Traditional and New Approaches to Irrigation Scheduling in Vegetable Crops

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SUMMARY. Intensive vegetable cropping systems use large amounts of water and nutrients. Excess application of water and nutrients results in economic losses (higher fertilizers and pumping costs) and contributes to nutrient leaching and environmental degradation. Increasing nutrient use efficiency (NUE) and water use efficiency (WUE) should be a priority for sustainable horticulture. This increased NUE, WUE, or both depend on the utilization of efficient irrigation technology, including appropriate methods for irrigation scheduling (IS). Various methods are available for IS based on determination of crop water balance (weather-based method), soil/substrate moisture level, or plant water relations. Rather than discussing the physical and biological basis of irrigation management, this article focuses on currently available irrigation control devices for open-field and greenhouse production systems, with particular emphasis on soil moisture sensors (SMSs). SMS regulates the frequency of irrigation and, possibly, the water dose by continuously monitoring volumetric water content (θ) or matrix potential (ψ_m) of the growing media. A new generation of dielectric SMS has been developed to measure both θ and the electrical conductivity (EC) of pore water in soil and artificial media. This provides the possibility of controlled fertigation based on measured EC. Despite the development in IS, in most regions worldwide, especially in less developed countries, many growers still rely on personal experience for determining crop water requirements and the timing of irrigation. Therefore, the main constraints to the improvement of irrigation efficiency are related to the overall cost of these technologies and to the policies adopted for their dissemination and transfer to professional growers.

The role of irrigation in ensuring food security is vital as about 40% of world food is produced by irrigated agriculture and horticulture according to Food and Agriculture Organization of the United Nations (FAO, 2002). On the other hand, crop irrigation is the major user of fresh water accounting for over 70% of water use worldwide. Therefore, improving irrigation WUE, defined as the ratio of applied water to crop yield, is decisive to sustain the food demand due to the fast-growing

world population (FAO, 2002). This goal may be achieved through the cultivation of plant species that are more efficient in water use (plant breeding and crop planning), through the utilization of efficient irrigation technology, including appropriate methods for IS, or both. IS is the process to determine the amount of water applied to the crop and the timing for application; as it determines seasonal irrigation volume and crop yield, IS has a remarkable effect on WUE.

Apart from few examples of non-irrigated cropping systems [e.g., dry land bean (*Phaseolus* spp.), tomato (*Solanum lycopersicum*), and potato (*Solanum tuberosum*) in Latin America; winter melon (*Cucumis melo*) in Mediterranean regions], in field-grown vegetable crops irrigation is essential to supplement rainfall during the growing season and is obligatory under

greenhouse. Vegetables are generally high-value crops that make more profitable use of irrigation water than other agricultural commodities. In California, for instance, in 2003, field crops accounted for 56% of total irrigated area (≈ 3.5 million ha) consuming 63% of total water use and generating 17% of California's crop revenue (Cooley et al., 2008). By contrast, vegetables covered 16% of irrigated land and consumed 19% of applied irrigation water while contributing to crop return by 39%.

Irrigation scheduling is important in vegetable production. Under-irrigation generally results in yield loss and low produce quality. Conversely, overirrigation increases the crop's susceptibility to diseases, energy cost for pumping, water loss, and environmental pollution due to nutrient leaching. Thompson et al. (2007) identified that poor management of drip irrigation was responsible for nitrate leaching in greenhouse tomato production in Almeria, in southeastern Spain (at present, the most concentrated greenhouse area in the world). A primary cause of this was that many growers base IS on experience rather than on actual crop water need. Since nutrient use and water relations are closely related, better WUE generally results in improved NUE. Moreover, precise scheduling is crucial for regulated deficit irrigation, which aims to induce a mild water stress to the plant to save water and improve crop yield and produce quality (FAO, 2000; Jones, 2004).

Efficient IS aims to supply the crop with enough water to ensure optimum production while minimizing water loss and nutrient leaching. The amount of irrigation water needed is determined by using a criterion to trigger irrigation and a strategy to determine how much water has to be applied to a given crop at any time during the production cycle. In vegetable crops, the most common criterion is soil θ or ψ_m (also called tension or suction); the goal is to avoid crop damage and to ensure that all irrigation water is used by the crop. A

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
1	cbar	kPa	1

schedule to maximize net economic return, which depends also on water price, is less common.

Conventional methods for IS rely on determination of soil water balance (weather-based method) or on the direct measurement of soil moisture level. Other criteria may be used for IS in soilless cultures. For instance, the EC of the nutrient solution contained in or drained out from the substrate could be the irrigation decision-making variable (e.g., Saha et al., 2008; Stanghellini et al., 2003), as it will be discussed in detail later in this article. The progress in plant physiology research has allowed the design of innovative IS methods based on the monitoring of plant water relations.

Water balance

This method (also known as water balance method) consists of estimating the change in soil θ over a period as the difference between the inputs (irrigation and rainfall) and the losses [crop evapotranspiration (ET), drainage, and runoff]. The method follows three basic steps: 1) the available water (AW) in the root zone is estimated from soil texture and rooting depth; 2) allowable water deficit (AWD) is selected depending on crop species, growth stage, soil water capacity, and the irrigation system's pumping capacity [AWD is the portion (ranging from 40% to 60%) of AW that can be extracted without causing crop damage]; 3) soil water balance is computed each day to assess water deficit; irrigation is needed whenever AWD is exceeded.

The water balance method lacks high accuracy, but it proved to be reliable and affordable in many conditions (Jones, 2004). The main difficulty is estimating ET.

The classical "two-step" approach to calculation of ET [$ET = ET_0 \times K_c$ (Allen et al., 1998)] needs the knowledge of crop coefficient (K_c) and reference ET (ET_0). The latter quantity can be calculated with Penman-Monteith (P-M) equation (Allen et al., 1998) or other formulas, such as the California Irrigation Management Information System (CIMIS) equation (CIMIS, 2009b). The CIMIS formula uses a modified P-M equation with a wind function developed at the University of California, Davis (CIMIS, 2009b). There are no important differences between the values of ET_0 determined

with the two equations, at least in open-field crops (Vaughan et al., 2007). Alternatively, ET_0 can be determined by evaporation pan (Brouwer and Heibloem, 1986).

In commercial vegetable production, ET is commonly calculated using the data originated from weather stations manufactured for farm use (many companies worldwide sell these products) or managed by local authorities or growers' organizations. Generally, these entities also provide simple irrigation advice through the Internet (e.g., CIMIS, 2009a) or by short messages to grower's cellular phones (Singels and Smith, 2006).

Crop coefficients are crop specific and depend on growth stage, climatic conditions, and management practices; hence, they must be determined experimentally. Several articles have reported K_c values for vegetables crops that were determined in different growing conditions [e.g., for field-grown, drip-irrigated tomato (Amayreh and Al-Abed, 2005; Hanson and May 2006; Rinaldi and Rana, 2004)].

Crop coefficient is related to the degree of soil cover by crop canopy and thus to leaf area index (LAI). Several authors attempted to model the evolution of K_c and LAI during the growing season. For instance, simple K_c models based on thermal time [i.e., cumulated growing degree day (GDD)] were designed and validated by Orgaz et al. (2005) for melon and pepper (*Capsicum annuum*) grown under greenhouse. Alternatively, K_c can be derived from measurement of crop LAI gathered in situ with hand-held ceptometer [several companies market these instruments (e.g., Decagon Devices, Pullman, WA; Delta-T Devices, Burwell, United Kingdom; LI-COR, Lincoln, NE)] or by remote sensing (for reviews see Jonckheere et al., 2004; Weiss et al., 2004). LAI could be determined by nondestructive measurement of leaf number, dimensions, or both (e.g., Carmassi et al., 2007a; Rouphael and Colla, 2004).

Normalized difference vegetation index could be derived from aerial or satellite multispectral images of the fields to estimate crop canopy cover (for reviews see Courault et al., 2005; Neale et al., 2005), which is thus converted to K_c .

Compared with the "two-step" approach, "one-step" P-M equation is more accurate for estimating ET;

however, its use is restricted by the lack of information on crop canopy resistance [r_c (Katerji and Rana, 2006)]. Lovelli et al. (2008) proposed a practical methodology to estimate r_c from LAI ($r_c = 100/\text{LAI}$) and thereby to estimate ET of crop canopy (ET_c) with P-M formula. This method was tested successfully in field-grown melon. The application of "one-step" P-M approach seems less difficult under greenhouse, where growing conditions are more uniform. Assuming a homogenous crop canopy, Rouphael and Colla (2004) modeled ET_c in greenhouse-grown zucchini (*Cucurbita pepo*) by estimating: 1) LAI on the basis of crop GDD, 2) the radiation intercepted by the canopy as a function of LAI and the light extinction coefficient (k), 3) leaf resistance (r_s) as an exponential function of PAR, and 4) r_c as the ratio of r_s to LAI.

Simplified (empirical) ET_c models have been derived from the P-M equation for irrigation management of greenhouse crops (e.g., Carmassi et al., 2007b; Medrano et al., 2005). These models consider global solar radiation (I), vapor pressure deficit (VPD), LAI, and k . One example is the following equation proposed by Medrano et al. (2005) for greenhouse-grown cucumber (*Cucumis sativus*):

$$ET = a(1 - \exp^{-k \text{ LAI}})I + b \text{ LAI VPD},$$

where "a" and "b" are the regression equation parameters.

Historical ET data could be used for IS of crops that are conducted under fairly constant growing conditions, such as greenhouse crops. This was the conclusion of a work carried out by Bonachela and Gonzales (2006) using both simulation and original experiments with the major greenhouse crops in Almeria.

Soil moisture sensors

Soil moisture sensors could be used to regulate the frequency of irrigation and, possibly, the water dose by continuously monitoring θ or ψ_m of the growing media (Dukes et al., 2010; Pardossi et al., 2009).

The relationship between ψ_m and θ (also known as water release curve) depends on the nature of the growing media. Water release curve is determined in the laboratory following standard methods, for instance: in soil, using Richard's pressure plate apparatus

(Klute, 1986) and in soilless media, using the method described by De Boodt et al. (1974).

Expensive and complicated SMSs, such as neutron probe and time-domain reflectometry instrument, are available for soil and plant scientists, whereas low cost and practical devices are needed for irrigation control of commercial crops. Interesting possibilities have been opened up by new types of SMSs that measure soil dielectric properties (Dukes et al., 2010; Pardossi et al., 2009). Irrigation industry has recognized that SMSs are valuable tools for smart water application technology in agriculture and horticulture.

The utilization of SMS technology for irrigation management in both soil and soilless culture has been documented by many researchers (e.g., Muñoz-Carpena et al., 2008; Zotarelli et al., 2009), and currently a variety of simple irrigation controllers are available on the market that are interfaced to one or more SMSs. For instance, some devices provide a “start-and-stop” control by using two or more SMSs buried in and underneath the root zone to monitor water movement into the deeper layers and thereby to minimize percolation losses.

Threshold values for θ or ψ_m depend on crop species and growing media. Typical range for ψ_m is from -10 to -50 kPa in soil culture (Locascio, 2005) and from -4 to -10 kPa in substrate growing systems (Pardossi et al., 2009).

Norrie et al. (1994) designed an automated fertigation device based on electronic tensiometer. In this

system, both ψ_m threshold and the ion concentration (namely, EC) of nutrient solution were modulated according to ET, which was estimated using P–M equation. During periods of intense ET, irrigation was more frequent (i.e., the trigger ψ_m set point less negative) and EC was reduced as compared with periods with low ET. The system was tested successfully in peat-grown greenhouse tomato.

New dielectric SMSs are cheaper and need much less maintenance and user’s expertise compared with traditional water-filled tensiometers (Pardossi et al., 2009). Granular matrix sensors, similar to gypsum block, are also available commercially (e.g., Watermark Irrrometer, Riverside, CA). These sensors are inexpensive (a few tens of U.S. dollars each) and can be used over a wider range of ψ_m (0 to -200 kPa) than tensiometers, which have a working range between 0 and -85 kPa. Whalley et al. (2009) designed and tested a porous-matrix sensor that determines soil ψ_m using a novel dielectric measurement principle and does not have inconveniences of water-filled tensiometers, including susceptibility to cavitation.

Sensors, such as 5TE (Decagon Devices) or WET (Delta-T Device), have been also developed for simultaneous measurements of temperature, θ , and pore water EC in soil or soilless media (Pardossi et al., 2009). These sensors provide the possibility of controlled fertigation. For instance, the concentration of the nutrient solution could be adjusted on the basis of measured EC in the root zone. In

a free drainage rockwool culture of greenhouse pepper, Stanghellini et al. (2003) controlled the frequency of irrigation and the nutrient concentration of irrigation water based on simultaneous measurements of θ and EC of the substrate; the drainage fraction was $\approx 10\%$, against more than 50% in the standard control system. In the FLOW-AID project, a new fertigation device was developed and tested successfully in container cultivation (Balendonck, 2010). The prototype was connected to WET sensors, and special algorithms were implemented to activate irrigation when a preset θ threshold was reached and to modulate irrigation dose, nutrient solution EC, or both to avoid salt accumulation in the substrate.

Due to soil spatial variability, precision irrigation control requires a large number of sensors that are spread out on each plot of the farm and communicate with the irrigation system. The use of a wireless sensor network (WSN) could reduce the investment and maintenance costs of such control system (Balendonck, 2010). WSN systems for irrigation management are presently marketed by some companies worldwide (e.g., Crossbow, San Jose, CA; Netafim, Tel Aviv, Israel; Netsens, Sesto Fiorentino, Italy). However, these systems are still expensive and have high energy requirements. Some authors (e.g., van Tuijl et al., 2008; Vellidis et al., 2008) expressed the opinion that, at the current stage of development, WSNs are not enough reliable and affordable for wide commercial application. Several research

Table 1. Principal advantages and disadvantages of the main methods available for irrigation scheduling.

	Advantages	Disadvantages
Soil water balance	Easy application; sufficient robustness under a wide range of conditions.	Lower accuracy compared with the direct measurement of soil moisture level; weather data and estimates of crop coefficients are needed.
Soil moisture content	Easy application; accuracy; availability of many irrigation controllers that are interfaced to soil moisture sensors; some sensors can measure both moisture content and salinity of the growing media and provide the possibility of controlled fertigation.	Due to soil spatial variability, many sensors have to be integrated in a wireless network.
Plant water relations	Measure the plant’s response to soil moisture level and climate.	Difficult application in most conditions, particularly in open field; scarcely used yet for routine irrigation management.

groups (e.g., J. Balendonck's team at Wageningen University and Research Center, Wageningen, The Netherlands) are working to design WSN with the following advantages: low cost, easy installation, reduced energy consumption, low maintenance, and ability to host a wide array of sensors and controllers connected to a central decision support system by radio transmitter or GSM modem.

Plant-based irrigation scheduling

A relatively novel approach to IS involves determination of plant water status (e.g., Rüger et al., 2010) or transpiration (e.g., Shelford et al., 2004). Applications of this approach to IS have been reviewed by Jones (2004) and, more recently, by Fernández and Cuevas (2010). According to the first author, these methods "have been offset by a number of practical difficulties of implementation that have thus far limited the development of commercially successful systems" and are "still at research/development state and little used yet for routine agronomy."

Nevertheless, some companies have developed irrigation controllers that exploit micrometeorological measurements of stem diameter (e.g., Delta International, Montfavet, France), leaf thickness (e.g., Leaf-Sen Irrigation System, Givat Hayim Ichud, Israel), or stem sap flow (e.g., Dynamax, Houston, TX). Other companies (e.g., Hortimax, Pijnacker, The Netherlands; PhyTech, Yad Mordechai, Israel) have integrated different kinds of sensors (including those for weather and leaf temperature) in a control system for the management of both irrigation and climate in greenhouse production systems.

The application of plant-based IS seems more practical and affordable in greenhouse soilless growing systems, where climate and crop are generally more uniform compared with open field. In these systems, the growers can make use of small-size electronic weighing lysimeters to measure, on a minute-to-minute basis, ET and the volume and EC of drainage water. Examples of this kind of irrigation controller are marketed by Hortimax and Spagnol Greenhouse Technologies (Vidor, Italy).

Conclusions

Accurate IS is crucial to maximize WUE and reduce nutrient leaching in

intensive vegetable production systems. Different approaches may be adopted for efficient irrigation management, each having both advantages and disadvantages (Table 1).

Despite the development in IS, in most regions worldwide (especially in less developed countries), many growers still rely on personal experience for determining crop water requirements and the timing of irrigation. Rather than the lack of consistent methods for IS and off-the-shelf irrigation controllers, the main constraints to the improvement of irrigation efficiency seem related to the overall cost of these technologies and to the policies adopted for their dissemination and transfer to professional growers.

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