET_p. Conversely, ET rates in MFCL declined dramatically by the 5th or 6th day. By the end of the drydown, daily ET rates had declined to between 1.09 and 2.15 mm d^{-1} among ML. In the silt loam soils, maintenance of high ET rates for longer periods demonstrates their higher water holding capacity compared to fritted clay (van Bavel et al. 1978; Hershey 1990). Nevertheless, cumulative ET estimates from MFCL were 17% greater than from MSNL.

Estimates of ET from MFCL and WMSL were closer to ET_r than other ML when water was non-limiting (DOY 235-238), which suggests that MFCL and WMSL may have provided more accurate estimates of ET. However, it is uncertain whether ET_r represents actual ET from the surrounding turfgrass. Additional research is needed using such methods as the Bowen ratio (Tanner 1960) to compare ET from ML with ET from surrounding turfgrass. In other studies where evaporation was measured from bare soil with the Bowen ratio, estimates from ML were comparable to evaporation from the surrounding surface (Ham et al. 1990; Baker and Spaans 1994). In this study, average soil temperatures (1200-2000 h CST) inside ML were as much as 3.4 ^{o}C higher than in the surrounding soil (data not shown). Although elevated soil temperatures did not appear to affect ET rates among ML in this study, the higher soil temperatures illustrate the impact that the ML can have on the soil environment. The effects on ET estimates of such variables as vegetative cover and soil temperatures in ML are uncertain and may require further evaluation.

Conclusions

DPHP data revealed that following irrigation, θ_v decreased more rapidly in MSL and PSL compared to AP. Faster depletion of soil water in MSL and PSL were likely related to their higher green LAI and aboveground biomass compared to surrounding turfgrass, and to the limitation of their roots to extract water only from inside the ML. The θ_v in MSNL was comparable to AP throughout the study. In MSNL, green LAI and aboveground biomass were similar to AP, and MSNL may have been in hydraulic contact with the ambient soils. Significant effects were also observed at different depths in MSL and PSL compared to AP. The largest differences in θ_v occurred at 25 cm, with MSL substantially lower than PSL and AP, and PSL lower than AP. In MSL, evaporation through the screen base and gravel layer likely contributed to the more rapid drydown at 25 cm compared with PSL and AP. These results suggest that bases of microlysimeters should be sealed during measurements of ET to prevent evaporation through the base and gravel layers (including ML filled with fritted clay) or to prevent hydraulic contact of the soils inside ML with ambient soils. Later laboratory tests revealed that drainage occurred for at least 24 h in ML filled with silt loam soils. Therefore, sealing bases would also prevent inadvertent drainage during ET measurements.

Linear regression analysis revealed good agreement between measurements of θ_v from DPHP sensors and gravimetric measurements in each ML, with an overall (all ML) RMSE of 0.033 and a mean discrepancy of 0.025 $m^3\ m^{-3}$. These values are similar to those reported by others using the DPHP technique (Campbell et al. 1991; Tarara and Ham 1997; Song et al. 1998; Basinger et al. 2003), and illustrates the accuracy and usefulness of the DPHP technique in turf studies.

Gravimetric estimates of ET varied significantly among ML and were strongly correlated to green LAI and aboveground biomass, which varied considerably among ML types. Green LAI and aboveground biomass were significantly higher in four of the five ML, which was likely the result of the 86-day preconditioning period prior to deployment to the field. Thus, microlysimeter design may have been less significant in causing variability in ET estimates than the method of turfgrass establishment in ML in this study, which ultimately caused significant differences in green LAI and aboveground biomass compared to surrounding turf. Results suggest that in ML studies, green LAI and aboveground biomass in ML should be similar to surrounding turf to obtain accurate estimates of ET. Further research is required to compare ET estimates from ML with different LAI and aboveground biomass with *actual* ET from surrounding turfgrass using methods such at the Bowen ratio. Finally, in studies where ET rates are compared among cultivars or species using ML, the same design, fill material, etc. should be used to ensure that differences in ET represent actual differences from plants and not from ML design or turf establishment methods.

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Table 1. Gravimetric estimates of daily evapotranspiration (ET) from microlysimeters in K-31 tall fescue during a 14 d drydown period from day of year (DOY) 234-248. Five different microlysimeter designs included: 15 cm diam. x 30 cm, mesh base, soil fill, lined hole (MSL); 15 cm diam. x 30 cm, plexiglass base, soil fill, lined hole (PSL); 10 cm diam. x 20 cm, mesh base, soil fill, holes not lined (MSNL); 15 cm diam. x 30 cm, mesh base, fritted clay fill, lined hole (MFCL); and 25 cm diam. cm x 20 cm, plexiglass base, soil fill, lined hole (WPSL).

DOY*	MSL	PSL	MSNL	MFCL	WPSL	ET_r†	ET_p‡
	....	....	....	mm	....	....	....
235-238	6.5a§	6.6a	2.8c	4.9b	4.8b	5.3	6.6
239-240	5.9a	5.3a	2.5c	2.3c	4.1b	5.1	6.2
241-242	7.0a	6.1b	3.2d	2.5e	4.7c	5.2	7.1
243-246	4.5ab	4.4ab	2.4c	2.2c	3.1bc	5.4	8.1
247-248	1.4a	1.8a	1.5a	1.5a	1.1a	5.2	7.6
Cumulative	72.5	70.6	35.3	41.2	51.6	73.5	100.5

* Day of year; the first DOY is January 1.
† Reference ET calculated from weather data and the Penman-Monteith Equation (FAO-56).
‡ Potential ET calculated from weather data and the Penman equation (Penman 1948).
§ Means followed with the same letter within a row are not significantly different ($P<0.05$).

Fig. 1. Comparisons of volumetric soil water content from DPHP sensors: A) among MSL and PSL containers and the Ambient soil (average 5, 15, and 25 cm [0-30 cm profile]); and B) between MSNL and the Ambient soil (average 5 and 15 cm [0-20 cm profile]). Vertical dashed lines highlight irrigation dates. Symbols (x) along the abscissa of each graph indicate significant differences between MSL and ambient soil ($P<0.05$), and plus (+) indicates significant differences between both MSL and PSL and the ambient soil on a given day (at 1800 h).

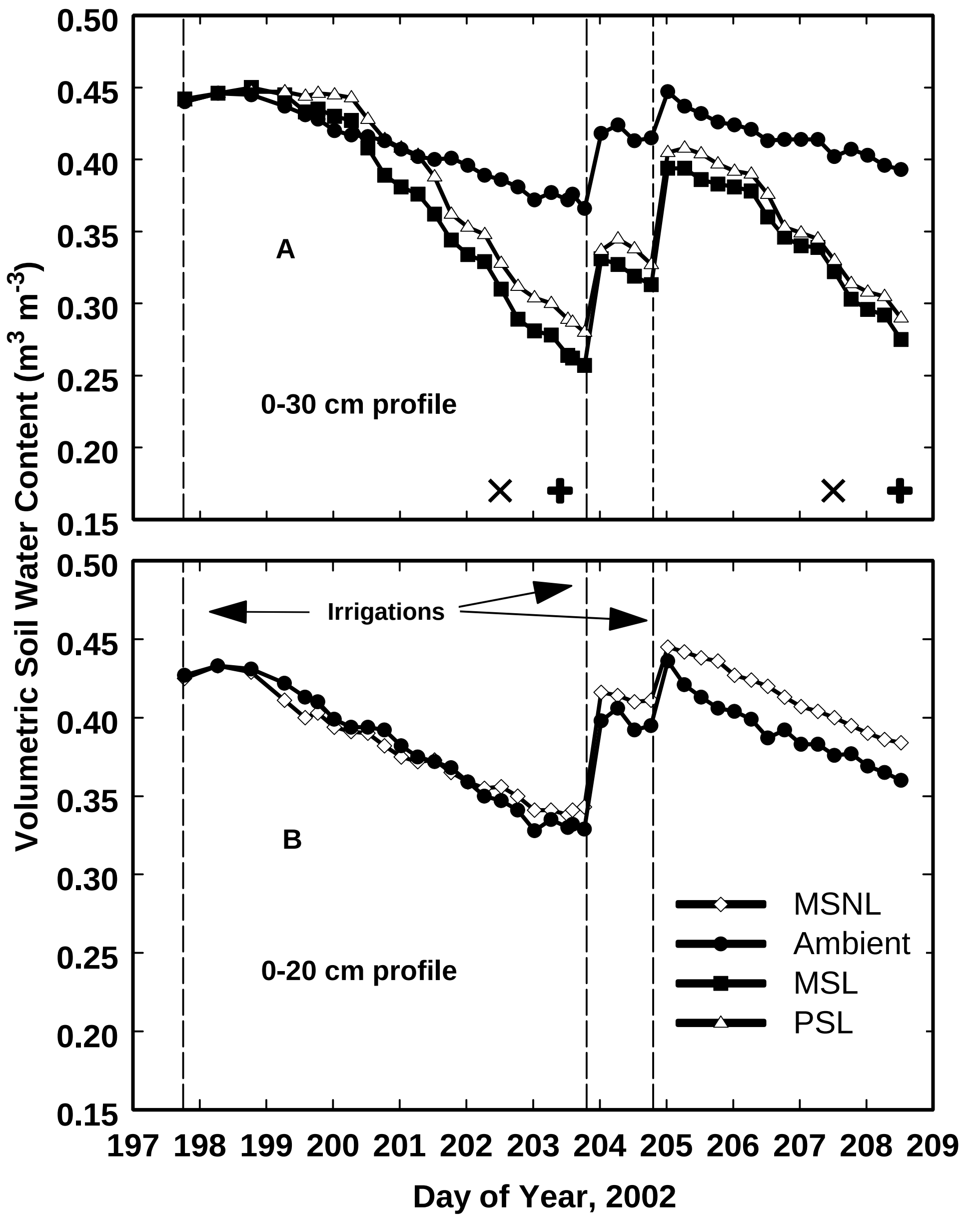
Fig. 2. Green leaf area index (A) and aboveground biomass (B) in MSL, PSL, MSNL, MFCL, and WPSL microlysimeters and in the surrounding turfgrass. Means in each plot (A and B) with the same letter are not significantly different ($P<0.05$).

Fig. 3. Comparisons of volumetric water content from DPHP sensors at 5 (A) and 15 cm (B) among MSL, PSL, MSNL, and Ambient soil, and at 25 cm (C) among MSL, PSL, and Ambient soil. Vertical dashed lines highlight irrigation dates. Symbols (plus-x) along abscissa of each graph indicate significant differences among 3 treatments ($P<0.05$), and x indicates significant differences between 2 treatments on a given day (at 1800 h).

Fig. 4. Comparisons of volumetric water content from DPHP sensors: A) among MSL and PSL containers and the Ambient soil (average 5, 15, and 25 cm [0-30 cm profile]); and B) between MSNL and the Ambient soil (average 5 and 15 cm [0-20 cm profile]). Vertical dashed lines highlight irrigation date. Symbols (x) along the abscissa of each graph indicate significant differences between MSL and ambient soil ($P<0.05$), and plus (+) indicates significant differences between both MSL and PSL and the ambient soil on a given day (at 1800 h).

Fig. 5. Comparisons of volumetric water content from DPHP sensors at 5 (A) and 15 cm (B) among MSL, PSL, MSNL, and Ambient soil, and at 25 cm (C) among MSL, PSL, and Ambient soil. Vertical dashed lines highlight irrigation date. Symbols (x) along abscissa of each graph indicate significant differences between MSL and Ambient soil ($P<0.05$), diamond-x indicates significant differences between MSL and both Ambient soil and MSNL, and plus (+) indicates significant differences between both MSL and PSL and the Ambient soil on a given day (at 1800 h).

Fig. 6. Comparison of volumetric water content (θ_v) as determined by DPHP sensors and gravimetric (Lysimeter) methods for MSL (A), PSL (B), and MSNL (C) microlysimeters.



Volumetric Soil Water Content (m3 m-3)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
A
0-30 cm profile
B
0-20 cm profile
Irrigations
MSNL
Ambient
MSL
PSL
197
198
199
200
201
202
203
204
205
206
207
208
209
Day of Year, 2002

Figure 1

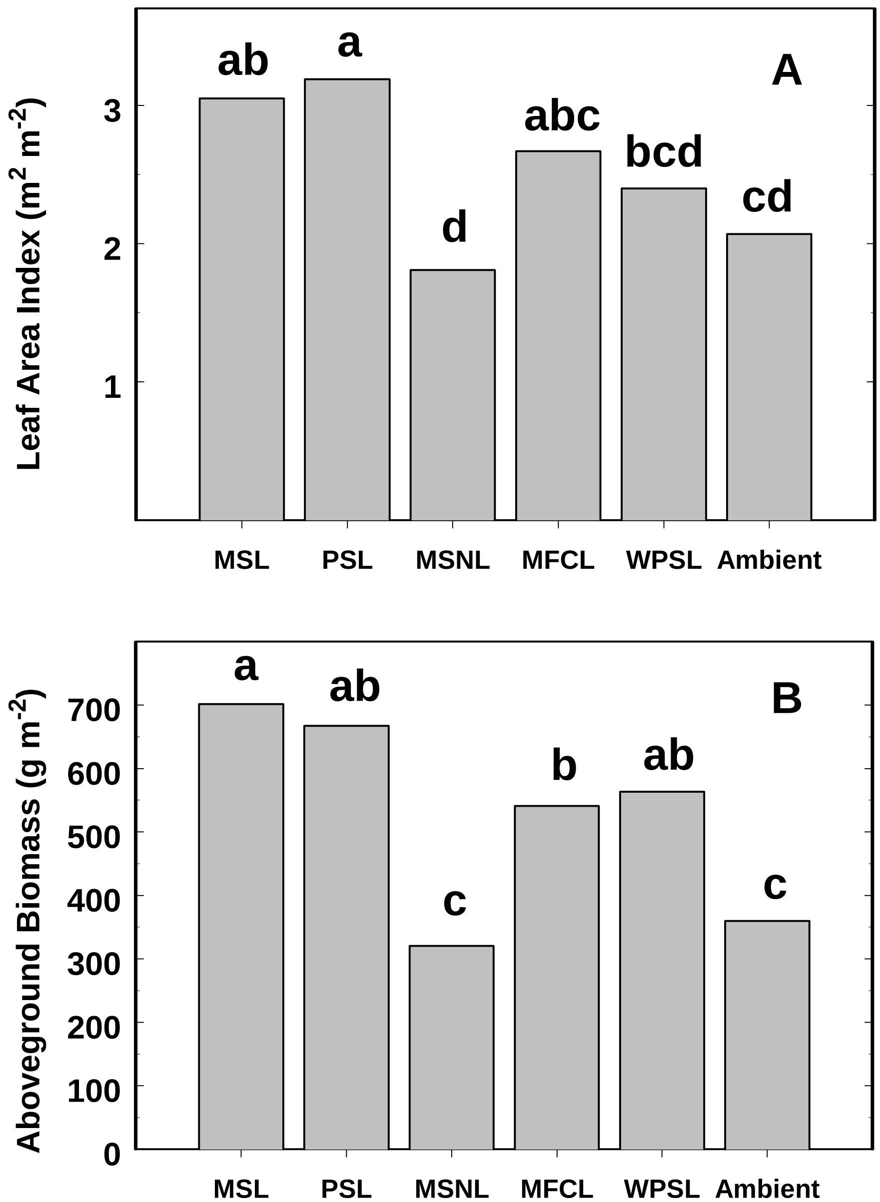

Leaf Area Index (m2 m-2)
3
2
1
ab
a
d
abc
bcd
cd
A
MSL
PSL
MSNL
MFCL
WPSL
Ambient
Aboveground Biomass (g m-2)
700
600
500
400
300
200
100
0
a
ab
c
b
ab
c
B
MSL
PSL
MSNL
MFCL
WPSL
Ambient

Figure 2

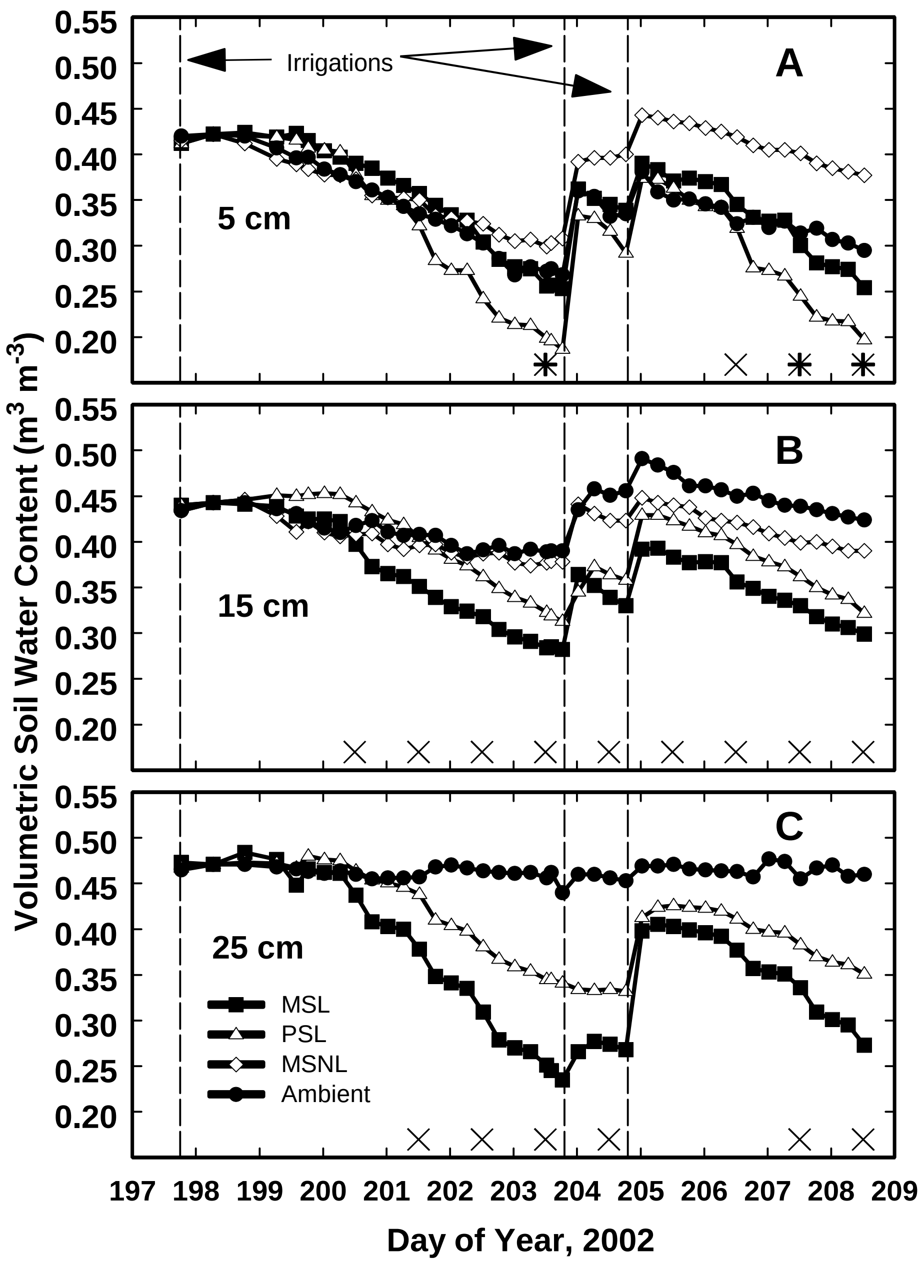
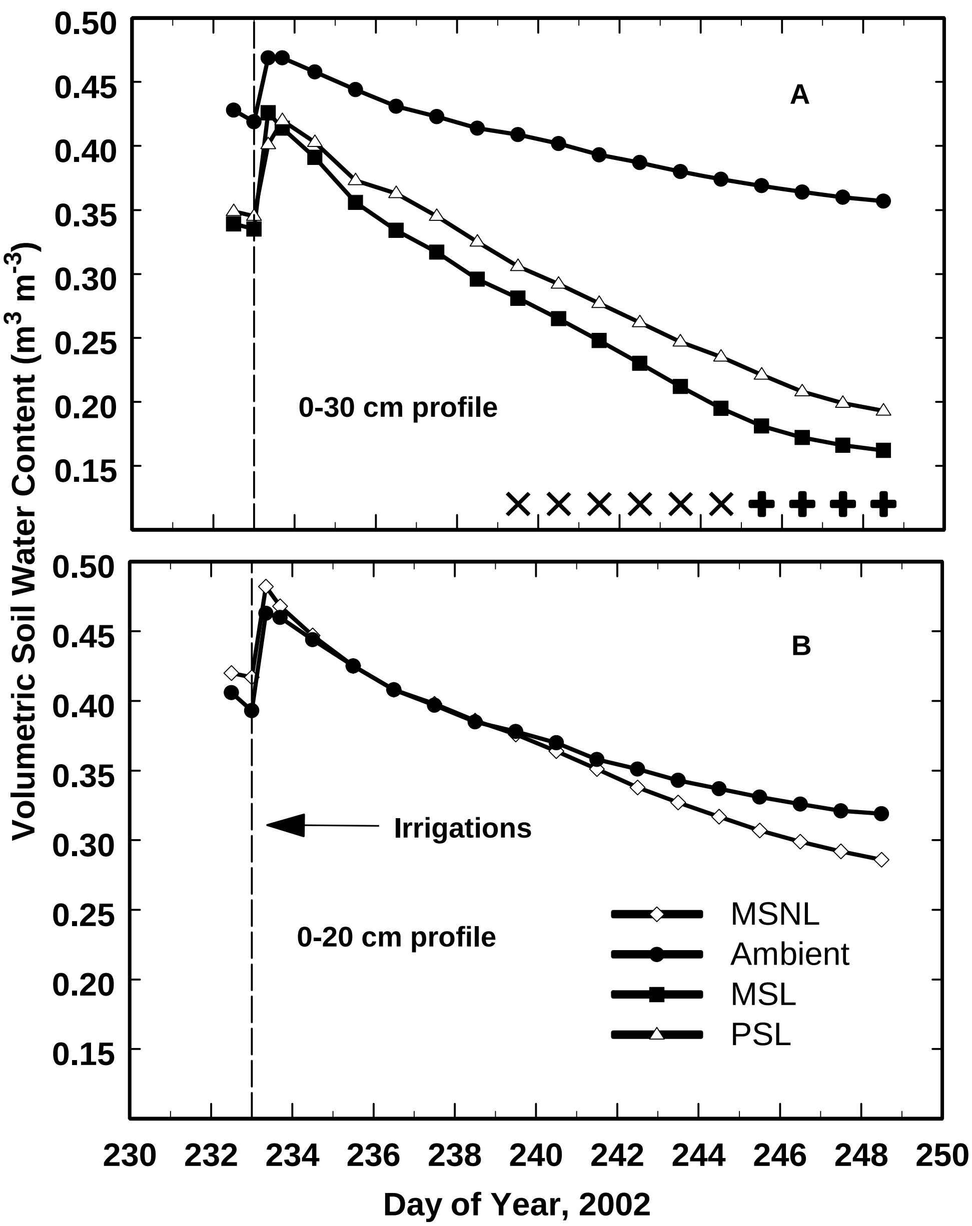
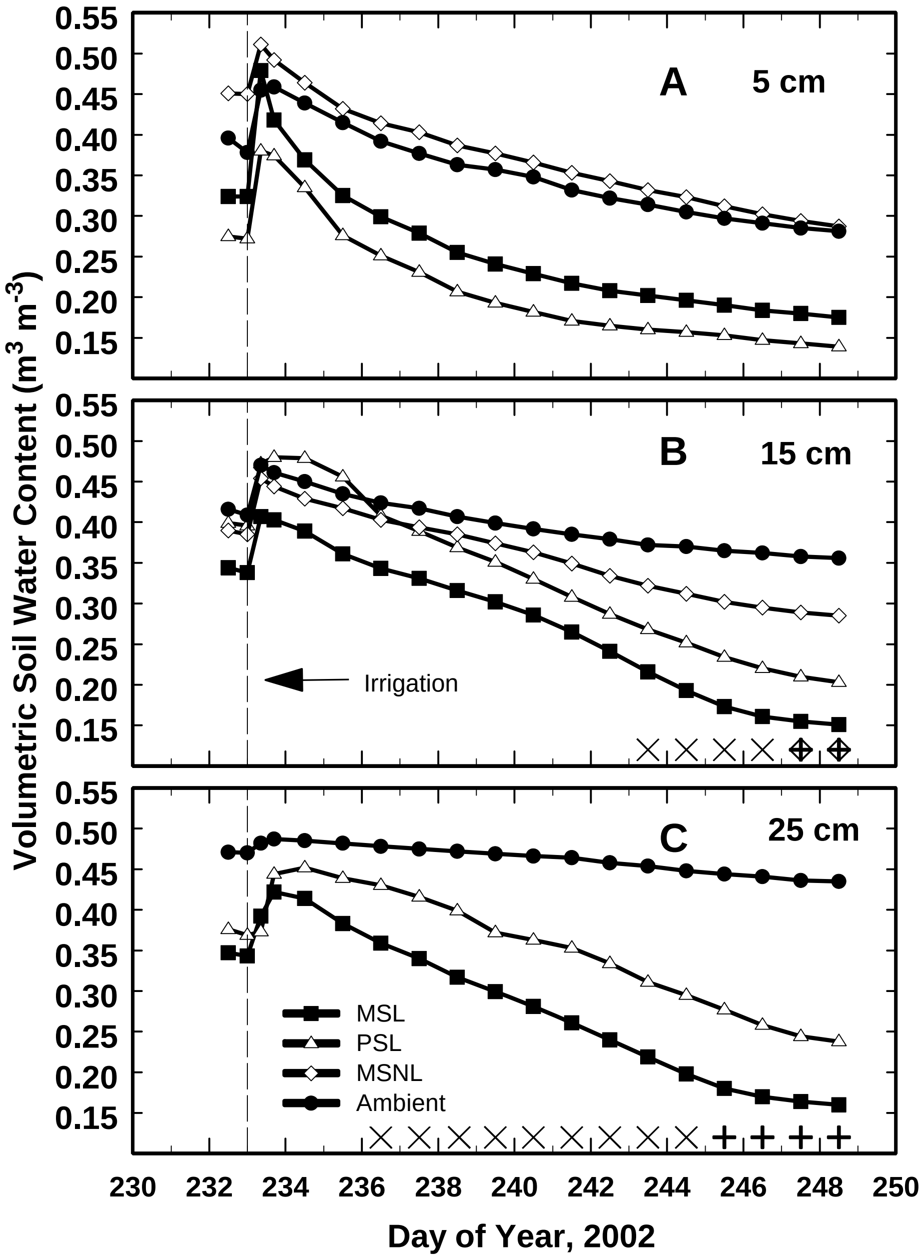

Irrigations
A
5 cm
B
15 cm
C
25 cm
MSL
PSL
MSNL
Ambient
Volumetric Soil Water Content (m3 m-3)
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
197 198 199 200 201 202 203 204 205 206 207 208 209
Day of Year, 2002

Figure 3



Volumetric Soil Water Content (m3 m-3)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
A
0-30 cm profile
B
Irrigations
0-20 cm profile
MSNL
Ambient
MSL
PSL
230
232
234
236
238
240
242
244
246
248
250
Day of Year, 2002

Figure 4



Volumetric Soil Water Content (m³ m⁻³)
A
5 cm
B
15 cm
Irrigation
C
25 cm
MSL
PSL
MSNL
Ambient
Day of Year, 2002

Figure 5

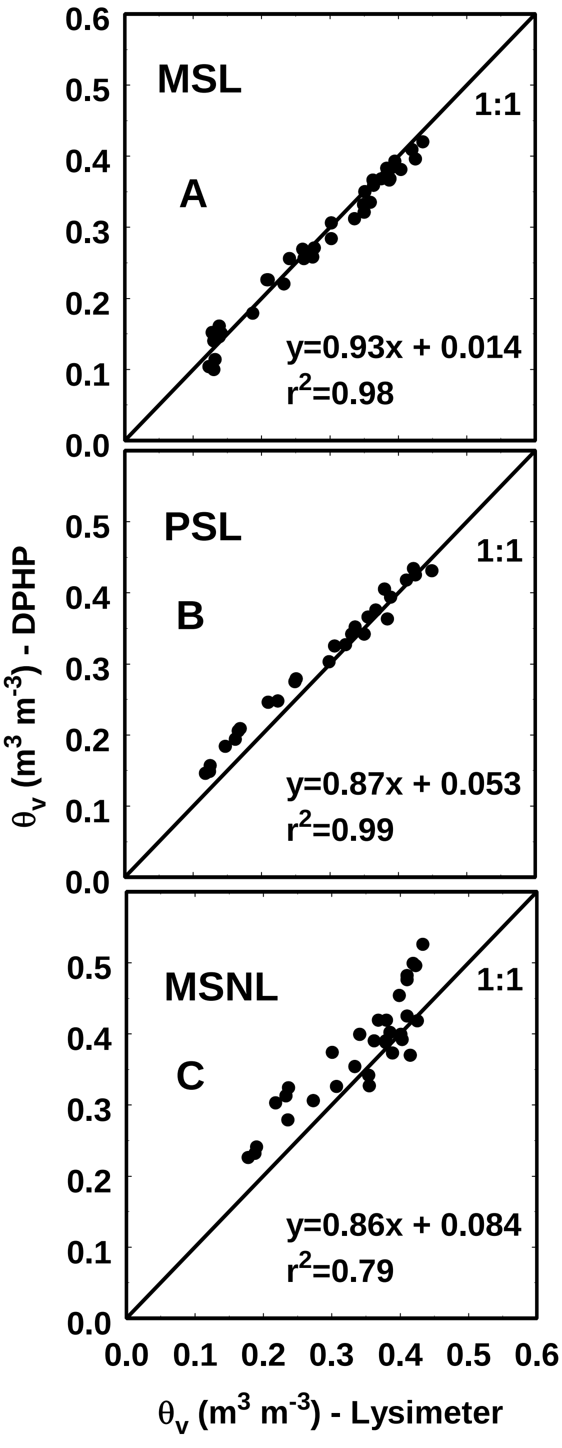

MSL
A
1:1
y=0.93x + 0.014
r2=0.98
PSL
B
1:1
y=0.87x + 0.053
r2=0.99
MSNL
C
1:1
y=0.86x + 0.084
r2=0.79
θv (m3 m-3) - DPHP
θv (m3 m-3) - Lysimeter
0.0
0.1
0.2
0.3
0.4
0.5
0.6

Figure 6