# Evapotranspiration Measurement in Controlled Environment Chambers: A Comparison between Time Domain Reflectometry and Accumulation of Condensate from Cooling Coils

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## ABSTRACT

**The measurement of water fluxes from canopy and soil surfaces is performed in sunlit controlled environment chambers by measuring condensate draining from cooling coils in a constant humidity environment. This provides a direct measure of evapotranspiration (ET). However, in growth chambers with soilbins, this does not give information on soil water status or root activity. The objective of this study was to compare ET measurements from the condensate system with ET calculated from measurements of water content by TDR. Data from an irrigation × carbon dioxide ($CO_2$) study on potato (*Solanum tuberosum* L.) were used for this study. The soil water contents in the growth chamber soilbins were monitored once an hour at five vertical depths with three measurement locations per depth using an automated TDR system. The correspondence between daily ET rates for the two systems was good. Maximum daily ET rates were near 6.1 to 7.1 mm $cm^{-2}$ $d^{-1}$ (7–8 L $d^{-1}$ on a chamber basis) and differences were on the order to 0.89 to 1.8 mm $cm^{-2}$ $d^{-1}$ (1–2 L $d^{-1}$). At the higher daily ET rates, the daily values from the two methods were closer. The correspondence between hourly measurements of ET measured from the condensate system and calculated from TDR water contents was poor due to instrument and soil variability. A significant source of error was vertical variation in water content in the soil between horizontally placed TDR probes, especially during irrigation events. Evapotranspiration estimates from TDR measurements were much more robust for calculation of water use over a period of time. Data from the condensate system were most useful for quantification of diurnal transpiration rates and were better correlated with radiation.**


Sunlit growth chambers are important research tools to study environmental effects on plant growth and development under controlled conditions (Liu et al., 2000; Pickering et al., 1994). Chambers with tight control of temperature and $CO_2$ and a means to measure $CO_2$ gas exchange rates are known as SPAR (soil plant atmosphere research) chambers (Liu et al., 2000). Furthermore, SPAR chambers have soilbins that provide a relatively realistic volume of soil to monitor soil and root processes (Reddy et al., 2001). When leakage is accounted for (Baker et al., 2004, Acock and Acock, 1989), SPAR chambers allow precise quantification of C balances and transpiration under a wide range of experimental conditions and natural light. They have also been very useful to quantify water use in plants because of the use of a seminatural rooting volume and ability to control humidity (Allen et al., 2003; Kim et al., 2006).

Collection of condensate from cooling coils has been used to quantify ET of water from plant surfaces when water vapor concentration in the atmosphere inside the SPAR chamber can be kept constant and leakage minimized. Measurements of condensed water have been shown to be correlated with $CO_2$ assimilation (Weiland and Stutte, 1980; Reddy et al., 2001; Baker et al., 1990) making this a useful method to quantify water fluxes from plant surfaces. Methods to collect condensate include use of a collection receptacle with a pressure transducer to measure height of water (Reddy et al., 2001), tipping bucket rain gauges (Allen et al., 2003; Baker et al., 1997) or manual measurement of water collection containers (Wheeler, 1992). The total water collected represents both transpiration of water from plant surfaces, and evaporation from free water and/or soil surfaces. Evaporation from free water or soil surfaces dominates when plants are small and the soil is wet (Wheeler and Sager, 1990). As the canopy grows the total water collected better represents transpiration from plant surfaces. Research using these data has provided useful insights into water use efficiency and water relations of plants (Allen et al., 2003; Kim et al., 2006; Reddy et al., 2001).

Although many growth chambers allow cultivation of plants in pots, growth chambers that provide quasi-realistic soil volumes are useful to investigate root growth and water use under conditions more similar to those experienced by plants in natural environments (Reddy et al., 2001; Katul et al., 1997; Tingey et al., 1996; Baker et al., 1990). Water content in growth chamber soilbins have been monitored for agricultural crops using tensiometers (Baker et al., 1997) for the purpose of quantifying water stress effects on plant growth. Because tensiometers measure water potential, they do not provide data on water uptake directly. Time Domain Reflectometry (TDR) has been used to measure soil water content in situ (see Noborio, 2001 for a review). Time Domain Reflectometry systems have not been widely used in growth chambers equipped with soilbins and with gas exchange measurement systems for agricultural crops but have been used with trees (Pataki et al., 1996; Katul et al., 1997). The advantage of the TDR system is that it can be automated, has high repeatability and the size and number of waveguides can be adapted to different soil volumes. They have been used in conjunction

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**Abbreviations:** DAE, days after emergence; ET, evapotranspiration; PAR, photosynthetically active radiation; RMSE, root mean square error for the regressions; SPAR, soil plant atmosphere research; TDR, time domain reflectometry.

with sap flow measurements in field-grown maize (*Zea mays* L.) and have shown good results (Li et al., 2002; Nadler et al., 2002). We have not found any studies that compared ET rates measured with TDR to ET measurements from condensate systems. The objective of this study therefore was to compare transpiration measurements from condensate and TDR systems under different irrigation and $CO_2$ treatments and evaluate the use of TDR in sunlit growth chambers with soilbins.

## MATERIALS AND METHODS

### Growth Chamber

The data for this analysis is a subset of data from a more comprehensive experiment to quantify water stress effects on potato under two atmospheric $CO_2$ concentrations and six irrigation regimes. The experiment was performed in 12 SPAR sunlit and controlled environment chambers with soilbins located at the USDA-ARS, Henry A. Wallace Agricultural Research Center, in Beltsville, MD. This facility is comparable in design and operation to similar experimental systems at the University of Florida (Pickering et al., 1994), Corvallis, OR (Tingey et al., 1996), and Mississippi State University (Reddy et al., 2001). The SPAR chambers consist of transparent chamber tops, 2.2 by 1.4 by 2.5 m (length × width × height) constructed of 0.0127-m-thick Plexiglas. Total photosynthetically active radiation (PAR) inside the SPAR chambers is within 10% of the ambient values (Kim et al., 2004). Each SPAR chamber top is mounted on a steel soilbin measuring 2.12 by 0.54 by 0.85 m (length × width × depth). The chambers were sealed as tightly as possible to minimize exchange of air with the outside system. A physical description and the light environment of these SPAR chambers and methods of operation and monitoring have been described previously (Baker et al., 2004; Kim et al., 2004). Humidity was controlled to vary within 1 to 3% $d^{-1}$ by alternating cooling and heating of the air in the chamber. The air in these semiclosed chambers passed over the cooling coil and heating elements 30 times $min^{-1}$ (2.5 m $s^{-1}$ air velocity). The cooling coil was 1.83 m wide and 1.22 m high.

The soilbins were filled in layers (approx 0.15 m thick and 2.12 by 0.54 m in area) and wet thoroughly as each layer was added. The manufactured soil was 75% sand and 25% vermiculite (Grace Construction Products, Cambridge, MA) by volume. Irrigation was provided by compensated drippers arranged in three 2.0-m rows with an approximate spacing between rows of 0.20 m. Within-row spacing was approximately 0.10 m. The drip irrigation system supplied approximately 70.2 mm $cm^{-2}$ $h^{-1}$ (80 L) of water per soilbin. During the growing season, irrigation amount was controlled so the bottom layer did not saturate to prevent drainage of water from the soil.

### Condensate Measurement System

Condensate from the cooling coils was collected in a trough and directed to a pipe leading out of the chamber. The water from this pipe was collected in a tube with a volume of 0.80 L outside the chamber (Fig. 1). A transducer, calibrated for liters of water, and located at the bottom of the tube measured the height of water in the column. The height of water was converted to volume of water via a linear calibration with voltage. This calibration was checked once during the growing season by adding known volumes of water to the tube and found to be stable. Solenoids at the top and bottom of the tube controlled water flow into and out of the tube. At the end of every 15 min, the upper solenoid valve was closed, water amount measured, and the water dumped via the lower solenoid. One minute later, an empty tube measurement was made and the upper solenoid opened. The volume of water was the difference between these two measurements. This second measurement provided a constant empty tube baseline that minimized effects of temporal variation in transducer response. Control was via a custom FORTRAN program running on a Sun/Solaris system (Sun Microsystems, Santa Clara, CA).

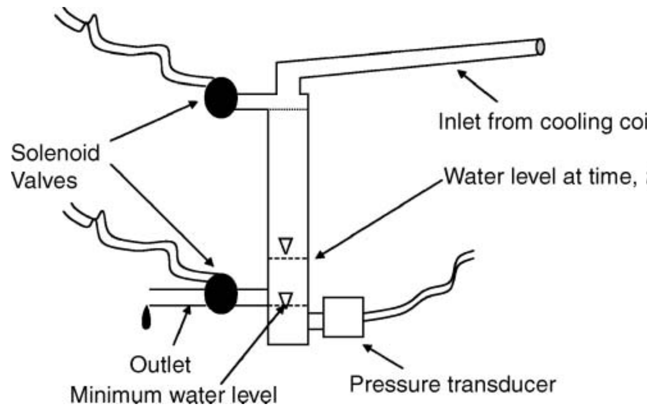

**Fig. 1. Schematic of condensate collection system.**

### Plant Culture

Day/night temperatures were held constant at 23/18°C. The cultivar Kennebec was planted at a rate of 12 plants chamber$^{-1}$ (1.14-m$^2$ area) on 30 May 2005. Fifty percent emergence was recorded on 10 June 2005. In the complete experiment, there were two levels of $CO_2$, 370 and 740 μmol mol$^{-1}$ and six irrigation treatments. Irrigation was varied by applying 10, 25, 50, 75, and 90% of that applied to the fully irrigated (100%) treatment. The fully irrigated treatment was irrigated to fully replace water lost by ET. For this study, data from the 25, 75, and 100% irrigation treatments were chosen from each of the two $CO_2$ treatments. The soil surface was covered with a plastic sheet in each chamber to minimize soil evaporation. Irrigation was applied nightly at 2300 h to minimize redistribution of water during the daylit period. The total irrigation amounts varied from 2 to 18 L of water per day (1.7–16 mm).

### Time Domain Reflectometry Soil Water Content Measurement System

Fifteen 0.30-m-long TDR waveguides (3 rod) were installed horizontally in the soilbin perpendicular to the widest dimension. These were installed at five depths, replicated at three horizontal positions (Fig. 2). A total of 12 SPAR soilbin units were monitored. The 180 waveguides were split between two separate measurement systems because of the time required to acquire data (10–12 min for 90 waveguides), disk space available, and to minimize cable length. Each system was comprised of a 1502B/C Tektronix (Beaverton, OR) cable

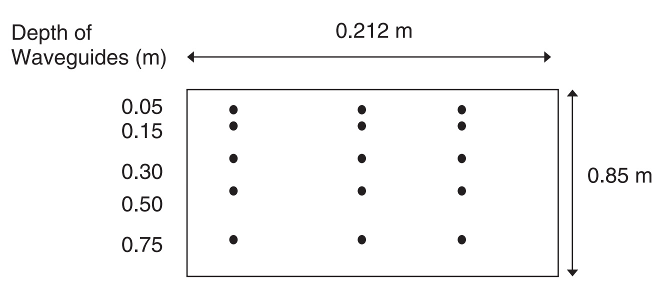

**Fig. 2. Location of TDR waveguide placement in the SPAR soilbin.**

tester, and multiplexers [Campbell SDMX50 (Campbell Scientific, Logan, UT) and Dynamax TDR200, (Dynamax, Houston, TX)]. A small PC/104 embedded computer (Winsystems, Dallas, TX) or laptop controlled the system using TACQ software (Evett, 1998) running under ROM-DOS (Datalight, Bothell, WA). The signals were measured hourly and both water contents and waveforms recorded. A calibration relationship between volumetric water content and the apparent permittivity was developed using soil from the chambers. Water contents from air-dry to saturation were used in the calibration. The apparent permittivity was calculated by the TACQ software (Evett, 1998).

### Data Analysis

Six of the 12 treatments were chosen for this comparative study. These were the 25, 75, and 100% irrigation treatments in each of the $CO_2$ treatments. Data for the analysis were chosen from the days when the growth chambers were closed. Generally, the chambers were opened 2 d $wk^{-1}$ when physical measurements were taken on the potato plants. Data associated with system malfunctions were removed from both the TDR and condensate data. The condensate data were smoothed using Proc Loess (The SAS System for Windows, 9.1, SAS Institute, Cary, NC). The TDR data were only smoothed before calculation of hourly evapotranspiration rates that were calculated by differencing hourly measurements. The hourly TDR water contents were multiplied by soil volume for each layer to obtain total volume of water in the soilbin for each hourly measurement. The hourly water volumes were averaged by depth and summed to obtain a total hourly water volume in the soilbins. Water use per day was calculated from the TDR data as the difference between the morning and evening water volumes. Average water content from the 0800- to 1000-h period was used for the morning water content and an average from the 1800- to 2000-h period used for the evening water content. The late morning time was chosen to minimize the impact of water redistribution from late evening irrigation the night before on the morning water contents. Daily water use was calculated from the condensate data by summing the smoothed 15 min values over the same period. The use of later morning data (0900 h, Eastern Standard Time) would tend to slightly underestimate water use by 0.1 to 0.15 L but allow more a representative comparison between the two methods.

The SAS procedure Proc Mixed (Littell et al., 1996; SAS Institute, 2004) was used to calculate the coefficients of the regression for the strength and bias of the relationship between daily values of ET for the two methods. The experimental design is treated as a repeated measures analysis with chamber as the subject and carbon dioxide and irrigation as fixed effects.

## RESULTS

Hourly values of the volume of water in the soilbins from the TDR system for a period of 3 d show the dynamics of the soil water due to infiltration and water uptake (Fig. 3). The diurnal trends in water content over time show the effects of water uptake on soil water contents during sunlit hours. Differences in daily water use by the potato plants as a function of irrigation level in the soil are discernable. There is also a steady decrease in water contents over time in the treatments with the lowest irrigation rates. The seasonal trends of daily ET rates for individual treatments over the growing season calculated from the TDR water content data

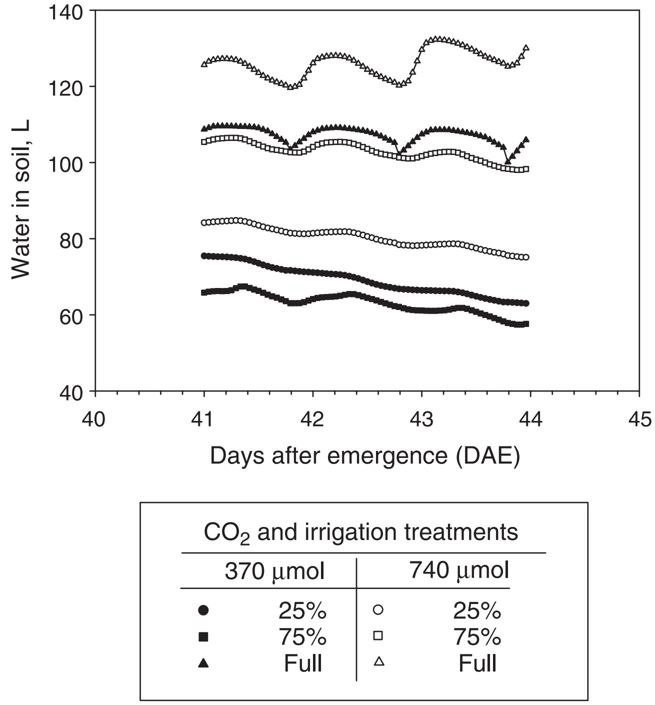


**Fig. 3. The hourly dynamics of profile water volume in the six treatments from TDR water content data from the period 21 to 24 July 2005 (41–44 DAE).**

and from the condensate data showed a generally good correspondence between the two methods (Fig. 4). The increase in ET as the canopy developed to full cover at about 45 d after emergence (DAE) (28 July 2005) is similar for both methods. Although the TDR data show more day to day variation than the condensate data, both methods show similar overall trends for the different treatments.

Evapotranspiration calculated from condensate water and PAR aggregated over 15-min intervals for the three irrigation levels in the 370 μmol $mol^{-1}$ $CO_2$ are shown in Fig. 5. The 2 d have contrasting radiation levels, and the response of the condensate system to radiation can be seen in the data. The ET data also correspond to the irrigation treatments. The 25% irrigation treatments had the lowest ET rates and the 100% treatments the highest. This is a function of both irrigation level and plant canopy size. Note that since the soil was covered with plastic there should have been minimal contribution from the soil to ET.

Correspondence between hourly ET rates calculated from TDR water contents and condensate data are shown in Fig. 6 for 2 d and both $CO_2$ treatments. The agreement is good for some treatments but not all. A diurnal pattern present in the TDR data is similar to the pattern in the condensate data but not as well defined. The agreement between the two methods for the daily ET rates is pronounced (Fig. 7). Intercepts and slopes for the regressions between the rates for the two methods are given in Table 1. The intercepts were all significant and ranged from about 0.44 to 0.88 mm $cm^{-3}$ $d^{-1}$ (0.5–1.0 L $d^{-1}$). The slopes were all less than 1.0 with the two lowest slopes in the 25% irrigation treatment. The root

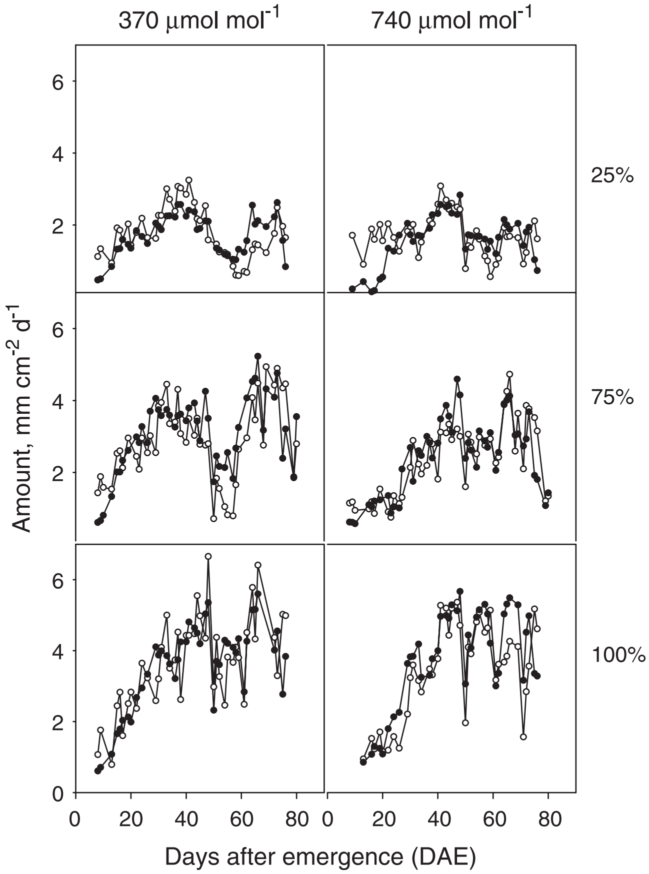


**Fig. 4. Daily ET rates over the growing season for individual treatments from TDR water contents (open circles) and condensate system (closed circles).**

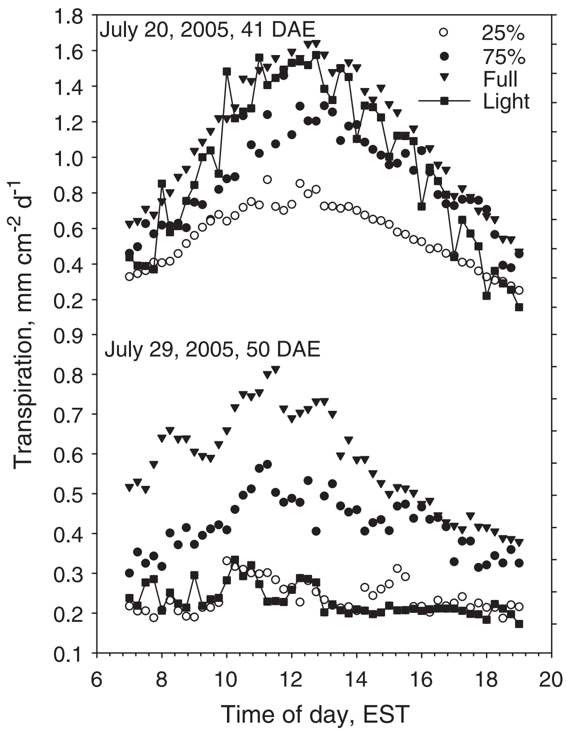


**Fig. 5. Hourly ET from condensate data and photosynthetically active radiation (PAR) data for the three irrigation levels in the ambient (370 μmol mol$^{-1}$) treatment.**

mean square error for the regressions (RMSE) ranged from 0.35 to 0.7 mm cm$^{-2}$ d$^{-1}$ (0.4–0.8 L d$^{-1}$). Since maximum ET rates were near 7 mm cm$^{-2}$ d$^{-1}$ (8 L d$^{-1}$), this represents a 5 to 10% error. The error appears consistent over the range of data (Fig. 7).

## DISCUSSION

While the two systems both provide estimates of ET rates from the plant/soil system, the sources, levels of detail, and temporal/spatial scales of the data are different. The condensate data provide near-instantaneous measurements of ET since water transpired by the plants is constantly being removed from the chamber atmosphere by the cooling system to maintain a constant vapor pressure density. The condensate system response is rapid enough to detect a change in transpiration rate as PAR changes (Fig. 5) within a time of at least 15 min (the measurement interval). This is similar to the response of stemflow gauges in a shrub, *Ligustrum japonicum* Thunb. (Heilman and Ham, 1990). In the TDR system, the loss of water from the soil is lagged by transport through the plant over the 1-h-measurement interval and thus TDR data do not provide instantaneous information on water use on the same time scale as the condensate data. Also, plants have capacitance for water; hence the water flow from the soil through the plant lags behind transpiration (Schulze et al., 1985).

On a spatial scale, the ET rate from the condensate data is integrated over all the plants in the growth chamber. The TDR water content data however, are spatially variable depending on placement of the waveguides and variability of the soil surrounding the waveguides. The ET rates were calculated from changes in water contents at the five different depths and three horizontal positions where the probes were located. Each of the three locations represented a "column" of soil over which the changes in water content were summed to obtain ET rate. Differences in root density and available water in the soils surrounding the probes can contribute to variances in the calculated ET rates among the three "columns" of soil. It is known that measured soil water uptake rates by plants can vary depending on location of the water content measuring device relative to the plant stem (Van Wesenbeeck and Kachanoski, 1988; Timlin et al., 2001) because of differences in root density as a function of horizontal distance from the stem. We attempted to minimize bias due to waveguide location by distributing the waveguides evenly among row, interrow and quarter-row positions based on planned planting locations.

Measurement of ET calculated from soil water contents is complicated by the non-uniformity of the distribution of water and roots in the soil, and the small measurement volume of the TDR waveguides. To calculate the total volume of water in the soilbin it is assumed that the water content measured by a waveguide is constant in a layer that extends from midway between two adjacent waveguides above and below the waveguide. Nonuniform water content within this layer of soil

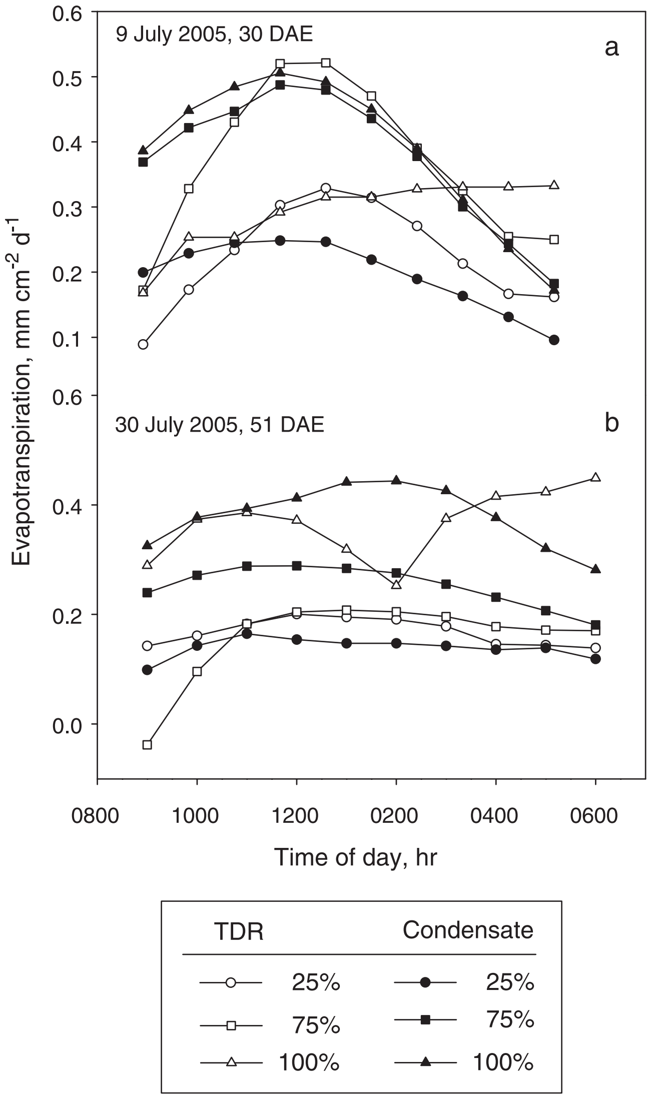


Fig. 6. Hourly ET from TDR and condensate systems for the 370 μmol mol$^{-1}$ treatment for 2 d in the experimental period.

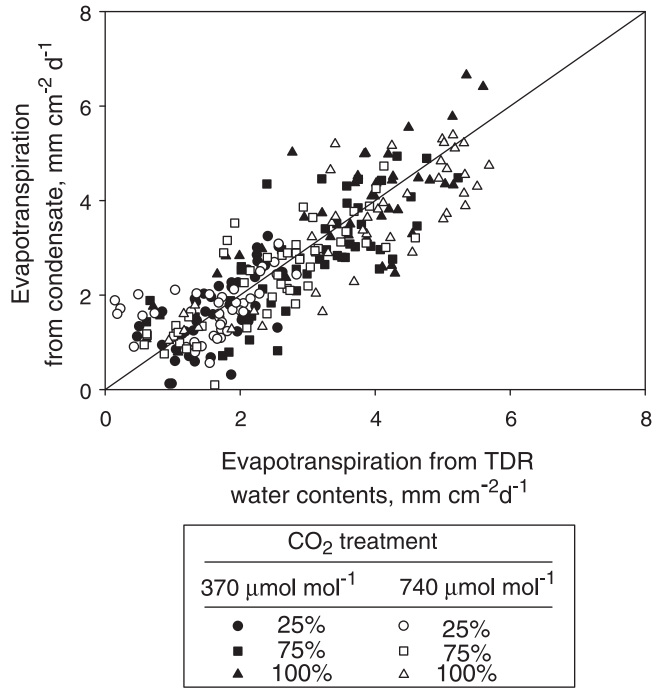


Fig. 7. Comparison of daily ET rates condensate and TDR systems for the experimental period.

surrounding the horizontally oriented TDR waveguide reduces the accuracy of the water content measurements. Each waveguide only senses a thin layer of soil above and below it, about 0.01 to 0.02 m (Baker and Lascano, 1989; Nadler et al., 2002), therefore, the entire layer is not measured. The widths of the soil layers surrounding the waveguides, and used to calculate volume of water in the soil, are dependent on the number of horizontal waveguides arranged vertically in the soil.

Better discretization can be obtained by using more waveguides with depth but this increases the cost of the system. In this experiment, more waveguides were installed near the surface with the assumption that most of the water content changes would be at the surface where root density is higher rather than deeper in the soil, especially with irrigation. The layer thicknesses for the measurements increased with depth (Fig. 2). Furthermore, the water contents at the bottom of the soilbins may be more variable within a layer. This is due to the larger thickness of the bottom layer (0.225 m) relative to the surface layer (0.1 m) and the nonlinear variation in water content as a function of depth.

The variation in water content in the bottom soil layer is partially due to the nature of the bottom boundary of the soilbin; the bottom boundary is open to the atmosphere. This atmospheric boundary results in a discontinuity in the conductivity of the soil pores and does not allow for movement of water unless the soil water in the soilbin at the bottom boundary is under positive pressure. Although we controlled irrigation to limit saturation and hence drainage, the water content in this layer was generally higher than the drained water content except later in the season in the soilbins with the lower irrigation amounts. Estimates of total water in the bottom layer therefore would likely be somewhat less accurate than those in layers above with more uniform water contents.

Sources of error in the condensate system include calibration errors arising from uncertainty of the slope and intercept that define the relationship between water amount and pressure transducer voltage. The range in

Table 1. Parameters for the regression between daily ET rates measured by condensate (dependent) and TDR (independent). Slopes and intercepts were all significant ($p < 0.01$).

| Treatment | Intercept | Slope | $R^2$† | RMSE‡ |
|---|---|---|---|---|
| | mm cm$^{-2}$ d$^{-1}$ | | | mm cm$^{-2}$ d$^{-1}$ |
| | Ambient (370 μmol mol$^{-1}$) | | | |
| 25% | 0.86 | 0.49 | 0.46 | 0.42 |
| 75% | 1.04 | 0.71 | 0.55 | 0.72 |
| Full | 0.84 | 0.73 | 0.60 | 0.79 |
| | Elevated (740 μmol mol$^{-1}$) | | | |
| 25% | 0.68 | 0.54 | 0.20 | 0.61 |
| 75% | 0.47 | 0.82 | 0.66 | 0.62 |
| Full | 0.88 | 0.84 | 0.70 | 0.76 |

† $R^2$, the proportion of variance explained by regression.
‡ RMSE, root mean square error for the regressions.

slopes from calibration for different transducers should be similar to the range for one transducer for different calibrations. Therefore, the standard error of the mean of the slopes for the 12 pressure transducers in all the SPAR chambers of 3.4 mL volt$^{-1}$ should be no more and probably less than the standard deviation of multiple calibrations for a single transducer. The average slope is 64.7 mL V$^{-1}$ so the maximum error is about ±5% or about 0.050 L L$^{-1}$.

An additional source of error for the condensate system is leakage of water vapor into or out of the chamber. Based on an average external/internal daytime temperature of 26:23°C and external/internal relative humidity of 75:65%, the vapor pressure difference between the inside and outside of the chamber was about 0.7 kPa. This results in an average leakage of 0.036 L h$^{-1}$ (0.032 mm cm$^{-2}$ h$^{-1}$) of water into the chamber based on an average leakage rate for $CO_2$ measured for the chambers. This estimate compares to condensate collection rates of about 0.20 to 0.60 L h$^{-1}$ (0.2–0.5 mm cm$^{-2}$ h$^{-1}$), and may result in an error of about 5 to 10%.

There was small but significant bias in the daily ET values calculated from the TDR data as compared to values calculated from the condensate system (Table 1). The bias was typically less than 0.87 mm cm$^{-2}$ d$^{-1}$ (~1.0 L d$^{-1}$). The large error at small ET rates contributed to the bias. Overall, both methods calculated similar amounts of daily ET. The RMSE was on the order of 0.42 to 0.79 mm cm$^{-2}$ d$^{-1}$ (0.47–0.88 L d$^{-1}$). There was not a significant $CO_2$ effect ($p < 0.01$) on the slopes of the relationship between daily ET estimates by the two methods (Table 1) for the three irrigation treatments. There was a significant irrigation effect ($p < 0.01$); the slope of the relationship for the 25% irrigation treatment was significantly less than both the 75 and 100% irrigation treatment slopes. Overall, the ET rates from TDR data were underestimated relative to transpiration from the condensate system. The underestimation was worse for the lowest irrigation amounts. The best correspondence between the two methods occurred when the ET rates were high. The reason for these differences may be partially due to the depth of irrigation and the sensitivity of the TDR waveguides. Irrigation amounts were smallest for the 25% irrigation treatment, typically about 1.75 to 3.5 mm of water (2–4 L) though sometimes more. This would only wet the soil to about 0.05 to 0.08 m when the soil was very dry and so was often not detectable by the TDR. When this volume was not seen by the TDR, uptake of the irrigated water by the plants was also not detected so that ET would be underestimated by the TDR method. Leakage of water vapor into the chambers would also result in a positive bias toward the condensate data. Since the leakage rate is small, it would result in greater relative errors when overall ET rates were small.

Redistribution of infiltration, where the moving wetting front could be slightly above or below a waveguide, may result in bias when estimating the average water content in a layer. Although irrigation was applied at night, there was still some redistribution continuing in the morning in the middle layers, especially in the well-watered treatments where larger amounts of irrigation were applied. Because of uncertainties in the water content of the layer surrounding the TDR waveguides when calculating total water volume in a layer, the loss of water from one layer was not always equal to the gain of water in another. Therefore, for short periods of time (2–6 h) water contents appeared to be increasing or decreasing in the soilbins in the absence of water uptake or infiltration. The errors were small (~1–2 L) relative to the total amount of water in the soilbin but large enough to cause errors in hourly or daily ET rates that were on the order of 3 to 8 L d$^{-1}$. This has a smaller impact on long term, i.e., weekly to seasonal estimates of ET however.

The correlation between hourly values of ET from the two methods was poor. The TDR data can be noisy and differentiation over short time periods accentuates the noise in hourly measurements. Some of this noise is due to the resistances in the cables and connectors, waveform analysis method (Evett, 2000), and the variation in water content over the growth chamber's soilbin. The data were smoothed but there still remained some variation. It was likely that redistribution of irrigation as discussed previously contributed to this variation, especially in the morning. Theoretically, measurements of water content using the same waveguide can provide repeatable measurements on the order of 0.005 cm cm$^{-3}$ water content (Nadler et al., 2002). The errors in the data in this study varied from 0.005 to 0.05 cm cm$^{-3}$ based on analyses of short periods of water content data when infiltration and water uptake were relatively insignificant. Depending on the volume of soil in different layers, this water content measurement error resulted in errors in changes in volumes of water that ranged from 0.3 to 1.3 L layer$^{-1}$. This is close to the hourly changes in water volume due to water uptake calculated from the TDR water contents (Fig. 6). These errors reduce the precision of the TDR and thus reduce the ability of the system to discriminate differences in water content over short periods of time.

The precision of the ET rate measurement by TDR is better if the water uptake is primarily limited to one or two layers rather than the whole profile. This is because the removal of 0.6 L of water from a 0.1-m layer of soil would result in a larger change in soil water content than would removal of the same amount from a 0.2-m layer of soil. For example, the change in average layer water content that would result from the removal of 0.6 L of water would be about 0.005 cm cm$^{-3}$ for the 0.1-m layer and 0.0026 cm cm$^{-3}$ for a 0.2-m layer of soil. A resolution of 0.6 L would be within the theoretical precision of TDR (0.005 cm cm$^{-3}$) for a layer of 0.1 m, but not for a thicker layer. Since the condensate system has no spatial component, its resolution is more consistent over different conditions. The removal of 0.6 L of water in an hour could be easily resolved by the condensate system since the calibration error would add ±0.025 L (given a calibration error of 0.05 L L$^{-1}$) and errors due to leakage would be about ±0.036 L h$^{-1}$.

The TDR waveguides in this study were installed horizontally, perpendicular to the direction of steepest changes in water content. However, where the TDR probes (0.15 m long) were installed vertically, Li et al. (2002) reported good agreement for hourly ET rates from TDR water contents and sap flow measurements for field maize. They also obtained ET rates by using derivatives of polynomials used to smooth the data so long time series of data can be useful to reduce errors. Vertical installation may also provide better estimates of infiltrated water in the surface soil or within the bottom layer (Murray et al., 2004; Nadler et al., 2002). The advantage of vertical installation is that the measurement averages over a volume of soil in the direction of steepest changes in water content. This provides a better average of water content within a layer.

It is possible to collect the TDR water content data on a shorter time interval than 1 h but the amount of additional information that can be obtained depends on the water content difference between the two periods and the precision and accuracy of the TDR data as discussed above. There are more rapid changes in water content over an hourly time period during infiltration and redistribution than due to water uptake by the plants necessitating more frequent measurements during infiltration and redistribution.

## SUMMARY AND CONCLUSIONS

We compared two methods to calculate ET rates in sunlit growth chambers with soilbins. The first method measured accumulated condensate from the cooling coils of the growth chamber, the second used TDR to measure soil water contents from which ET rates were calculated. The condensate system gave excellent estimates of hourly ET rates that showed a response to PAR. The hourly ET rates from TDR water contents were not well correlated with the condensate system. On a daily basis, however the two methods gave similar estimates of ET with a small amount of bias. There were significant irrigation effects on the relationship between the ET values from the two systems but no significant $CO_2$ effects. The slope of the relationship between ET from the condensate system and ET from the TDR system for the 25% irrigation treatment was significantly less than the slopes of the treatments with higher irrigation amounts. On the average, the ET rates from the condensate systems were slightly higher than values from the TDR system. The horizontal installation of the TDR waveguides probably contributed to the error in mass balance calculations of water in the soilbins, and higher error for hourly estimates of ET, especially in the surface 0.1 m where most of the irrigation dynamics were located. An alternative method of installation (e.g., vertical) may be preferable for future work, especially in the surface soil.

The TDR data provide information on continuous changes in soil water content due to ET over time. Missing data can be easily interpolated provided the sequence is not too long. With knowledge of irrigation, a mass balance of water use is easily constructed as long as the water contents at the beginning and end of the periods are known. The benefit of the instantaneous measurement of ET by the condensate system can also be a disadvantage. Small perturbations in the system state as when air with a different humidity level is introduced to the chamber when the doors are opened or during temperature changes inside the chamber will result in inaccurate estimates of transpiration. If the chambers are opened or data are lost due to computer or instrument failure it is also difficult to reconstruct missing or invalid data for the condensate system. The TDR water contents would be useful, therefore, to obtain water use over periods longer than 1 d.

Although the two methods provide similar data on daily ET, the two measurement systems provide additional complementary information. The condensate system gives measurements of ET at 15-min intervals that are sensitive to variations in PAR and are integrated over all the plants in the chamber. Evapotranspiration as a function of depth can be obtained from the TDR water contents to provide an estimate of root activity. Daily ET estimates from TDR water contents are not influenced greatly by missing data or by short-term perturbations in the growth chambers' environment. Therefore the TDR system would be a preferred method to obtain cumulative water uptake over time periods longer than 1 d.

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