Developing and Integrating Plant Models for Predictive Irrigation

Jongyun Kim

Post-Doctoral Research Associate
Department of Plant Science and Landscape Architecture
University of Maryland, College Park, MD 20742
jongyun@umd.edu

Abstract. The daily water use (DWU) of ornamental plants can be quantified using sensor-based automated irrigation systems and/or continuous evapotranspiration (E_T) measurement systems. Plant age, container size and environmental factors, such as daily light integral, vapor pressure deficit, and temperature were used in the development of empirical water-use models. Although plant size was the most important plant factor in DWU, daily light integral and vapor pressure deficit were the most influential environmental factors in the day-to-day variation of DWU. We have developed water-use models for several ornamental species, with most of the DWU being explained by plant and daily environmental factors ($R^2 > 0.8$). With these simple, easy-to-use models, growers may predict water requirements of plants using simple sensor measurements.

Keywords. automated irrigation system, evapotranspiration, daily water use, modeling

Introduction

In ornamental plant production, providing sufficient water on a daily basis is critical to ensure plant quality and continuous growth, and optimize income for growers. However, increasingly limited fresh water resources are facing increased scrutiny from regulators in many states. Agricultural water use is often regarded as the major culprit of unsustainable water use for many reasons including soil salinization, over-extraction of groundwater, and the over-allocation of available surface water supplies (Majsztrik et al., 2011). Therefore, much greater irrigation water use efficiency by agriculture is required to sustain these limited fresh water resources. Efficient irrigation practices may not only decrease costs, but also improve plant quality and yield due to reduce disease and other management issues. For decades, many research studies have been conducted to improve irrigation practices, as a part of best management practices in horticulture industry (Lea-Cox, 2012).

Efficient irrigation systems, such as micro-sprinkler, drip or sub-irrigation can increase uniformity of distribution and also target limited water directly to the root zone, in comparison to overhead sprinkler or travelling gun applications. These systems can improve irrigation efficiency by directly delivering water to the plants, so plants can utilize most of water applied. In addition, only applying irrigation water when required (through precision scheduling) is also critical to increase irrigation efficiency, because if plants do not get sufficient water when they need it, drought stress will reduce yield and crop quality. Likewise, if plants receive excess irrigation water, nutrients can be leached from the root zone and root growth limited by reduced aeration. Understanding plant water use is therefore very helpful, so growers can more accurately schedule irrigation frequencies and the correct amount of water to apply, improving irrigation efficiency.

Currently most irrigation events in ornamental production are scheduled based upon time, with irrigation frequencies determined by grower experience, judged by plant size, development stage, and environmental and other conditions such as rooting volume (Lea-Cox, 2012). Recently developed sensor-based irrigation systems can irrigate plants based on measurements of soil water content and other evapotranspiration (E_T)-based estimates. Automated irrigation using these methods can help reduce unnecessary irrigation on cloudy days, allowing for precise irrigation which maintains the substrate within a good range of available moisture (Jones, 2004). However, in commercial production situations, sensor-based irrigation systems are still quite costly, and sometimes sensors can malfunction or become detached, which then leads to erroneous readings and imprecise irrigation events, unless the grower is alerted to the problem. Therefore, integrating precision irrigation systems with a predictive estimation of plant water use could achieve more efficient irrigation management, saving water, labor and other resources.

Estimates of the required irrigation amount can be based on plant and environmental factors. Plant species, cultivar, and plant size affect daily water use since each cultivar has unique water use characteristics, and plant size affects total transpiration. Environmental factors, such as light, air humidity, air temperature, wind, and soil water availability also affect water use (Jones and Tardieu, 1998). Light is regarded as the most influential environmental factor on water use, since light stimulates stomatal opening and drives photosynthesis. Vapor pressure deficit (VPD), the gradient of water vapor concentration from the leaf to the air, is the physical driving force for transpiration and also affects stomatal regulation. Previously, a number of plant water use models have been developed to predict water use of the plant through the estimation of leaf transpiration and evaporation from the soil/substrate, based on measuring environmental variables.

Mechanistic models that can predict evapotranspiration

The Penmen-Monteith equation is perhaps the most well-known method (Allen et al., 1998) for estimating plant E_T; it predicts net E_T from a crop surface in relation to ambient environmental factors, such as temperature, wind speed, relative humidity, and solar radiation. The Food and Agriculture Organization (FAO) of the United Nations suggests a standard method for modeling E_T, using a modified version of this equation (Allen et al., 1998). The Penman-Monteith equation is an energy balance-based method, and thus it requires good estimates of an empirical crop coefficient (Kc) that incorporates specific features for each crop model. By measuring environmental conditions with a standard weather station, the reference E_T (RET or ET_o; i.e. the evaporation and transpiration from a reference crop under ideal unlimited water supply) can be calculated. By multiplying this reference equation with a crop coefficient (Kc; the multiplier depending on crop species and developmental stage, including leaf area index of the crop), the RET can estimate the potential crop E_T (PET) rate in the field. This equation was developed for field crops with large, uniform canopies and many field crops have relatively well established Kc values. However, Kc values for ornamental plants are highly variable with a large number of cultivars and various growing periods. Accurate modeling with this approach would therefore require a large amount of research to determine these empirical model factors for many different species (Baille et al., 1994).

In general, greenhouse ornamental production is very intensive with short production times; the inaccuracy of Kc for the large number of species grown with relatively fast growth rates, makes it difficult to modify E_T methods for ornamental plant production. Also, various substrates used in greenhouse production are mostly soilless substrates, which typically have much larger particle size and porosities to soils. Soilless substrates therefore require alternative irrigation strategies to field crops (Lea-Cox, 2012).

Quantifying water requirement from automated irrigation system

One of the approaches to measure plant water requirement is to quantify the daily irrigation amount which will maintain the substrate at a moisture level that optimizes plant growth. Our primary objective was to develop an easy-to-use model that describes the water requirements of ornamental plants with easily measured plant and environmental parameters such as plant age, light (photosynthetically active radiation, PAR), temperature and relative humidity. In our study, we used a capacitance sensor-based automatic irrigation system (Nemali and van Iersel, 2006) to maintain substrate moisture content at a stable level, while quantifying the amount of water needed to maintain this on a daily basis, as the crop grew. Using a datalogger system with capacitance sensors, irrigation valves were opened for a short time period (6-10 s) with a frequent irrigation interval (10 min) when the sensor reading was below the minimum substrate water content set point. We used a commercial greenhouse peat / perlite substrate (Fafard 2P; Farfard Company, Anderson, SC) with a volumetric water content set point of 0.40 $m^3 \cdot m^{-3}$. With frequent, small irrigation events, the specific substrate moisture level was maintained without leaching occurring; all the irrigation events were recorded by a datalogger. Using this automatic irrigation system, daily plant water requirements were calculated. Environmental data were simultaneously collected with sensors, and logged including daily light integral (DLI; the total amount of PAR for a day), temperature, relative humidity, and vapor pressure deficit (VPD), to develop plant daily water use (DWU) models, using multiple regression analysis. Plant age and its interaction with DLI, and VPD were used as the variables in the regression model.

In 2009, we developed the DWU models for abutilon and lantana, with 95% and 93% of DWU being explained by these models over the growth of the crop (Kim and van Iersel, 2009). We further developed the petunia DWU model using two cultivars grown in three different container sizes (10, 12.5, and 15 cm in diameter), to investigate the effects of other possible variables. Although two cultivars had slightly different regression models, DWUs of both cultivar were explained by plant age, DLI, VPD, temperature, container size, and interactions between these factors ($R^2 = 0.9$; Figs. 1A and B from Kim et al., 2011). By partial R^2 calculations, plant age and container size were found to be the most important factors affecting DWU, in that these variables are indicative of plant size. Among environmental factors, DLI was the most important environmental factor affecting DWU.

Load cell systems measuring continuous E_T through changes in weight

Although the water use of container crops with a drip irrigation system can be quantified from observing the leaching of irrigation applications, it is much harder to quantify the water used in sub-irrigation or hydroponic systems using this method. Since these operations are recirculating irrigation systems, leaching is required, and small but frequent irrigations are therefore not suitable. Nevertheless, quantifying the water use of plants with these systems is also beneficial to understand plant water requirements, to avoid unnecessary irrigation or fertigation. Another approach that can be employed in greenhouses is to measure plant DWU with a load cell system. A load cell is a sensor which can precisely measure the weight change of the plant / container system; hourly or daily E_T can then be easily calculated using a datalogger and a simple software program. We installed the load cell system to monitor weight change on an hourly basis, with a 10 min resolution. In this study, 2-6 irrigation events were applied per day. The software calculated the actual E_T from the weight changes after removing the weight changes due to irrigation events.

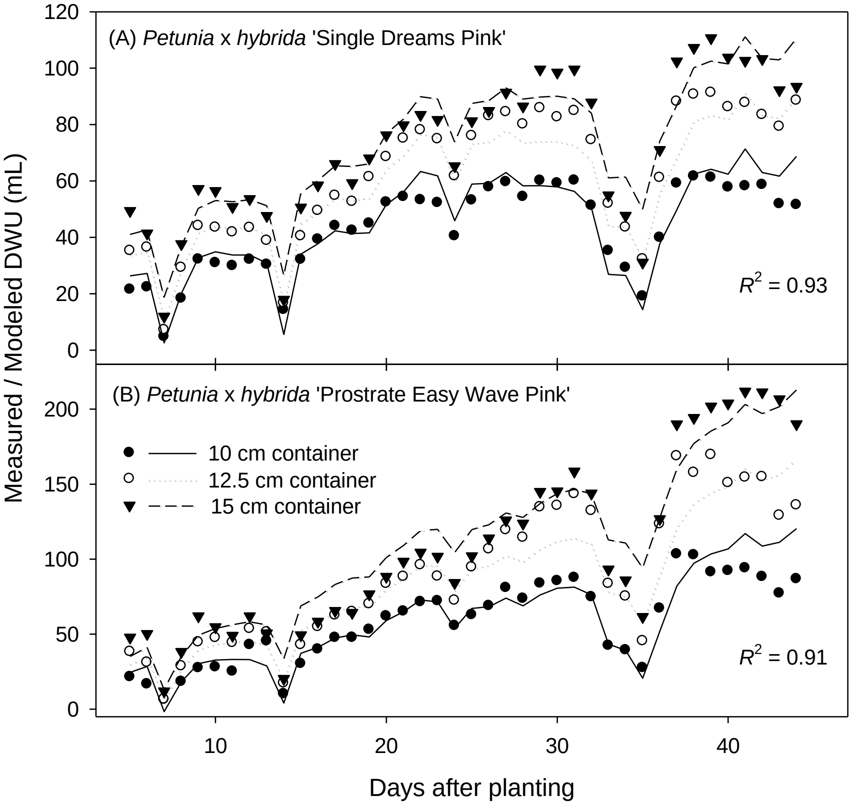

Fig. 1. Measured daily water use (DWU) (symbols) and modeled DWU (lines) of two petunia cultivars grown in three container sizes. The models were based on the effects of plant age (days after planting), container size, environmental conditions, and interactions between DAP and environmental conditions (Kim et al., 2011).

Using this load cell E_T measurement system, DWU models of snapdragon in a hydroponic system were developed (Kim et al., 2012). We conducted this experiment at a commercial cut flower production greenhouse, and simultaneously monitored E_T environmental factors including DLI, VPD, and intercepted DLI. Since cut-flower snapdragon cultivars have tall canopies with large leaf areas, intercepted DLI was selected as a variable which integrates these factors. To acquire intercepted DLI, the light sensors were installed above and below the canopy. A similar regression analysis was performed for the snapdragon DWU model as previously described for petunia, abutilon, and lantana models. Similar to the other DWU models, plant age, intercepted DLI, and VPD were the most significant variables in the snapdragon DWU model. These three variables accounted for nearly 80% of the variability seen between the model and the actual daily change in E_T measured by the load cells. We are still refining the snapdragon DWU model using a slightly simpler approach. To maintain optimal moisture levels in a hydroponic system with a very porous substrate (*e.g.*, perlite), multiple irrigations per day are required. To provide real-time information for scheduling irrigations at a higher frequency, estimating hourly water use will be required. Therefore, our current goal is to develop an hourly water use (HWU) model, which can then be used to more accurately schedule irrigations during the day.

Integration of model in wireless sensor network system

Our group is working on developing integrated irrigation decision support system that includes wireless sensor network with plant water use model components (Lea-Cox et al., 2010). Bauerle and Bowden (2011) integrated MAESTRA (Multi-Array Evaporation Stand Tree Radiation A; a three dimensional process-based model that computes transpiration, photosynthesis, and absorbed radiation within individual tree crowns) for nursery tree crops, and are currently testing this approach. For greenhouse crops, we will integrate our petunia and snapdragon water use models into the Sensorweb software system (Kohanbash et al., 2012), to provide the irrigation decision support for growers. Although our models still need independent validation, these models should provide good information regarding the predictive water use of ornamental greenhouse crops, and assist growers to make better irrigation scheduling decisions.

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