Comparison of a new plant-based irrigation control method with light-based irrigation control for greenhouse tomato production

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[1]Department of Biological and Environmental Engineering, Cornell University, Ithaca, New York, USA 14853; [2]Department of Chemical and Biological Engineering, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z4; and [3]Pacific Agri-Food Research Centre, Agriculture and Agri-Food Canada, Agassiz, British Columbia, Canada V0M 1A0

Shelford, T.J., Lau, A.K., Ehret, D.L. and Chieng, S.T. 2004. **Comparison of a new plant-based irrigation control method with light-based irrigation control for greenhouse tomato production**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **46**: 1.1-1.6. A new control algorithm utilizing an off-the-shelf electronic balance to directly measure plant water use was developed to control irrigation of a greenhouse tomato crop. Water use was measured by summing the change in weight of the medium over short time-periods, rather than by examining its absolute weight over time. Experiments were then conducted to compare the new algorithm to the current industry-standard light-based approach in terms of irrigation consistency and frequency. Results showed that both control algorithms were effective; the plants did not experience long periods without watering. The weight-based approach produced a more consistent amount of leachate, indicating that it was more capable of supplying water as the crop needed it. Furthermore, it had an ability to trigger irrigation at night. A control strategy encompassing both weight-based and light-based inputs is recommended to improve irrigation efficiency. **Keywords**: greenhouse irrigation control, weight-based algorithm, light-based algorithm, water conservation.

Un nouvel algorithme de contrôle pour la mesure directe de la consommation d'eau par les plantes et utilisant une balance électronique commerciale a été développé pour contrôler l'irrigation dans une serre de production de tomates. L'utilisation de l'eau était mesurée en cumulant les variations de la masse du média de culture sur de courtes périodes de temps, plutôt qu'en examinant le changement de masse absolu dans le temps. Des expériences ont été réalisées pour comparer le nouvel algorithme par rapport à l'approche couramment utilisée dans l'industrie basée sur la lumière en mesurant la constance et fréquence d'irrigation. Les résultats ont montré que les deux algorithmes de contrôle étaient efficaces; les plants n'ont pas subi de longues périodes sans arrosage. L'approche basée sur la masse a résulté en une infiltration plus constante, indiquant que ce système était plus à même de fournir de l'eau quand les plants en avaient besoin. De plus, ce système était capable de démarrer l'irrigation la nuit. Une stratégie de contrôle incorporant les deux paramètres basés sur la masse et sur la lumière est recommandée pour améliorer l'efficacité d'irrigation. **Mots clés**: contrôle d'irrigation en serre, algorithme basé sur la masse, algorithme basé sur la lumière, conservation de l'eau.

INTRODUCTION

Most of the greenhouse-grown vegetables in Canada are produced using hydroponic methods, where inorganic fertilizers are applied through the irrigation water (Anonymous 1996). The crop is usually irrigated to excess, where up to 30-50% of the water used by the plants leaches through the root zone (Kläring 2001). This maintains uniform irrigation throughout the greenhouse in cases where there are supply differences among drippers (van de Vooren et al. 1986). Because the leachate is often not recirculated, the movement of excess applied nutrients to groundwater and surface water is a major challenge facing the industry. Supplying fertigation to a crop at the correct time and in the correct amount will reduce this impact and improve water management.

The timing of irrigation supply also influences crop productivity and quality. Much research has been conducted in an effort to establish optimum schedules in drip-irrigated greenhouse crops (Abbott et al. 1985, 1986; Bar-Tal et al. 2001; Jovicich et al. 2003; Papadopoulos and Tan 1991; Snyder and Bauerle 1985). These studies often involve varying the duration and/or frequency of irrigation, both on the basis of preset time intervals. Often results are difficult to apply universally because of the complexities of irrigation management. Each crop may have different requirements, which in turn, depend on stage of development, physiological or phenological status, and climatic conditions. Substrate water content also influences aeration and therefore has both direct and indirect effects on plant performance. Even so, the ability to deliver water to the crop in synchrony with the amount of water used by the crop is the goal of most growers.

A commonly-used irrigation control algorithm for greenhouse vegetables is based on light integral or light summation (Anonymous 1996). A light sensor is used to measure incident solar radiation to estimate how much energy the crop has received. Once a threshold value of light energy has been intercepted, an irrigation event is triggered. This system differs from timed irrigations (that is, using a preset number per day), allowing a grower to more closely match water supply to the evapotranspiration rate, which is largely driven by light intensity. The light-based method has several advantages:

1. It is very reliable and simple to manage.
2. Only one sensor type is required to operate the control algorithm.
3. A few sensors located around the greenhouse can adequately estimate the light levels.

Growers have considerable experience in using this algorithm and make decisions about irrigation setpoints on the basis of the well-established relationship between light and evapotranspiration.

However, the light-based approach has several disadvantages. First, it does not function well under low light conditions (Chiranda and Zerbi 1981; De Graaf 1988) or at night. This is important since growers occasionally have a need to water at night (Anonymous 1996). The algorithm also does not take into account other factors affecting water usage such as humidity, temperature, CO_2 regime, or crop health. Finally, unique irrigation setpoints are required for different crops and stages of growth. For these reasons, growers sometimes modulate control of light-based irrigation with measurements of the electrical conductivity (EC) or ionic strength of the leachate; for example, values which are higher than that of the irrigation feed indicate that light-based irrigation must be increased. As growers switch to multiple cropping systems or staggered production, the prediction of these setpoints is no longer straightforward. New monitoring and control methods which measure other aspects of the plants and/or their environment (Ehret et. al. 2001) are required to more closely match the application of irrigation to the greenhouse crop requirements. For these reasons, other monitoring techniques are being developed or implemented (Ehret et al. 2001; Giacomelli 1998) using, for example, tensiometers (Papadopoulos et al. 1992) and moisture probes to evaluate substrate moisture status. In other cases, additional climatic factors such as water vapour saturation deficit are used to refine models of irrigation control based on light (Hamer 1998) or to develop models of potential evapotranspiration (Norrie et al. 1994; Xu et al. 1995).

The objectives of this research were to develop and evaluate the performance of a new irrigation control algorithm based on direct measurements of plant water use and compare the new algorithm with light-based irrigation.

MATERIALS and METHODS

Experimental procedure

The experimental setup consisted of 30 tomato plants (*Lycopersicon esculentum* Mill. c.v. *Rapsodie*) arranged in five rows of six plants each, occupying 15 m^2 or 10% of the floor space in one compartment (dimensions: 9.6 x 16.0 m) of the University of British Columbia Plant Science Venlo-type Greenhouses. The plants were grown in 15-L bags of yellow cedar sawdust with three plants per bag and supported by an overhead crop wire. The plants were maintained as closely as possible to industry production standards (Anonymous 1996). The environment was monitored and regulated with an Argus™ control system.

Two sets of plants were irrigated by two different irrigation control algorithms, based on either light integral or weight-change. Thus, 15 plants were involved in each treatment. Both irrigation systems ran on the same datalogger (Campbell Scientific, Model CR10X, Logan, UT). Irrigation was supplied by independent pumps drawing from a common irrigation tank. The pumps were controlled by a solid-state relay box, which was in turn switched by the control ports on the datalogger.

Two leachate collection stations were established for each irrigation control system. At each station, leachate from two bags (three plants each) was collected in elevated fiberglass trays and funneled into buckets hung from load cells (Revere, Model 363-B10-50-20P1, Tustin, CA) for measurement by the datalogger. Given the high frequency of irrigations throughout the daylight hours (over 20 on a sunny day), the datalogger recorded the weight of each bucket every five minutes, from which the weight change and the amount of leachate received over time were obtained. In the case of the weight-based algorithm, the leachate collection stations were located on bags other than the one used for irrigation control purposes to maximize the number of plants used for data collection. The amount of nutrient solution administered at each irrigation event was verified every second day by manually triggering an irrigation event with the drippers taken out of the medium and placed in a collection cup. The volume produced after the set irrigation time of 80 s was then measured and recorded by hand. Irrigation volume was approximately 100 mL per dripper. All of the irrigation events that took place during the course of the experiment were recorded for evaluation.

The experiment was run during the summer and fall of 1999 when the crop had a fully established canopy. During the trial, the weather was variable with light conditions ranging from 0.8 to 35 MJ m^{-2} d^{-1} (these are light-sum units as commonly used by the greenhouse industry). Twenty-nine days of data were collected for analysis during the period September 12 to November 8 (Shelford 2000).

Light-based approach The traditional light-based control algorithm works by accumulating the light energy intercepted by a light sensor. Upon reaching a preset level (the light integral value) the irrigation system is prompted to provide an irrigation event. In the experimental setup, light level was measured above the crop canopy by two light sensors (Li-Cor, Model LI-200SB, Lincoln, NE) every 20 s. This frequency of measurement was used in order to account for the sometimes highly variable nature of the light conditions due to clouds and so on. Since the light sensors were located inside the greenhouse structure and would occasionally be subjected to shading from overhead beams, the larger of the two measurement values was assumed to be the correct value and was added to the light integral. Target light integrals were obtained from the local production guide (Anonymous 1996). These varied depending on the season and time of day, but were generally between 0.8 to 1.0 MJ m^{-2} h^{-1} during the fall period. To ensure adequate irrigation under very low light conditions, an irrigation event was automatically triggered and the light sum reset if irrigation had not occurred in the past hour. This is in line with conventional grower practice. Minimum hourly irrigation was disabled after dusk and then started again at dawn.

Weight-based approach The weight-change algorithm used an electronic scale (Ohaus, Model "Champ", 25 kg capacity, Pine Brook, NJ) to measure the weight of the growing medium, plant roots, and collected leachate, as shown in Fig. 1. Direct and continuous in-situ measurements have been successfully recorded by Van Meurs and Stanghellini (1992) for tomato crop transpiration. Rather than measuring the weight of the growing medium and triggering an irrigation event when a predetermined drop in weight had occurred, as has been done in potted media (Baille et al. 1992; Boukchina et al. 1993; Zoon et al. 1990), a predetermined change in weight of the medium due to plant water uptake was used to induce an irrigation event.

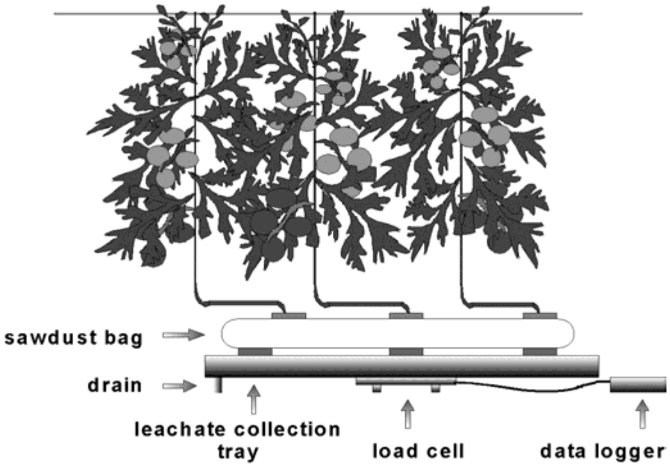

Fig. 1. Layout of equipment utilized in the weight-based control algorithm.

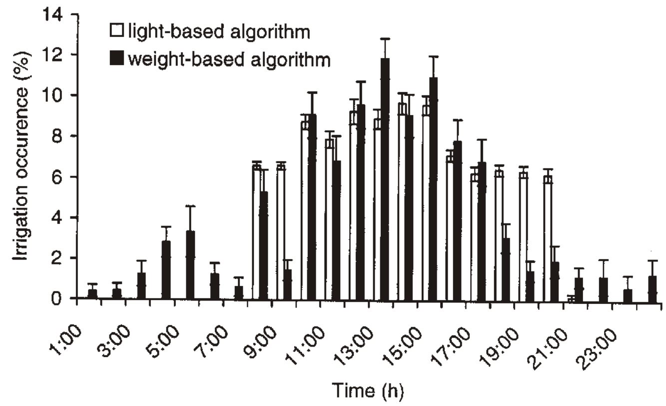

Fig. 2. Histogram of irrigation events through the day as a percentage of the daily total. Vertical bars represent the standard error of the mean of each value. Data averaged from 29 d of measurement.

Leachate water was manually drained from the collection tray every day or two depending on accumulations. Plant water uptake was determined from the difference between successive weight measurements recorded every 20 s. This frequency of measurement was required to reduce the effect of random noise in the measurements. The 20-s differences were then summed to give cumulative water uptake. Irrigation was triggered when cumulative water uptake of 80 mL per plant was reached. The setpoint was based on grower guidelines (Anonymous 1996), which suggest a delivery of 100 mL per plant at each watering, including 20 mL for leaching. Minimum hourly irrigation was not implemented by this algorithm.

Since the plants were suspended from the overhead wire, and by convention, angled in such a way as to allow the lower stem to trail horizontally along the ground, the bulk of the shoot weight was carried by the wire and not by the electronic scale. Furthermore, residual shoot weight picked up by the scales was unlikely to change over the short time intervals used for measurements. Hence, weight gain by the crop due to growth did not complicate the measurement of water use by the scale. A previous study in which lysimeters were used to measure water use ran into problems with breakdowns and measurement errors (De Graaf 1988). To minimize error in our measurements, an error-checking procedure was built into the control algorithm to improve the validity of the measured water use rate. The difference between successive measurements was compared to a check value to see if it fell within an acceptable range (± 25 g). Changes in weight beyond this threshold value were not included in the cumulative calculations and were replaced with the most recent valid difference. With this procedure, errors due to disturbance of the scale, plant, or medium during normal greenhouse operations, and the removal of leachate water, could be minimized.

RESULTS and DISCUSSION

Irrigation frequency

The minimum, maximum, and average time between irrigation events was determined for each algorithm over the 29 days of data recording (Table 1). Comparing irrigation events during the daylight hours, the average time between events was similar for the two algorithms. However, the light-based algorithm exhibited a considerably reduced maximum time between events, due in part to the imposition of the minimum once-per-hour irrigation in the light-based system. But since irrigation frequency is determined by either water use or light integral setpoints, depending on the system, both setpoints can be modified to allow more or less frequent irrigation. The difference in the minimum times between irrigation for the light and weight-based systems indicates that the setpoint chosen for the weight-based approach permitted a more responsive irrigation of the crop.

Table 1. Comparison of irrigation frequencies between light-based and weight-based algorithms.

Algorithm[1]	Time between irrigation events (min)		
	Mean (± SD)	Minimum	Maximum
Light	51 ± 14	21	62
Weight (24 h)[2]	85 ± 81	73	511
Weight (daylight only)[3]	56 ± 39	73	262

[1]The number of irrigation events used in the analyses was 479, 377, and 325 for the light, weight (24 h), and weight (daylight only) algorithms, respectively.
[2]Irrigation events averaged over a 24-h period
[3]Irrigation events averaged during daylight hours only (light levels above 10 W/m^2)

A histogram of all irrigation events recorded over the experimental period is illustrated in Fig. 2, in which standard errors of the means are included for each hour. Because the number of irrigation events for the two algorithms was different, the percentage of occurrence was used rather than the absolute number of events. As expected, the light-based approach was limited to the daylight hours with the highest frequency taking place in the early afternoon. The weight-based approach was similar in that the highest

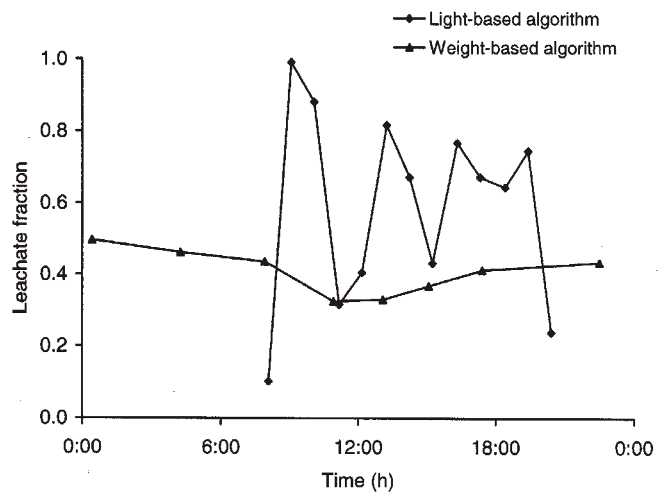

Fig. 3. Leachate fraction, expressed as percentage of irrigation supply, over a day with low light levels.

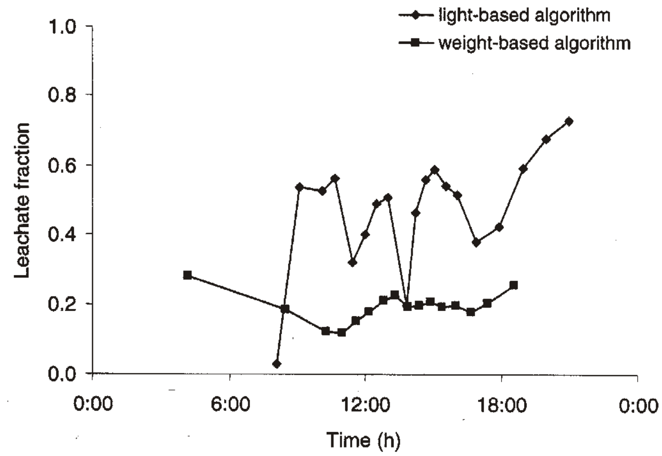

Fig. 4. Leachate fraction, expressed as a percentage of irrigation supply, over a day with high light levels.

frequencies also occurred in the early afternoon. However, the weight-based algorithm frequently triggered nighttime watering, and pre-dawn watering was more likely to occur at approximately 6:00 h than at any other time during the night. According to the weight-based irrigation records, evapotranspiration that occurs at night is enough to trigger 7% of the scale's total daily watering events. Previous tests (data not shown) demonstrated that evaporation from the medium does not contribute significantly to this water loss.

It is also noteworthy that the daytime distribution of irrigation events was different in the two systems. The light-based system had a higher percentage of irrigation events in the early morning and late evening than did the weight-based system, and conversely the weight-based system had a greater percentage of events in the mid-day to afternoon than did the light-based system. The effects of the change in distribution on crop yield are unknown because consistent records were not taken. Since the weight-based approach measures actual water use, this may indicate a better matching of weight-based irrigation to crop water demand through the day.

Water use

Over the duration of the experiment, water use averaged 4.48 L/d for plants irrigated with the light-based algorithm and 3.78 L/d for those irrigated with the weight-based algorithm (based on the three plants per bag in each case), values which were not significantly different (P=0.052). The data were also separated into early (first half) and late (second half) experimental periods. In the first half, there was no difference (P=0.090) in water use between plants in either system (5.51 and 4.92 L/d in light-based and scale-based, respectively). However, in the second half, plants in the scale-based system used significantly (P=0.03) less water (2.64 L/d) than plants in the light-based setup (3.46 L/d). Light levels differed significantly (P<0.0001) between the two periods (means of 26.361 and 7.655 MJ m^{-2} d^{-1} in the early and late periods, respectively) but it is unknown if this was a contributing factor. The scale-based algorithm could be influencing water uptake over the long term through our choice of a less-than-optimum weight change set point for irrigation. Further research may be required to refine that value.

The volume of leachate produced by each irrigation system was determined in order to assess whether or not each algorithm supplied enough water to the crop. Leachate fraction is defined as the amount of leachate between irrigations divided by the volume of irrigation applied. The irrigation setpoints are normally adjusted in commercial greenhouses to provide variable volumes of leachate throughout the day. Growers generally target very little leachate in the morning and increase the leachate fraction up to 40% on bright afternoons. It was not possible to continuously update the control system, so our setpoints remained constant in the experiment and were not adjusted in order to change the leachate fraction through the day or during variable weather conditions.

The leachate fractions of the two systems were calculated after each watering. Figure 3 shows measured results through a day under low light conditions. In the early morning there is little excess drainage from the medium for plants controlled by the light-based algorithm. The bags had apparently dried out overnight and required several irrigations before the medium was wet enough to allow excess water to drain. We have observed a similar situation in commercial tomato greenhouses, where leachate is often not collected until about 11:00 h, despite irrigation starting up to two hours earlier (data not presented). In contrast, the medium was not allowed to dry out overnight in the weight-based system. Thus, the amount of water drained from the bags remained relatively constant in the morning hours. It is evident that under low light conditions, a watering event was forced every hour regardless of the plants' needs. For comparison purposes, Fig. 4 shows the leachate fraction data for a day with high sunshine hours, whereby the majority of the 19 watering events associated with light-based system was triggered by light level rather than forced hourly constraint. In both cases, the weight-based system showed less variation in percent leachate between successive irrigations throughout the day than did the light-based algorithm. The large fluctuations of light-based irrigation could indicate that it is not synchronized with the plant.

As demonstrated in Fig. 5, values of water use as estimated by taking the difference in irrigation and leachate amounts and water use as measured by the electronic scale were similar, with a correlation coefficient of greater than 0.99. Thus, the leachate

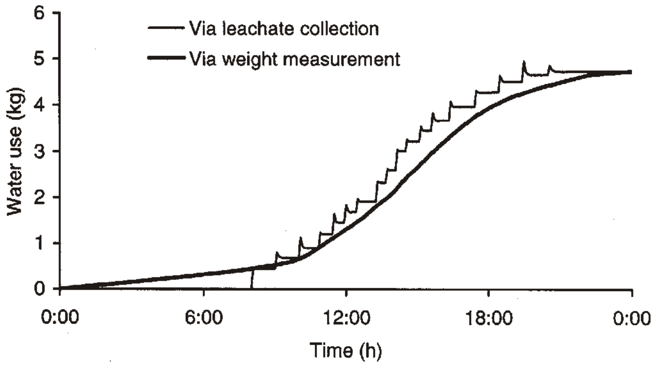

Fig. 5. Cumulative water use as measured by the scale and leachate collection techniques for a typical day. Leachate was collected from plants irrigated by the weight-based algorithm.

collection and measurement technique was considered a valid means of estimating water use. The measurement of water use using scales, however, is the more flexible of the two methods. As shown in Fig. 3, leachate is often not collected until late morning. Under theses circumstances, measurement of early morning water use through leachate collection is not an option even though the plants are actively transpiring.

The effectiveness of the two algorithms under differing light conditions was also compared. Light was selected as a basis for comparison because it is the environmental parameter over which growers have the least direct control. Because light levels can vary considerably throughout the day, again, a light sum approach rather than hourly light level was used for comparison purposes from day to day. The calculated average and standard deviation for the day makes it possible to compare how the leachate fraction varied with the daily light sum. The light-based approach had a correlation coefficient of –0.437 between leachate fraction standard deviation and daily light sum, meaning that on days with low light levels, variations of the leachate fraction increased. In other words, the light-based algorithm had difficulty predicting the water use of the plants and produced much more variable amounts of leachate (as illustrated in Fig. 3). In contrast, the correlation coefficient for the weight-based system was very low (0.015), indicating that this algorithm's ability to function was unaffected by light level.

CONCLUSIONS

A new irrigation control algorithm was developed using electronic scales, which have the ability to monitor continuously and automatically the water use of a crop. The experimental results have confirmed certain advantages of the weight-based approach to irrigation control over traditional light-based scheduling. Its primary advantage is that it provides more consistent volumes of leachate, indicating that it more closely matches the needs of the crop with the supply of irrigation water. The algorithm performed well under both high and low light conditions and was capable of irrigation at night. This approach is not crop specific and could easily be applied to other vine crops. Another advantage is that the irrigation volume may be verified, using the scale, every time there is a watering with no manual disturbance.

Various shortcomings of the weight-based approach also became evident during the study. It involves maintenance tasks such as the draining of the collected leachate, which may have to be done every one or two days in bright weather, although this task could be automated. We do not yet know if it will work on crops that are not supported by a wire, where increases in crop mass due to growth could complicate the water use measurements. Growth complications are unlikely, however, since in an unsupported vertical crop the scales would measure only water taken up for evapotranspiration rather than evapotranspiration plus growth (biomass), as is the case in our tomato crop. Water uptake for growth is only a small fraction of that taken up due to evapotranspiration and its non-inclusion would not compromise the calculations of water use. Furthermore, even though the absolute weight of the system would slowly increase due to growth, measurements were not based on absolute weight, but rather on changes in weight. Because the weight-based system measures the water use of some plants directly, it will not work as well if these plants cease to become representative of the crop for reasons such as disease, insect infestation, or physical damage. However, more plants could readily be used to increase sample size. Very low evapotranspiration rates typical of young plants will not register well on the scales, so the weight-based algorithm could probably not be used for a starting crop.

Demonstrations of our equipment in commercial greenhouses have shown that it is robust and easy to maintain, and does not interfere with routine greenhouse tasks. However, a full cost/benefit analysis of the new algorithm was not the purpose of this study. A proper cost accounting could include items such as (1) the number of independent monitoring stations required for adequate control purposes and the cost of each, (2) the effect on the cost of water and fertilizer, (3) the long-term consequences for tomato yield and quality, and (4) the effects on the environmental sustainability of the industry.

Since the two irrigation control algorithms have their own strengths and weaknesses, a combination of the two algorithms may be beneficial to the growers. For example, control algorithms such as the light-based approach could be used at the beginning of the growing season. The water use measured by the scale could be used to better calibrate the light-based approach, for instance, by adjusting the light-based setpoints automatically. Another potential use is the derivation of an optimal evapotranspiration, through feedback of the water use, so that a climate control algorithm could adjust the environmental setpoints. Here, a number of scales would need to be placed in various zones within the greenhouse, so that the quantification of crop evapotranspiration or water uptake was more representative.

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