A calibration procedure for load cells to improve accuracy of mini-lysimeters in monitoring evapotranspiration

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Abstract
We used twelve load cells (20 kg capacity) in a mini-lysimeter system to measure evapotranspiration simultaneously from twelve plants growing in separate pots in a glasshouse. A data logger combined with a multiplexer was used to connect all load cells with the full-bridge excitation mode to acquire load-cell signal. Each load cell was calibrated using fixed load within the range of 0-0.8 times the full load capacity of load cells. Performance of all load cells was assessed on the basis of signal settling time, excitation compensation, hysteresis and temperature. Final calibration of load cells included statistical consideration of these effects to allow prediction of lysimeter weights and evapotranspiration over short-time intervals for improved accuracy and sustained performance. Analysis of the costs for the mini-lysimeter system indicates that evapotranspiration can be measured economically at a reasonable accuracy and sufficient resolution with robust method of load-cell calibration.

Keywords: crops; evaportranspiration; ET; irrigation; load cell; lysimeter

1. Introduction

Evapotranspiration (ET) is an important hydrological process affecting water balance of all vegetated landscapes. Catchment-scale hydrological models tend to use ET data obtained at a local scale (Bormann, 2008) as direct, large-scale monitoring of ET is expensive (Silva et al., 2010). Alternative methods to estimate ET over large area requires calculation of reference ET (ET_o) with Penman-Monteith equation from measured weather data (Allen et al., 2006) or via weather forecasting (Silva et al., 2010). As transpiration and photosynthesis processes occur simultaneously on leaves, ET rate is considered as an indicator of growth and productivity of vegetation.

On agricultural landscapes, ET represents the major consumptive use of irrigation water and rainfall (Burt et al., 2005). There has been considerable research in the past decade to define ET for various crops to establish the relationship between ET and crop yield (DeTar 2008; Karam et al., 2007; Kirda et al., 1999; Ko and Piccini, 2009; Liu et al., 2002). Due to the world-wide shortage of water in some regions and competition for water from other sectors, there is an impetus to find new ways to conserve water or use it more efficiently (Fereres and Soriano, 2007; Hsiao et al., 2007). Irrigation scheduling is a crop ET based decision to determine when and how much water to apply to a crop field.
Lysimeter is a container or tank used to measure gains and losses of water including ET. Plants can be grown within lysimeters to measure gain or loss of water from the container using the principle of water balance. ET represents the loss of water that can be measured directly with lysimeters when other inputs (gains) and outputs (losses) for the lysimeter are known. Lysimeters have been used for the determination of ET by direct weighing and since 1970s,

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load cells have been used to determine total lysimeter mass with an accuracy of 0.05 mm of water (Malone et al., 1999).

All load-cell based lysimeters require calibration and frequent calibration may lead to excessive workload although a sensible level of quality control is warranted (Malone et al., 1999). In previous studies, load cells have been tested for linearity, repeatability, thermal shift and creep as important aspects of measuring the overall performance of lysimeters (Martin et al., 2001). Since data loggers and on some occasions, multiplexers are used for the collection of lysimetric data, these can affect the accuracy and resolutions of lysimeters (Evett et al., 2009). A recent review by Payero and Irmak (2008) of the performance of various types of lysimeters indicate that the sensitivity of lysimeters (in mm of water) can vary considerably depending on the area, weighing and data recording system used. The purpose of this work is to describe the design and performance aspects of a mini-lysimeter system using twelve load cells with specific focus on calibration to test the system's suitability for long-term monitoring of evapotranspiration in controlled environmental conditions (i.e. glasshouse).

2. Materials and methods

2.1 Features of the mini-lysimeter system

An aluminium frame with adjustable feet was constructed in an engineering workshop to mount 12 load cells and, arranged in a 4×3 grid. A circular aluminium plate was attached to each load cell that allowed experimental containers (lysimeters) filled with soil to be placed over it for monitoring of lysimeter weights at short time intervals.

For the mini-lysimeter system, aluminium, single point, load cells (Model PT2000, PT Limited, Australia) of 20 kg capacity with an expected resolution of 0.1 g were used. Essential parameters for the type of load cells used in our experiment are given in Table 1.

Table 1. Typical values of variables (from load cell specification documents) for the load cells used for the mini-lysimeter system.

Parameters	Value
Full scale output (mV V^{-1})	1.982
Zero load output (mV V^{-1})	-0.825
Input resistance (Ohm)	426.97

Each load cell comprised of four cylindrical holes for mounting: one pair of holes at the bottom and the other pair at the top at the opposite ends of the load cell. The holes at the bottom of a load cell were used to mount the load cell on the aluminium frame. A 6 mm thick, circular aluminium plate (205 mm in diameter) was fixed to the top of each load cell through the two holes on the top. PVC pots (with a drainage dish underneath) were placed over selected load cells as lysimeters so that any variation in its weight could be monitored over time.

The Wheatstone bridge of each load cell had a single shielded cable that enclosed four individually insulated signal cables, colour coded to represent excitation voltage (red for +ve and black for –ve voltage) and signal voltage (green for +ve and white for –ve voltage). The cable from each load cell was connected to a differential channel of an AM16/32B analogue relay multiplexer (Campbell Scientific, Townsville, Australia). Each differential channel represented two consecutive odd and even, single ended channels that could be switched to high (H) and low (L) with a programmable delay period to provide excitation voltage to the load cell and collect signal data from the load cell. After connecting all 12 load cells to the multiplexer, the multiplexer was connected to a CR1000 data logger (Campbell Scientific, Townsville, Australia). The data logger included a 16-bit microcontroller with 32-bit internal CPU architecture that permitted 13-bit analogue to digital conversions with a single DAC (Digital to Analogue Converter) for both signal excitation and acquisition for ratio-metric measurements of signal. Power to the data logger was supplied from a deep cycle, 12 V battery. Typical excitation voltage of ±2500 mV was supplied to each load cell for making a full bridge

measurement. On most occasions, output signal from 12 load cells was sampled with the data logger at 1 min interval and then averaged over 10 min. During signal collection, a 1 s delay was used to allow the relay multiplexer to switch from one load cell to another.

2.2 Sensitivity of load cells to operating environment

Collection of long-term data from load-cell based lysimeters requires consideration of the adequacy of the data logging system to maintain a consistent performance. It has been noted in various technical notes from the data logger manufacturer that when CR1000 data logger is used in a bridge measurement that involves switched voltage excitation, it requires a settling time for the signal to reach its stable value. Sample load cells were subject to settling times within the range of 100-2000 μs to determine appropriate settling time that could be used for signal sampling. During testing for settling time, each signal measurement was repeated 10 times at the selected settling time. The relay multiplexer used with our lysimeter system can also induce a voltage drop that may reduce the excitation voltage at the Wheatstone bridge of the load cell. In order to test if voltage drop has any effect on signal an additional AM16/32A multiplexer was used to bypass the signal relaying multiplexer to provide power for signal excitation. This setting was used to compare signal measurements with and without excitation compensation. For these measurements, signal was collected from unloaded load cells at 1-min interval and signal was averaged over a period of 4 min. For a given load cell, 4-min average signal was collected 14-15 times by extending the signal collection period to1 h.

Sensitivity of load cell to variation in temperature was evaluated over a period of 1 week to capture the range of temperature variation expected within the glasshouse. Since all components of the mini-lysimeter system including load cells were aluminium, there was a possibility of partial exposure of aluminium plates (with or without significant load) to radiation affecting thermal stability of load cells. Thus, an experiment was conducted with random selection of four lysimeters (as replicates) to allocate three shading treatments to determine the sensitivity of lysimeters to variation in temperature (Table 2).

Variation in air temperature and solar radiation during the experimental period was measured within a distance of 2 m from the lysimeter system using HMP50-L Vaisala Humitter (mounted within a radiation shield) and SP110 Apogee silicon-cell pyranometer levelled with AL-100 base, respectively (Campbell Scientific, Townsville, Australia). The effects of hysteresis on load cell signal was tested on five load cells to measure variation in signal under loading and unloading conditions within the weight range of 0-15.7 kg.

Table 2. Treatments used to evaluate the effects of variation in air temperature on the performance of load cells. Lysimeter plates used for testing are shown by plate nos. P1…P12.

Treatments	Plates used for testing	Load (kg)
Zero load + zero shade	P2, P4, P5, P11	0
Small load + full shade	P1, P7, P10, P12	0.1
Large load + full shade	P3, P6, P8, P9	7.4

2.3 Calibration of lysimeters

Signal measured with a load-cell based lysimeter requires calibration in order to convert signal (mV V^{-1}) data into actual load or weight. Before placing any experimental lysimeters over the load cell plates, all load cells were calibrated using a set of four loads (including a zero load) within the range of 0-8.5 kg. Later the calibration was expanded to include a wider range of loads (0-14.9 kg) to combine with the data used for sensitivity-tests of load cells to hysteresis. During calibration of lysimeters, the weight of the desired load was first measured with a pre-calibrated electronic platform balance of 32 kg capacity (± 0.01 g). For a given load, the load cell signal (mV V^{-1}) was captured at 1 min interval over a period of 5-10 min. Then the signals were averaged over 5-10 min and plotted against load (g).

2.4 Analysis of calibration data

The deflection behaviour of a proving ring as used in classical mechanics is analogous to the stretching behaviour of a strain gauge under load within the elastic range of deflection or deformation. The spring (or in case of a load cell the strain gauge) has a stiffness constant that relates to the linear deflection behaviour under a set of loads. If S is considered as the measured signal (in mV V^{-1}) when the load cell is under a given load (W, g) and S_0 the signal (mV V^{-1}) at zero load (W = 0 g), then

$$S = S_0 + W/k, \quad (1)$$

where k = stiffness constant of the load cell (mV V^{-1} g^{-1}). Rearrangement of the terms in Eq. 1 gives

$$k = W/(S\text{-}S_0). \quad (2)$$

When a load cell is subject to zero load, including the situation when a plate is fixed to the load cell, $W = W_0 = 0$ and $S = S_0$. Similarly, at a maximum load, $W = W_{max}$ and $S = S_{max}$.

The stiffness coefficient (k, mV V^{-1} g^{-1}) is the slope of the line joining the points (W_0, S_0) and (W_{max}, S_{max}). Thus,

$$k = \frac{W_{max} - W_0}{S_{max} - S_0} = \frac{W_{max}}{S_{max} - S_0} \quad (3)$$

because W_0 = 0 g.

This is the basis of a 2-point calibration of a load cell that can be used to determine k for prediction of weight (W_p, g) within the range of W and W_{max} for any signal within the range of S and S_{max}. Statistical fit of a linear relationship between S and W can be used to minimise the deviation (measured weight – estimated weight) to an acceptable limit.

2.5 Mini-lysimeter performance

Since the major focus of this work was on calibration, brief details of an experiment with wheat (*Triticum aestivum* L., cv. Lang) are given here to indicate typical evapotranspiration data that could be collected with the mini-lysimeter system. To reduce costs, we used PVC pots (25.2 and 16.7 cm, top and bottom diameters respectively, and 23.2 cm height) with a detachable PVC drainage dish as lysimeters. The conical frustum shape used for the lysimeter did not influence its performance. The drainage holes of all lysimeters were first sealed with a porous, synthetic fabric to prevent any soil loss during drainage. A clay soil (black vertosol, Isbell, 1996) from the top 15 cm was collected from Kingsthorpe research station, Australia (27°30'44"S, 151°46'55"E, and 431 m elevation) for all experiments. Properties of this soil are well documented (Foley and Harris, 2007). The soil collected from the field was air dried, crushed and sieved to reduce all soil aggregates to <9.5 mm and packed in the lysimeters to a height of 19.2 cm to achieve a bulk density of 0.89 g cm^{-3}. During packing of each lysimeter, the weight of air-dry soil used (W_a, kg) and its gravimetric water content (w, %) was measured (on a subsample). This allowed oven-dry soil weight (W_d) for each lysimeter to be estimated as $W_d = (W_a \times 100) / (100 + w)$.

Wheat was grown in twelve lysimeters using four irrigation treatments applied to three blocks (replicates) for simultaneous evaluation of all twelve load cells. The field capacity (FC) of the soil was initially measured using separate PVC pots filled with the same soil as that used for the lysimeters. Seven uniform sized wheat seeds were planted in each pot at 5 cm depth. After planting, each pot was brought to FC by adding tap water to help germination and seedling establishment. After irrigation each pot was fertilized with 0.94 g of Urea (equivalent to 100 kg N ha^{-1}) and 3 g of Super phosphate (equivalent to 60 kg P ha^{-1}). Additional 0.94 g of Urea was applied to all the experimental pots at 60 days after planting (DAP). Most plants emerged within 8 DAP and subsequently thinned at 21 DAP to leave 3 plants per pot.

Irrigation treatments were imposed at 55 DAP as soil water status remained similar and adequate in all lysimeters during the initial period of wheat growth. Irrigation was given to a lysimeter when its weight or equivalent volumetric soil water content reached 40%FC (T40), 50%FC (T50), 70%FC (T70) and 80%FC (T80). The timing and frequency of irrigation for lysimeter varied over time which allowed a range of soil water deficits to develop. Irrigation

was applied on 2, 5, 10 and 15 occasions for T40, T50, T70 and T80 treatments, respectively during a period of 56 -107 DAP. Tap water was used at all times for irrigation with measured volume of water applied within a zone at the centre of each lysimeter to avoid water flow along the soil-container interface. The volume of irrigation and drainage was measured for each lysimeter with a 1 L measuring cylinder throughout the experiment. Net amount of irrigation water retained by soil within each lysimeter was estimated for all irrigation events with the electronic balance (mentioned in the calibration section) after temporary removal of lysimeters from load cells before irrigation and 2-4 h after irrigation (when drainage ceased).

Load cell signal was recorded at 10 min interval throughout wheat growth with occasional breaks of short periods to allow change of power supply unit for the data logger or during weighing of lysimeter with the electronic balance.

3. Results

3.1 Effects of environmental parameters on load-cell performance

Load-cell signal remained constant (0.147 mV V^{-1}) over the settling time 100-2000 μs and SE at any given settling time was small (0.00004 mV V^{-1}). Thus, a default settling time of 450 μs was considered adequate for all signal collection. Although actual voltage used to excite a load cell can deviate slightly when power is supplied via a multiplexer, the measured load cell signal did not differ significantly under unloaded condition (data not shown). Paired t-test of signal data with and without excitation compensation was found to be not significantly different ($P>0.05$, Snedecor and Cochran, 1989). This analysis clearly suggested that compensation of excitation voltage was not required.

Variation in ambient temperature is known to cause a thermal shift in load cell signal although it appears to be of minor importance (Martin et al., 2001). We conducted a separate experiment to study variation of signal of sample load cells over time when some of the load cells were continuously shaded with or without a significant load or remained unshaded without a significant load (Table 3). Although air temperature fluctuated within the range of 6-24 °C during the experiment, signal remained more or less constant over time as seen from the magnitude of SE in Table 3 (details of temporal variation in temperature and load cell signal not shown for brevity). These results suggested that thermal shift in the load cell signal was unlikely to influence long term lysimetric measurements.

Table 3. Effects of variation in shading and partial loading on load cell signal. Mean value and standard error (SE) for signal was based on four separate load cells ($n = 4$).

Treatments	Signal (mV V^{-1}) ± SE
Zero load + zero shade	0.0425 ± 0.000018
Small load + full shade	0.0445 ± 0.000019
Large load + full shade	0.7679 ± 0.000025

Performance of some lysimeters is influenced by hysteresis due to a shift of calibration line (Payero and Irmak, 2008) when load cells are exposed to an increase in load (for example during irrigation) or a decrease in load (as during evapotranspiration). We used five sample load cells to investigate the hysteresis effects using six separate loads within 0-15.7 kg. Regression lines were fitted to these data in a way similar to that shown by Payero and Irmak (2008). Since there was no significant difference in signal during loading and unloading conditions for these five load cells, there was an overlap of regression lines fitted to signal vs. load data (graph not shown). Regression coefficients (intercept and slope parameters) were also compared with a t-test that indicated no significant difference between load cells due to hysteresis.

3.2 Calibration of lysimeters

Analysis of the results (slope and intercept parameters) with a 4-point calibration equation of signal (S, mV V^{-1}) against load (W, g) indicated that all 12 load cells had a unique slope of 0.0001 mV V^{-1} g^{-1} with $R^2 = 1$, except for three load cells with $0.99 < R^2 < 1$. In order to select a method of calibration that would suit most load cells used for the mini-lysimeter system, a comparison was made using 4-point calibration with load increasing from zero (method 1), 6-point calibration with load increasing from zero (method 2) and 6-point calibration with load decreasing from a maximum load of 15.7 kg (method 3). A plot of the difference between estimated and measured load with each method is shown as a function of measured load (Fig. 1). It can be seen from this figure that 4-point calibration (method 1) was unsuitable since the deviation of the estimated load from true load was ±60 g that was three times the deviation achieved with methods 2 or 3. Thus, a 6-point calibration was performed for all load cells. The calibration results are shown in Fig. 2 and related calibration data in Table 4. It can be seen that the standard errors for fitted parameters were reasonable for all load cells except for the load cell no. 7 (referred to as Plate 7 in Fig. 2a) that caused a maximum deviation of ±80 g. In order to minimise this large deviation (D) for Plate 7, a 4th order polynomial function ($D = 25.8 - 0.034W_1 + 1.31\times10^{-5}W_1^2 - 1.87\times10^{-9}W_1^3 + 7.79\times10^{-14}W_1^4$) was fitted as a function of estimated weight (W_1) that could be used to obtain a final estimate of weight from signal after applying correction to the first estimate of weight (using the calibration parameters shown in Table 4). This correction brought deviations for all load cells to within ±12 g of the measured load (Fig. 2b).Using this calibration approach, lysimeter weights could be predicted well with the measured weight (Fig. 3).

Table 4. Parameters of a 6-point calibration equation W= a + b S, where W and S, respectively refer to fixed loads on the load cell (g) and measured signal (mV V^{-1}). Slope and intercept parameters of the calibration equation were b and a, respectively. Coefficient of determination (R^2) for all regression equations was 1.00 and P-value of the fitted regression was ≤0.001. Standard errors (SE) of the fitted parameters are shown (n = 6).

Load cell no.	intercept (a, g)	SE of a	Slope (b, g mV^{-1} V)	SE of b
1	-505.46	1.49	10002.33	1.59
2	-369.80	1.61	10097.97	1.79
3	-504.08	0.95	10103.12	1.04
4	-587.01	0.84	10230.93	0.91
5	-383.34	5.23	9947.36	5.72
6	-389.59	4.92	10015.72	5.31
7	-517.60	38.60	10312.50	43.30
8	-404.84	0.87	10325.66	0.96
9	-372.51	1.31	10262.97	1.48
10	-378.43	3.02	10221.60	3.40
11	-348.33	1.45	10436.40	1.64
12	-199.52	2.05	10292.36	2.36

3.3 Estimation of soil water and ET from lysimeters

Gravimetric soil water content in each lysimeter was estimated from the load-cell signal, the oven-dry weight of soil, the calibration data from Table 4 and the deviation minimisation function from the previous section. Volumetric soil water content (θ, mm) was estimated using gravimetric soil water content, the bulk density of soil (i.e. 0.89 g cm^{-3}) and the effective soil depth in each lysimeter (i.e. 192 mm).

Daily estimates of evapotranspiration (ET, mm) for wheat in each lysimeter were made by taking the difference between θ at 24 h interval. Typical trend in ET (mm) over time for various irrigation treatments is shown in Fig. 4. The difference in ET for various irrigation treatments remained high during 75-95 DAP, but little or none before 75 DAP because irrigation

treatments were imposed at 55 DAP. Values of ET were substantially higher from frequently irrigated treatment (T80) than the least frequently irrigated treatment (T40).

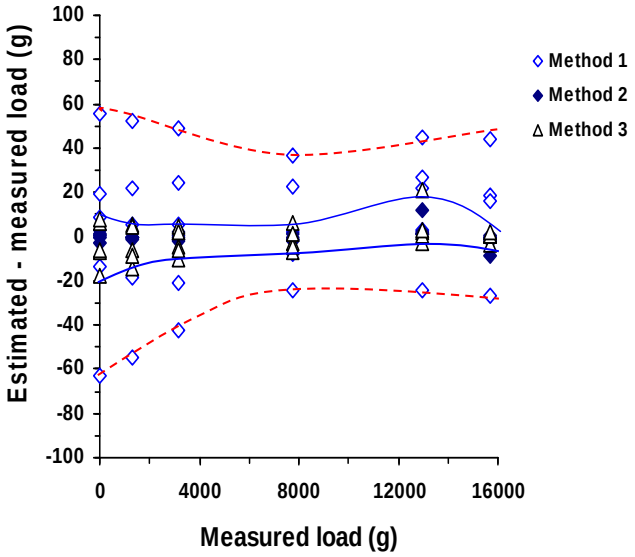

Figure 1. Variation in deviation of estimated load from measured load for selected load cells as a function of measured load with three methods of estimation. Dashed line indicates the upper and lower boundaries of the deviation of load as a function of measured load for method 1 and the solid line shows the boundaries of combined deviation for methods 2 and 3.

It was possible to estimate ET on the basis load-cell signal data at short time intervals (lysimetric estimate) and also from manual measurements of lysimeter weight at long-time intervals (gravimetric estimate) coinciding with an irrigation event. Both types of ET estimates were made on the basis of differences in stored soil water between consecutive irrigation events. Fig. 5 gives a comparison of ET values between lysimetric and gravimetric measurements for wheat. Good agreement between both methods suggests that errors due to biomass accumulation were not significant.

4. General discussion and conclusions

For lysimeters, the resolution often indicates a minimum increment of measureable ET (in mm of water) that is an indicator of the sensitivity of the lysimeter because the interaction between the lysimeter area, weighing system (mechanical or electrical device used) and data recording system can be quite complex. The mini-lysimeter system described here was able to measure the variation in lysimeter weight with a resolution of ±12 g, which is equivalent to 0.027 mm of water (based on the soil surface area of 441.3 cm^2 used for all lysimeters). Since it is possible to make measurements at 10 min interval, the resolution of 0.027 mm of water corresponds with an ET of 0.162 mm h^{-1}. The overall resolution of a lysimeter system is dependent on the capability of the data logger in terms of voltage resolution and its significant digits (Payero and Irmak, 2008). However, these are not considered further as effective calibration and deviation minimisation schemes described here incorporated these features of the measurement system.

The cost of all material used for the mini-lysimeter system including data logger and multiplexer was $5695 (excluding taxes and labour) that allowed us to monitor ET simultaneously from 12 separate plants. Although ET is an important hydrological process in all vegetated landscapes, direct measurement of ET over large area is difficult with lysimeters. Since ET is an important component of hydrological process in arid and semiarid regions of the world where irrigation represents a major user of vast quantities of water (Shen and Chen, 2010), lysimeters are often used to quantify water use over small sample area. Considering the usefulness of ET measurements in estimating water use by plants at the resolution described in

this report, it is possible to measure ET accurately and economically over long period using robust methods of calibration for load cells.

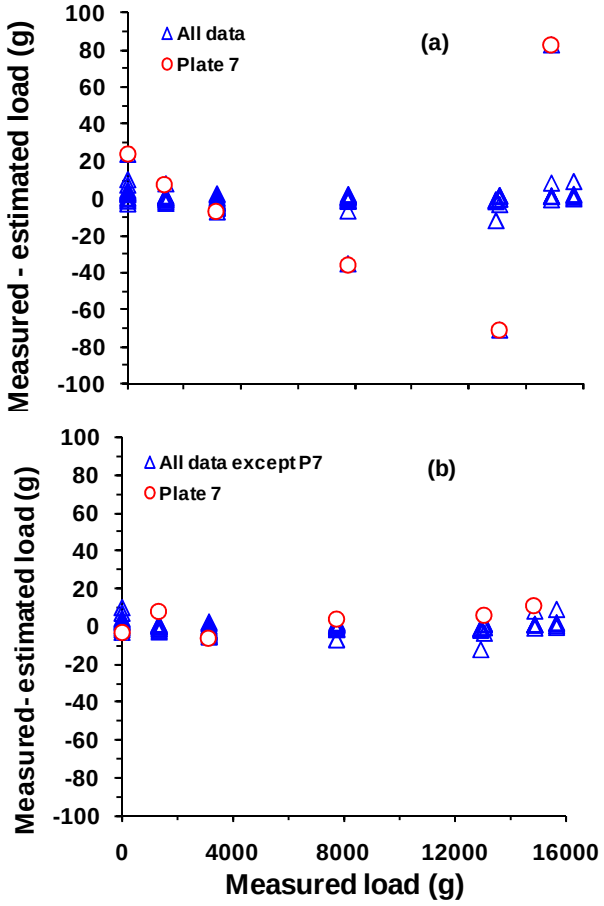

Figure 2. Variation in deviation of estimated load from measured load over the range of measured loads for all load cells using a 6-point calibration equation (a) without minimisation of deviation for Plate 7 (load cell 7) and (b) after minimisation of deviation for Plate 7. Dashed line indicates the line of zero deviation.

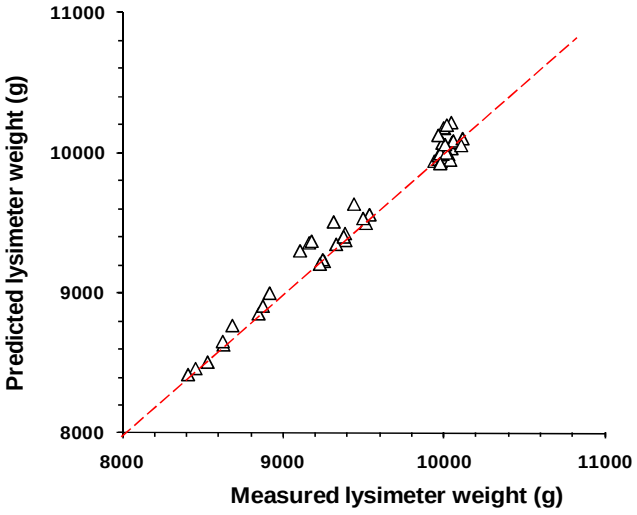

Figure 3. Variation in predicted lysimeter weight (with the 6-point calibration method) over the range of measured lysimeter weights. The dashed line represents the 1:1 line.

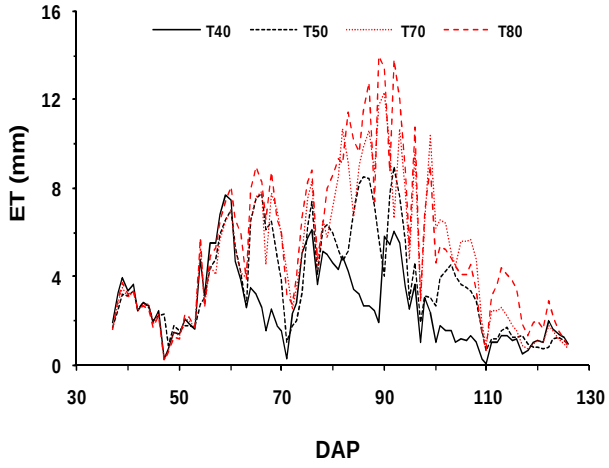

Figure 4. Variation in daily ET from lysimeters over time for four irrigation treatments (T40, T50, T70 and T80) imposed on wheat.

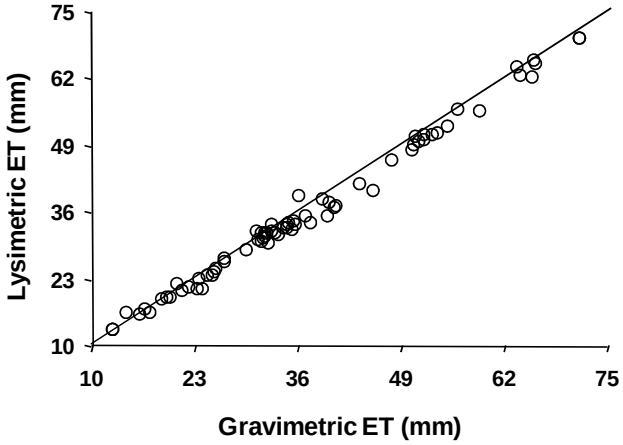

Figure 5. Variation in lysimetric estimates of ET as a function of variation in gravimetric estimates for wheat. The solid line represents the 1:1 line.

The design of mini-lysimeter system described in this report for twelve load cells (of 20 kg capacity) is well suited for continuous measurement of ET from twelve separate plants. The method of calibration can be easily adapted for other load cells of different capacity. Our low-cost approach of combining a single data logger with a multiplexer reduced cost considerably with little loss of resolution in ET. Measurements on the response of load cells to signal settling time, excitation compensation, hysteresis and variation in ambient temperature suggest that the performance of all load cells were not significantly affected by these variables. Final calibration of load cells improved performance of lysimeters to detect weights with a resolution of 0.027 mm of water that allowed measurement of temporal variation in soil water and ET with good accuracy and adequate resolution. Since the cost of the mini-lysimeter system is not excessive, our results indicate that it is possible to obtain good lysimetric measurements of evapotranspiration for long-term monitoring of water use by plants with reasonable accuracy and sufficient resolution.

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References

Allen, R.G., Pruitt, W.O., Wright, J.L., Howell, T.A., Ventura, F., Snyder, R., Itenfisu, D., Steduto, P., Berengena, J., Yrisarry, J.B., Smith M., Pereira, L.S., Raes, D., Perrier, A., Alves, I., Walter, I., Elliott, R., 2006. A recommendation on standardized surface resistance for hourly calculation of reference ET_o by the FAO56 Penman-Monteith method. Agric. Water Manage. 81, 1-22.

Bormann, H., 2008. Sensitivity of a soil-vegetation-atmosphere-transfer scheme to input data resolution and data classification. J. Hydrol. 351, 154-169.

Burt, C. M., Mutziger, A. J., Allen, R. G., Howell, T. A., 2005. Evaporation Research: Review and Interpretation. J. Irrig. Drainage Eng. 131**,** 37-58.

DeTar, W. R., 2008. Yield and growth characteristics for cotton under various irrigation regimes on sandy soil. Agric. Water Manage. 95, 69-76.

Evett, S.R., Mazahrih, N.T., Jitan, M.A., Sawalha, M.H, Colaizzi, P.D., Ayars, J.E., 2009. A weighing lysimeter for crop water use determination in the Jordan valley, Jordan. Trans. ASABE 52, 155-169.

Fereres, E., Soriano, M. A., 2007. Deficit irrigation for reducing agricultural water use. J. Exp. Bot. 58, 147-159.

Foley, J. L., Harris, E., 2007. Field calibration of ThetaProbe (ML2x) and ECHO probe (EC-20) soil water sensors in a Black Vertosol. Aust. J. Soil Res. 45, 233-236.

Hsiao, T. C., Steduto, P., Fereres, E., 2007. A systematic and quantitative approach to improve water use efficiency in agriculture. Irrig. Sci. 25, 209-231.

Isbell, R.F., 1996. The Australian Soil Classification. CSIRO Publishing, Collingwood, Victoria.

Karam, F., Lahoud, R., Massad, R., Kabalan, R., Breidi, J., Chalita, C., Rouphael, Y., 2007. Evapotranspiration, seed yield and water use efficiency of drip irrigated sunflower under full and deficit irrigation conditions. Agric. Water Manage. 90, 213-223.

Kirda, C., Moutonnet, P., Hera, C., Nielsen, D. R. (Eds.), 1999. Crop yield response to deficit irrigation, Kluwer academic publishers, Dordrecht.

Ko, J., Piccinni, G., 2009. Corn yield responses under crop evapotranspiration-based irrigation management. Agric. Water Manage. 96, 799-808.

Liu, W. Z., Hunsaker, D. J., Li, Y. S., Xie, X. Q., Wall, G. W., 2002. Interrelations of yield, evapotranspiration, and water use efficiency from marginal analysis of water production functions. Agric. Water Manage. 56, 143-151.

Malone, R.W., Stewardson, D.J., Bonta, J.V., Nelsen, T., 1999. Calibration and quality control of the Coshocton weighing lysimeters. Trans. ASAE 42, 701-712.

Martin, E.C., de Oliveira, A.S., Folta, A.D., Pegelow, E.J., Slack, D.C., 2001 Development and testing of a small weighable lysimeter system to assess water use by shallow-rooted crops. Trans. ASAE 44, 71-78.

Payero, J.O., Irmak, S., 2008. Construction, installation, and performance of two repacked weighing lysimeters. Irrig. Sci. 26, 191-202.

Shen, Y.J, Chen, Y.N., 2010. Global perspective on hydrology, water balance, and water resources management in arid basins. Hydrol. Process. 24, 129-135.

Silva, D., Meza, F.J., Varas, E., 2010. Estimating reference evapotranspiration (ET_o) using numerical weather forecast data in central Chile. J. Hydrol. 382, 64-71.

Snedecor, G.W., Cochran, W.G., 1989. Statistical Methods. Iowa State University Press, Ames, Iowa.