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Substrate Volumetric Water Content Controls Growth and Development of Containerized Culinary Herbs

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Abstract: There are no chemical plant growth retardants that may be used on containerized culinary herbs intended for consumption. Our objective was to quantify the effect of substrate moisture content on the growth of four commonly produced culinary annual herbs grown in containers in the greenhouse. Seedlings of basil (*Ocimum basilicum* L.), dill (*Anethum graveolens* L.), parsley (*Petroselinum crispum* (Mill.) Fuss), and sage (*Salvia officinalis* L.) were transplanted into 11.4 cm diameter containers filled with commercial soilless substrate comprising (by vol.) 75% sphagnum peat moss and 25% coarse perlite and amended with 3.0 kg·m^{-3} of controlled-release fertilizer. After the containers were thoroughly irrigated to container capacity, plants were placed into a sensor-controlled irrigation system, which maintained substrate volumetric water content (VWC) at 0.15, 0.28, 0.30, 0.38, or 0.45 m^3·m^{-3}. Chlorophyll fluorescence, photosynthesis, stomatal conductance, and transpiration were measured 27 d after initiating treatments, and the results showed that chlorophyll fluorescence of parsley and photosynthesis of basil increased as substrate VWC increased from 0.15 to 0.45 m^3·m^{-3}; the remaining parameters for basil, parsley, and sage were unaffected. Additionally, height, width, leaf area, and shoot dry mass of basil, dill, parsley, and sage increased as substrate volumetric water content increased from 0.15 to 0.45 m^3·m^{-3}. Our results show that growth of basil, dill, parsley, and sage can be promoted or inhibited by providing or withholding water, respectively, with no signs of stress or visual damage resulting from reduced substrate volumetric water content. Therefore, restricting irrigation and substrate volumetric water content is an effective nonchemical growth control method for containerized culinary herbs grown in peat-based substrate.

Keywords: restricted deficit irrigation; soil moisture sensors; nonchemical growth control; water use efficiency

1. Introduction

One of the primary challenges associated with growing containerized herbaceous plants is controlling shoot growth to produce plants that are proportional and aesthetically balanced to the container height. Controlling shoot growth is important to produce plants that are sized proportionally to containers for aesthetic appearance as well as to increase container density in the greenhouse and during shipping [1]. Although chemical plant growth retardants (PGRs) are commonly used to control containerized ornamental crop growth, there are currently no PGRs that are labeled for use on containerized culinary herbs [2]. Therefore, nonchemical methods of controlling containerized herb growth must be used.

There are several nonchemical growth control techniques that may be used to control containerized herb growth [3–5]. Compact cultivars are available for some herb species, including basil and dill [3], and may be more appropriately sized for container production. The concentration of mineral nutrients provided to container-grown herbs, both total and specific nutrients, also affects growth. For example, basil supplied with 200 mg·L^{-1} N from a complete, balanced water-soluble fertilizer are 33% larger than plants supplied with 50 mg·L^{-1} N from the same fertilizer [4]. Additionally, restricting P to 5 mg·L^{-1} produced basil, dill, parsley, and sage shorter than plants provided with 40 mg·L^{-1} [5]. While cultivar selection and nutrient management are useful forms of nonchemical growth control, it may be necessary to use multiple nonchemical methods of controlling growth to achieve the degree of control required in the absence of PGRs.

Reducing irrigation or substrate volumetric water content (VWC), commonly referred to as "deficit irrigation", is another effective method of controlling containerized plant growth [6–8]. The water available for plant uptake increases and growth is promoted as substrate VWC increases and, as such, restricting irrigation and reducing the substrate VWC can diminish turgor pressure and subsequent stem extension and growth [9]. For example, containerized angelonia (*Angelonia angustifolia* Benth.) and petunia (*Petunia* × *hybrid* Vilm.) bedding plant growth is promoted by substrate VWC and, by reducing VWC, compact plants of marketable quality can be produced [7,10]. Additionally, using regulated deficit irrigation can suppress stem elongation of flowering potted plants, such as poinsettia (*Euphorbia pulcherrima* Willd. ex Klotzsch), providing adequate height control during production [11]. While controlling the substrate VWC clearly has potential for use in containerized herb production, data specific to the effects of substrate VWC on containerized herb growth are lacking.

We have found some limited reports on the effects of substrate moisture on containerized perennial herb growth [8,9]. Zhen et al. [8] reported that limiting irrigation of rosemary (*Rosmarinus officinalis* L.) plants successfully controlled excessive growth. Additionally, Zhen and Burnett [9] showed that English lavender (*Lavandula angustifolia* Mill. 'Hidcote' and 'Munstead') growth diminished with decreasing substrate VWC. These data are promising for controlling containerized herb growth by limiting substrate VWC. However, we have found no other data on the use of drought stress to control excessive growth of more common containerized herb species grown with shorter production periods. Our objective was to quantify the effect of substrate VWC on the growth of four common culinary annual herbs grown in containers in the greenhouse. We hypothesized that the growth of parsley, sage, basil, and dill would be promoted by increasing substrate VWC and, as such, restricting irrigation would be an effective growth-control strategy for containerized culinary annual herb species with short growth cycles.

2. Materials and Methods

Seeds (Johnny's Selected Seed, Albion, ME, USA) of parsley (*Petroselenium crispum* (Mill.) Fuss 'Giant of Italy'), common sage (*Salvia officinalis* L.; Expt. 1), basil (*Ocimum basilicum* L. 'Italian Large Leaf'), and dill (*Anethum graveolens* L. 'Fernleaf'; Expt. 2) were individually sown in 288-cell propagation trays (PL-288-1.25; 7.1 cm^3 individual cell vol.; T.O. Plastics, Clearwater, MN, USA) filled with a soilless germination substrate comprising (by vol.) 65% fine sphagnum peat moss, 20% fine perlite, and 15% vermiculite (Propagation Mix; Sun Gro Horticulture, Agawam, MA, USA). Trays were initially hand-irrigated with clear, tempered tap water. Beginning at radicle emergence, seedlings were irrigated with tap water supplemented with a blend of water-soluble fertilizers (50 and 100 mg·L^{-1} N provided from 21N–2.2P–16.6K and 15N–2.2P–12.5K, respectively; Everris NA, Inc., Marysville, OH, USA) to provide the following (in mg·L^{-1}): 150 nitrogen, 8.6 phosphorous, 92.2 potassium, 33.3 calcium, 13.3 magnesium, 0.75 iron, 0.4 manganese and zinc, 0.2 copper and boron, and 0.5 molybdenum.

Seedlings were grown on expanded metal benches in a glass-glazed greenhouse at Iowa State University, Ames, IA (latitude 42° N) with fog cooling, radiant hot-water floor and perimeter heating, and retractable shade curtains controlled by an environmental computer (ARGUS Titan; ARGUS Control Systems, Surrey, BC, Canada). The day and night greenhouse air temperature set points were 23.0 ± 1 °C and 18.0 ± 1 °C, respectively. Aluminized shade cloth (XLS 15 Revolux; Ludvig Svensson, Kinna, Sweden) was drawn across the crop when outdoor light intensities exceeded 1000 µmol·m^{-2}·s^{-1} to avoid leaf scorch. High-pressure sodium lamps delivered a supplemental photosynthetic photon flux (PPF) of ~190 µmol·m^{-2}·s^{-1} at plant height (as measured with a quantum sensor (LI-190 SB;

LI-COR Biosciences, Lincoln, NE, USA)) when ambient light intensity was below 100 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ between 0600 and 2200 HR to maintain a target daily light integral (DLI) of ~12 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$.

Four weeks after sowing, seedlings were planted into 11.4 cm diameter containers (655 mL vol.; HC Companies, Middlefield, OH, USA) filled with soilless greenhouse substrate comprising (by vol.) 75% sphagnum peat moss and 25% coarse perlite (Sunshine® LB-2; Sun Gro Horticulture, Inc., Agawam, MA, USA) amended with 3.0 $\text{kg}\cdot\text{m}^{-3}$ controlled-release fertilizer (Florikan Plus 16.0 N–2.2 P–9.1 K with a 90 d release period; Florikan ESA, Sarasota, FL, USA). For each experimental unit, 20 plant containers were placed into two 10-cell petroleum-plastic shuttle trays adjacent to each other with individual plants spaced on 12 cm centers (69.4 plants per m^2). The inner six plant containers were measured for data gathered, while the surrounding plants were used as border plantings to simulate greenhouse practices.

An automated irrigation system controlled by soil moisture sensors was used to maintain VWC treatments similar to that described by Nemali and van Iersel [12]. Drip irrigation stakes attached to 1.9 $\text{L}\cdot\text{h}^{-1}$ pressure-compensating emitters (Netafim USA, Fresno, CA, USA) were inserted into the substrate, and plants were irrigated overhead to container capacity with clear tempered water. After overhead irrigation, capacitance moisture sensors (EC-5; Decagon Devices Inc., Pullman, WA, USA) were inserted into the substrate of the two innermost plant containers within each experimental unit. Sensors connected to a multiplexer (AM16/32B; Campbell Scientific, Logan, UT, USA) cycling measurement readings to a data logger (CR1000; Campbell Scientific, Logan, UT, USA) calculated VWC using a manufacturer-provided calibration curve specific to soilless peat-based substrates. Substrate VWC thresholds were 0.15, 0.23, 0.30, 0.38, and 0.45 $\text{m}^3\cdot\text{m}^{-3}$, and they were chosen to represent the range of VWC to be observed in commercial production. The VWC values were maintained by the data logger controlling a solenoid valve (Orbit Irrigation Products, Inc., Bountiful, UT, USA) connected to polyethylene tubing with drip emitters for each experimental unit. Irrigation events occurred as needed when the average measured VWC of the two moisture sensors within a given experimental unit fell below its respective threshold. The data logger program was executed every 10 min to determine need. Solenoid valves corresponding to each experimental unit were controlled by a relay driver (SDM-CD16AC controller; Campbell Scientific, Logan, UT, USA) connected to the data logger. Valves opened for 10 s during each irrigation event, providing 6.2 mL of clear water per plant per event. Substrate moisture content and total irrigation volumes are presented in Figures 1 and 2, respectively.

Plants were grown in the greenhouse as previously described. The air temperature was measured every 15 s by four temperature probes (41342; R.M. Young Company, Traverse City, MI, USA) in an aspirated radiation shield (43502; R.M. Young Company, Traverse City, MI, USA), while the PPF was measured every 15 s by eight quantum sensors (LI-190SL; LI-COR Biosciences, Lincoln, NE, USA) per greenhouse. Temperature probes and quantum sensors were connected to a data logger (CR1000 Measurement and Control System; Campbell Scientific, Logan, UT, USA) with means logged every 15 min. The mean day, night, and daily temperatures and DLI are reported in Table 1.

Table 1. Mean (± standard deviation) daily light integral (DLI), average daily air temperature (ADT), and average day (DT) and night (NT) air temperature for parsley and sage (Expt. 1) or basil and dill (Expt. 2) grown in 11.4 cm diameter containers filled with a soilless substrate comprising (by vol.) 75% sphagnum peat moss and 25% coarse perlite amended with 3.0 $\text{kg}\cdot\text{m}^{-3}$ and maintained at 0.15, 0.23, 0.30, 0.38, or 0.45 $\text{m}^3\cdot\text{m}^{-3}$ substrate volumetric water content (VWC) for four weeks.

Experiment	DLI ($\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)	ADT (°C)	DT (°C)	NT (°C)
1	10.8 ± 0.5	23.7 ± 0.3	25.2 ± 0.3	20.7 ± 0.3
2	10.4 ± 0.7	22.9 ± 0.4	24.0 ± 0.5	20.5 ± 0.5

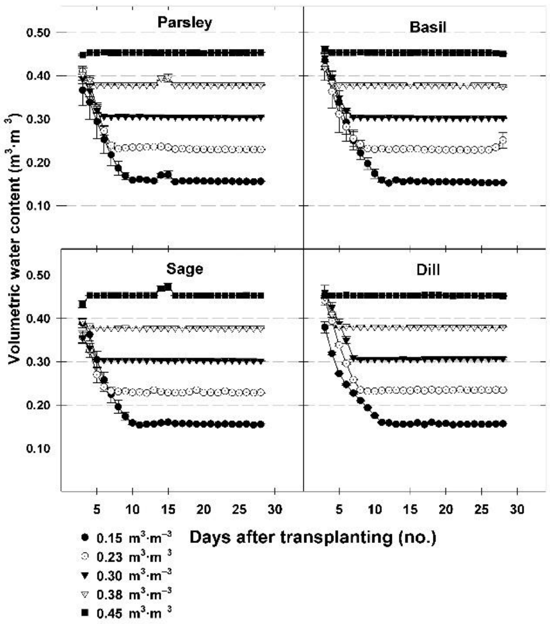

Figure 1. Substrate moisture for parsley and sage (Expt. 1) and basil and dill (Expt. 2) grown in 11.4 cm diameter containers filled with a soilless substrate comprising (by vol.) 75% sphagnum peat moss and 25% coarse perlite amended with 3.0 kg·m^{-3} controlled-release fertilizer and maintained at 0.15, 0.23, 0.30, 0.38, or 0.45 m^3·m^{-3} substrate volumetric water content for four weeks.

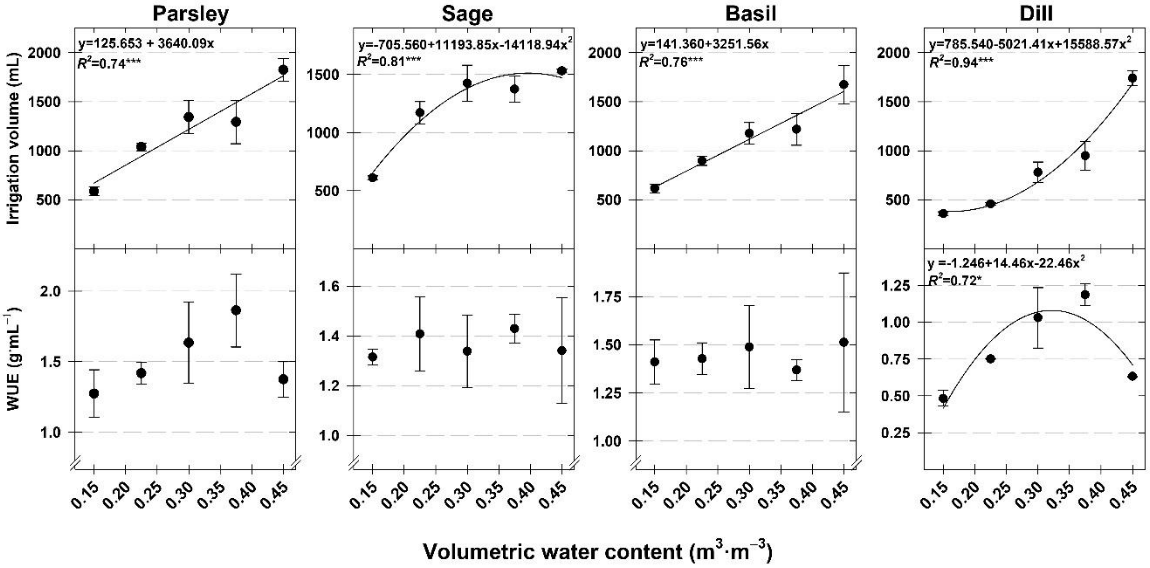

Figure 2. Total irrigation volume and water use efficiency (WUE) for parsley and sage (Expt. 1) and basil and dill (Expt. 2) grown in 11.4 cm diameter containers filled with a soilless substrate comprising (by vol.) 75% sphagnum peat moss and 25% coarse perlite amended with 3.0 kg·m^{-3} controlled-release fertilizer and maintained at 0.15, 0.23, 0.30, 0.38, or 0.45 m^3·m^{-3} substrate volumetric water content for four weeks. Regression lines are presented for significant correlations only with corresponding R^2 presented. * and *** indicate significant at $p \leq 0.05$ or 0.001, respectively.

Four weeks after transplanting seedlings, data were collected. Chlorophyll fluorescence of three plants per treatment per replication was measured on the adaxial epidermis of the most fully expanded leaf using a chlorophyll fluorescence meter (Handy Plant Efficiency Analyzer; Hansatech Instruments Ltd., Norfolk, U.K.). Using the manufacturer's clip, leaves were dark-acclimated for 15 min before measurements were taken. Fluorescence was measured by opening a shutter in the dark-acclimating clip and exposing the leaf to light with a peak wavelength of 650 nm provided by up to

3000 μmol·m^{-2}·s^{-1} for 1 s to saturate photosystem II. Chlorophyll fluorescence was expressed as a ratio of the change in chlorophyll fluorescence from initial to maximum, to maximum fluorescence (F_v/F_m).

Gas exchange measurements were conducted with a portable photosynthesis system (LI-6400XT; LI-COR Biosciences, Lincoln, NE, USA) on two plants per treatment per replication. The second most recently matured leaf placed in a 6 cm^2 leaf chamber with a light-emitting diode light source (6400-02B; red at 665 nm and blue at 470 nm) providing 400 μmol·m^{-2}·s^{-1}. The reference CO_2 concentration inside the leaf chamber was 500 μmol·mol^{-1}, and the flow of air into the chamber was set to maintain a constant mole fraction of 8.0 mmol·mol^{-1} of water inside the chamber. Leaf temperature inside the leaf chamber was maintained at 23.0 °C.

Height was measured from the substrate surface to the tallest growing point. Width was determined by measuring the widest point and 90° perpendicular and averaging these two measurements. Branch length was determined by measuring a branch at a node approximately half the total height of the plant. The number of nodes was counted. Leaf area was determined by scanning all leaves of each plant with a leaf area meter (LI-3000; LI-COR Biosciences, Lincoln, NE, USA). Shoots were severed at the substrate surface, placed in a paper bag, and dried in a forced-air oven at 67 °C for 3 d, after which shoots were weighed and the dry mass recorded. Water use efficiency (WUE) was calculated by dividing the shoot dry mass by the total irrigation volume applied per plant. Internode length was determined by dividing the height by the node number.

The experiment employed a randomized complete block design for each species. There were three blocks (replications) for each VWC for each species, with six individual plants per block. Data were analyzed using regression analyses (Sigma Plot 21.0; Systat Software, San Jose, CA, USA), with VWC concentration as the independent variable.

3. Results

3.1. Parsley

Target substrate VWC for 0.15, 0.23, 0.30, 0.38, and 0.45 were achieved 13, 8, 6, 5, and 3 d later, respectively (Figure 1). Total irrigation volume increased linearly from 587 to 1825 mL as VWC increased from 0.15 to 0.45 m^3·m^{-3} (Figure 2). The photosynthesis (P_n), conductance (g_s), and transpiration (E) of parsley was unaffected by VWC, while F_v/F_m increased from 0.82 to 0.84 as VWC increased from 0.15 to 0.45 m^3·m^{-3} (Figure 3). Height and width of parsley increased quadratically in response to VWC (Figure 4). For example, height increased by 14.8 cm as VWC increased from 0.15 to 0.38 m^3·m^{-3}, while plants grown at 0.45 m^3·m^{-3} were 1.6 cm shorter compared to those grown at 0.38 m^3·m^{-3} (Figure 4); width followed a similar trend. Increasing VWC promoted node appearance, as plants grown at 0.38 and 0.45 m^3·m^{-3} had approximately one additional node compared to those grown at 0.15 m^3·m^{-3} (Figure 4). Leaf area increased quadratically by 57.0 or 57.5 cm^2 for plants grown at 0.38 or 0.45 m^3·m^{-3}, respectively, compared to plants grown at 0.15 m^3·m^{-3} (39.2 cm^2; Figure 4). The shoot dry mass also increased quadratically from 4.5 to 14.9 g as substrate VWC increased from 0.15 to 0.45 m^3·m^{-3}, respectively. There was no significant relationship between substrate VWC and WUE of parsley (Figure 2).

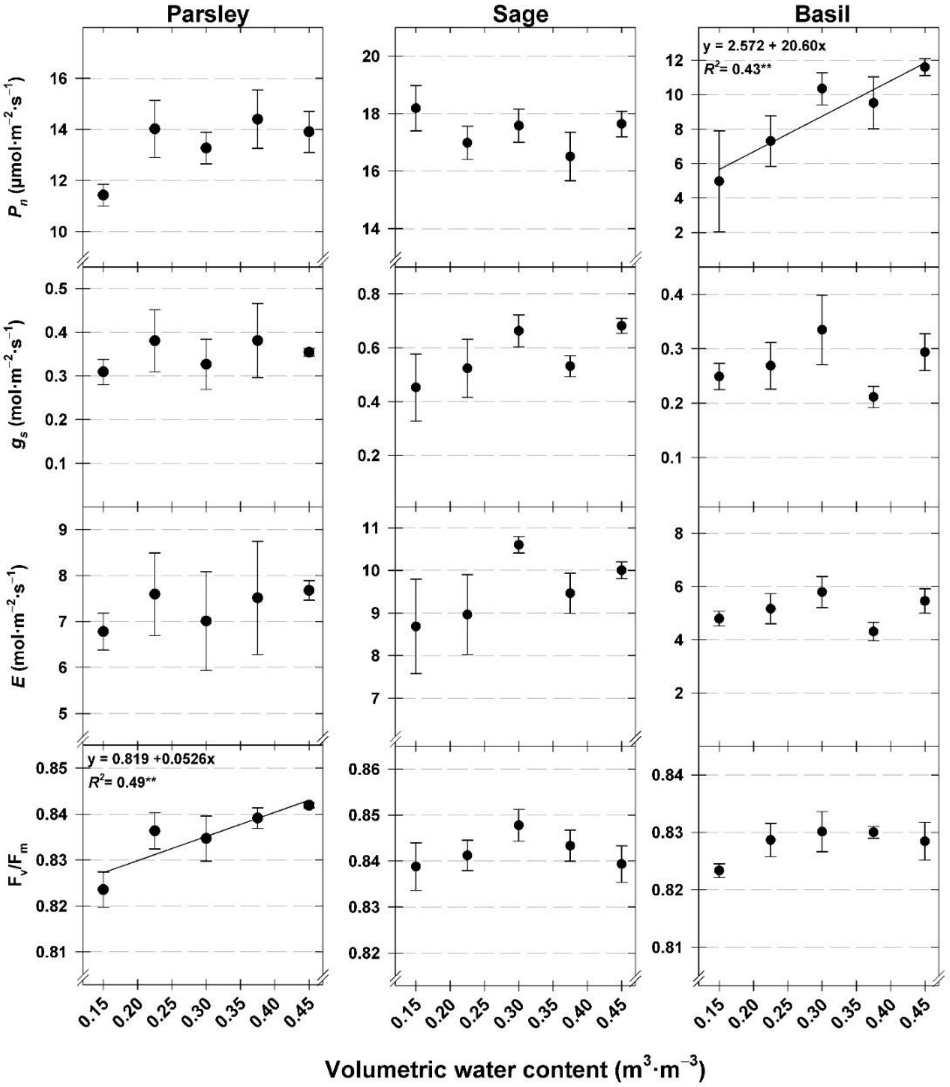

Figure 3. Photosynthesis (P_n), conductance (g_s), transpiration (E), and chlorophyll fluorescence (F_v/F_m) of parsley and sage (Expt. 1) and basil (Expt. 2) grown in 11.4 cm diameter containers filled with a soilless substrate comprising (by vol.) 75% sphagnum peat moss and 25% coarse perlite amended with 3.0 kg·m^{-3} controlled-release fertilizer and maintained at 0.15, 0.23, 0.30, 0.38, or 0.45 m^3·m^{-3} substrate volumetric water content for four weeks. Regression lines are presented for significant correlations only with corresponding R^2 presented. ** indicates nonsignificant or significant at $p \leq 0.01$.

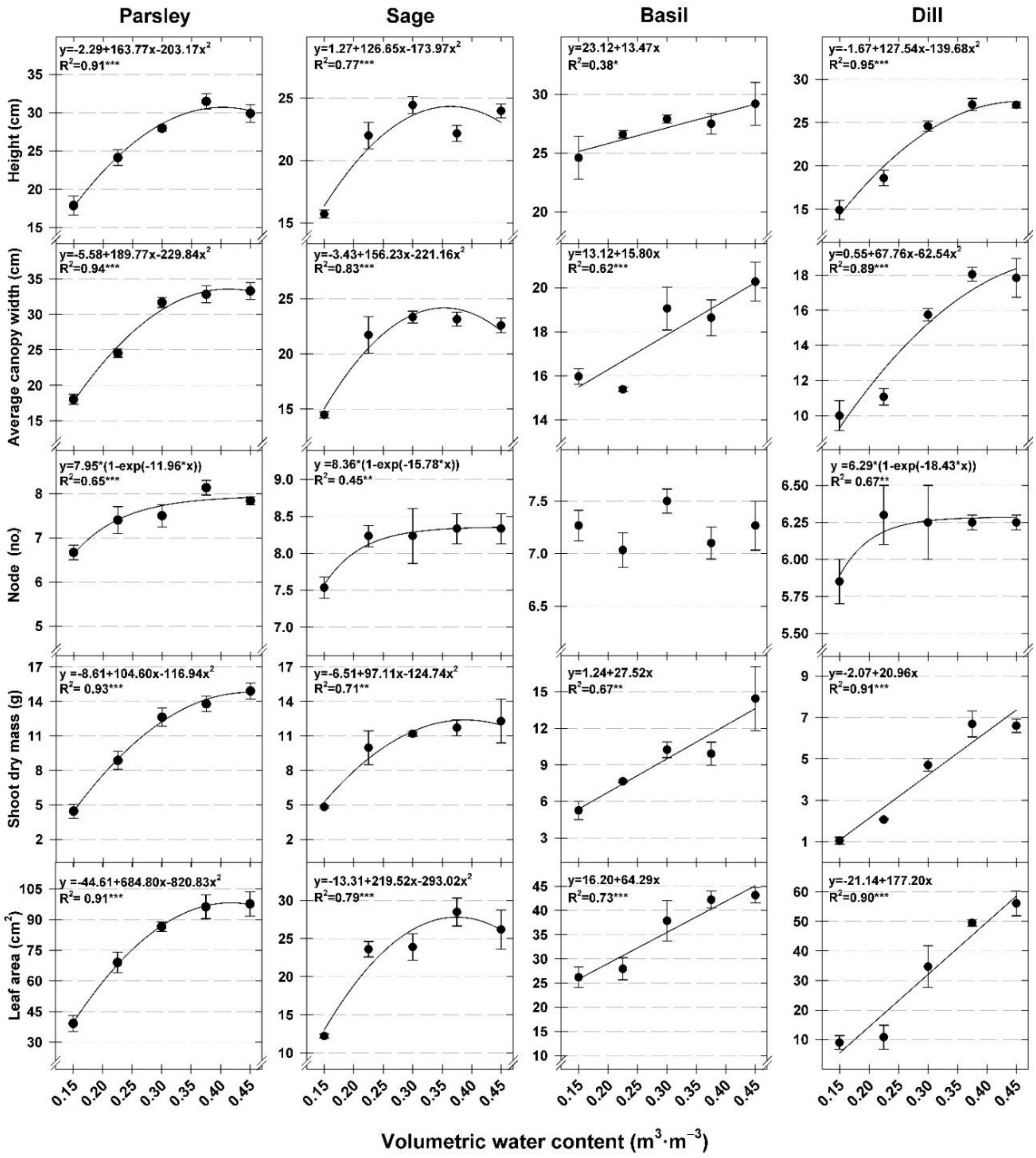

Figure 4. Height, width, node number, leaf area, and shoot dry mass of parsley and sage (Expt. 1) and basil and dill (Expt. 2) grown in 11.4 cm diameter containers filled with a soilless substrate comprising (by vol.) 75% sphagnum peat moss and 25% coarse perlite amended with 3.0 kg·m^{-3} controlled-release fertilizer and maintained at 0.15, 0.23, 0.30, 0.38, or 0.45 m^3·m^{-3} substrate volumetric water content for four weeks. Regression lines are presented for significant correlations only with corresponding R^2 presented. *, **, or *** indicates significant at $p \leq 0.05$, 0.01, or 0.001, respectively.

3.2. Sage

The time to reach target substrate conditions decreased with increasing substrate VWC, taking 10 d to reach 0.15 m^3·m^{-3} and 4 d to reach 0.45 m^3·m^{-3} (Figure 1). The total irrigation volume required to maintain substrate VWC increased from 612 to 1531 mL as VWC increased from 0.15 to 0.45 m^3·m^{-3} (Figure 2). Neither F_v/F_m nor gas exchange of sage were affected by VWC (Figure 3). The height, width, and internode length increased from 15.7 to 24.4 cm, 14.5 to 23.3 cm, and 2.0 to 3.0 cm as VWC increased from 0.15 to 0.30 m^3·m^{-3}, respectively, then decreased to 24.0 cm, 22.6 cm, and 3.0 cm, respectively, as VWC further increased up to 0.45 m^3·m^{-3} (Figures 4 and 5). Similarly, leaf area increased from 12.2 to 28.5 cm^2 as VWC increased from 0.15 to 0.38 m^3·m^{-3} (Figure 4). While node number and branch length for sage grown at 0.15 m^3·m^{-3} was 7.5 and 2.9 cm, respectively, plants grown at 0.23 to 0.45 m^3·m^{-3} had 8.2 to 8.3 nodes and branches between 6.7 and 8.9 cm long (Figure 5). Shoot dry mass increased from 4.8 to 12.3 g as VWC increased from 0.15 to 0.45 m^3·m^{-3} (Figure 4). The WUE of sage was unaffected by substrate VWC (Figure 2).

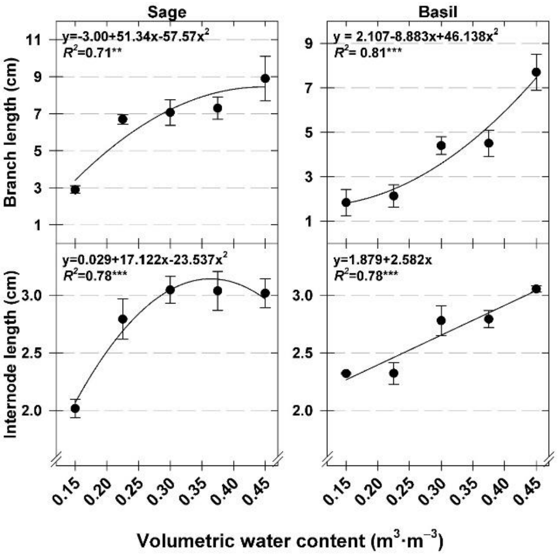

Figure 5. Branch and internode length of sage (Expt. 1) and basil (Expt. 2) grown in 11.4 cm diameter containers filled with a soilless substrate comprising (by vol.) 75% sphagnum peat moss and 25% coarse perlite amended with 3.0 kg·m^{-3} controlled-release fertilizer and maintained at 0.15, 0.23, 0.30, 0.38, or 0.45 m^3·m^{-3} substrate volumetric water content for four weeks. Regression lines are presented for significant correlations only with corresponding R^2 presented. ** or *** indicates significant at $p \leq 0.01$ or 0.001, respectively.

3.3. Basil

Increasing substrate VWC from 0.15 to 0.45 m^3·m^{-3} reduced the time from 12 to 4 d to reach VWC targets, respectively (Figure 1), whereas the amount of water required to maintain target substrate VWC increased linearly from 616 to 1674 mL (Figure 2). Although F_v/F_m, g_s, and E were unaffected by substrate VWC, P_n increased linearly from 5.0 to 11.6 µmol·m^{-2}·d^{-1} as VWC increased from 0.15 to 0.45 m^3·m^{-3} (Figure 3). Similarly, as substrate VWC increased from 0.15 to 0.45 m^3·m^{-3} the height, width, internode length, leaf area, branch length, and shoot dry mass increased by 4.6 cm, 4.3 cm, 0.7 cm, 17 cm^2, 5.9 cm, and 9.1 g, respectively (Figures 4 and 5). The WUE of basil ranged from 1.41 to 1.51 g·mL^{-1} across substrate VWC and were unaffected by treatments (Figure 2).

3.4. Dill

Substrate VWC for dill reached 0.15, 0.23, 0.30, 0.38, and 0.45 m^3·m^{-3} 13, 9, 7, 5, and 2 d after imposing treatments, respectively (Figure 1). The height and width of dill increased quadratically by 12.2 and 8.1 cm, respectively, as substrate VWC increased from 0.15 to 0.38 m^3·m^{-3} but then diminished as VWC was further increased to 0.45 m^3·m^{-3} (Figure 4). Leaf area increased linearly from 9.0 to 56.1 cm^2 as substrate VWC increased from 0.15 to 0.45 m^3·m^{-3}, respectively (Figure 4). Similarly, dill shoot dry mass increased linearly by 5.5 g as substrate VWC increased from 0.15 to 0.45 m^3·m^{-3} (Figure 4). There was no effect of substrate VWC on the number of nodes. The WUE of dill increased by 0.71 g·mL^{-1} as substrate VWC increased from 0.15 to 0.38 m^3·m^{-3} but then decreased as substrate VWC increased to 0.45 m^3·m^{-3} (Figure 2).

4. Discussion

The growth and development of containerized basil, dill, parsley, and sage is promoted with increasing substrate VWC. While the effect of substrate moisture on growth is better understood for containerized ornamental flowering crops, our results on the effect of substrate VWC on controlling growth of culinary herbs align well with the limited literature on container-grown herbs, including rosemary and English lavender [8,9]. For example, Zhen et al. [8] reported that, as substrate VWC increased from 0.05 to 0.40 $m^3 \cdot m^{-3}$, the height, width, leaf number and area, and fresh and dry mass of rosemary increased linearly. Similarly, height, width, leaf number, and area of 'Munstead' and 'Hidcote' English lavenders increased as substrate VWC increased from 0.10 to 0.40 $m^3 \cdot m^{-3}$ [9]. The effect of substrate VWC on WUE of containerized herbs was not consistent among species in the study, with parsley, sage, and basil not being affected by VWC, whereas WUE of dill increased as VWC increased up to 0.38 $m^3 \cdot m^{-3}$. This variation reflects what is seen in the literature, where WUE was found to increase with increasing substrate VWC for burkwood vibrurnum (*Viburnum* × *burkwoodii* Burkwood & Skipwith) and butterfly bush (*Buddleja davidii* Franch.); decrease with increasing substrate VWC for potato (*Solanum tuberosum* L.), salvia (*Salvia splendens* Sellow ex Roem. & Schult.), vinca (*Catharanthus roseus* (L.) G. Don), and wax begonia (*Begonia* × *semperflorens-cultorum* Hort.); or remain unaffected by substrate VWC for cheddar pink (*Dianthus gratianopolitanus* L.), columbine (*Aquilegia canadensis* L.), geranium (*Pelargonium* × *hortorum* Bailey), petunia, and rosemary [8,13–17].

The growth of basil, dill, parsley, and sage are promoted or inhibited by the provision or restriction of water to the root zone and, as such, restricting the substrate VWC to plants and growing them drier using restricted deficit irrigation is a viable nonchemical growth control method for container-grown culinary herbs. Although growing containerized herbs with restricted VWC reduces shoot mass, the harvestable or useable portion of most culinary herbs, it is important to distinguish between containerized and fresh-cut herb production. Containerized herb plants are sold as individual units (i.e., per container), not on the unit weight basis (i.e., gram) that fresh-cut culinary herbs are sold. For producers of fresh-cut herbs grown in substrate, using higher substrate VWC can promote shoot growth and yields, potentially enhancing productivity and profitability.

Although growth and development of herbs were greater at increasingly higher VWC, gas exchange was unaffected for parsley and sage (Figure 3). Under low water availability, gas exchange is reduced in most plants compared to higher availability [18]. For example, P_n and g_s of Mediterranean herbs sea beet (*Beta maritima*) and wall-rocket (*Diplotaxis ibicensis*) decreased with increasing water deficit stress [19]. Similarly, gas exchange (P_n, g_s, and E) of English lavender grown with sensor-based irrigation increased with VWC increasing from 0.10 to 0.40 $m^3 \cdot m^{-3}$ [9]. According to Yan et al. [20], annual herbs do not vary greatly in gas exchange with changing water status, suggesting limited response regulation, although the method of imposed stress may affect this. Montesano et al. [21] reported that, when irrigation was completely withheld for basil, the P_n, g_s, and E decreased after three days. However, the authors also reported that, when VWC was controlled using sensor-based irrigation and maintained 0.20, 0.30, or 0.40 $m^3 \cdot m^{-3}$, fresh mass increased with increasing VWC, whereas P_n, g_s, and E were unaffected by increasing VWC. In contrast, P_n in our study increased for basil as VWC increased from 0.15 to 0.45 $m^3 \cdot m^{-3}$; however, within 0.20 to 0.40 $m^3 \cdot m^{-3}$, P_n was similar to reports by Montesano et al. [21]. Taken together, our results align well with the literature for suppressed growth and development at lower VWC and for gas exchange under sensor-based irrigation for herbs. Drought stress reduced F_v/F_m in plants compared to well-watered conditions, which is in agreement with chlorophyll content for nontolerant species [22,23]. Nemali and van Iersel [14] reported that, as VWC increased, the quantum yield efficiency of photosynthesis increased for petunia, salvia, impatiens, and vinca, similar to parsley in this study, although basil and sage were unaffected, similar to previous reports by [9].

Sensor-based precision irrigation effectively restricted irrigation of containerized herbs in this experiment. This is especially useful for edible crops with no chemical PGRs labeled for use on them during greenhouse forcing [8] and for using drought as a nonchemical growth control method [6].

To consistently produce containerized crops at a lower substrate, VWC can be a challenge using non-sensor-controlled systems as judging the appropriate time to irrigate becomes more difficult [24,25]; automated sensor-based systems are well suited for controlling substrate VWC at desired set points [26]. Sensor-based irrigation also precisely controls substrate moisture, with minimal variation in VWC within treatment groups after initial dry down (Figure 1). However, aside from implementing precision irrigation strategies for producing containerized crops, there are other benefits when using these systems in commercial applications. Automated sensor-based irrigation is not only used to restrict irrigation for controlling height [6] but also to improve water use [24], plant growth uniformity [27], biomass [28], flower number [29], plant stress symptoms, and disease pressure [30] and can increase profitability of commercial producers compared to visual inspection- or timer-based irrigation scheduling [31].

5. Conclusions

The research presented here comprehensively quantifies the effect of substrate moisture on container-grown basil, dill, parsley, and sage regarding growth, development, and gas exchange. The growth and development of containerized culinary herbs, including height, width, node number, leaf area, and branching, were all controlled by substrate VWC, with growth and development restricted at lower VWC compared to those at higher VWC. However, while growth was suppressed when substrate VWC was lower, there were a few instances where P_n, g_s, E, or F_v/F_m were negatively impacted. Taken together, reducing substrate VWC and implementing restricted deficit irrigation is an effective growth-controlling strategy for containerized culinary herb production. Sensor-based irrigation allows for precise substrate moisture control to implement restricted deficit irrigation for controlling crop growth, although other tangible benefits may be realized in commercial production facilities. The research presented herein was performed using a round plastic container with a peat and perlite substrate. However, the different substrates that are either currently used or will be used in the future as peat alternatives [32], as well as different container shapes and sizes [33], can affect the water-holding capacity of substrates; therefore, additional work on culinary herb growth and substrate moisture content grown with different substrates and containers would be useful. While the results we have presented support the use of restricting substrate moisture to control containerized herb growth, commercial producers should conduct their own trials to determine the effectiveness of this growth-controlling technique under their unique circumstances, including the specific species and cultivars produced under specific greenhouse environmental conditions and crop culture.

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