BMP Assessments Using CCROP (Container Crop Resource Optimization Program) Simulation Tools[1]

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Abstract

We describe and demonstrate the use of web-based simulation tools that use the plant growth model CCROP (Container Crop Resource Optimization Program) to quantify the expected impacts that two example best management practices (BMP) would have on water and N use during production of a container-grown woody ornamental plant. For Example 1, an irrigation BMP of applying amounts of water proportional to plant demand (evapotranspiration) was compared to fixed irrigation rates of 1.0 and 1.5 $cm \cdot d^{-1}$ at two locations in Florida and for six planting dates. For Example 2, a fertilizer BMP of customizing controlled-release fertilizer N rates based on expected N response was compared to a single N rate that resulted in optimal growth for six plant dates. Simulations based on eight years of historical weather data projected that the irrigation BMP would reduce water usage 24–57% with greater savings coinciding with longer crop times as affected by planting date and location. Similarly, simulations projected that the fertilizer BMP would reduce controlled-release fertilizer N applied 15–37% depending upon container size and planting date. Simulation tools also estimated cost savings and reduced environmental impact (N leaching loss) resulting from BMPs. We concluded that CCROP simulation tools can help growers and grower-advisers quantify potential impacts so that informed, economic decisions regarding BMP implementation can be made which are applicable to management practices and weather at the container nursery.

Index words: controlled-release fertilizer, irrigation, model, nursery, ornamental, nitrogen, runoff.

Significance to the Nursery Industry

Container nurseries use best management practices (BMPs) to improve resource use efficiency and minimize environmental impact. We present and demonstrate how web-based tools that use the plant growth model CCROP (Container Crop Resource Optimization Program) can simulate the impact that selected management practices might have at a given nursery location. Two examples of BMP assessments using CCROP tools showed that while simulated impacts (including economic) of proposed irrigation and fertilizer BMPs can be significant, the magnitude of these impacts can vary greatly depending on location, planting date, and irrigation and fertilizer practices used. Because research cannot typically provide this type of information in a cost-effective and timely manner, CCROP tools offer growers and grower-advisers an opportunity to make quantitative estimates of BMP impacts, which can help in making BMP implementation decisions (e.g., purchasing sensor irrigation equipment, providing for custom-fertilized substrates). The value of these tools should become greater as the quantity of irrigation water used by container nurseries becomes more limited and quality of water leaving the nursery becomes more regulated.

Introduction

Plant growth models have gained widespread acceptance by the scientific community as decision-support tools for simulating the effect that various environmental conditions and management practices can have on the growth/yield of important agronomic crops (5, 6). Mathematical model functions are used to describe and integrate important biophysical processes (e.g., growth and development, evapotranspiration, nutrient demand and uptake, soil water drainage and nutrient movement) based on critical inputs (e.g., weather, soil fertility, soil characteristics, planting date, planting density) to simulate daily plant growth as well as water and nutrient

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balances in the specified soil-plant system. Recently, an integrated plant growth model CCROP (Container Crop Resource Optimization Program) has become available for simulating container-grown ornamental plant production (10).

CCROP simulates the production of woody, ornamental plants in small [trade #1–3; 16–28 cm (6.3–11.0 in) diameter] containers with overhead, sprinkler irrigation. The development of CCROP was based upon research with *Viburnum odoratissimum* Ker Gawl. (sweet viburnum), a fast-growing woody shrub with upright-spreading habit and medium-sized leaves and *Ilex vomitoria* Ait. (dwarf yaupon holly), a slow-growing shrub with semi-broad spreading habit and small-sized leaves. CCROP addresses the constraints imposed by a container's confined rooting volume on water and nutrient-holding capacities. CCROP also simulates elevated temperatures that can result from solar radiation absorption by dark container walls and production surfaces when containers are spaced with incomplete plant canopy cover (9). Another factor to consider is the capture of irrigation water (and rain) which is affected by container spacing, plant characteristics and plant canopy size (3). Because controlled-release fertilizers (CRF) are commonly used in container-grown production, CCROP simulates nutrient release from CRF during plant growth. These and other CCROP functions are described and tested by Million et al. (10).

The purpose of this paper is to describe how growers and grower-advisers can use CCROP to evaluate how management practices might affect plant production and resource utilization at a given location. Web-based CCROP tools provide a user-friendly means for selecting management practices, running production simulations and viewing and managing outcomes. Simulations tools (except for Real-Time, which is based on current weather data) use historical weather data (daily solar radiation, minimum and maximum temperature, and rain) so that effects of selected inputs can be evaluated over a number of years. As such, these tools are designed to help with strategic decision-making in the nursery answering such questions as: 'How much irrigation water will be needed to produce a crop at this location?', 'Does planting date make a difference in production time or amount of irrigation water needed?', 'How much irrigation water might be conserved if irrigation amounts were based upon plant evapotranspiration instead of fixed daily amount?', 'Is it worth customizing fertilizer rates or fertilizer products for individual crops planted at different times of the year?'. These questions are strategic in nature because they address general approaches to management decision-making. In the following discussion we describe the basic use of these tools and provide examples of how they might be used to conserve resources, improve production efficiency, and minimize environmental impact in container nurseries.

CCROP tools are available at www.bmptoolbox.org, a website hosted by the University of Florida. The tools are offered free-of-charge but users must establish a login account. We highly recommend using Mozilla Firefox™ as your web browser for using these CCROP tools. Four types of CCROP tools are currently available (Table 1). The Grower Tool, Comparison Tools, and Real-time Tools are all streamlined to allow only the most critical management factors to be manipulated: planting date, container size, container spacing schedule, CRF rate and longevity, irrigation schedule, marketable plant size (for terminating simulated crop). Factors that cannot be changed include substrate water-holding characteristics, transplant liner size and nutrient content, pruning schedule and supplemental fertilization. In contrast, the Technical Tool allows the user to change all input CCROP parameters. The Technical Tool, however, is less intuitive requiring some effort to learn parameter names and appropriate units of measurement (metric versus English units).

Historical weather data for running CCROP simulations come from several sources. All tools have access to weather data downloaded daily from 28 weather stations that comprise the Florida Automated Weather Network (FAWN; http://fawn.ifas.ufl.edu). FAWN stations typically have 5–10 years of weather data depending upon the age of the station (8). A second source of long-term (> 30 years) weather is available for nine locations in Florida. As the CCROP tool evolves we plan to provide options for automatically acquiring weather data outside Florida. Currently, users outside Florida have to create (some strict formatting required) and upload their own weather data sets.

Outcomes of CCROP simulations can be viewed graphically or in tabular form. Output includes weather data, plant growth parameters (e.g., size, biomass, leaf area), crop time (weeks to marketable size), water parameters (e.g., irrigation, drainage, runoff), and nutrient parameters (e.g., N and P release from CRF, N and P uptake, runoff N and P). Output is provided on a per-container basis, often useful for efficiency analyses, or per-area basis which may be important for environmental analyses. Graphs, tables, and reports generated from outputs may be printed or stored electronically.

In light of increasing restrictions on water consumption (1) and impending numeric water quality standards to meet Total Maximum Daily Load restrictions (11), implementing best management irrigation and fertilizer practices will play a major role in maximizing efficient use of these resources.

Table 1. Summary of CCROP tools available at www.bmptoolbox.org.

Tool	Description	Purpose
Grower	Evaluates one set of input conditions	Provides detailed outcome including daily time-plots
Comparisons	Runs two or more levels of a given factor (e.g., irrigation, location, plant date, fertilizer rate) holding all other inputs constant	Useful for conducting what-if experiments. Outcome limited to summary data (no daily time-plots).
Real-time	Tracks day-to-day progress of a crop and provides daily irrigation amounts to apply	Irrigation scheduling
Technical	Evaluates one set of inputs but unlike Grower tool user can change any or all input variables	For technical persons who wish to have greater control over all input parameters

We present two examples to illustrate how CCROP tools can be used to evaluate the impacts of proposed irrigation and fertilizer BMPs. In the first example, we evaluate the value of adopting a conservative irrigation-scheduling strategy in the nursery. Growers commonly apply amounts of water to container-grown crops based on subjective grower judgments (‘art’) rather than objective indicators (‘science’). A proposed irrigation BMP would be to irrigate at a rate proportional to plant evapotranspiration (13). In container nurseries, water loss through plant evapotranspiration (ET) can be measured using substrate moisture sensors placed in containers (7, 12) or predicted with modeling programs that estimate ET based upon plant size, canopy cover, container size, container spacing and weather (2, 10). With either approach, implementing an irrigation schedule based upon plant ET requires increased management effort as well as costs associated with implementing required irrigation technology. An analysis of potential water savings using ET-based irrigation technologies may help with decisions regarding whether or not it is cost-effective to implement these technologies in a given nursery. Simulations used for such an analysis may also provide numerical support for contractual BMP or cost-sharing programs.

In the second example, we evaluate the potential benefits of adjusting CRF N rates to match expected N responses due to different container sizes and planting dates. A fertilizer BMP is to match N release from CRFs with plant N demand for optimal growth and quality. Production of plants in trade #1 and #3 containers often entails the use of substrates containing pre-incorporated CRF at N rates ranging from 1–2 $kg \cdot m^{-3}$ (2–3.5 $lb \cdot yd^{-3}$). Our experience is that many growers use the same pre-fertilized substrate (same CRF N rate) for producing containerized woody ornamental plants regardless of planting date. With this strategy, it is natural for growers to select higher CRF N rates to insure adequate nutrition for all crops produced during the time frame imposed by the CRF’s longevity. CCROP tools can be used to evaluate the potential benefits of implementing a BMP of customizing CRF application rates based on planting date, expected crop time and weather.

Materials and Methods

Example 1 — irrigation BMP assessment. The Comparison Tool was used to assess the value of implementing an irrigation schedule that applies water in an amount proportional to the container substrate’s water deficit prior to irrigation (ET-based). For this example, ET-based irrigation was compared to fixed-rate schedules of 1.0 and 1.5 $cm \cdot d^{-1}$. For fixed irrigation rate simulations, a rain sensor cutoff was simulated so that no irrigation was applied if the past day’s rain exceeded the irrigation rate. Production of *V. odoratissimum* in trade #3 (28 cm top diameter; 11.4 liter) containers was simulated with six planting dates, one every two months. Input management practices for Example 1 are given in Table 2. To evaluate the effect of location, simulations were carried out for two locations in Florida: Jay (30°46'30"N, 87°8'24"W) in Northwest Florida and Fort Lauderdale (26°5'37"N, 80°14'31"W) in Southeast Florida. There were eight years (2003–2010) of historical FAWN weather data for each of the two locations. The Comparison Tool calculates the mean and standard deviation for a given response variable for the eight years of plantings. We selected a fixed cost for pumping water of $0.053 per 1000 liters ($0.20 per 1000 gal) for economic analyses.

Example 2 — fertilizer BMP assessment. Example 2 is a sensitivity analysis evaluating the impact of CRF N rates on crop production time and N leaching in trade #1 (16 cm top diameter; 2.7-liter) and #3 containers. Management inputs for Fertilizer Comparison Tool simulations used in this analysis are listed in Table 2. For trade #1 containers, we compared CRF N rates of 2.8, 3.1, 3.4, 3.7 and 4.0 $g \cdot container^{-1}$ (2.0, 2.2, 2.4, 2.6, and 2.8 $lb \cdot yd^{-3}$) and for trade #3 containers,

Table 2. Management practices used in simulations to assess irrigation and fertilizer BMPs with CCROP’s Comparison Tool.

Factor	Irrigation BMP (Example 1)	Fertilizer BMP (Example 2)
Locations	Jay, FL and Fort Lauderdale, FL	Jay, FL
Species	*Viburnum odoratissimum*	*Viburnum odoratissimum*
Container size	trade #3 (28-cm)	trade #1 (16-cm), trade #3 (28-cm)
Finish height	76 cm	46 cm (trade #1), 76 cm (trade #3)
Plant date	once every two months starting January 1	once every two months starting January 1
Spacing	14.7$\cdot m^{-2}$ (jammed, equidistant) then 3.7$\cdot m^{-2}$ (container diameter apart) when LAI=3	45$\cdot m^{-2}$ (containers touching, equidistant) then 11.3$\cdot m^{-2}$ (container diameter apart, equidistant) when LAI = 3 (trade #1); 14.7$\cdot m^{-2}$ then 3.7$\cdot m^{-2}$ when LAI = 3 (trade #3)
Irrigation	1 $cm \cdot day^{-1}$ with rain sensor, 1.5 $cm \cdot day^{-1}$ with rain sensor, or ET-based	1 $cm \cdot day^{-1}$ with rain sensor
Fertilizer	18% N (15% controlled-release N, 12 month release at 21C)	18% N [15% controlled-release N, 8-9 month release at 21C (trade #1); 12 month release at 21C (trade #3)]
Fertilizer	18 $g\ N \cdot container^{-1}$	2.8–4.0 $g\ N \cdot container^{-1}$ (trade #1), 11.9–19.0 $g\ N \cdot container^{-1}$ (trade #3)
Pruning	Pruned (4 cm) when canopy height reached 27 cm and again at 42 and 57 cm	Pruned (4 cm) when canopy height reached 27 cm and again at 42 and 57 cm (only twice for trade #1)

11.9, 13.1, 15.4, 17.7 and 19.0 g·container^{-1} (2.0, 2.3, 2.6, 2.9, and 3.2 lb·yd^{-3}). While a broader range of CRF N rates were initially tested for these simulations, we limited the CRF N rates presented in this discussion to the range of rates affecting crop time (weeks) and N leaching loss (g·container^{-1}). Simulations were carried out for six planting dates at Jay, FL. For each planting date, we determined an optimal CRF N rate, i.e., growth did not increase at higher N rates. The highest optimal CRF N rate of the six planting dates tested was then selected as the CRF N rate that would be used if just one CRF N rate was applied for all six planting dates. This highest optimal CRF rate was compared to the optimal CRF N rates determined for each planting date to assess the potential benefits of using custom CRF rates for different planting dates on leaching N losses and direct CRF costs. This analysis was carried out separately for production in trade # 1 and #3 containers. As with Example 1, simulations were carried out for eight complete years to assess year-to-year variations in simulated responses. We used a direct CRF cost of $16.8 per kg N ($7.5 per lb N) for economic analyses.

All simulations involved with the examples described above used CCROP version 1.0 that was current at the time of manuscript preparation. As CCROP and related tools are frequently being updated, results using future versions of CCROP tools may be different than those presented herein.

Results and Discussion

Example 1 — irrigation BMP assessment. Results of simulations indicate the irrigation BMP has great potential to save water and reduce fertilizer N loss compared to typical fixed rates of irrigation (Fig. 1). By CCROP design, ET-based irrigation scheduling applies the daily amount of irrigation water required to return the water deficit in the container substrate back to container capacity. Therefore, with ET-based irrigation scheduling, water stress is eliminated throughout production and simulated growth is not negatively affected. For fixed rate irrigation scheduling, however, irrigation amounts may not always supply enough water to return container substrates to container capacity.

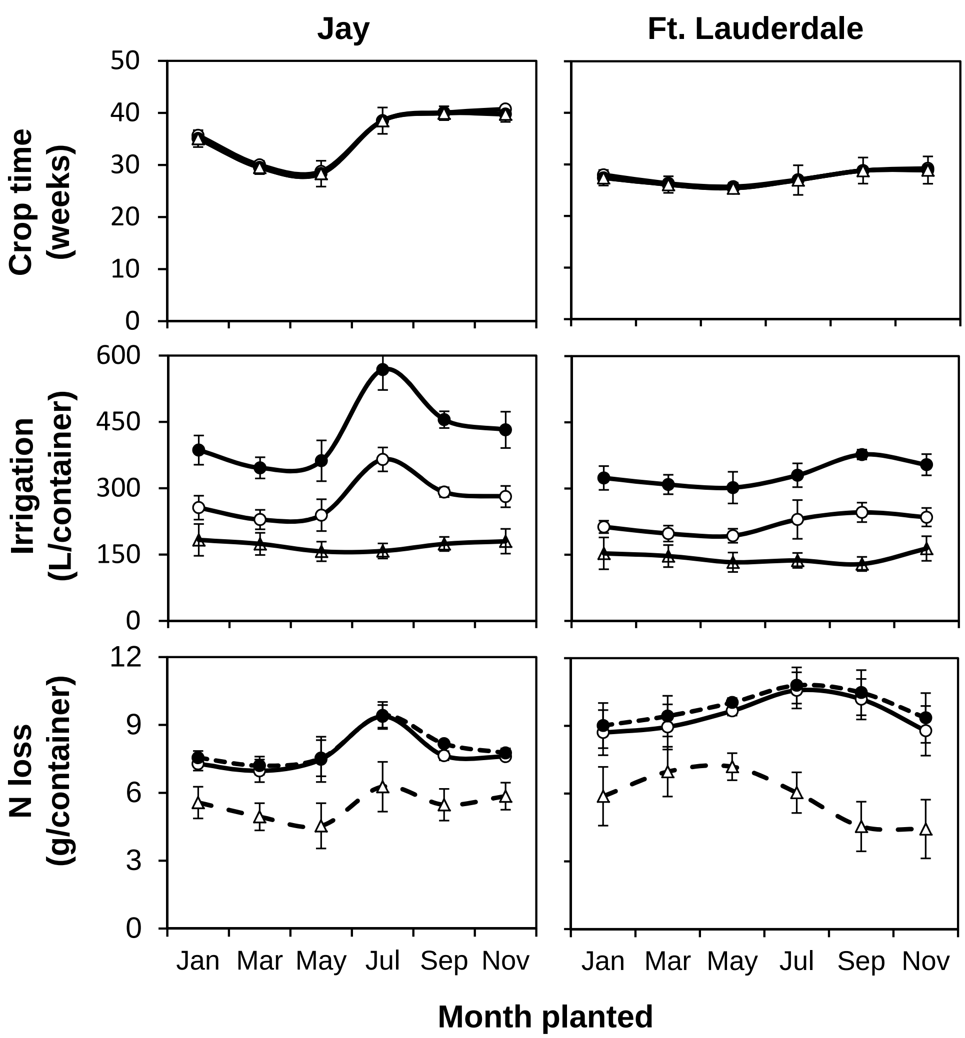

Fig. 1. **CCROP simulated crop time (weeks to marketable size), total irrigation water applied, and N leaching loss for irrigation BMP assessment example. *Viburnum odoratissimum* was produced in trade #3 (28-cm diameter) containers using one of three irrigation schedules: 1 cm·d–1 (○), 1.5 cm·day–1 (●), or an ET-based schedule (△). Simulations were carried out for six planting dates and two locations: Jay (Northwest Florida) and Fort Lauderdale (Southeast Florida). Means are cumulative season totals and represent the average of eight years of plantings (2003–2010); error bars represent ± 1 sd.**

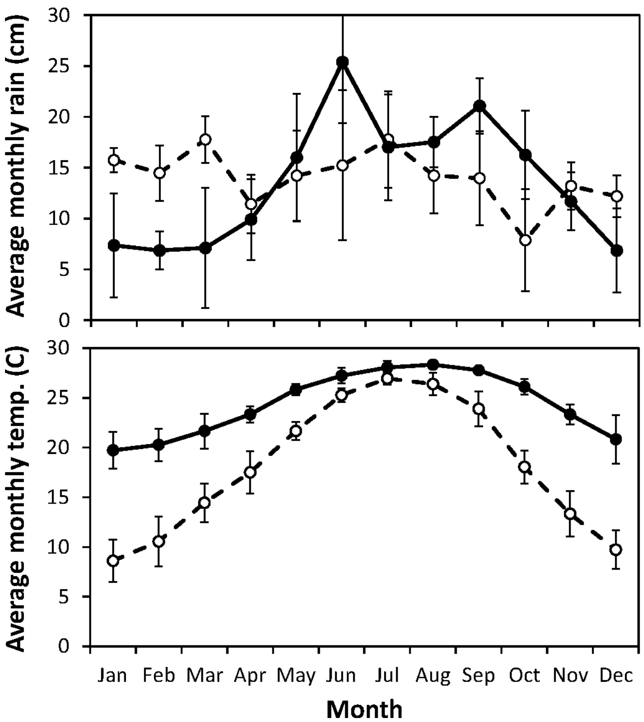

Fig. 2. Average monthly temperature and rainfall for Jay (○) and Fort Lauderdale locations (●) during 2003–2010.

CCROP simulates a daily water balance in the substrate and if water deficits reach threshold levels (i.e., insufficient water to meet potential ET rates), water stress is simulated by limiting plant growth to a fraction of the potential growth for that day (10). Crop time (weeks to marketable size) output gives an indication of whether selected fixed irrigation practices resulted in water stress and reduced growth. In Example 1 simulations, all irrigation practices resulted in similar crop times indicating selected fixed irrigation rates supplied sufficient water to prevent water stress. The more tropical weather in Fort Lauderdale resulted in relatively uniform crop times compared to Jay, which has greater seasonal variations in temperature (Fig. 2). Besides temperature, Fort Lauderdale has a more pronounced rainy season during summer months while Jay receives more rainfall during winter months. While not directly affecting crop time, rainfall amounts and distribution affect irrigation demand and fertilizer N leaching as discussed below.

The magnitude of the water savings realized by adopting the proposed irrigation BMP depended on both location and planting date as well as fixed irrigation rate (Fig. 1). Considering that crop times were not affected by fixed irrigation rates, the 1.5 cm·d^{-1} rate would be considered excessive compared to the 1 cm·d^{-1} rate. Because a rain sensor was used in these simulations, the total amount of irrigation water applied with the 1.5 cm·d^{-1} rate was actually greater than 50% of that applied with the 1 cm·d^{-1} rate. The rain sensor effect was a result of rain amounts > 1 cm but < 1.5 cm which cut off irrigation for the 1 cm·d^{-1} rate but not the 1.5 cm·d^{-1} rate. Because the 1.5 cm·d^{-1} rate was excessive, we used the 1 cm·d^{-1} rate when assessing the benefits of ET-based BMP irrigation practice in the following discussion.

ET-based irrigation resulted in irrigation water savings that ranged from 24% (March planting) to 57% (July planting) at Jay and from 26% (March planting) to 48% (September planting) at Fort Lauderdale (Fig. 1). For Jay, simulated water savings from using the ET-based irrigation compared to 1.0 cm·d^{-1} were greater for fall plantings, with crop times approximately two months longer than for spring plantings. Like Jay, simulated water savings for Fort Lauderdale were greatest for July and September plantings. Unlike Jay, greater water savings for fall plantings were primarily due to these crops finishing before the summer rainy season began rather than to differences in crop time. During the rainy season, irrigation demand is reduced for both fixed and ET-based irrigation minimizing differences between the two.

Loss of fertilizer N during production is an environmental impact that growers would like to minimize. Simulations for Example 1 indicate that even with ET-based irrigation, which by CCROP design results in zero leaching except during rainfall events, there is significant N loss from containers during production (Fig. 1). For ET-based irrigation, N loss as a percent of applied ranged from 25% (May planting) to 35% (July planting) for Jay and from 25% (September and November plantings) to 40% (May planting) for Fort Lauderdale. Simulated leaching losses of N were higher for the 1 cm·d^{-1} rate irrigation practice than ET-based irrigation. For the 1 cm·d^{-1} rate, N loss as a percent of applied ranged from 39% (March planting) to 52% (July planting) for Jay and from 48% (January planting) to 59% (July planting) for Fort Lauderdale. It should be noted that CCROP functions were developed to simulate measured N loss in leaching experiments; N lost via denitrification or immobilization is not directly accounted for even though this may be account for low N recoveries in N balance experiments (4).

Compared to the 1 cm·d^{-1} rate irrigation practice, ET-based irrigation reduced simulated N loss 23–39% at Jay and 22–55% at Fort Lauderdale. The benefit of reduced fertilizer N loss with the irrigation BMP was relatively consistent for all planting dates at Jay; however, for Fort Lauderdale reduced N leaching loss was especially reduced for July, September, and November plantings. Unlike Jay, which receives significant rain in winter and early spring months, Fort Lauderdale has a pronounced dry season from December through March (Fig. 2). The low rainfall during this dry period accounts for the low leaching N losses simulated for the irrigation BMP practice when crops were grown during these months.

Example 2 — fertilizer BMP assessment. CCROP simulation outcomes for both trade #1 and #3 containers indicate that optimal CRF N rates vary depending upon planting date (Fig. 3). For trade #1 containers, optimal CRF N rates ranged from 2.8 to 4.0 g·container^{-1} (2.0 to 2.8 lb·yd^{-3}). Lowest optimal CRF N rates were observed for May, July, and September plantings and highest for January and November plantings. Low CRF N rates coincided with shorter growing seasons. The exception was the September planting which had a longer crop time but less leaching than January and November plantings. The highest optimal CRF N rate for trade #1 containers was 4 g·container^{-1}. If this rate of CRF N was used at the other planting dates, then the fertilizer BMP would have reduced applied CRF N 15–30% without negatively affecting growth. For trade #3 containers, optimal CRF N rates ranged from 11.9 to 19.0 g·container^{-1} (2.0 to 3.2 lb·yd^{-3}). Lowest optimal CRF rates were observed for March and May plantings and highest for September and November plantings. As with trade #1 containers, lower

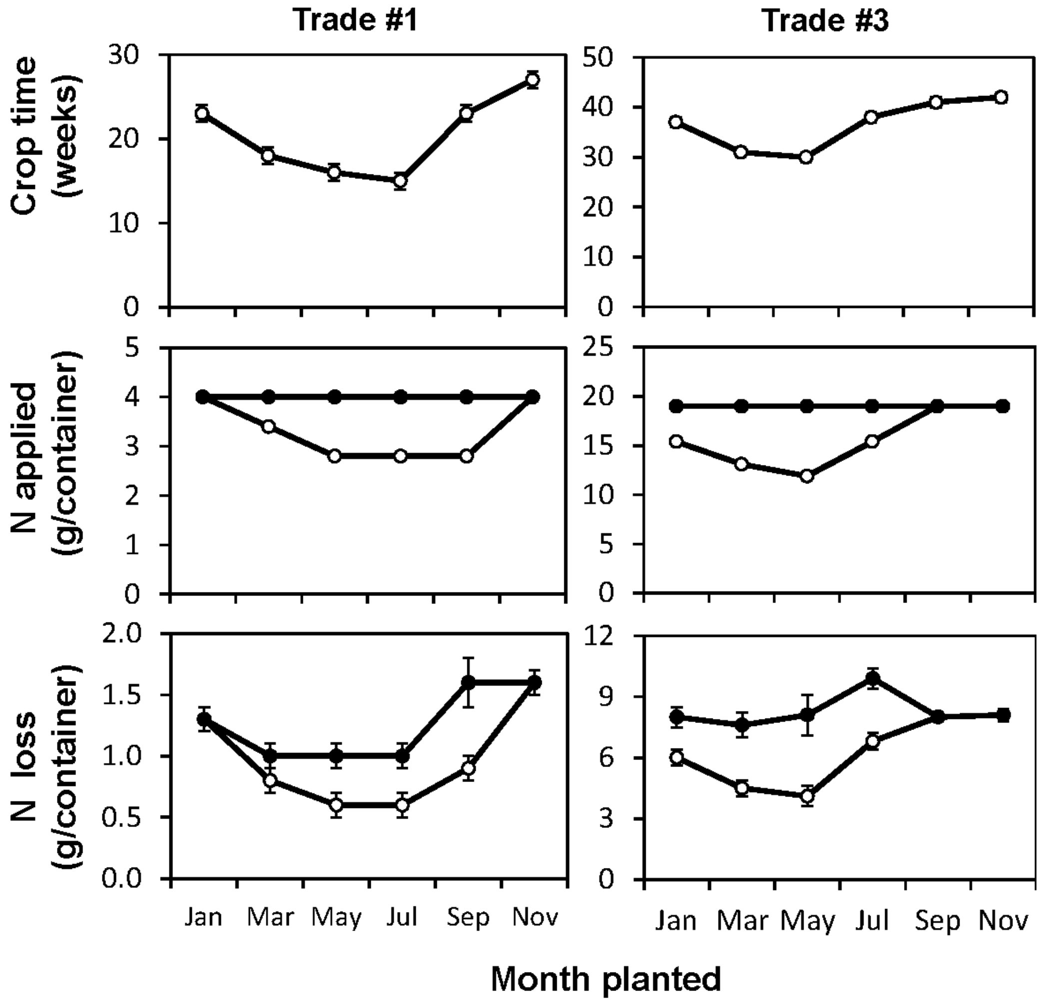

Fig. 3. CCROP simulated crop time (weeks to marketable size), total irrigation water applied, and N leaching loss for fertilizer BMP assessment example. Optimal fertilizer N rate (○) was the lowest N rate providing optimal growth of *Viburnum odoratissimum* at each of the six planting dates. Highest optimal fertilizer N rate (●) was the highest of the six optimal fertilizer N rates and represents the N rate that would be applied if only one rate were to be used successfully for all six planting dates. Optimal N rate at each planting was compared to the highest optimal fertilizer N rate as a means for assessing the fertilizer BMP. Analyses were conducted separately for trade #1 and #3 containers. Means represent the average of eight yearly plantings (2003–2010); error bars represent ± 1 sd.

optimal CRF N rates coincided with shorter crop times for March and May plantings. The highest optimal CRF N rate for trade #3 containers was 19.0 g·container^{-1}. If this rate of CRF N was used at the other planting dates, the fertilizer BMP would have reduced applied CRF N 19–37% without negatively affecting simulated growth. Similar analyses could be conducted for different CRF longevities to further evaluate potential benefits of custom CRF applications for different plant dates.

Simulation outcomes indicate that the proposed fertilizer BMP not only reduces applied N at certain planting dates but also N leaching loss (Fig. 3) when compared to the highest optimal CRF N rate. For trade #1 containers, N loss reductions due to the fertilizer BMP ranged from 0% (January and November plantings) to 44% (September planting) with an average reduction for all six plantings of 23%. For trade #3 containers, N loss reductions ranged from 0% (September and November plantings) to 49% (May planting) with an average reduction for all six plantings of 25%.

The purpose of this paper is to demonstrate how CCROP simulation tools might be used to assess BMPs in container nurseries. We presented two examples to illustrate how several factors might affect conclusions regarding the magnitude of potential benefits derived from adopting a given BMP at a given location. Herein lies the strength of simulation models. We, as researchers, could never conduct enough experiments over enough seasons at enough locations to give the appropriate answers to critical questions that are asked today. And these questions are changing rapidly as water resources decrease and water quality constraints increase. As greater research emphasis is placed on quantitatively describing how important biophysical processes (e.g., plant growth and development, evapotranspiration, water stress, nutrient stress, nutrient uptake and leaching) interact with each other and the environment, the greater the confidence we will have that integrative computer models such as CCROP can accurately simulate these complex situations and provide us with the science-based answers many of us seek.

Both examples illustrate that benefits of irrigation and fertilizer BMPs vary depending upon planting date and location. Planting date and location can significantly affect crop time due to seasonal difference in temperature and solar radiation

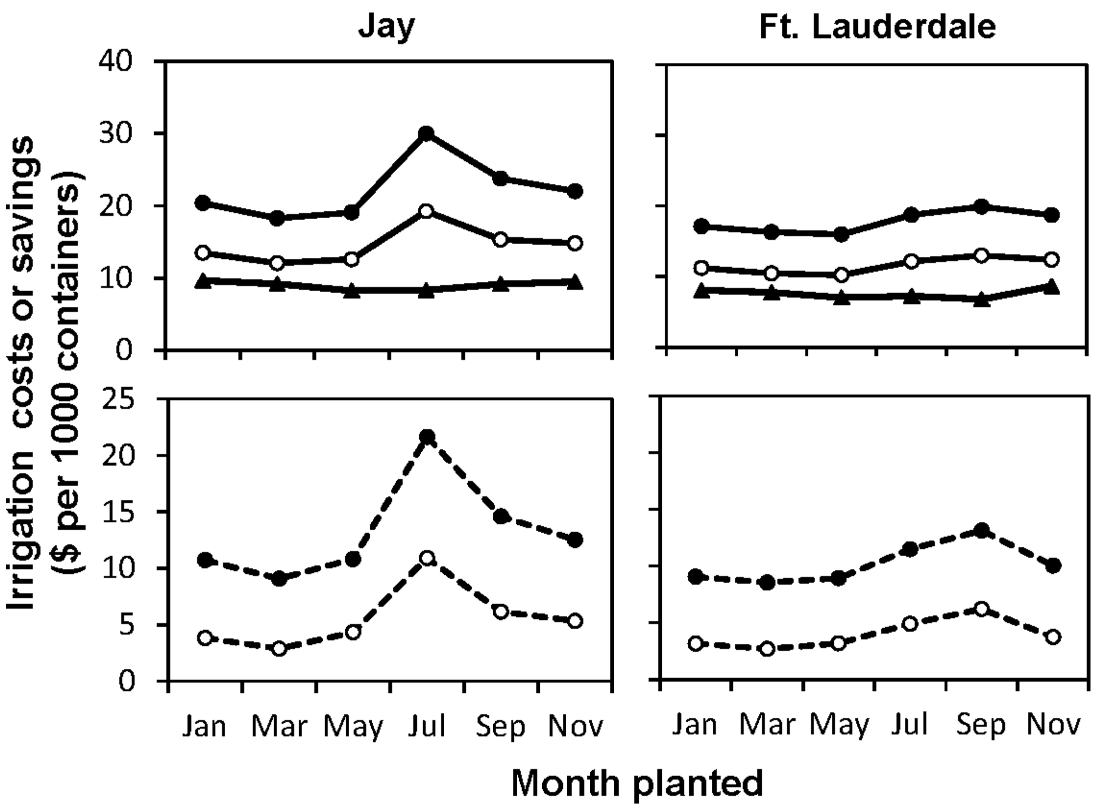

Fig. 4. Simulated impact of irrigation BMP on direct irrigation pumping costs and cost savings. The pumping cost for the irrigation BMP of using an ET-based schedule (▲) was compared to costs for fixed irrigation rates of 1 cm·d^{-1} (○) and 1.5 cm·day^{-1} (●) for six bimonthly planting dates and for two locations in Florida. Cost savings (dashed lines) are the projected reduction in pumping costs from implementing the irrigation BMP compared to each of the two fixed irrigation rates.

affecting plant growth and development. Greater crop time usually results in greater amounts of irrigation water required although as observed in Example 1 this effect is minimized if ET-based irrigation is practiced and/or much of the growing period coincides with a rainy season. As demonstrated in Example 2, crop time and N leaching also affect optimal CRF N rate as CRF longevity is limited and any accumulated available N in the container is subject to leaching by rainfall even if irrigation water is precisely applied.

Another benefit of simulation tools is that outcomes are quantitative. In other words, tools output numerical values which can be used for making economic and environmental impact decisions regarding BMP implementation in the nursery. An ET-based irrigation system that applies water in proportion to ET may provide an opportunity to improve water-use efficiency, but how much water can be saved? Does it make economic sense to buy and install sensors to accomplish this? Or, is the benefit in water savings small in relation to water savings that would result from investing in an irrigation system upgrade that would greatly improve irrigation distribution uniformity? Simulation tools can help to answer these questions by providing numbers that can be used in the required decision-making analyses.

In Examples 1 and 2, we used CCROP tools to simulate how irrigation and fertilizer BMPs might reduce the amounts of irrigation water and CRF required to produce a representative ornamental crop in containers and how these reductions might result in lower amounts of N leached from containers. Depending upon planting date and location, the ET-based irrigation BMP was shown to reduce water usage 24–57% and the fertilizer BMP shown to reduce CRF usage 15–37%. While these percent reductions would likely be incentive enough, assigning a monetary value to these reduced inputs may provide a better means of describing the economic impact. The simulated effect that irrigation and fertilizer BMPs had on direct costs associated with water and CRF amounts applied in Example 1 and 2 is depicted in Figs. 4 and 5. The average 41% reduction in irrigation water applied using the irrigation BMP compared to the 1.0 cm·d^{-1} for the six planting dates resulted in an average savings in pumping costs of $6 per 1000 containers at Jay with the greatest savings of $11 per 1000 containers observed for the July planting. Water savings at Fort Lauderdale averaged $4 per 1000 containers with less variation between plantings than observed for Jay. This analysis assumes that water is plentiful and free-of-charge. Other benefits of water use reductions that are more difficult to place monetary values on include the ability to better meet consumptive water use limitations, the ability to better irrigate crop production areas in a timely manner, and the ability to reduce runoff and runoff N from production areas.

A similar economic analysis shows that considerable savings in CRF N cost are simulated by implementing the fertilizer BMP in Example 2 (Fig. 5). Savings ranged from $0 per 1000 containers to $19 per 1000 containers for trade #1 containers and from $0 per 1000 containers to $118 per 1000 containers for trade #3 containers. The analysis does not account for any costs (labor or equipment) associated with purchasing or otherwise providing for custom-fertilized substrates. The direct fertilizer cost figures do, however,

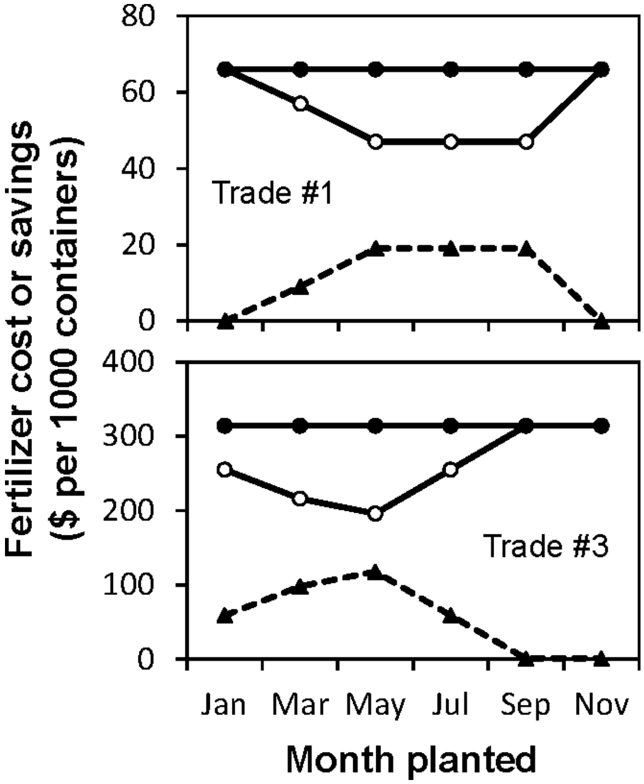

Fig. 5. Simulated impact of fertilizer BMP example on direct controlled-release fertilizer costs and cost savings for producing *Viburnum odoratissimum* in trade #1 or #3 containers at Jay, FL. The cost for the optimal N rate determined for each of six planting dates (○) was compared to the cost of the highest optimal N rate (●) as a means for assessing the potential cost savings (▲) from adopting the fertilizer BMP of adjusting fertilizer rate based on plant date. The highest optimal N rate was the highest of the six optimal N rates and represents the N rate that would be applied if only one rate was used successfully for all six plant dates.

provide information that may be helpful in making economic decisions regarding implementing the fertilizer BMP. As with the irrigation BMP analysis, no economic value is placed on reducing runoff N in the nursery. However, as the quantity of water used by container nurseries becomes more restricted and the quality of water leaving production areas more regulated, the likelihood exists that monetary values assigned to water quantity and quality (e.g., N content) will one day be available for economic analyses using CCROP simulation tools.

The use of models such as CCROP to simulate production is a new concept for most in our industry. It is important that we acknowledge that its development and testing have been limited to two representative model species and for growing conditions in Florida. Therefore, we cannot be sure of its applicability for other woody ornamental plant species and locations outside of Florida. We believe the greatest difference in plant species grown in more temperate climates will be differences in temperature sensitivity and dormancy. Our experience has been that ET rates among different woody ornamental plants are often similar when based on canopy coverage (light interception). However, potential ET equations in CCROP are applicable to humid climates so they would likely need modifying in arid climates. If these and other limitations are recognized, we believe CCROP tools can provide new insight into the interactive effects that management practices and weather can have on growth and resource use efficiency. As additional research efforts are made, we expect CCROP to improve its simulating capabilities and usefulness not only for Florida but also for other locations.

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