Soil Moisture Sensor-based Systems are Suitable for Monitoring and Controlling Irrigation of Greenhouse Crops

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Abstract. Sensor-based feedback control irrigation systems have been increasingly explored for greenhouse applications. However, the relationships between microclimate variation, plant water usage, and growth are not well understood. A series of trials were conducted to investigate the microclimate variations in different greenhouses and whether a soil moisture sensor-based system can be used in monitoring and controlling irrigation in greenhouse crop production. "Genovese Gigante" basil and Campanula portenschlagiana ‘Get Mee’ bellflowers were monitored using soil moisture sensors for an entire crop cycle at two commercial greenhouses. Significant variations in greenhouse microclimates were observed within the two commercial greenhouses and within an older research greenhouse. Evaporation rates were measured and used as an integrated indicator of greenhouse microclimate conditions. Evaporation rates varied within all three greenhouses and were almost double the lowest rates within one of the greenhouses, suggesting microclimates within a range of greenhouses. Although these microclimate variations caused large variations in the growing substrate water contents of containers within the greenhouses, the growth and quality of the plants were unaffected. For example, no significant correlations were observed between the growth of bellflower plants and the average volumetric water content (VWC), minimum VWC, or maximum VWC of the growing substrate. The change in VWC at each irrigation (ΔVWC), however, was positively correlated with the fresh weight, dry weight, and growth index (GI) of the bellflowers. For basil, no significant correlations were observed between plant growth and ΔVWC. This suggests that sensor-based feedback irrigation systems can be used for greenhouse crop production when considerations are given to factors such as the magnitude of microclimate variation, crop species and its sensitivity to water stress, and growing substrate.

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Materials and Methods

Determination of sensor variability. The substrate moisture sensors (GS3; Decagon Devices, Inc., Pullman, WA) used in this experiment determine the growing substrate VWC by measuring the dielectric constant. The sensors minimize the effect of salinity and texture of the substrate by using a frequency of 70 MHz (Decagon Devices, 2016). The variability of the moisture sensor readings was tested by measuring the VWC (m$^3$ m$^{-3}$) of two types of growing substrate when the substrates were dry and wet to container capacity. A round plastic container (15.2 cm diameter) was filled with Sunshine Mix #4 (63% peatmoss and 37% perlite; Sun Gro Horticulture Ltd., Agawam, MA) in the received state. This was considered the dry sample. All sensors were inserted from the top surface of the growing substrate in the container, one at a time, and the VWC of the substrate was measured and recorded. In between each sensor insertion, the growing substrate was mixed thoroughly to prevent introducing air between the prongs in between insertions. The sensors were connected to a ProCheck Handheld Meter (Decagon Devices, Inc.), which allows information from the sensor to be read instantaneously. Once each sensor had been tested in the dry sample, water was added evenly to substrate until drainage occurred, and the growing substrate was again mixed thoroughly. The container was allowed to stand for 5 min before measuring VWC using the same sensors. This was considered the “wet” sample. This procedure was also conducted with Sunshine Mix #1 (75% peatmoss, 25% perlite; Sun Gro Horticulture Ltd.).

Bellsflower cultivation, growth, and substrate moisture content measurements. Five to six leaf seedlings of bellflowers (C. portenschlagiana ‘Get Mee’) were transplanted into 10.2-cm diameter by 11.2-cm height containers containing a peatmoss-based soilless growing substrate (BM6 All-Purpose mix (78% peatmoss, 22% perlite); Berkelee, Ltd., QC, Canada) and grown in a commercial greenhouse in southwestern Ontario, Canada (greenhouse A). Substrate VWC was monitored and recorded using moisture sensor (GS3) plugged into data loggers (EM50; Decagon Devices, Inc.) at 4-min intervals over the entire growth cycle. Sensors were inserted into the substrate from the top, with sensor prongs close to the center of the container. There were 30 containers, each with one moisture sensor. The 30 containers were evenly distributed across three subirrigation tables (1.6 m x 4.3 m). There were ≈680 containers in total on each table and 10 containers with sensors. Plants were managed by the grower following their normal protocol and irrigation of plants was controlled by the commercial grower based on their previous experience. Greenhouse heat was maintained to 17.5 °C, and vents were set to open at 20.5 °C. Mean temperature outside the greenhouse during the experiment was 4.8 °C. The plants were irrigated with a nutrient solution using subirrigation tables. The nutrient solution was made using a fertilizer containing 17% N–2.18% P–14.1% K mix with micronutrients and tap water to an electrical conductivity (EC) of 1.8 dS m$^{-1}$. The plants were spaced twice at 5 and 8 weeks after transplanting. Plant height, and the length and width of each plant canopy were measured weekly. The GI was calculated according to the formula GI = (Height$_{anopy}$ x Width$_{anopy}$ x Length$_{anopy}$) / 300 (Ruter, 1992). Plants were graded by the head grower alone at the end of the production period based on the following criteria: if no growing substrate could be seen from above, the plant received an A grade, if substrate could be seen from above, the plant received a B grade and was not acceptable for sale. Further grading of bellflower was based on approximation of the % of flowering; a grading of 0 means that no buds have flowered, a grading of 1 was given for 0% to 25% flowering, a grading of 2 was given for 25% to 50% flowering, a grading of 3 was given for 50% to 75% flowering, and any flowering above 75% of buds was given a grading of 4. The combination of letter and number grade is used by the grower to determine when plants should be sold.

Shoot fresh weights were measured at the end of the trial, about 10 weeks from transplanting. The surface area of stems and leaves was measured using a leaf area meter (LI-3100C; LiCOR Biosciences, Lincoln, NE). The shoots were then dried at 75 °C for 5 d to constant weight for dry weight measurement.

Basil cultivation, growth, and substrate moisture content measurements. Basil (O. basilicum ‘Genovese Gigante’) seeds were planted in 10.2-cm diameter by 11.2-cm height containers containing a peatmoss-based growing substrate (contains Canadian Sphagnum peatmoss, perlite, calcite lime, compost, yucca extract, gypsum, and mycorrhizae; Premier Tech Ltd., QC, Canada). The trial was conducted in a commercial greenhouse in southwestern Ontario, Canada (greenhouse B). Substrate VWC was monitored and recorded using moisture sensors (GS3), which were installed before planting seed, connected to data loggers (EM50) recording data at 2-min intervals over the growth cycle, which was ≈5 weeks. There were 24 plants with moisture sensors evenly distributed over four subirrigation tables (1.6 m x 5.2 m). There were ≈820 plants in total on each table and six with sensors. The plants were irrigated using subirrigation tables. Greenhouse heat was maintained at 17.5 °C and vents were set to open at 20.5 °C. Mean temperature outside the greenhouse during the experiment was 14.1 °C. The nutrient solution used fertilizer containing 17% N–2.18% P–14.1% K mix with micronutrients and tap water to an EC of 1.8 dS m$^{-1}$. Plants were grown and managed by the grower following their normal protocol. The
plants were spaced once at 4 weeks after planting. Plant height, and the length and width of each plant canopy were measured weekly. The GI, fresh and dry weight, and surface area of the shoots and leaves were determined using the same methods as for the bellflower plants.

Evaporation measurement. Evaporation variations within three different greenhouses were measured using plastic dishes (13.7 cm in diameter) containing tap water and placed at different locations as shown in Fig. 1A–C. Evaporation rates were measured in the same greenhouses used for the bellflower (greenhouse A; Fig. 1A) and basil experiments (greenhouse B; Fig. 1B) and the south greenhouse of the Vineland Research and Innovation Center (greenhouse C; Fig. 1C). Greenhouse A, which was constructed in the early 2000s, had glass ceilings and polycarbonate walls 4.3 m high to the base of the peak and was ≈10 m × 80 m. Greenhouse B was constructed in 2015, with diffuse glass ceilings and polycarbonate walls that were 6.1 m high to the gutter and an area of ≈10 m × 6 m. Greenhouse C was the oldest of the three greenhouses used, built in the 1960s, with regular glass ceilings and walls 3.7 m high to the base of the peak and an area of ≈7.5 m × 25 m. The areas mentioned reflect the experimental area used for monitoring plants for the entire growth cycle. Dishes were filled in the morning with water to a depth of ≈1.5 cm and weighed. The dishes were placed in their designated locations in the morning and left for 8 h. At the end of the 8 h, the dishes were weighed to determine the amount of water lost through evaporation. Measurements were conducted on the 27th (greenhouse A), 28th (greenhouse B), and 29th (greenhouse C) of Apr. 2016. The dish that lost the least amount of water was set as 1, and the amount of water lost in all other dishes was compared with this dish to produce a relative evaporation ratio. This allowed for more direct comparisons of the evaporation variation within a greenhouse.

Substrate VWC profiles. The pre- and postirrigation VWC of the growing substrates were determined by gathering the minimum (VWCmin) and maximum (VWCmax) values of VWC before and after each irrigation. VWCmin was the lowest growing substrate VWC value before irrigation occurred. VWCmax was the value of the growing substrate VWC at which the substrate settled after an irrigation when leachate was observed. The change in VWC (ΔVWC) at each irrigation was calculated as VWCmax − VWCmin. The overall mean VWC (VWCavg) for the entire growth cycle was determined as the mean of all growing substrate VWC measurements. The coefficient of variation (CV), also called relative standard deviation, is a measure of variation of data in a set from the mean and is a standardized measure of frequency distribution of a dataset (Reed et al., 2002). CV % was calculated for each substrate moisture profile by dividing the standard deviation of a moisture profile by the mean VWC of that profile, and then multiplying by 100. The mean, minimum, maximum, and standard deviation of CV % were then determined for each trial.

Results

Evaporation variations within different greenhouses. At different locations within each greenhouse, the measured evaporation rates were nonuniform. For greenhouse A, the northeastern corner had the lowest evaporation and the southeast had the highest evaporation. The evaporation rates observed at greenhouse A increased toward the southeastern end of the greenhouse, with the highest evaporation occurring in the southeastern corner. The western column of dishes did not show a clear trend, with rates decreasing to the north and south of the middle dish. The highest evaporation rate was about 1.9 times greater than the lowest (Fig. 1A). For greenhouse B, the southeastern corner had the lowest evaporation and the southwest corner had the highest. The evaporation rates in greenhouse B generally increased toward the south and west, which would be toward the center of the greenhouse. The exception was the dishes in the eastern column, which were close to a structural wall, and closest to the northeastern corner of the greenhouse. Evaporation rates appeared to follow a pattern of increasing rates toward the south and west of the testing area, which corresponds to the center of the greenhouse section. The highest evaporation rate was 1.6 times greater than the lowest (Fig. 1B). Within greenhouse C, the variation was high (certain locations had an evaporation rate 1.6 times greater than the other locations) and had no clear trend as seen in the two commercial greenhouses (greenhouses A and B). This is perhaps due to a poor or an outdated greenhouse design, which did not allow for as efficient control of the greenhouse climate.

Substrate VWC profiles and variation. The bellflower plants were irrigated 18 times during the 74-d growth cycle. The basil plants were irrigated 26 times during the 36-d growth cycle. For both crops, irrigation frequency increased as the plants increased in size. In the bellflower trial, substrate mean VWC cv % ranged from 19.0 to 85.3%. In the basil trial, cv % ranged from 13.4% to 72.0% (Table 1). VWCmin and VWCavg were positively correlated in both crop-growing substrates (Fig. 2). No correlations were observed between VWCmin and ΔVWC for both crops (Fig. 3).

| Substrate moisture profile (m^3·m^-3) | Bellflower | Basil |
|--------------------------------------|-----------|------|
| Minimum VWC (m^3·m^-3)              | 0.153 ± 0.010 | 0.265 ± 0.013 |
| Maximum VWC (m^3·m^-3)              | 0.335 ± 0.008 | 0.383 ± 0.014 |
| AVWC (m^3·m^-3)                      | 0.183 ± 0.005 | 0.118 ± 0.004 |
| Average VWC (m^3·m^-3)              | 0.254 ± 0.010 | 0.301 ± 0.015 |
| Mean cv %                           | 42.8       | 26.3  |
| sd of mean cv %                     | 15.2       | 11.0  |
| Minimum cv %                        | 19.0       | 13.4  |
| Maximum cv %                        | 85.3       | 72.0  |

Table 1. Growing substrate volumetric water content (VWC) profiles and summary of coefficient of variation % (CV %) of growing substrate VWC profiles of bellflower and basil plants.
Plant growth and relation to growing substrate VWC. From transplanting to marketable size, the bellflower production time was just over 10 weeks (see Table 2 for fresh and dry weights, height, and GI). Of the 30 plants in the trial, 28 received an A grade and two received a B grade from the commercial grower, which were further graded by stage.

Table 2. Growth attributes of bellflower and basil plants determined at the end of the respective production cycles.

| Growth attribute          | Bellflower (g/plant) | Basil (g/plant) |
|---------------------------|----------------------|-----------------|
| Shoot fresh weight        | 54.2 ± 1.9           | 43.2 ± 0.9      |
| Shoot dry weight          | 6.5 ± 0.2            | 3.87 ± 0.1      |
| Height (cm)               | 12.0 ± 0.3           | 23.0 ± 0.5      |
| Growth index              | 25.2 ± 1.2           | 42.0 ± 1.4      |

Data for bellflower are mean ± SE of 30 plants. Data for basil are mean ± SE of 23 plants.

Two containers were graded A-1, five containers A-2, 18 containers A-3, three containers A-4, one container B-0, and one container was graded B-2.

For basil, it took about 5 weeks from seed planting to marketable size (Table 2). Basil is sold as an edible crop and not as ornamentals and are, therefore, sold by size and not graded.

No significant correlations were observed between VWC_{min} (Fig. 4), VWC_{max} (Fig. 5), or VWC_{avg} (Fig. 6) and fresh weight, dry weight, GI, or height for either of bellflower or basil.

In bellflowers, ΔVWC was observed to have a positive linear correlation with fresh weight, dry weight, and GI but was not correlated with height. In basil, ΔVWC was not significantly correlated with fresh weight, dry weight, GI, or height (Fig. 7).

Sensor variability. The null hypothesis tested was that any two GS3 soil moisture sensors measured the same VWC when inserted into a growing substrate. A P value of 0.995 was determined through ANOVA for the individual sensor readings, indicating that the sensors did not read significantly different values for the same VWC of the substrates they were in. P values of <0.001 were determined for both the comparisons between the blocks (the two substrate types) and for the values of the VWC of wet and dry soils. This indicates that any two sensors read the same value when inserted into the same substrate and can be treated as equal sensors.

Discussion

Evaporation variations within different greenhouses. The three greenhouses in this study were chosen to about represent the range of greenhouse designs in southern Ontario, one of the most concentrated regions of greenhouses in Canada. Greenhouse A was an example of the most common or midlevel greenhouse design. Greenhouse B, the most recently constructed greenhouse, was an example of a newer, more technologically advanced greenhouse. Finally, greenhouse C was an example of an older greenhouse design in Ontario. Each of these greenhouses differed from the others in terms of date of construction: greenhouse A was about 15 years old, greenhouse B was about 1 year old, whereas greenhouse C was about 55 years old.

Dish evaporation rate is an integrated measure of microclimate conditions which can influence the plant’s evapotranspiration rate and water demand. The presence of variations in dish evaporation rates within each greenhouse indicates that despite the best efforts of modern greenhouse construction and technology, greenhouse microclimate variations have not been completely eliminated and may significantly affect the water demand and usage of crops in these greenhouses (Stanley and Harbaugh, 1992).

In modern commercial greenhouses, growers normally provide the same amount of water to all individual plants within a crop. However, microclimate differences within greenhouses can cause large variations in plant evapotranspiration and substrate VWC within a greenhouse (Stanghellini and van Meurs, 1992). Microclimate variations can be caused by factors such as greenhouse structure, air flow, temperature, humidity, lighting, and method of irrigation (Teitel, 2007). With such a large microclimate variation (certain locations had evaporation rate 1.9 times higher than those of other locations) within a greenhouse, one may ask whether soil moisture sensor-based feedback control system be reliably used in managing greenhouse crop irrigation. To answer this question, we need to examine the actual substrate VWC profile, variation, and their relationships with plant performance under these greenhouse conditions.

Substrate VWC profiles and variation. Two different crop species were grown in their respective greenhouses. The average growing substrate VWC for the entire crop
cycle between the two crops were different, between 0.14 and 0.33 m$^3$·m$^{-3}$ for bellflower vs. 0.20 and 0.46 m$^3$·m$^{-3}$ for basil. The WC$_{\text{min}}$ and VWC$_{\text{avg}}$ for both crops were positively correlated, which is to be expected; a higher VWC$_{\text{min}}$ throughout a growth cycle indicates a higher VWC$_{\text{avg}}$. No significant relationship was observed between VWC$_{\text{min}}$ and ΔVWC, which indicates that the amount of water absorbed by a growing substrate at each irrigation (i.e., ΔVWC) was not entirely dependent on how dry the substrate was. Other factors such as physical composition of the growing substrate and amount of root growth also contribute to substrate rewetting.

The differences in values of CV % suggest that the bellflower crop experienced a larger variation of VWC within the crop when compared with basil. A possible explanation for this may be the more consistent climate control within greenhouse B, which subjected plants to more uniform environmental conditions. Another explanation is that more frequent watering of basil crop prevented the effects of the environmental variations from becoming too large. The bellflowers were allowed to reach a lower growing substrate VWC according to the grower’s practice, allowing for the differences in evapotranspiration to become more apparent.

The minimum and maximum CV % values observed were also higher in bellflowers than in basil, which suggests that variability was higher in the bellflower crop than in the basil, which was likely due to a combination of environmental factors. Given that irrigation methods were the same in both locations (subirrigation using flooding tables), the variation must be due to differences in greenhouse microclimate and irrigation regimes, as well as species water requirements and growing substrates used. The low CV % observed in basil may be in part due to the more frequent irrigation compared with bellflower. Because the bellflower was irrigated less frequently, the effects of variations in greenhouse microclimate on the growing substrate VWC and evapotranspiration were more obvious than for the basil crop. Irrigating more frequently would be able to counteract the effects of greenhouse microclimate differences by saturating the substrate more often. Greenhouse B was also newer than greenhouse A and had more advanced systems for climate control, which could have contributed to the lower CV % observed. In addition, the results of the sensor consistency test indicate that variations in growing substrate VWC measurements were not due to differences between two sensors but were caused by external factors as our initial sensor testing showed that none of the sensors produced significantly different measurements from any other when inserted into a sample of dry or wet growing substrate.

**Plant growth and relation to growing substrate VWC.** Given that basil are sold as edible plants, whereas bellflowers are sold as ornamental flowers, consistency in mass is more important for the basil grower whereas more consistent height, size, and the timing of flowering is more important to the bellflower grower. Timing of flowering and variations of flowering within a crop can be interpreted from the commercial grower’s ratings given to each of the plants. Of the 30 bellflower plants observed, only two received a B grade and 28 received an A grade, with most of the plants being graded A-3. This grading means that the most of the plants were in about the same stage of flowering.

Few relationships between measured growth attributes and substrate VWC were observed. A chronically low VWC$_{\text{min}}$ indicates that the growth substrate was allowed to dry and drought stress may have been imposed on the plants. Conversely, a high VWC$_{\text{min}}$ may indicate potential over-watering, which can also negatively affect the growth of a plant. There was no observed relationship between VWC$_{\text{min}}$ and growth of bellflowers, which suggests that VWC$_{\text{min}}$ was within an acceptable range for the plants. In basil, VWC$_{\text{min}}$ was also not correlated with any of the measured variables, which suggests that for the range of VWC$_{\text{min}}$ values observed, the growth of basil was not dependent on the VWC$_{\text{min}}$ reached before irrigation occurred. This may also suggest that the irrigation regimes of the basil and bellflower plants did not allow the VWC$_{\text{min}}$ to decrease to a level where the effect of larger plant canopies using more water than smaller plant canopies became apparent. For both crops, plant growth appeared to be independent of the range of growing substrate VWC$_{\text{min}}$ observed. However, outside this range, plants may experience drought stress (if VWC$_{\text{min}}$ is too low) or flooding stress (if VWC$_{\text{min}}$ is too high). This indicates that through experiential knowledge, the growers at both greenhouses triggered irrigation within a range of

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**Fig. 5. Response of plant fresh weight, dry weight, growth index, and height to average maximum growing substrate volumetric water content (VWC$_{\text{max}}$) of bellflower (A, C, E, and G) and basil plants (B, D, F, and H).**
acceptable VWC_{min} for both crops. Evidence of the flexibility of crops with respect to VWC ranges, as opposed to requiring well-defined ranges, for other greenhouse crops and some nursery crops has been observed by Cayanan (2009) and Zheng et al. (2013).

The VWC_{max} was not observed to have a significant correlation with any measured growth attributes in either bellflower or basil, which suggests that the VWC_{max} experienced by plants of either species was not high enough to impose flooding stress (oxygen deficiency). Flooding a growth substrate decreases the concentration of dissolved oxygen, which can have a negative impact on the plant growth (Zheng et al., 2007). Flooding stress is defined as chronic over-irrigation and is known to decrease plant metabolism and slow growth rates (Olivella et al., 2000; Singh et al., 1991). Because flooding would have a negative effect on the growth of the crop, it is expected that if chronic flooding had occurred in either the bellflower or basil, a negative relationship would be observed.

Similar to VWC_{max}, our results show that in bellflowers, plants of similar mass and size were produced when VWC_{avg} ranged from about 0.15 to 0.3 m^3 m^{-3}, and for basil, similar plants were produced when VWC_{avg} ranged from about 0.2 to 0.4 m^3 m^{-3}. The use of VWC_{avg} may not be a suitable metric for determining how well a plant may grow, especially in crops such as bellflower, which has a relatively long production cycle. Instead, the VWC_{min} reached may be useful to ensure that drought stress is not experienced by a crop. In addition, the VWC_{avg} of a longer production cycle may be misleading as there is more opportunity for fluctuations in the growing substrate’s water content between the early stage when plants were small and the later stage when plants were large.

If the average VWC of a substrate is not a useful metric, the range from VWC_{min} to VWC_{max} (ΔVWC) may be more useful. Kiehl et al. (1992) showed that exposing chrysanthemums to a larger range of soil moisture tensions yielded better growth than plants kept at a constant or smaller range of soil moisture tensions. This observation was also partially reflected in the bellflower measurements, where ΔVWC was positively correlated with fresh weight, dry weight, and GI of the bellflower plants. For the basil plants, however, ΔVWC did not have any significant correlations with growth measurements. Although it is possible that exposing plants to a larger ΔVWC might have allowed better growth, it is more likely that plants with a larger canopy size had a higher water requirement and, therefore, removed more water from the growing substrate, which would increase their respective ΔVWC.

From this research alone, it is not possible to make a definitive conclusion on the efficacy of the irrigation regimes observed, but it can be concluded that a significant amount of variation within the substrate VWC of both crops was present under the two commercial greenhouse settings. Although this variation appears to be large in some cases, the lack of significant correlations between size (height and GI), weight (fresh and dry weights), and the growing substrate VWC, whether that be minimum, maximum, or average VWC, suggests that plants are able to tolerate variable conditions within a certain range. The lack of observed significant relationships also suggests that plants did not experience sufficient drought or flooding stress to negatively affect their growth. This flexibility will allow sensor-based feedback control irrigation systems to be used if the appropriate number of sensors are used and the sensors are placed in the right locations. The number of sensors and where to place them depends on the unique microclimate situation of the greenhouse.

The differences in environmental conditions observed between two modern commercial greenhouses suggest that sensor-based feedback control systems for irrigation can be a useful tool for irrigation scheduling, if properly implemented. Some research has been carried out in the usage of wireless sensor networks in the automation of irrigation in nursery production of shrubs and trees (Belayneh et al., 2013; Lea-Cox et al., 2013; Lichtenberg et al., 2013), but these studies do not explore the possibility of microclimate variation and its relationship with irrigation. To properly implement a soil moisture sensor-based control system, conditions such as variation of evaporation and microclimatic differences must be understood. Ambient evaporation is an integrated reflection of factors such as temperature, air flow, VPD, and PAR at a given location (Stanley and Harbaugh, 1992). Sensors should be placed in areas of a greenhouse with differing levels of evaporation (e.g., areas of high, low, and average evaporation) to accurately monitor the water status of a crop. The number of sensors is dependent on the magnitude of variation and the sensitivity of the crop of interest to water stress. Greenhouses with
high variation or species that are sensitive to water stress would require a larger number of sensors for a soil moisture sensor-based irrigation control system. For species that can tolerate larger ranges of substrate moisture content or greenhouses with less microclimatic variation, fewer sensors would be required for the irrigation control system.

Given this flexibility in acceptable growing substrate VWC range, a sensor-based system could be used to control the irrigation in greenhouse production of some crops.

**Conclusions**

Our results showed that there were large microclimate variations within individual greenhouses as measured in southwestern Ontario, Canada. Generally, the variations were larger in older greenhouses than in newer greenhouses. The variations in microclimate and other factors caused large variations in growing substrate water content profiles, such as VWC$_{\text{min}}$, VWC$_{\text{max}}$, VWC$_{\text{avg}}$, and ΔVWC. Despite these large variations in microclimate, the growth and quality of both the tested bellflower and basil crops were unaffected by irrigation amount and frequency. This suggests that substrate moisture sensor-based feedback control irrigation systems can be applied in these greenhouse crop production systems for the controlling of greenhouse irrigation. However, the lowest substrate moisture content to be used as a triggering value for irrigation event to be initiated and the number of sensors needed in a greenhouse is dependent on factors such as greenhouse conditions, crop species, and growing substrate type. If microclimate variation within the greenhouse is large, or if plants have a narrower range of acceptable growing substrate VWC, then more sensors are needed. Greenhouses with lower microclimate variation or plants with a larger range of acceptable growing substrate VWC would require fewer sensors. Further research is required to determine optimal growing substrate VWC for initiating irrigation events for different crops and to determine the number of growing substrate VWC sensors needed within a greenhouse of a given size and magnitude of microclimate variation.

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![Fig. 7. Response of plant fresh weight, dry weight, growth index, and height to average change in growing substrate volumetric water content (ΔVWC) of bellflower (A, C, E, and G) and basil plants (B, D, F, and H).](image-url)
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