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Solutions to Overcome Pitfalls of Two Automated Systems for Direct Measurement of Greenhouse Tomato Water Uptake

Kristof Vermeulen^{1,4}, Kathy Steppe¹, Katrien Janssen², Peter Bleyaert², Jan Dekock³, Jean-Marie Aerts³, Daniel Berckmans³, and Raoul Lemeur¹

ADDITIONAL INDEX WORDS. irrigation, crop monitoring, sap flow, sensors

SUMMARY. Two promising techniques to measure water uptake in a direct way were evaluated on substrate-grown truss tomato plants (*Lycopersicon esculentum* 'Clothilde'). The first technique, which is called the mass-balance technique, determines tomato water uptake using automated weight measurements of substrate mass and collected leachate. It was found that leachate could not be recorded appropriately in a 1-minute time interval by the tipping bucket gauges used in this study. Therefore, the tipping bucket readings had to be corrected and modified. The second technique computes the water uptake by a single tomato plant based on the thermal energy balance of a stem segment and, therefore, it is called the heat-balance technique. The stem segment was carefully selected at the base of a tomato stem so that the whole-plant water uptake could be determined. However, it was found that an independent measurement of minimum water uptake during the night was needed to correctly calculate water uptake during the whole day. As a result, the major pitfalls of the two techniques were identified. With appropriate modifications, a good correlation between the measurements was found, even during a period of imposed drought stress.

The increasing worldwide shortage of water and the high cost of irrigation have already led to the use of precise irrigation methods. An example is the introduction of trickle irrigation in agriculture and

horticulture. This recent evolution, however, has also highlighted the urgent need for precise irrigation control and scheduling (Jones, 2004). This need is certainly true in the

case of substrate-grown greenhouse crops, because the water storage in a substrate slab is quite limited. The most accurate irrigation control systems have relied on algorithms, which are frequently based on the Penman-Monteith model (e.g., Boulard and Jemaa, 1993; Hamer, 1996; Medrano et al., 2005; Pollet et al., 2000). Although these algorithms use conventional environmental data to estimate the crop water requirements, it is often hard to implement them in a practical irrigation control system, because these algorithms must be calibrated for each specific crop at different stages of crop development (Medrano et al., 2005). Therefore, new approaches have recently been introduced in irrigation management, which can directly reveal the actual crop water requirements without knowing all crop-environment interactions. As a result, direct crop monitoring is an important objective in current horticultural research programs (Ehret et al., 2001).

One of the techniques to determine water uptake directly is by using a lysimeter or an electronic balance. This device is commonly used in the scientific community to calibrate and validate alternative methods or climate-based transpiration models. Recently, de Graaf et al. (2004) and Helmer et al. (2005) successfully tested this so-called "mass-balance" technique in a commercial greenhouse setting on vine crops such as tomato. Nevertheless, Helmer et al. (2005) noticed that information extraction from weight measurements must be done very carefully, because incremental changes resulting from water uptake over a short time interval are very small in comparison with the total substrate mass. Hence, attention must be paid to the precision of the used weighing equipment.

A totally different technique originally developed by Sakuratani

¹Ghent University, Laboratory of Plant Ecology, Coupure links 653, B-9000, Gent, Belgium

²Provincial Research and Advisory Centre for Agriculture and Horticulture, Ieperseweg 87, B-8800 Beitem, Belgium

³M3-BIORES, Katholieke Universiteit, Leuven, Kasteelpark Arenberg 30, B-3001, Leuven, Belgium

⁴Corresponding author. E-mail: Kristof.Vermeulen@UGent.be

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
0.3048	ft	m	3.2808
0.0929	ft ²	m ²	10.7639
3.7854	gal	L	0.2642
25.4000	inch(es)	mm	0.0394
0.4536	lb	kg	2.2046
28.3495	oz	g	0.0353
(°F - 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32
(°F ÷ 1.8) + 255.37	°F	K	(K - 255.37) × 1.8

(1981) is based on the thermal energy balance of a stem segment for which the sap-flow rate is determined. This so-called “heat-balance” technique has already been examined for potential use in a wide range of crops, including cotton (*Gossypium hirsutum*) (Dugas, 1990), cucumber (*Cucumis sativus*) (Kitano and Eguchi, 1989), potato (*Solanum tuberosum*) (Gordon et al., 1997), and roses (*Rosa hybrida*) (Rose and Rose, 1998). Unfortunately, little extended information is available on the application of this technique on a tomato crop, so an evaluation of the heat-balance technique is difficult for this crop.

As a result, the objective of this study is to evaluate both techniques by using them in a semipractical greenhouse and to overcome the possible problems to measure tomato water uptake in a direct way.

Materials and methods

Plant material and culture

Truss tomato plants were cultivated inside greenhouse compartments (22.5 × 16 × 4 m) of the Provincial Research and Advisory Center for Agriculture and Horticulture (lat. 50°54'N, long. 03°07'W), Beitem, Belgium. The plants were sown on 15 Nov. 2003 and were transplanted at a density of 2.27 plants/m² on 6 Jan. 2004. The tomato plants were grown in 15-L rockwool

slabs (Expert; Grodan, Hedehusene, Denmark) with four plants per slab and clipped to support threads, which were suspended from an overhead crop wire. From the beginning of June 2004, one side-shoot per four plants was allowed to develop as an additional head resulting in an increased crop density of 2.83 heads/m² through the summer months.

The experiment in this study was conducted from 18 to 22 July 2004. During this 5-d period, the greenhouse compartments were ventilated at 21 °C and heated at 17 °C. These set points resulted in an air temperature between 16 and 33 °C, whereas relative humidity fluctuated between 64% and 93%. A trickle irrigation system, which is commonly used in soilless tomato production, provided standard nutrient solution at 120 mL per plant each time a light integral of 0.95 MJ·m⁻² outside solar radiation was obtained. On the first day of the experiment, all plants were irrigated, whereas on the second day, we removed the emitters of the plants grown in two slabs causing sudden drought stress. The control plants remained well watered. We reinserted the emitters on the third day of the experiment when we had observed visual signs of turgidity loss on the drought-treated plants. The final 2 d of the experiment were used to observe whether recovery from drought stress could be detected as well.

Methods to determine water uptake

The two methods discussed in this study to measure tomato water uptake are the mass-balance and the heat-balance technique; both techniques are illustrated in Figure 1.

MASS-BALANCE TECHNIQUE. Figure 1A demonstrates that changes in substrate mass can only be induced by three simultaneous processes, namely irrigation, leaching, and plant water uptake. Evaporation from the rockwool substrate was assumed to be negligible, because the rockwool substrate was totally wrapped in plastic. Root growth was also not taken into account, because it can only cause minimal changes in comparison with the other processes. Furthermore, it is noteworthy to mention that the mass balance could not be influenced by mass gain as a result of crop growth during the experiment, because the horizontal part of the plant stem was carried by a series of support braces and the vertical part of the plant stem was clipped to support treads, which can be seen in Figure 1A. As such, the mass balance of the substrate can be formulated as

$$\frac{dM}{dt} = I - L - WU \quad [1]$$

where all components are expressed in terms of kilograms per minute: M is the substrate mass, I is the irrigation rate, L is the leaching rate, and WU is

Fig. 1. Schematic representation of the two techniques to determine water uptake by tomato plants: (A) mass-balance technique and (B) heat-balance technique.

the water uptake rate. The substrate mass was measured by means of an electronic balance (Groscale; Priva BV, De Lier, The Netherlands), which basically consisted of two load cells bearing a trough (Fig. 1A). This 50-kg balance, which had a resolution of 1 g, recorded mass changes within a 3% error range according to preliminary experiments using standard weights.

Since the recorded changes in substrate mass were only partially attributed to plant water uptake, the changes resulting from irrigation and leachate had to be accounted for and omitted. Irrigation events, which are clearly indicated in Figure 2 by upward spikes, were excluded by a method adapted from Helmer et al. (2005) using a variable threshold value (T). This threshold was defined as the mean mass change rate ($\text{kg} \cdot \text{min}^{-1}$) of the previous 5 min plus $0.01 \text{ kg} \cdot \text{min}^{-1}$. When the actual mass change rate exceeded the current threshold value, an irrigation event was encountered. Rather than eliminating these data points, they were substituted by the mean mass change rate of the previous 5 min. The following threshold was then based on the corrected mass change rate. Figure 2 also illustrates that an additional decrease in substrate mass is the result of leaching. Therefore, a correction was made by adding the amount of leachate registered by a tipping bucket gauge (DSS; Priva BV, De Lier, The Netherlands) with 6 mL per pulse. In this way, the effect of

plant water uptake on the rate of substrate mass change was determined. As a consequence, the water uptake rate of the plants in the trough of the electronic balances was quantified.

In this study, two electronic balances, each combined with a tipping bucket gauge, were installed according to the directions in the manual before transplanting and remained there for the remainder of the growth season. Since the plants grown in the trough of the balances were positioned in the middle of the crop, they were assumed to be representative of the whole crop. From 19 to 20 July, sudden drought stress was imposed on the eight plants that grew in the trough of one balance, whereas the plants in the other trough were defined as the control plants as mentioned. Signal outputs were logged at 20-s intervals and 1-min averages were stored by the Intégro control system (Priva BV).

HEAT-BALANCE TECHNIQUE. The water uptake by a single tomato plant was also determined by sap-flow gauges based on the heat-balance method. As shown in Figure 1B, this heat balance can be represented under steady-state conditions as

$$P_{\text{IN}} = Q_V + Q_R + Q_F \quad [2]$$

where all components are expressed in terms of watts: P_{IN} is the heat input applied to the stem segment, Q_V represents the heat loss by vertical conduction through the stem, Q_R is the heat loss by radial conduction to

the environment, and Q_F is the convective heat flux carried away by sap flow. Stem heat storage can be neglected as a result of the high sap-flow rates encountered in the tomato stem in comparison with the conclusions of Steppe et al. (2005). The power input is applied by a heater to the entire circumference of the stem segment and can be computed as

$$P_{\text{IN}} = \frac{V^2}{R} \quad [3]$$

where V is the constant input voltage (V) and R is the corresponding electrical resistance of the heater (Ω). Conduction of heat up and down the stem is computed by using Fourier's Law

$$Q_V = A_{\text{ST}} \cdot K_{\text{ST}} \cdot \frac{\Delta T_B - \Delta T_A}{x} \quad [4]$$

where A_{ST} is the cross-sectional area of the heated section of the stem (m^2), K_{ST} represents the thermal conductivity of the stem, which is assumed to be $0.54 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ for herbaceous plants (Sakuratani, 1984), ΔT_A and ΔT_B are the temperature gradients along the heater (K), and x represents the distance between the two thermocouple junctions on each side of the heater (m). The radial component of the heat balance is obtained from

$$Q_R = K_{\text{SH}} \Delta T_C \quad [5]$$

where K_{SH} is the effective thermal conductance of the cork sheath surrounding the heater ($\text{W} \cdot \text{K}^{-1}$) and ΔT_C is the temperature gradient along the sheath ($^\circ\text{K}$). The value of K_{SH} is unknown and depends on the thermal conductivity of the insulating sheath and the actual diameter of the stem segment. Therefore, it should be determined daily during a time of zero sap flow when

$$K_{\text{SH}} = \frac{P_{\text{IN}} - Q_V}{\Delta T_C} \quad [6]$$

Substituting Eq. 3, 4, and 5 into Eq. 2, Q_F can be calculated and, finally, converted into an equivalent sap-flow rate

$$F = \frac{60 \cdot Q_F}{c_p \cdot \Delta T} \quad [7]$$

where F is the sap-flow rate ($\text{g} \cdot \text{min}^{-1}$), c_p is the heat capacity of water ($4.186 \text{ J} \cdot \text{g}^{-1} \cdot \text{K}^{-1}$), and ΔT is the average temperature gradient between the upstream and downstream thermocouples (Kelvin).

Fig. 2. Rate of substrate mass change (dM/dt , gray line): (A) during a 24-h period and (B) during a 20-min period. The effect of irrigation (I) and leaching (L) on substrate mass change rate were omitted to quantify the effect of continuous tomato water uptake (WU, black line). A variable threshold (T, dotted lines) was used to exclude the effect of irrigation ($1 \text{ kg} = 2.2046 \text{ lb}$).

In this study, the heat-balance measurements were made by Dyna-gage sap-flow gauges (SGB16-WS; Dynamax, Houston) based on the design of Baker and van Bavel (1987). The accuracy of this type of gauge is 10% of the readings (Baker and van Bavel, 1987; Dugas, 1990). In the trough of both electronic balances, one sap-flow gauge was attached to the base of one tomato stem (i.e., above the hypocotyls and under the lowest leaf) enabling us to determine the whole-plant water uptake. The gauges were installed following the recommendations of van Bavel and van Bavel (1990). First, an appropriate stem segment without any wounds, marks, or node prominences was selected. Attention was also paid to the stem diameter, which had to range between 15 and 19 mm so that a good stem-to-thermocouple contact was ensured. The gauge was installed tightly around the stem at midday, when stem shrinkage is highest. Plastic foil was wrapped around the selected segment, because we had noticed in preliminary experiments that stem transpiration and adventitious root growth can occur inside the gauge. In this way, corrosion and mechanical damage to the gauge were prevented. After installing the gauge on the stem segment, two layers of aluminium foil were wrapped around both the gauge and the stem segment to ensure steady-state thermal conditions within the gauge-stem assembly. Finally, an additional layer of aluminium foil covered the whole base of the tomato stem so that the effect of external radiation on the heat balance of the stem segment was minimized as well. When electrical power was supplied to the gauge, a regulated voltage source was adjusted to 4.5 V. This way, stem ΔT was increased without causing any physical damage to the tomato stem. Signal outputs from the sap-flow gauges were logged at 20-s intervals and 1-min averages were stored by a data-acquisition system (34970A; Agilent Technologies, Palo Alto, Calif.).

Results and discussion

EVALUATION OF THE MASS-BALANCE TECHNIQUE. To quantify plant water uptake from the substrate mass data, changes resulting from irrigation were omitted first.

Therefore, the actual rate of substrate mass change was substituted by the mean mass change rate of the previous 5 min as described in "Materials and methods." Hence, the difference between the actual and the substituted data could be attributed to irrigation (Fig. 2B). As such, we found that the plants in the trough of the balances were irrigated at 120 ± 6 mL per plant during an irrigation event. This estimated amount did not significantly differ (paired-samples t-test: $t = 0.723$, $df = 103$, $P = 0.471$) from the registered irrigation amount of 120 mL/plant. Consequently, the registered amount might also be used in the mass balance to calculate plant water uptake. However, it is a general mean for a whole greenhouse compartment, which makes the estimated amount probably more accurate, especially in larger greenhouses where supply differences among the emitters can occur. In addition to better accuracy, the estimated amount can be useful as a feedback signal. For example, when the emitters were removed, no irrigation was detected in the trough, but there still was irrigation registered by the irrigation control system during the treatment. In other words, a greenhouse manager could be alarmed when a large difference between the estimated and registered irrigation is detected. In brief, the method to exclude the effect of irrigation from the substrate mass data worked quite well. Moreover, this method can be useful to implement in an irrigation control system.

Next, changes resulting from leachate were accounted for by adding the recorded leachate to the substrate mass data and the plant water uptake rate was determined. Figure 3, however, illustrates that the computed plant water uptake was very high during the first 2 to 4 min of each leaching period. This can be explained by the fact that the tipping bucket gauges could not cope with a large volume of leachate in a short period of time. As a consequence, a large substrate mass decrease resulting from leaching was insufficiently compensated by the tipping bucket readings so that the contribution of water uptake was then overestimated. At the end of a leaching period, the reverse situation occurred; because the tipping bucket gauges recorded too much leachate, water uptake was

Fig. 3. Computed water uptake by eight tomato plants (WU) based on recorded (gray line) and redistributed (black line) leachate (L) (1 g = 0.0353 oz).

underestimated. To solve this time delay problem, the registered amount of leachate had to be redistributed. Therefore, the first and last leaching events of each day were examined more in detail. During these periods, plant water uptake was assumed not to fluctuate strongly so that the effect of plant water uptake on substrate mass change could be estimated by the mean mass change rate of the previous 5 min as mentioned. The additional decrease in substrate mass was then attributed to leaching. In this way, leachate was estimated independently of the tipping bucket readings. Each time, an exponential pattern was observed (Fig. 3), which could be expected because leaching is a reaction to a discrete irrigation event, which can be regarded as a pulse. The average pattern of all examined leaching periods was then used to redistribute the tipping bucket readings and, finally, resulted in the following correction

$$L = \sum L \cdot 0.38 \cdot e^{-\frac{t}{3.5T}} \quad [8]$$

where L is the corrected leachate amount (kg·minute), ΣL is the total amount of leachate registered by the tipping bucket gauge between two irrigation events (kg), and t is the time after an irrigation event (min). Because this method only redistributes the recorded leachate, no accumulative errors were made.

From the previous results, it is obvious that a tipping bucket gauge is not an optimal system to record leachate over very short periods.

Consequently, more appropriate alternatives should be used. de Graaf et al. (2004) suggested a system in which load cells are also used to measure leachate. Because substrate mass and leachate are both measured by the same type of balances, no time delay problem is encountered. A second alternative is the method described by Helmer et al. (2005), which only allows leaching out of a trough ≈ 5 min after each irrigation event. In this way, no additional gauges are needed to record leachate and, therefore, the time delay problem is eliminated. In brief, an electronic balance and a tipping bucket gauge enabled us to measure the water uptake by a group of tomato plants, although a time delay problem had to be solved first.

EVALUATION OF THE HEAT-BALANCE TECHNIQUE. According to Eq. 6, zero-sap-flow conditions were required to determine the sheath conductance K_{SH} . Because substrate mass steadily decreased during each night as a consequence of nighttime water uptake, zero-sap-flow conditions were not observed for either the control or the stressed tomato plants during the entire experiment. Consequently, Eq. 6 could not be used to compute tomato water uptake. Steinberg et al. (1989) suggested and reviewed two alternative procedures to determine K_{SH} : enclosing the entire plant in a plastic bag so transpiration falls to zero or measuring K_{SH} on an excised stem segment after an experiment. Both procedures are obviously not easily applicable because the sheath conductance is different for each individual gauge and it can change each day mainly as a result of diameter variations of the stem segment to which the gauge is attached. Therefore, Eq. 6 was adapted to minimum-sap-flow conditions as an alternative method to determine the sheath conductance

$$K_{SH} = \frac{P_{IN} - Q_V - Q_{F,MIN}}{\Delta T_C} \quad [9]$$

where $Q_{F,MIN}$ (W) is the heat flux carried by the minimum nighttime sap flow. This convective heat flux was determined based on Eq. 7 and the 1-h average readings of the electronic balances as input for F .

The minimum water uptake values and the uncorrected and corrected K_{SH} -values are shown in Table 1.

Table 1. Minimum nighttime water uptake by eight tomato plants (WU_{MIN}) derived from mass-balance data used to correct the sheath conductance (K_{SH}) to compute plant water uptake by the heat-balance technique in a correct way^z.

Day	WU _{MIN} (g·min ⁻¹) ^y	K _{SH}		Underestimation of daily WU (%)
		Uncorrected (W·K ⁻¹) ^x	Corrected (W·K ⁻¹)	
Control plants				
18 July 2004	1.2	0.046	0.033	19
19 July 2004	1.2	0.049	0.036	17
20 July 2004	1.4	0.051	0.035	17
21 July 2004	1.4	0.050	0.035	17
22 July 2004	1.2	0.048	0.035	15
Stressed plants				
18 July 2004	1.0	0.048	0.040	20
19 July 2004	1.0	0.050	0.040	13
20 July 2004	0.5	0.042	0.038	5
21 July 2004	0.2	0.030	0.029	4
22 July 2004	0.4	0.038	0.035	7

^aWithout this correction, daily water uptake (WU) was underestimated.

^y1 g = 0.0353 oz.

^z $K - 273.15 = ^\circ C$ ($K - 255.37$) $\times 1.8 = ^\circ F$.

After minimum sap flow conditions were taken into account, the sheath conductance values obtained on the control plants were relatively constant, whereas the sheath conductance of the sap-flow gauge attached to the stressed plant decreased from 40 to 29 $mW \cdot K^{-1}$. This large decrease may be incited by shrinkage of the stem segment as a result of the imposed drought stress. This result confirms that the sheath conductance is specific for each stem-gauge assembly and it can hardly be regarded as a constant value.

The effect of the K_{SH} -value on the resulting water uptake rate is also shown in Table 1. If zero-sap-flow conditions were assumed, the water uptake rate was continuously underestimated during the entire day. On a daily basis, substantial errors up to 19% were made on the control plants, whereas on the stressed plants, less error was made after inducing drought stress; in the latter case, the requirement of zero-sap-flow conditions was probably met more closely. Indeed, the minimum nighttime water uptake by the eight stressed plants decreased from 1.0 to 0.2 $g \cdot min^{-1}$. Nevertheless, a substantial error of 4% was made even then, indicating the importance of a correct determination of the K_{SH} value.

COMPARISON OF THE MASS-BALANCE AND THE HEAT-BALANCE TECHNIQUE. After having dealt with the specific problems mentioned, the

water uptake by the control and the stressed plants could be determined by the mass-balance and the heat-balance techniques. The obtained results are shown in Figure 4. The mass-balance measurements clearly fluctuated more than those obtained by heat-balance sap-flow gauges, which indicates that the mass-balance technique is less precise. This lack of precision can be attributed to the resolution and the repeatability of the readings of the electronic balances. Helmer et al. (2005) also noticed that an electronic balance must be able to record very small substrate mass changes to determine plant water uptake. Because better performance of an electronic balance is related to the price as stated by van Meurs and Stanghellini (1992), the heat-balance technique might be preferred when tomato water uptake over short time intervals has to be measured with high precision.

Despite these fluctuations, good agreement between the mass-balance and heat-balance data was found on an hourly basis (Fig. 5). A good correlation during the night was expected, because the sheath conductance of the sap-flow gauges was corrected for a minimum nighttime water uptake obtained from the mass-balance data. Nevertheless, Figure 5 shows that the heat-balance data also closely matched the mass-balance data during the rest of the day, which resulted in a correlation coefficient higher

Fig. 4. Water uptake by a tomato plant from 18 to 22 July 2004 quantified by the mass-balance technique (gray dots) or by the heat-balance technique (black dots): (A) a control plant, (B) a plant subjected to drought stress by removing the emitters of the trickle irrigation system. The arrows indicate the effect of the first three irrigation events after the emitters were reinserted ($1 \text{ g} = 0.0353 \text{ oz}$).

than 0.95. The root mean square error was lower than $10 \text{ g}\cdot\text{h}^{-1}$ or 5% of the maximum hourly water uptake. When the same data were compared on a daily basis (Table 2), a root mean square error lower than $35 \text{ g}\cdot\text{d}^{-1}$ was found, which corresponds to $\approx 3\%$ of the average daily water uptake. When Baker and van Bavel (1987) and Dugas (1990) validated the same sap-flow gauge as used in this study on other crops using weight measurements as a reference, they found an accuracy of 10% of the daily readings.

These results show that the mass-balance and heat-balance data only slightly differ on an hourly or daily basis. The errors made were quite small in comparison with the 30% irrigation in excess, which is commonly given to avoid salt accumulation in the substrate slabs (Kläring, 2001). As a result, both techniques can be used in a plant-based irrigation control system. However, it must be noticed that the heat-balance technique can only quantify water uptake by one plant at a time, whereas the mass-balance technique gives insight into all water flows in and out substrate slabs (Table 2) and, hence,

provide information about a group of plants. The good agreement between the two techniques, however, implicates that the variability within the two groups of eight plants placed on the electronic balances was rather small.

Finally, it is noteworthy to mention that both techniques were able to detect reduced water uptake resulting from the imposed drought stress. This reduction can be clearly seen on 20 July from $\approx 4 \text{ h}$ before turgidity loss was visually observed and the emitters were reinserted. During this period, the water uptake decreased from 2.6 to $0.8 \text{ g}\cdot\text{min}^{-1}$, whereas the well-watered plants continuously used more than $2.6 \text{ g}\cdot\text{min}^{-1}$ (Fig. 4). Hence, both techniques can also be used in an early-warning system. After the emitters of the trickle irrigation system were reinserted, the first three irrigation events clearly caused an immediate increase in water uptake. As a result, a greenhouse manager can gather direct and quantitative information from the crop itself by both techniques, which will probably enable him or her to detect a suboptimal plant status in an early stage.

Fig. 5. Comparison of water uptake determined by the heat-balance technique (WU_{HB}) with those determined by the mass-balance technique (WU_{MB}) for a control (closed circles, $R^2 = 0.99$, $n = 120$, root mean square error = $4 \text{ g}\cdot\text{h}^{-1}$) and for a stressed (open triangles, $R^2 = 0.97$, $n = 120$, root mean square error = $9 \text{ g}\cdot\text{h}^{-1}$) tomato plant. The full line represents the 1:1 relationship ($1 \text{ g} = 0.0353 \text{ oz}$).

Conclusions

Plant water uptake could be measured by the mass-balance and the heat-balance techniques. Nevertheless, some problems had to be

Table 2. Data obtained from the mass-balance or the heat-balance technique: gain of substrate mass (dM/dt), amount of irrigation (I), amount of leachate (L), and water uptake by eight tomato plants (WU).

Day	Mass-balance data				Heat-balance data
	dM/dt (kg·d ⁻¹) ²	I (kg·d ⁻¹)	L (kg·d ⁻¹)	WU (kg·d ⁻¹)	WU (kg·d ⁻¹)
Control plants					
18 July 2004	1.0	16.3	5.0	10.3	10.3
19 July 2004	-1.9	21.4	7.9	15.4	15.1
20 July 2004	0.8	22.8	6.6	15.4	15.0
21 July 2004	-0.6	16.1	4.8	11.9	12.4
22 July 2004	0.2	23.4	7.4	15.8	15.2
Stressed plants					
18 July 2004	0.4	16.4	6.4	9.6	9.4
19 July 2004	-11.1	2.4	0.1	13.4	13.8
20 July 2004	-7.5	2.8	0.0	10.3	10.4
21 July 2004	9.6	18.3	0.0	8.7	8.8
22 July 2004	5.7	26.5	7.8	13.0	13.6

²1 kg = 2.2046 lb.

solved first. The major pitfall of the mass-balance technique was the recording of leachate. A tipping bucket gauge was not an optimal gauge as a result of a time delay so that the readings had to be modified. Furthermore, attention must be paid to the resolution and the repeatability of the electronic balance used. The heat-balance technique can measure water uptake correctly if a sap-flow gauge is installed properly and if the sheath conductance of a sap-flow gauge can be determined correctly. Therefore, an independent measurement of minimum tomato water uptake is required, which is the major pitfall of the heat-balance technique. With appropriate modifications, a good correlation between the measurements was found, even during a period of imposed drought stress. As such, both techniques provided quantitative information, which can be used in a plant-based irrigation control system.

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