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Sensor-based irrigation management of soilless basil using a new smart irrigation system: Effects of set-point on plant physiological responses and crop performance

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ABSTRACT

Dielectric moisture sensors are particularly suitable for irrigation management in greenhouse soilless production. Identifying the practical effects of substrate water content set-points on crop performance is crucial for successful sensor-based irrigation. We designed and constructed a prototype cloud-connected system for wireless, sensor-based irrigation management, and tested it on basil, grown in a perlite-coco (1:1 v:v) soilless substrate under greenhouse conditions. Dielectric moisture/salinity sensors (GS3, Decagon Devices, Pullman – WA, USA) were used. The study, with two subsequent experiments, assessed i) the effects of a progressive decline in substrate water availability, corresponding to moisture levels from water holding capacity to $\approx 0.10\ m^3\ m^{-3}$, on the gas exchange parameters and leaf water status of basil plants; ii) the short-term recovery response of plants when re-watered after substrate water content has decreased to different levels; iii) the effects of different irrigation set-points (0.40, 0.30 and $0.20\ m^3\ m^{-3}$) and leaching rates ($\approx 8\%$ or $\approx 18\%$) on the basil crop performance over a complete growing cycle. No physiological stress responses were observed on basil plants when moisture level was higher than approximately $0.20\ m^3\ m^{-3}$, while plants showed drought symptoms at approximately $0.17\ m^3\ m^{-3}$, corresponding to a substrate matric potential and hydraulic conductivity of -300 hPa and $0.0005\ cm\ day^{-1}$, respectively. Photosynthesis and leaf water potential recovered to values similar to non- stress conditions following a short drought (with moisture level as low as $\approx 0.10\ m^3\ m^{-3}$). Basil growth was similar when plants were grown with irrigation set-points of 0.40, 0.30 or $0.20\ m^3\ m^{-3}$ for the complete growing cycle. Fresh weight tended to increase when a higher leaching rate was used, probably because leaching lowered substrate EC. Water use efficiency (basil fresh weight/unit water used) was similar at different irrigation set-points and leaching rates. Our results indicate that the use of a wireless sensor network for real-time sensing of substrate water status, combined with precise information on the effects of water availability levels on plants, is an effective tool for precision irrigation management of greenhouse soilless basil.

1. Introduction

Irrigation is of paramount importance in horticulture, because of its implications on the economic and technical aspects of this agricultural sector (Fereres et al., 2003). Irrigation management affects crop performance. In the case of vegetable production, optimal irrigation may lead to qualitative and quantitative improvements (Dukes et al., 2010), while both under- and over-irrigation may compromise the success of the crop (Pardossi et al., 2009). Beside the direct effects on crop performance, irrigation practices also impact the environment and society. In both developed and developing countries, decreased water availability for irrigation is expected in the near future, due to urbanization and industrialization (Playán and Mateos, 2006; Levidow et al., 2014). Irrigated agriculture is the greatest water user and a potential source of pollution in many countries, due to the release of agrochemicals into the environment through the leaching and runoff associated with excessive irrigation. It is therefore necessary to adopt agricultural practices, such as efficient irrigation management, which minimize pollution to meet societal goals, satisfy government regulations, and promote sustainable use of resources in agriculture (Blackstock et al., 2010).

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Greenhouse production of vegetables has increased in importance in recent decades, especially in areas with suitable climatic conditions, such as the Mediterranean region (Baudoin et al., 2013). Greenhouse vegetable production may decrease the environmental impact compared to open-field cultivation (Stanghellini, 2014). However, to achieve this goal, rational and efficient practices need to be adopted. In this framework, making tools available for efficient irrigation management is a key factor (Montesano et al., 2015). One of the most disruptive innovations ever introduced in the greenhouse sector is soilless cultivation. It includes any method of growing plants without the use of soil as rooting medium, in which the nutrients are supplied via the irrigation water, referred to as nutrient solution (NS) (Savvas et al., 2013). A significant amount of greenhouse vegetables, particularly in Europe, U.S. and Canada, are produced using soilless substrates. The main advantages of this system are a better control of fertilization and irrigation and prevention of soil-borne diseases, generally resulting in increased yield, high quality and more efficient use of resources, especially water and fertilizers (Raviv and Leith, 2007; Valenzano et al., 2008). Beside vegetables for which soilless cultivation is already well established (such as tomato), producers are exploring soilless greenhouse herb (i.e., basil) production systems as a means to grow high quality crops in an efficient manner (Treadwell et al., 2011).

Irrigation in soilless cultivation is a highly repetitive task, and can be automated to reduce labor costs. However, automatic irrigation does not necessarily mean efficient irrigation. For instance, automation based on timers, in which NS is automatically supplied based on fixed schedules, may not be efficient, because irrigation is not based on crop water requirements. A promising approach for improved irrigation management and automation in greenhouse consists of making objective decisions regarding irrigation scheduling based on real-time measurements of the growing substrate water status through sensors (van Iersel et al., 2013). Soil moisture sensors are a dynamic and constantly developing area of technology for both technical and commercial reasons (Montesano et al., 2015), and interest in using sensors for practical irrigation management has grown in the last decade (Pardossi et al., 2009; Lichtenberg et al., 2013). A number of reliable and affordable sensors, principally based on Frequency Domain Reflectometry (FDR), to measure volumetric water content (VWC) and electrical conductivity (EC) in growing substrates have become available in the last decade. Readers are referred to van Iersel et al. (2013) for a more in-depth review on this topic. The use of those sensors proved to be particularly suitable for soilless conditions (Nemali et al., 2007). Irrigation based on those sensors may considerably reduce water consumption and increase the overall water use efficiency (WUE) compared to timer-based irrigation. Based on a recent analysis, it has been estimated that the average water use by US ornamental crop producers who adopt wireless sensor irrigation networks would decline by approximately 50% (Majsztrik et al., 2013). A significant amelioration of WUE was observed with sensor-based compared to timer-based irrigation in soilless lettuce, with WUE increasing from 25 to 70% depending on the irrigation set-point (Montesano et al., 2016a).

The automation of irrigation based on root-zone moisture sensing relies on a simple principle: the moisture level in the growing substrate decreases because of evapotranspiration; sensors detect this change and automatically activate irrigation when the level reaches a predetermined set value, resulting in on-demand irrigation (van Iersel, 2015). This is in accordance with the assumption that an optimally-designed irrigation system will provide water (and fertilizers) to the plants just when the plants require it. This way, all provided water is used by the plants and none is wasted, with the possible exception of a certain leaching fraction used to prevent salt accumulation in the substrate, thus maximizing WUE (Lieth and Oki, 2008).

By using substrate-specific water retention curves, it is possible to correlate the substrate VWC, sensed by FDR sensors, with matric potential, a parameter used to estimate whether water in the substrate is available to plants. This information can then be used to determine VWC set-points for precise irrigation (Montesano et al., 2016a). In soilless growing substrates, water is considered readily-available for plants at substrate matric potentials from -10 to -100 hPa (pF of 1–2), while water is considered progressively less available at matric potential values lower than -100 hPa (pF > 2) (De Boodt and Verdonck, 1972; Raviv and Blom, 2001). However, little work has been done to correlate the commonly defined concept of water availability with plant growth (Altland et al., 2010), and to identify the practical effects of irrigation set-points on crop performance, taking into account that the response could be highly dependent on species.

Recently, a number of studies focused on the implementation of prototype systems for automatic irrigation of greenhouse crops based on soil moisture sensors, possibly integrated with other types of sensors. Goumopoulos et al. (2014) described an adaptable decision support system integrated with a wireless sensor/actuator network to implement autonomous zone-specific irrigation. An automated system for irrigation control, based on low-cost open source microcontrollers and soil moisture sensors, was proposed by Ferrarezi et al. (2015). Navarro-Hellín et al. (2015) tested a system based on an innovative wireless sensor architecture to help growers manage irrigation in different agricultural systems, including greenhouse soilless culture.

Significant advances have been made in the development of wireless technology in the last few years, so new tools for irrigation control in commercial greenhouses, based on wireless sensor networks, are now available to growers (Kohanbash et al., 2013; Lea-Cox et al., 2013; Bayer et al., 2016).

Based on the above-mentioned considerations, we designed and constructed a new prototype cloud-connected system for wireless, sensor-based irrigation management. We aimed to use data from a wireless network of soil moisture sensors placed in a greenhouse for automatic control of irrigation. The system was used in two consecutive experiments with soilless basil (*Ocimum basilicum* L.), an important high-value greenhouse crop (Mininni et al., 2015). Basil was used because of the popularity of this herb, common in the Mediterranean diet to enhance the flavour of food, and because of its recognized antioxidant effects (Puccinelli et al., 2017). The objective of Experiment 1 was to study the effects of progressive substrate drying, and the consequent decline in VWC and water availability, on the gas exchange parameters and leaf water status of basil plants. The study also looked at the short-term recovery of plants when re-watered after VWC had decreased to different levels. The objective of Experiment 2 was to study the effects of different irrigation set-points and of different leaching rates, on the performance of greenhouse-grown soilless basil. We also tested the ability of the sensor-based irrigation system to fully automate irrigation over a complete growing cycle.

2. Materials and methods

2.1. Irrigation system description

The Greenhouse Irrigation Control Kit (GICK) used in this research is made up of hardware, firmware and software components able to acquire, store, plot and process data generated by soil moisture sensors, and consequently activate solenoid valves based on a reconfigurable set of conditions. In this section, a general description of the system is provided. For technical details, see the extended version of the system description, provided as supplemental material.

The GICK is composed of a Main Networking and Control Unit (MNCU) and multiple Wireless SDI-12 (Serial Digital Interface at 1200 baud) Host Nodes (WSHNs) (Figs. 1 and 2). The GICK can accommodate 62 WSHNs, the maximum number of unique addresses allowed by the SDI-12 protocol. In this implementation, the number of WSHNs is 2, serving twelve SDI-12 sensors. The MNCU and the WSHNs are both based on low cost, general purpose hardware and open source software, and on some custom-made Printed Circuit Boards (PCBs), scripts and firmware. By taking advantage of the cloud computing model and of