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A Technique for Accurately Measuring Water Use by Entire Greenhouse Crops

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Abstract. **Equipment for measuring water use of a greenhouse crop of up to ± 1 kg h^{-1} over 30 m^2 is described. It is based on growing a crop in nutrient film, with a nutrient tank replenished from a water tank, and controlled by accurate level sensors. The water tank is suspended from a load cell interrogated at frequent intervals by a data logging computer. Examples of data collected are given. Peak daytime transpiration rates varied from 50 mg s^{-1} m^{-2} to 150 mg m^2 s^{-1} with a maximum error of 5%. With low transpiration rates, the errors were increased, but accuracy could be improved by calculating the rates over a prolonged time interval.**

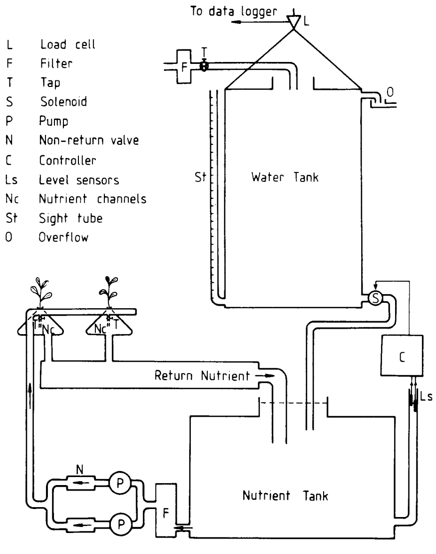

Fig. 1. Schematic diagram of the water use measuring system.

This paper describes an NFT system which enabled us to record continuously the transpiration rate of a tomato crop over entire seasons. Accurate measurements of greenhouse crop water use are required for at least 2 reasons.

- The information is required for partitioning greenhouse energy budgets. Radiation in excess of 60% of the radiant heat load may be dissipated as latent heat through crop transpiration (2, 3, 5, 6). In investigations of greenhouse energetics, it is therefore essential to know the transpiration of the entire greenhouse canopy, ideally over many successive short time intervals.
- The information is needed if crop water requirements are to be satisfied efficiently. Many greenhouse irrigation controllers work on predictive algorithms in which water use is estimated from a combination of independent environmental variables, such as radiation (4), in contrast to systems where a sensor detects plant or soil water status directly. Predictive controllers are simpler to install than those using direct measurements, but the algorithms currently used in them need considerable refinement.

Of the frequently used techniques for measuring water use, weighing lysimeters sample a small area of greenhouse and therefore require the crop to be homogeneous for their results to be extrapolated to an entire greenhouse. They have, however, the considerable advantage of high precision over extremely short time intervals for plants growing in any solid substrate.

Another method is measurement of transpiration flux of single plants, but such measurements present even greater problems of extrapolation than lysimeters.

Of the hydroponic systems, only the recirculating types lend themselves to use in transpiration measurements. Nonrecycling systems require precise measurements of total water entering and leaving the system. This measurement is feasible over time intervals of a day or so, but not short time intervals of less than an hour, since nutrient flow rate generally exceeds transpiration rate. In our nutrient film system, for example, a double row of 42 tomato plants had a peak transpiration rate of 8 liters h^{-1}, whereas the nutrient flow rate was about 350 liters h^{-1}. An error of 1% in flow rate is 3.5 liters h^{-1} comparable to the transpiration rate.

In a recirculating nutrient system, transpiration is equivalent to the volume of water added to maintain a set level, a relatively simple parameter to measure. For continuous, short-term measurement of transpiration, the flow of nutrient also should be continuous, and changes in resistance to flow should be minimal so that the water holding capacity of the system remains constant. These requirements are met by Nutrient Film Technique (NFT) systems.

A 10 m × 6 m greenhouse was constructed and covered with tedlar coated fiber glass. It contained 4 pairs of NFT channels 8.5 m long, each channel supporting 21 plants. The 2 outermost pairs of channels were combined into one NFT system and the center rows into another; hence, it was possible to measure the extent of edge effects directly. Each system consisted of a 200-liter stainless steel tank containing nutrient solution (1), a pair of pumps (MD15T, Iwaki, Tokyo) connected in parallel as protection against pump failure, and 4 NFT channels made from reinforced black polyethylene, white on the outside, folded into an "A" profile and sealed by clips to prevent evaporation (Fig. 1). Nutrient solution was pumped to the top of each channel, returning to the reservoir by gravity. A 250-liter water tank was suspended from an "I" beam above each nutrient reservoir, and water lost from the system through transpiration was replaced with water from this tank via a solenoid valve actuated by a level sensor in the reservoir. The water tanks were refilled manually each day to an overflow point.

The weight of each water tank was monitored continuously by a strain gauge (SM500, Interface, Ariz., USA) connected to a computer interface (Micromac 4000, Analog devices, USA) and logged every 15 min by a minicomputer (LSI 11/03, DEC, USA). Each tank also was equipped with a sight gauge to provide a check against the strain gauges, and to provide an easy means of measuring total daily water consumption.

The accuracy and resolution of this kind of system depends on the sensitivity of load cells and the minimum level change which can be detected. Accuracy depends on a

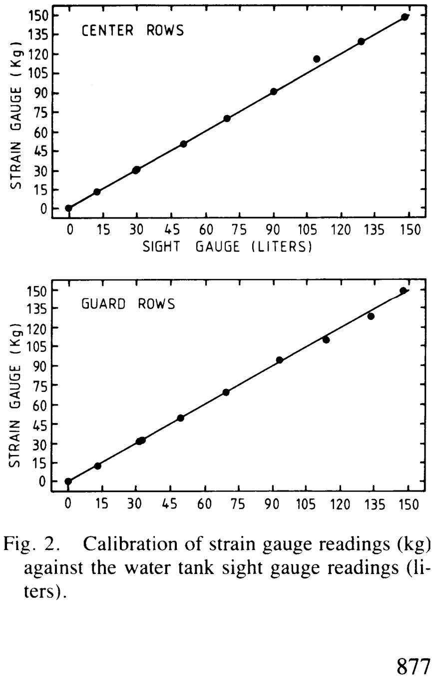

Fig. 2. Calibration of strain gauge readings (kg) against the water tank sight gauge readings (liters).

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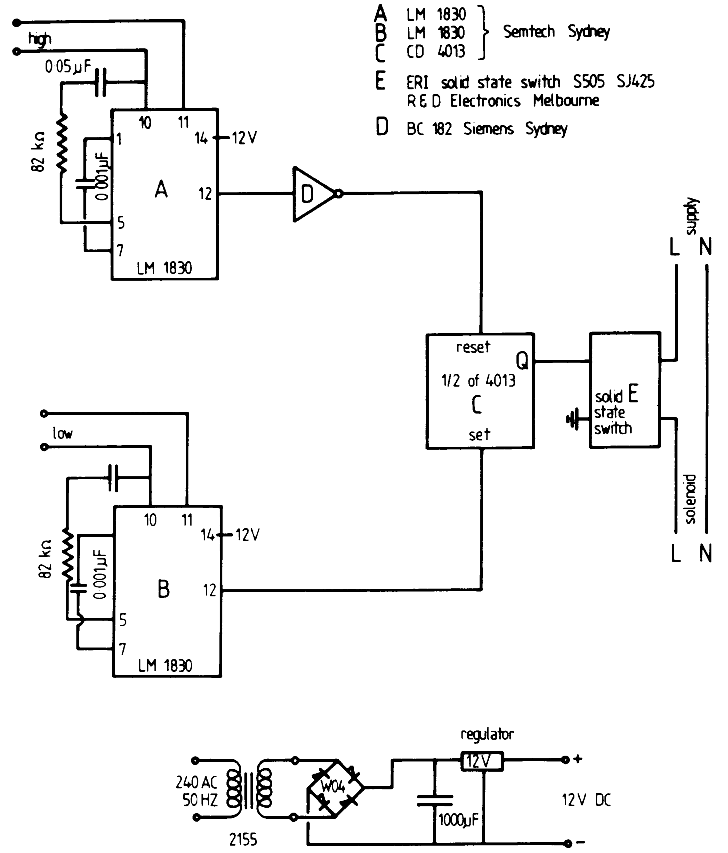

Fig. 3. Schematic diagram of the electronic control system used to maintain a constant level in the circulating nutrient.

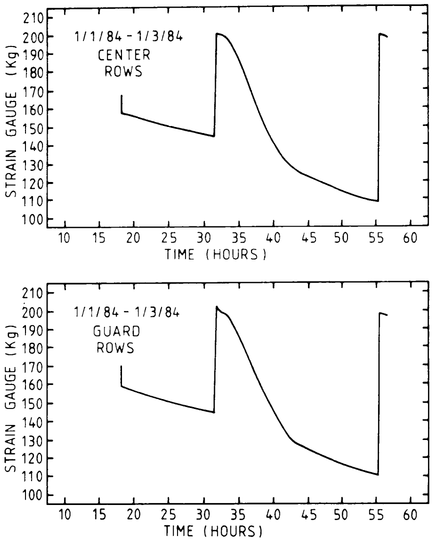

Fig. 4. Accumulated water use over 40 hr by a greenhouse tomato crop in midsummer.

combination of temperature drift, hysteresis, departure from linear response, and stability of the excitation voltage. The errors resulting from these factors were nominally considerably less than 50 g and, in practice, standard deviations for strain gauge calibrations were 63 g and 43 g for the center and guard row systems, respectively. Load cell response also was linear over the operating range (Fig. 2). Error and resolution of the weighing system were therefore less than 100 g (better than 0.04% which means that a water use of 1 liter per hour over 30 m^2 of greenhouse could be measured with confidence).

The top of the reservoir was constricted to 250 mm diameter, giving a change in nutrient volume approximating to 50 ml per mm change in level. Hence, a level sensor with about 2 mm hysteresis was required to match the sensitivity of the load cell.

The level sensor electronics system was based around 2 National Semiconductor Fluid detector ICs (LM1830 Linear data book 1980) configured as high level and low level detectors, respectively (Fig. 3). When the fluid level dropped below the lower setpoint probe, a bistable multivibrator (flipflop) was set, activating a relay, and opening the solenoid valve on the water tank. The solenoid remained open until the fluid level rose above the upper setpoint, when the bistable multivibrator was reset, thus deactivating the relay. A separation of 2 mm between the upper and lower setpoints (sensor probes) ensured stability of operation. Reliability of the unit varied considerably with the choice of sensor probes. Initially, we used 3.2 mm stereo telephone jacks, but found that the insulation between electrodes failed intermittently after immersion in nutrient solution for several weeks. Depending on which level detector failed, the water tank solenoid valve either opened or remained closed for excessive periods producing a stepped water-use curve. However, pairs of 1.6 mm electrical plugs, one for each setpoint, proved satisfactory, and smooth reliable outputs such as those shown in Fig. 4 were produced.

The 3rd source of error comes from variations in dead volume of the closed circuit. The volume of nutrient circulating through the channels and pipes varied from 72 and 65 liters for the center and guard row systems without plants (Fig. 5) to about 200 liters with a mature crop. This volume might vary in the short term by either movement of plants during routine crop maintenance or changes in pump flow rate, and its effect on apparent transpiration rate would depend on the dead time of the system. In this instance, both systems equilibrated within 12 min of commencement of charging with one pump, and, on doubling the flow rate with a 2nd pump, the dead volumes increased by 11.5 and 6.0 liters, respectively, for center and guard systems and had equilibrated again within 6 min (Fig. 5). Transpiration rates were calculated over intervals of at least 1 hr. Therefore, step changes in volume would affect only one hourly value, while random variations in pump speed, arising from mains voltage fluctuations, would most probably average themselves out. Consequently, it is not surprising that errors specifically attributable to system volume changes were rare.

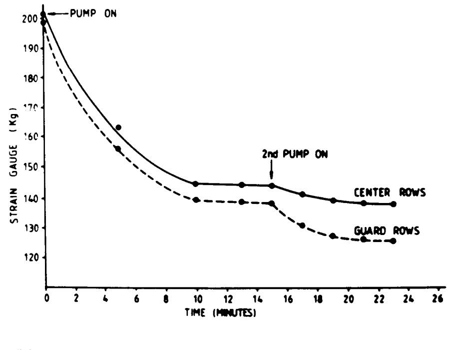

Fig. 5. Equilibration of the nutrient level from: **(a)** starting up of a pump with the system drained; **(b)** bringing in a 2nd pump to double the circulation rate.

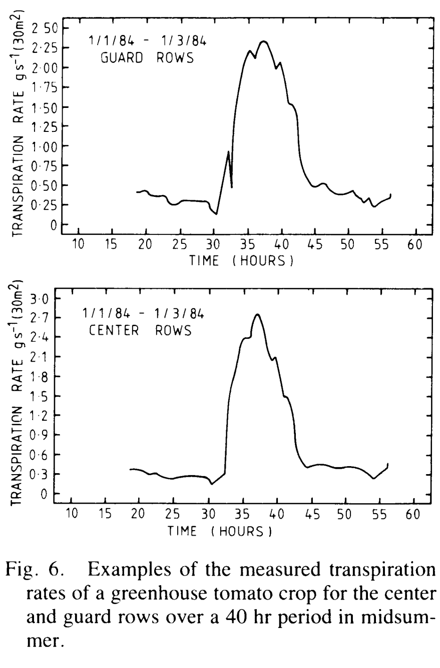

Fig. 6. Examples of the measured transpiration rates of a greenhouse tomato crop for the center and guard rows over a 40 hr period in midsummer.

Transpiration rates were calculated from the change in water tank weight over each hour, thus yielding directly mean hourly values which could be related to hourly CO$_2$ consumption and total enthalpy exchange with ambient air, both of which were measured concurrently with water use. This method of calibration proved satisfactory in most instances and was simple to calculate. However, when transpiration rate was low or when level sensor hysteresis exceeded 2 mm, irregularities in the hourly rate were a problem, and transpiration then was calculated from regressions of tank weight on time over 90-min intervals (Fig. 6). Unfortunately, neither method was particularly satisfactory when the water tanks were refilled during the time interval of calculation (e.g., 32 hr, Fig. 6), a process which took about 20 min. Such missing data could be estimated by interpolation should it be required.

Peak daytime transpiration rates varied from 50 mg s^{-1} m^{-2} in midwinter (at a peak Leaf Area Ratio of 3.5, with an incident radiation of about 300 W m^{-2}) to 150 mg·m^{-2} floor ·s^{-1} in mid summer (radiation approximately 800 Wm^{-2}), that is from 5.4 kg·h^{-1} to 16.2 kg·h^{-1} for each system (unpublished results). Thus, a maximum uncertainty in water tank weight of 0.2 kg is equivalent to less than 5% error. Nighttime transpiration rates however were in the order of 0.75 kg h^{-1}, and the potential error in this case was much more significant (around 25%). When such data were important, regression was used.

The system just described has operated reliably and accurately for 2 years, with a minimum of maintenance, and is being used to determine both the greenhouse energy budget, and to derive improved algorithms for irrigation controllers.

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Control of *Erysiphe cichoracearum* on *Zinnia elegans*, with a Polymer-based Antitranspirant

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Additional index words. powdery mildew, cloud cover, Acti-Dione PM

Abstract. **A polymer-based antitranspirant was compared to a fungicide, Acti-Dione PM for control of *Erysiphe cichoracearum* on *Zinnia elegans* and its effects on plant growth. Plants treated with the antitranspirant had a significant increase in height, fresh and dry weight, and length of the flowering period. In addition, the antitranspirant treated plants had significantly reduced powdery mildew. SEM studies showed that the antitranspirant treated plants had closed stomata, and presumably this had an effect on water uptake as well as the plant host interactions.**

Westcott (11) has reported that powdery mildews are widely distributed, but they are sometimes more abundant in semiarid regions than in areas of high rainfall. Some species require a high humidity, and this humidity can be provided at the leaf surface, when cold nights are followed by warm days. The control of powdery mildew on many annual bedding plants always has been difficult and may result in other nontarget effects, such as enhancement of other diseases and increases in mite populations (5, 8). Ziv and Frederiksen (12) found on oats and wheat that foliar diseases such as powdery mildew could be controlled by using epidermal coating materials (Wilt Pruf and Vapor Guard). Based upon preliminary findings, the objective of this experiment was to determine if a polymer based antitranspirant could control powdery mildew on *Zinnia elegans* Jacq. more effectively than Acti-Dione, [3-)2-(3-5-Dimethyl-2-oxocyclohexyl)-2-hydroxyethyl)-glutarimide (FMC Corp.)], a commercially used fungicide. *Zinnia* was selected because, under the environmental conditions of the high plains of West Texas, it is highly susceptible to powdery mildew (*Erysiphe cichoracearum*) de Candolle DC.

Seeds of *Zinnia elegans* Jacq. 'Lilliput' formula mixed colors were seeded 30 cm apart in 10 rows in a field on 10 June 1983. The field plot was 15^2 m. There were 3 rows per replicate, 330 plants per replicate. A randomized complete block design was used. Natural infection occurred when inoculum spread from adjacent rows of plants infected with powdery mildew.

Plants were grown to the 2 leaf stage, and the antitranspirant then was applied [Cloud Cover (AKAR, McAllen, TX 78504)]. The polymer was mixed with distilled water, 1:5 (v/v), with 0.01 ml surfactant. The film was sprayed to run-off on all leaves with a 2 dekoliter sprayer. The spray was repeated every 3 weeks until the plants reached maturity. Then it was applied twice more at 30-day intervals, for a total of 5 sprays. The fungicide was sprayed on all leaves with a 2 dekoliter sprayer to run-off. The fungicide (Acti-Dione PM) was mixed with distilled water and 0.01 ml surfactant per 5 gallons at 150 ppm Acti-Dione PM. The surfactant was a mixture of polyethylene and octyl phenoxy polyethocyl (PLYAC, Hopkins agricultural chemical Co., Madison, Wis.). This spray was repeated at 10-day intervals as recommended.

Measurements of disease levels were taken 4 times, beginning with the first visible symptoms and continued on 2-week intervals, 10 June, 2 July, 16 July, and 6 Aug. These measurements consisted of the number of mildew spots per plant.

For scanning electron microscopy (SEM) examinations, fifty 45-day-old leaves coated with the antitranspirant and fifty 45-day-old leaves sprayed with Acti-Dione were collected, then fresh mounted (1). SEM micrographs were taken at 500 and 100x with a Cambridge 54-10 instrument.

Plants were harvested after 122 days, and plant height, fresh weight, and dry weight were determined for 100 plants per replication. Data were subjected to analysis of variance, and means were separated by Duncan's multiple range test.

The epidermal coating with the polymer-based antitranspirant controlled powdery

Table 1. Efficacy of antitranspirant and fungicide treatment in control of *Erysiphe cichoracearum* (powdery mildew) of *Zinnia elegans*.

	Day from infection				
Treatment	7	14	21	35	43
	No. of spots/plant				
Untreated	0.0	8.2 a^z	23.1 a	31.6 a	40.3 a
Acti-Dione PH	0.0	6.1 b	10.5 b	15.6 b	17.3 b
Cloud Cover	0.0	0.2 c	0.3 c	0.4 c	0.4 c

^{z}Means separation within columns by Duncan's multiple range test, 5% level.

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