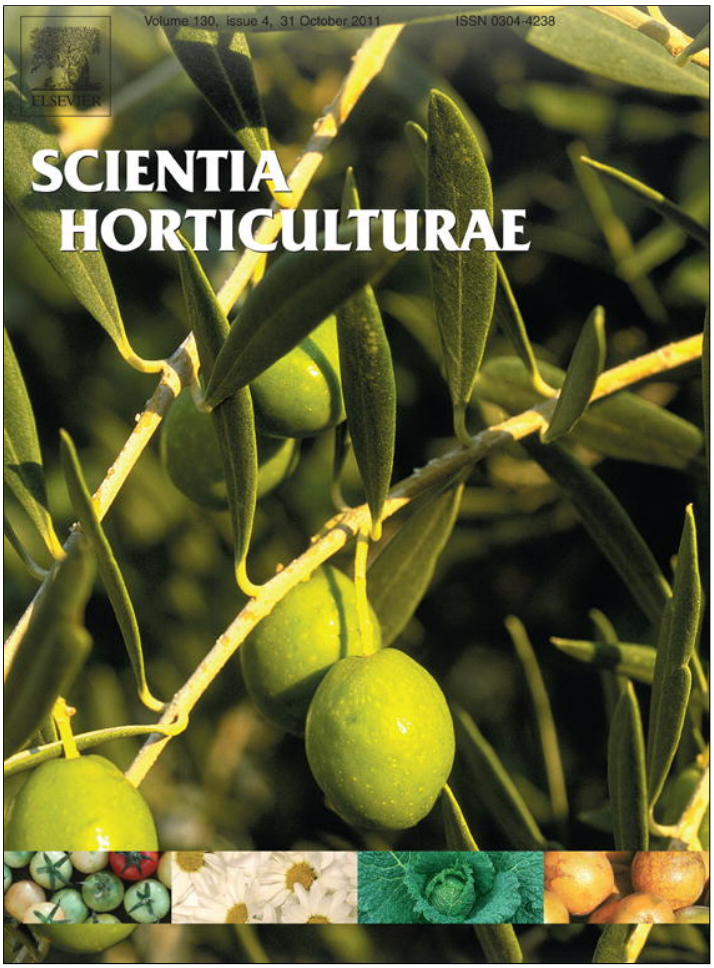

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CCROP—Simulation model for container-grown nursery plant production

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ABSTRACT

Container Crop Resource Optimization Program (CCROP) is an integrative model which simulates the growth and water and nutrient requirements of a woody ornamental shrub grown in small (2.8–11.4 L) containers in a field environment with overhead sprinkler irrigation. The model was developed for producers, producer advisers and researchers to support best management practice decision-making in container nursery production. We describe the primary processes simulated by CCROP particularly how they differ from traditional crops grown in-ground and assess the ability of CCROP to simulate measured values for a range of irrigation and fertilizer trials and transplanting dates. Results of model testing with 11 trials indicate that CCROP provided reasonable outcomes for biomass and leaf area growth as well as evapotranspiration, runoff (container drainage plus un-intercepted irrigation and rainfall) and nitrogen loss.

1. Introduction

In 2009, the nursery industry in the U.S. was estimated to have sales of $3.85 billion with 66% of production in containers (National Agricultural Statistics Service; www.nass.usda.gov). Best management practices (BMPs) are needed in production of container grown nursery crops due to high plant densities, inherently inefficient overhead irrigation systems (Beeson and Knox, 1991), and high application rates of controlled-release fertilizer (Evans et al., 2007). Under these conditions, cumulative leaching losses of applied N and P were found to exceed 250 and 33 kg ha^{-1} yr^{-1}, respectively, from the moderate fertilizer application rates of 1100 and 150 kg ha^{-1} yr^{-1} of N and P, respectively (Million et al., 2007b). BMP guides such as Best Management Practices: Guide for Producing Nursery Crops (Yeager et al., 2007) recommend irrigation and nutrient strategies based on a limited amount of research (Heckman et al., 2003). Economic and environmental issues can change rapidly requiring critical information from research be rapidly available. However, it is quite difficult to evaluate BMPs under all conditions with trial-and-error research specific to weather, transplanting dates, site and irrigation and nutrient application strategies.

Agronomic crop production simulation models have gained wide acceptance as important tools in research, education, and management (Jones et al., 2003; Keating et al., 2003; Marcelis et al., 1998). In container production, efforts have been made to model individual processes such as evapotranspiration (Beeson, 2010; Pardossi et al., 2008), container temperature (Martin and Ingram, 1992), and fertilizer release (Birrenkott et al., 2005), but few simulation models integrate a wide range of factors affecting production of container-grown nursery crops (Smajstrla and Zazueta, 1987). The primary difference between traditional soil-based agricultural production and production in containers is the finite substrate volume imposed by containers. This finite volume has implications for relating canopy ET with water uptake. Temperatures in container substrates have the potential to exceed traditional soil temperatures due to adsorption of radiation by container walls and the surrounding environment (Martin and Ingram, 1993). Another major difference is the common use of controlled-release fertilizers (CRF) in container production. Numerical models used to estimate nutrient release from polymer-coated CRF are complex (Shaviv et al., 2003) and simplified release algorithms are needed. Another deviation from traditional crop models is the loss of overhead irrigation water and rain that falls between spaced containers. In this regard, the leaf canopy can affect the amount of overhead irrigation and rain captured by the container substrate (Beeson and Yeager, 2003).

Our objective was to develop an integrative simulation model for container-grown plants by adapting established principles from agronomic crop simulation models. *Viburnum odoratissimum* (L.) Ker-Gawl., common name sweet viburnum, grown in 2.8 L (trade #1) and 11.4 L (trade #3) containers was used as a test crop for developing and testing model functions. *V. odoratissimum* is a

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commonly-grown, woody ornamental shrub with upright, spreading growth habit and medium-size leaves. It is easily propagated, grows without any major pests or diseases, and its medium-high requirements for water and nutrients are representative of many woody ornamental crops produced in container nurseries. The model was developed in a modular format so that it could be more easily used for other species and growing conditions. In this paper we discuss the major processes simulated by CCROP emphasizing differences from traditional field crop models and test the model by comparing model outcomes with observed data from a range of experiments.

2. Materials and methods

2.1. CCROP overview

The model is called CCROP – Container Crop Resource Optimization Program. CCROP simulates the production of a woody, ornamental container crop in small (2.8–11.4 L) containers using overhead sprinkler irrigation. In addition to plant growth, CCROP simulates water and nutrient uptake, runoff (container drainage plus un-intercepted irrigation and rain) and N loss from container substrates. Runoff in the context of this paper represents the potential amount of runoff from the production area; CCROP does not simulate the movement of this potential runoff water away from the production site via surface or subsurface flow.

Several important assumptions were made in the development of CCROP. It is a deterministic type model, thus the simulations attempt to represent an average plant. Except for water-holding characteristics, substrates are assumed to have similar chemical and physical properties. Transplants are assumed to be watered in thoroughly prior to setting containers into the production area. No account of nutrient loss during initial watering-in of transplants is accounted for although this amount could be significant (Million et al., 2007b, 2010a). Black containers of industry standard shape are assumed to be placed on black, woven groundcloth in the production area. CCROP assumes that no pest or disease problems affect growth. Irrigation is assumed to be overhead, sprinkler irrigation uniformly applied above the canopy. Irrigation is assumed to be applied early in the morning before significant ET has occurred.

CCROP is programmed in FORTRAN using Intel® Visual FORTRAN Compiler for Windows (Version 9.0; http://software.intel.com). CCROP simulates important dynamic plant-substrate-water processes based on a 24 h integration period. The program consists of a driver program and four subroutines: water, plant, nutrient, and output. The driver program reads input data, initializes variables, performs certain calculations, and controls the passing of variables between subroutines for daily rate and integration calculations, including output. Input data are read from management, plant and weather files, and optionally from irrigation and/or solution fertilizer files.

CCROP has been designed to use a minimum set of information in order to make it work effectively and efficiently. CCROP requires daily weather data for maximum and minimum air temperature (°C), solar radiation (MJ m^{-2}), and precipitation (mm). Cultural practices specified in a management input file include details for transplanting, finishing, container size and spacing, substrate water-holding properties, irrigation, fertilization, and pruning details. In cases where scheduling of various management practices is not for fixed dates, options for scheduling are provided by selecting criteria needed to activate a schedule change. For example, a container spacing change can be made when a critical leaf area index is reached, irrigation can be scheduled based on an allowable container water deficit concept (Welsh and Zajicek, 1993; Beeson, 2006), supplemental topdress and/or solution fertilizer applications can be triggered if N release falls below a critical fraction of plant N demand, pruning can triggered once a specified plant height is reached.

The remainder of this section describes the major processes simulated by CCROP. A list of important parameters used in this description is provided in Table 1.

2.2. Plant growth and development

2.2.1. Sink and source-limited growth

CCROP estimates daily sink and source biomass quantities and new plant growth is limited to the minimum of the two. Sink-limited growth is controlled by the development rate of the plant as regulated by the temperature of the growing apices when plants are growing with little competition for nutrient or light. A template using four cardinal temperatures was developed to describe development rates: *Tdmin*, low temperature when development ceases; *Tdmax*, high temperature when development ceases; *Tdomin* and *Tdomax*, minimum and maximum temperature thresholds when development occurs at a maximum rate. We found that 6 °C, 18 °C, 34 °C, and 38 °C, for *Tdmin*, *Tdomin*, *Tdomax*, and *Tdmax*, respectively, gave the most consistent estimates of leaf area growth for *V. odoratissimum* in a range of experiments described later. Based upon this temperature template, a relative development time (*RDT*) is given a daily value between 0 d (no development) and 1 d (maximum development rate).

We assume the temperature of growing apices to be equal to the air temperature except when temperatures of apices increase due to heating effect from absorption of solar radiation by non-evaporating, black container walls and groundcloth surfaces when plant cover is incomplete. We simulate this bias by estimating the fraction of direct beam radiation (*DRf*) reaching these surfaces: $DRf = 1.33 \times (SRcf - 0.25)$ where *SRcf* = fraction of clear day radiation. A biased temperature maximum (*Tmaxb*) is approximated by: $Tmax = Tmax + 0.6 \times DRf \times e^{-0.7 \times LAI} \times (1 - Ac/At)$, where *Ac* is the top area of the container (cm^2), *At* is the total production area occupied by one container (cm^2), and *LAI* is the leaf area index ($cm^2_{leaf}\, cm^{-2}_{ground}$). The value of 0.6 °C MJ^{-1} m^{-2} was approximated from measurements of elevated container temperatures reported by Martin and Ingram (1991, 1993) with varying degrees of vegetative cover. The *Tmaxb* equation indicates that the temperature bias becomes greater as containers are spaced more widely (*Ac*/*At* becomes smaller) and smaller as plant shoots more fully cover the production area (*LAI* increases). *Tmaxb* is also used in the simulation of N release from controlled-release fertilizers as described in a later section.

The accumulation of *RDT* is development time (*DT; d*). *DT* is sometimes referred to as physiological days and can be thought as the cumulative number of days under optimal temperature conditions. *DT* is used to control sink-limited, aboveground growth. The relationship between *DT* and sink-limited leaf area per plant (*LAsi*) is: $LAsi = LAc \times DT^{2.5}$ where *LAc* is a species-specific coefficient. *LAc* for *V. odoratissimum* was found to be 0.045. The derivative of the function is used to estimate daily sink-limited growth (*dLAsi*): $dLAsi = 2.5 \times LAc \times DT^{1.5} \times RDT$. In high density plantings, growth will typically become light-limited so that branching and leaf area growth will not continue exponentially. Under light-limited conditions *DT* is reduced to reflect actual leaf area (*LA*) growth: $DT = ((LA - LA_0)/LAc)^{0.4}$ where LA_0 is the leaf area of the transplant. Finally, potential leaf area growth is converted to an equivalent potential biomass growth (*dPWsi*; g m^{-2} d^{-1}) according to: $dPWsi = (2.1 \times 10^{-7} \times LA + 0.124) \times dLAsi$. This latter function developed for *V. odoratissimum* describes the observation that the ratio of biomass growth to leaf area growth increases slightly as *LA* increases.

Table 1
List of important parameters used to model biophysical processes by CCROP.

Parameter	Description	Unit
Ac, *At*	Top area of container, area allotted container	cm^2
CF	Capture factor – amount of irrigation water entering substrate with a plant relative to the amount that would enter without a plant	$cm\,cm^{-1}$
dLAsi	Daily sink-limited leaf area growth	$cm^2\,d^{-1}$
D_N	Nitrogen concentration in drainage water	$mol\,cm^{-3}$
dPW, *dSW*, *dRW*	Daily plant, shoot, and root biomass growth	g
dPWsi	Daily sink-limited biomass growth	$g\,m^{-2}\,d^{-1}$
dPWso	Daily source-limited biomass growth	$g\,m^{-2}\,d^{-1}$
Ds	Drainage water lost from substrate	cm^3
DT	Cumulative *RDT*	d
ETo	Potential evapotranspiration rate	$cm\,d^{-1}$
Es, *Eso*	Actual and potential substrate evaporation rates	$cm\,d^{-1}$
FD, *FDmax*	Time after fertilizer application, time after fertilizer application when N release rate is at a maximum	d
ETs	Substrate water loss through evapotranspiration	cm^3
FDtf	Temperature factor for modifying N release from controlled-release N	unitless
Hpr	Fractional plant height reduction due to pruning	$cm\,cm^{-1}$
I	Photosynthetically active radiation (400–700 nm) intercepted by the canopy	$MJ\,m^{-2}\,d^{-1}$
LA	One-sided leaf area	cm^2
IRs	Irrigation water entering substrate	cm^3
LAc	Species-specific coefficient to control sink-limited leaf area growth	unitless
LAI	Leaf area index	$cm^2_{leaf}\,cm^{-2}_{ground}$
N, *Ncr*	Available substrate N, controlled-release fertilizer N in substrate	mol
Nd	Nitrogen content of drainage water	mol
Nr	Nitrogen released from controlled-release fertilizer N	mol
NR, *NRmax*	Nitrogen release rate from controlled-release fertilizer N, maximum rate	$mol_N\,mol^{-1}_{Ncr}$
Ns	Nitrogen supply – amount of substrate N available for plant uptake	mol
PFsw, *PFla*	Factors for estimating shoot weight and leaf area of pruned plant tissue based on *Hpr*	unitless
Ps	Precipitation entering substrate	cm^3
RDT	Relative development time or relative time (0–1 d) under optimal temperatures for plant development – calculated daily	d
RUE	Radiation use efficiency	$g\,MJ^{-1}$
SFn, *SFw*	Nitrogen and water sufficiency factors for limiting growth and transpiration (0–1)	unitless
Ta, *To*	Actual and potential transpiration rates	$cm\,d^{-1}$
Tdmin, *Tomin*, *Tdomax*, *Tdmax*	Cardinal temperatures used to control plant development rate	°C
Tmaxb	Temperature maximum biased for solar radiation impingement on black container walls and groundcover	°C
Vs, *Vp*	Volume of substrate, volume of plant canopy	cm^3
Ws	Substrate water content	cm^3
Wul, *Wll*, *Wa*	Substrate water content at drained upper limit (container capacity), lower limit (permanent wilting point), available water-holding capacity of substrate	cm^3

The computation of daily biomass growth limited by photosynthesis is calculated as: $dPWso = I \times TFso \times RUE$, where *dPWso* is source-limited biomass produced ($g\,m^{-2}\,d^{-1}$), *I* is photosynthetically active radiation (PAR; 400–700 nm) intercepted by the canopy, *TFso* is a modification factor for temperatures outside the optimum range, and *RUE* is the radiation use efficiency ($g\,MJ^{-1}$). *I* ($MJ\,m^{-2}\,d^{-1}$) is calculated with Beer's Law using incoming PAR equal to 0.5 of solar radiation (Tsubo and Walker, 2005) and an extinction coefficient of 0.72 (Million et al., 2005). We found that a *RUE* value of $2.8\,g\,MJ^{-1}$ gave reasonable results based upon the trials reported in this paper with *V. odoratissimum*.

2.2.2. Shoot and root growth

Partitioning of biomass between roots and shoots is done in a step-wise procedure to approximate how root–shoot partitioning changes with various above and below-ground conditions (Brouwer, 1963). When shoots grow in low light from self-shading or low radiation, they partition a larger fraction of assimilates to shoots. Similarly when the supply of water and nutrients in the substrate is limited, plants partition a larger proportion of assimilates to roots in order to increase their capacity to absorb limited resources. To approximate this dynamic system, we assume that 10% of the daily biomass gain is always partitioned to the roots as a minimum for root expansion and maintenance leaving 90% for daily shoot growth (*dSW*): $dSW = \min(0.9 \times dPWSi, 0.9 \times dPWso)$. When sink-limited we assume up to 40% of the source not used for the sink will be added to the roots (*dRW*) with the remaining lost through respiration or other means.

2.2.3. Plant size and pruning

Simulating plant size is important information for producers because height and width are used to describe the marketable product as it conforms to industry standards. Plant height is described as the distance from the substrate surface to the uppermost foliage. Plant width is the average of two perpendicular width measurements with one measurement being the widest distance between the outer edges of the plant vegetation. Power functions are used to describe canopy height and width (Fig. 1).

Pruning is the removal of a portion of the shoot in order to promote branching and improve uniformity and quality. Removal of biomass and associated leaf area is dependent upon the severity of the pruning and the age of the plant. Besides accounting for removal of leaf area and biomass, CCROP simulates a short-term delay in growth from pruning. Plant specific pruning factors are used to calculate biomass (*SWpr*) and leaf area (*LApr*) of pruned plant tissue: $SWpr = SW \times Hpr \times PFsw$ and $LApr = LA \times Hpr \times PFla$, where *SWpr* and *LApr* represent the biomass and leaf area of pruned plant tissue, respectively, *SW* and *LA* represent the shoot biomass and leaf area,

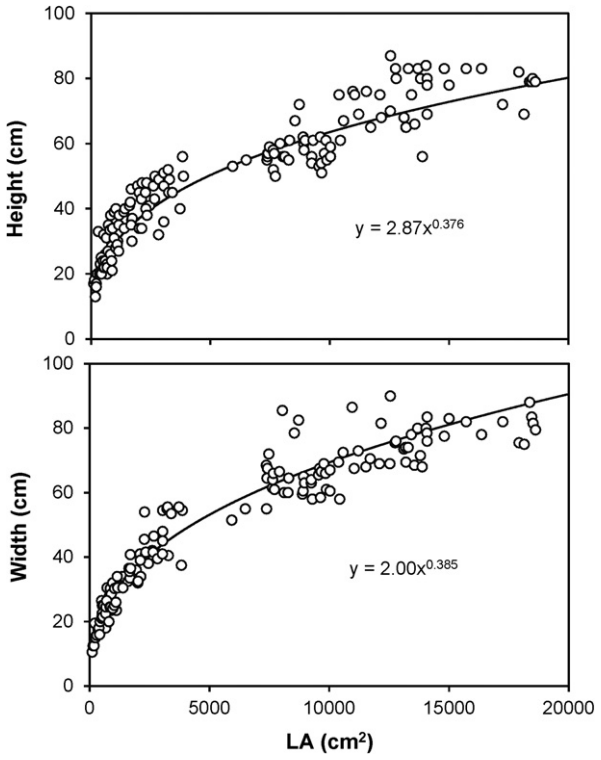

Fig. 1. Relationships between leaf area and height and width of *V. odoratissimum* grown in 2.8 L or 11.4 L containers. Symbols represent individual observations where size and leaf area were measured on the same plant.

respectively, before pruning, *Hpr* is the fractional plant height reduction due to pruning, and *PFsw* and *PFla* are pruning factors for biomass and leaf area, respectively. Based on data from experiments with *V. odoratissimum* (Million et al., 2009, 2011), pruning factors decline with plant age (Fig. 2) indicating that the more developed the plant the less effect pruning has on reducing leaf area and biomass. Once calculated, biomass and leaf area of pruned plant tissue along with associated N content are subtracted from plant totals.

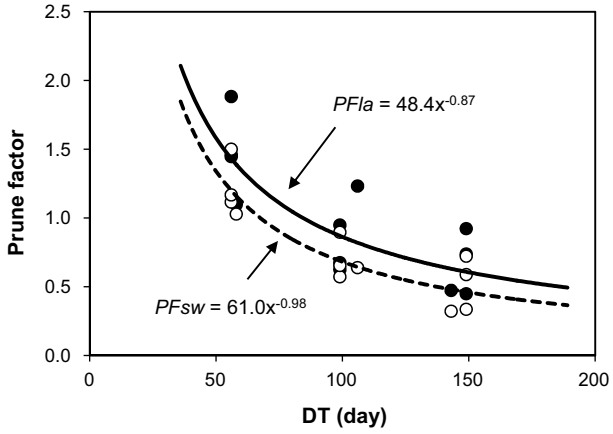

Fig. 2. Pruning factors used to calculate leaf area and biomass of pruned plant tissue based on fractional prune height reduction decline with development time (DT), the number of equivalent days under optimal temperatures. Symbols represent experimentally-observed prune factors for leaf area (*PFla*; ●) and biomass (*PFsw*; ○) for 12 pruning events with *V. odoratissimum*.

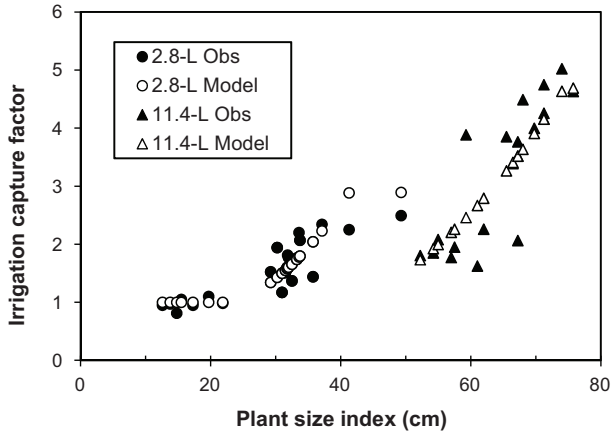

Fig. 3. Irrigation capture factor (*CF*) describes the capacity of the plant canopy to capture water that would otherwise fall between containers. *CF* is linearly related to the volume of the plant canopy and is limited by the ratio of total area to container top area. Plant size index = (canopy height + canopy width)/2. Observed values were measurements from individual *V. odoratissimum* plants from several experiments.

2.3. Water balance

The water balance of the container substrate can be described by the following equation (units of cm^3 per container): $dWs = Ps + IRs - ETs - Ds$, where dWs is the daily change in substrate water Ws, Ps and IRs represent amounts of precipitation and irrigation water, respectively, entering the substrate, ETs is evapotranspiration loss from the substrate, and Ds is drainage through holes in the bottom of the container. Drainage is added to unintercepted irrigation or precipitation to calculate runoff.

2.3.1. Water capture

Plants are able to intercept some of the water that would otherwise fall between containers and this captured water can contribute significantly to the water supply for container-grown plants (Beeson and Yeager, 2003; Million et al., 2010a). We use a capture factor (*CF*) to describe the plant's capacity to augment the amount of incoming irrigation and precipitation entering the container. We found that maximum CF (*CFmax*) is linearly related to plant canopy volume (*Vp*): $CFmax = (CF_1 \times Vp + CF_2)/Ac$, where CF_1 and CF_2 are species-specific coefficients and Ac is the top area of the container. Canopy volume is calculated as: $Vp = 4/3\pi \times (SI/2)^3$, where SI = average of canopy height and canopy width (cm). We limit captured water to 90% of that falling outside the container: $CF = \min(CFmax, 0.9 \times At/Ac + 0.1)$. Experimental measurements for *V. odoratissimum* grown in 2.8 L and 11.4 L containers indicated values for CF_1 and CF_2 of 0.013 and 97.4, respectively (Fig. 3).

2.3.2. Evapotranspiration and water sufficiency

Potential ET is the maximum ET possible for atmospheric conditions as determined by incoming radiation, dryness of the air, and leaf resistance to transpiration. Potential ET (*ETo;* $cm\,d^{-1}$) is estimated using a modification of the Penman equation (Penman, 1948). The Penman equation approximates the radiation balance over freely evaporating surfaces as a sum of a radiation component and an aerodynamic component. The general form of the Penman equation is $ETo = \delta/(\delta + \gamma) \times (Rn + G) + \gamma/(\delta + \gamma) \times f(u) \times (e_s - e_a)$, where δ is the slope of the saturation vapor pressure curve at mean daytime temperature ($kPa\,^{\circ}C^{-1}$, γ is the psychometric constant at mean daytime temperature ($kPa\,^{\circ}C^{-1}$), Rn is the net radiation ($MJ\,m^{-2}\,d^{-1}$), e_s is the saturated vapor pressure of the air at mean temperature (kPa), e_a is the actual vapor pressure of the air at mean temperature (kPa), G is the soil heat flux ($MJ\,m^{-2}\,d^{-1}$), and $f(u)$ is an empirical function to take account of wind speed. There have

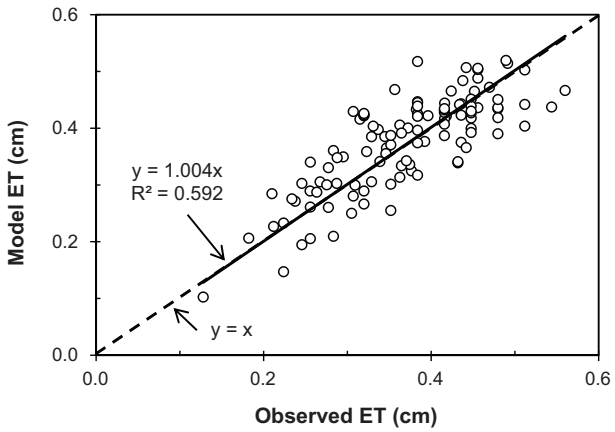

Fig. 4. Relationship between radiation component and measured evapotranspiration (ET) for *V. odoratissimum* grown in 2.8 L containers with full canopy coverage. Experimental results are from a weighing lysimeter study and runoff experiments where daily water loss was measured by weighing eight containers after irrigation and again at the end of the day.

been a variety of empirical linear equations ($a_w + b_w \times W$) fit for the wind function, usually derived from ET measurements when a crop fully covered the ground and water was freely available to the roots. Variations in reported values for a_w and b_w depend on the general humidity of the region and the crop being considered. Penman originally reported values for a_w and b_w of 0.26 and 0.14 under humid conditions in the UK. Values used in the FAO-Penman model (Doorenbos and Pruitt, 1977) are 0.27 and 0.23, with the considerably larger b_w value likely arising from ET measurements in more arid regions.

We measured *ETo* for *V. odoratissimum* by continuously weighing plants that fully covered the ground or by weighing containers with full cover twice a day, once after pre-dawn irrigation (allowing drainage to occur) and again at the end of the daylight period (Million et al., 2010b). Assuming *G* to be negligible, *Rn* is calculated as 60% of incoming solar radiation (Ritchie, 1998). *ETo* measurements indicated that the radiation component in the Penman equation accounted for practically all the measured ET, making it difficult to determine the empirical coefficients needed for the aerodynamic component. In studying agronomic crop ET, Ritchie (unpublished) found that the aerodynamic component could be reasonably approximated as $Ce \times (e_s - e_a)^{1.5}$ where *Ce* is a crop-specific coefficient. The *Ce* value found for *V. odoratissimum* to best fit our data was 1.5, yielding small values for the aerodynamic component. Since we approximated the dew point temperature (assuming it was the value of the minimum temperature) and wind was not used, this made the *ETo* equation simple to evaluate using only radiation and temperature weather information. A user wishing to use an alternative equation for *ETo* could easily substitute their method in the model. The comparison of measured and estimated *ETo* for well-watered *V. odoratissimum* fully covering the surface is depicted in Fig. 4.

Procedures developed by Ritchie (1972) are used to estimate actual ET by separating plant transpiration from substrate evaporation when plants only partially cover the surface. Potential transpiration (*To*) and potential substrate evaporation (*Eso*) are related to *LAI*: $To = ETo \times (1 - e^{-0.7 \times LAI})$; $Eso = Eo \times e^{-0.6 \times LAI}$. *Eo* in the *Eso* equation represents the potential water evaporation rate of a wet and bare surface: $Eo = [\delta/(\delta + \gamma) \times Rn + 4 \times VPD^{1.5}]/LE$. As substrate water content falls below 15% of the water content at drained upper limit (*Wul;* $cm^3\,cm^{-3}$), actual substrate evaporation (*Es*) is decreased according to: $Es = 1.5 \times [(Ws - 0.5To)/Wul]^{2.5}$. Drained upper limit (*Wul*) is the volumetric water content that exists after a container of saturated substrate is allowed to drain. This condition is similar to the term field capacity used in native soil and is approximately equivalent to −0.01 MPa for most organic substrates used in container plant production. Actual transpiration (*Ta*) is less than *To* when available water becomes limiting: $Ta = To \times SFw$, where *SFw* is a water sufficiency factor based upon available water in the substrate. The available water-holding capacity of the substrate (*Wa*; cm^3) is the volume of water held in the substrate between drained upper limit and lower limit: $Wa = Wul - Wll$, where the lower limit (*Wll*) is the volumetric water content at the permanent wilting point (−1.5 MPa) below which water is essentially unavailable to plants. As the average available substrate water content (accounting for potential ET loss) falls below a threshold value, *SFw* is reduced in proportion to the dryness of the substrate: $SFw = 1/WTF \times [(Ws - Wll)/Wa]$, where *WTF* is a water threshold factor. Based upon the findings of Beeson (1997) and Welsh and Zajicek (1993) who irrigated ornamental plants after various thresholds of available water were reached and found that measured plant growth responses decreased significantly when available water was allowed to decrease to 40–60% of the substrate's available water holding capacity, we assigned *WTF* a value of 0.5 for *V. odoratissimum*.

2.3.3. Container drainage

Drainage occurs when the capacity of the substrate to retain input water is exceeded (all units cm^3): $Ds = (Ps + IRs) - (Wul - Ws)$, where *Ws* and *Wul* are the substrate water contents before water additions and at drained upper limit, respectively.

2.4. Nitrogen balance

Additions of available N into the substrate include N released from controlled-release fertilizers (*Nr*), N from solution fertilizer (*Nsf*) and any N in precipitation (*Np*) or irrigation water (*Nir*). Losses of available N from the substrate include N uptake by plants (*Nu*) and N in container drainage (*Nd*); losses of available N due to denitrification are not considered. The daily change in substrate available N (*dNs*) is: $dNs = Nr + Nsf + Np + Nir - Nu - Nd$.

2.4.1. N release from CRF

A CRF is characterized by its release time i.e., time to release 80–90% of nutrients at a stated constant temperature. Data from the literature (Birrenkott et al., 2005; Fujinuma et al., 2009; Huett and Gogel, 2003; Shaviv et al., 2003; Tamimi et al., 1989) as well as promotional information provided by CRF manufacturers was used to develop N release functions. Based upon these publications we observed that the N release rate increases after application until a maximum rate is reached at about a third of the release time. The number of days after application until maximum N release rate (*FDmax*) is dependent upon the release time of the CRF (*FDl*) in days and is modified by a temperature factor (*FDtf*): $FDmax = 0.30 \times FDl/FDtf$. Maximum N release rate (*NRmax;* mol mol^{-1}) is: $NRmax = 0.35/FDmax$. Temperature modifies the release rate through its influence on the water vapor pressure and permeability of the polymer coating (Huett and Gogel, 2003; Shaviv et al., 2003). Saturated vapor pressure (*VP*; kPa) at the mean daily-estimated container temperature is used to calculate *FDtf*: $FDtf = 0.5225 + 0.2109 \times VP$. Saturated vapor pressure is estimated using a biased temperature mean (*Tbias*): $VP = 0.611e^{17.27 \times Tbias/(Tbiasb + 237.3)}$, where $Tbias = (Tmaxb + Tmin)/2$. The N release coefficients (*NRc1* and *NRc2*) for describing N release after fertilizer application (*FD*) before and after *FDmax* are: $NRc1 = 0.175/FDmax^2$ when $FD < FDmax$ and $NRc2 = [0.625 \times -NRmax \times (FDl - FDmax)]/(FD1 - FDmax)^2$ when $FD > FDmax$. N release rates (mol mol^{-1}) are calculated daily according to: $NR = 2 \times NRc1 \times FD$ when $FD < FDmax$ and $NR = NRmax + 2 \times NRc2 \times (FD - FDmax)$ when $FD > FDmax$. The

amount of N released daily is the product of the N release rate and the amount of controlled-release N (*Ncr*) originally applied: $Nr = NR \times Ncr$.

2.4.2. N uptake and N sufficiency

The potential supply of N from the substrate to the plant roots is calculated and compared to the demand of the plant's new growth for N. Daily plant uptake is equal to N supply when N demand exceeds N supply. If N supply exceeds N demand, daily plant uptake is equal to N demand. This approach is similar to those used in the simulation of N uptake by field crops (Godwin and Jones, 1991).

Daily N supply for plant uptake is a function of substrate solution N concentration, substrate volume, and root biomass. The equation used to estimate the daily N supply (*Nsu*) is: $Nsu = 0.00009 \times Vs^{0.72} \times (1 - e^{-0.1 \times RW}) \times (1 - 1/(1 + (C_N/6.43)^2))$, where *Vs* is the container substrate volume (cm^3), *RW* the root biomass (g), and C_N the substrate solution N concentration ($mmol\,L^{-1}$) at drained upper limit substrate water content. Results from fertilizer rate experiments with *V. odoratissimum* were used to approximate the fixed coefficients in the *Nsu* relation.

Daily N demand for plant uptake is the product of daily biomass growth and the optimal N concentration in plant tissue plus any deficit carried over from the previous day. The optimal N concentration of plant shoots (SW_{Nopt}) increases as plants begin to produce new vegetation on the transplanted rooted cutting but later decreases as the proportion of woody tissue increases. The following optimal shoot N functions were developed from experiments where destructive harvests were made periodically during the season and tissue biomass and N concentrations were determined on plants grown with a range of N fertilizer rates (unpublished data):

$$SW_{Nopt} = SW_{Nopt\,min} + X_1 \times DT, \quad DT < DT_{N\,min}$$

$$SW_{Nopt} = SW_{Nopt\,min} + X_2 \times (DT - DT_{N\,min}), \quad DT \geq DT_{N\,min}$$

where DT_{Nmin} is the DT when SW_{Nopt} is highest, $SW_{Noptmin}$ is the lowest optimum N concentration and X_1 and X_2 are linear coefficients. The linear coefficients X_1 and X_2 are calculated according to: $X_1 = (SW_{Noptmax} - SW_{Noptmin})/DT_{Nmin}$ and $X_2 = (SW_{Noptmax} - SW_{Noptmin})/(DT_{Nmax} - DT_{Nmin})^2$. We found the following values for *V. odoratissimum*: $DT_{Nmin} = 80$ d, $DT_{Nmax} = 420$ d, $SW_{Noptmin} = 0.857\,mmol\,g^{-1}$, and $SW_{Noptmax} = 1.607\,mmol\,g^{-1}$. Optimal root N concentration (RW_{Nopt}) is assumed to be $0.143\,mmol\,g^{-1}$ less than $SW_{Noptmin}$.

Relative shoot N status (*RSN*) is calculated daily to provide a measure of N sufficiency: $RSN = (SW_{Nact} - SW_{Nmin})/(SW_{Nopt} - SW_{Nmin})$. Experimental data from N-deficient *V. odoratissium* indicated that the minimum shoot N concentration (SW_{Nmin}) is $0.429\,mmol\,g^{-1}$. A N sufficiency factor (*SFn*) used to reduce growth if N is limiting is related exponentially to the *RSN*: $\min(1, SFn = 2.441 \times RSN^4)$. The fitted coefficients were obtained by trial-and-error using data from unpublished N fertilizer experiments. Optimum growth is assumed to occur for *RSN* values > 0.8.

2.4.3. Drainage N

When drainage occurs, container water content is near saturation (*Wsa*; cm^3). The maximum N concentration of drainage water (D_{Nmax}; $mol\,cm^{-3}$) is: $D_{Nmax} = Ns/(Wsa - Wll)$. We use drain pore volume (*DPV*) to estimate the dilution effect of substrate drainage volume (*Ds*) on average N concentration of drainage water (D_N: $mol\,cm^{-3}$): $D_N = D_{Nmax} \times 0.5e^{-3.5DPV}$, where $DPV = Ds/(Wsa - Wll)$. The N content of drainage water (mol) is: $Nd = Ds \times D_N$. Runoff N is the sum of drainage N plus any N in un-intercepted irrigation and precipitation.

2.5. Model testing

2.5.1. General methods

Various trials with plants growing under conditions similar to those used by industry producers were conducted at the University of Florida in Gainesville (29°38′26″N and 82°21′30″W) to develop and test model functions (Table 2). An on-site weather station (Vantage Pro Plus® 6162; Davis Instruments Co., Hayward, Calif.) measured daily minimum and maximum air temperatures (°C), solar radiation ($MJ\,m^{-2}$), and rainfall (mm). Data from the Florida Automated Weather Network's (Lusher et al., 2009; http://fawn.ifas.ufl.edu/) Alachua weather station was used to fill voids in weather data. We evaluated CCROP for particular management practices used in a given trial and compared model outcomes with observations made in the trials. Because observed values were typically a mean of a number of individual observations, a measure of variability is given by providing the standard deviation (SD) of the measured value. Comparisons of model versus observed responses were made in terms of SD as well as the percent difference of simulated value relative to the observed value.

2.5.2. Common management inputs for all trials

Several management practices were common to all trials. The growing substrate was a mixture (by volume) of 2 sphagnum peatmoss: 1 aged pine bark:1 coarse builder's sand amended with $4.1\,kg\,m^{-3}$ of dolomitic limestone and $0.6\,kg\,m^{-3}$ of a complete micronutrient blend (Micromax; Scotts Co., Marysville, Ohio). *Wdul* and *Wll* of the substrate were 0.5 and 0.25 $cm^3\,cm^{-3}$, respectively. Two sizes of black, polyethylene, blow-molded containers were used: 2.8 L (trade #1; Elite 300, ITML Horticultural Products, Brantford, Ont., Canada) with a top diameter of 16 cm and a substrate fill volume of 2.4 L and 11.4 L (trade #3; Classic 1200, Nursery Supply Inc., Chambersburg, PA) with a top diameter of 28 cm and substrate fill volume of 10 L. The substrate was amended with a resin-coated, 18N–2.6P–10K controlled-release fertilizer (Osmocote Classic 18–6–12, 8–9 month release time at 21 °C, Scotts Co., Marysville, Ohio), containing 15% coated, slow-release N.

Shoot cuttings of *V. odoratissimum* rooted in 180 mL containers in a misted greenhouse were used as transplants. Rooted cuttings (also termed liners) typically received one or two applications of a $21.4\,mmol\,L^{-1}$ N fertilizer (Peters Peat Lite 20N–4.4P–16.7K; Scotts Co., Marysville, SC) solution to stimulate growth when first leaves emerged. Liners were typically placed outside for a few days to acclimate to ambient conditions prior to transplanting.

The experimental site consisted of 6.1×6.1 m zones each irrigated with four overhead sprinklers operating at a regulated pressure of 270 kPa and at a height of 150 cm. Sprinklers were adjusted to deliver water uniformly at $1.8\,cm\,h^{-1}$. The surface of the site was covered with industry standard, black, woven polypropylene groundcloth underlain with angular gravel. Unless otherwise specified, irrigation was applied predawn at $1\,cm\,d^{-1}$. Irrigation water contained no appreciable N.

Once transplanted, plants grown in 2.8 L containers were placed in irrigation zones in a square arrangement at a density of 32 per m^2. Containers were later spaced to 16 per m^2 at a time when plant leaves began to overlap neighboring plants. For plants grown in 11.4 L containers, initial container density was 12 per m^2 and 4 per m^2 after spacing. Planting and finishing dates for all trials are given in Table 2.

Parameters typically measured include plant height, plant width, and shoot and root biomass. Leaf area was determined for all trials except Trials A–C. Leaf area of excised leaves was measured with a leaf area meter (L3000A; LI-COR, Lincoln, NE).

Runoff was measured in four trials (A–D) by placing containers on 0.94 m^2 platforms designed to collect runoff continuously. Actual irrigation was monitored daily by placing two irrigation

Table 2
Trials used to develop and test CCROP. Observed and model-simulated shoot weight and leaf area are given for one treatment common to all trials: non-water-limiting fixed irrigation rate and a medium fertilizer rate of 193 mmol N per 2.8 L container (1207 g N per 11.4 L container).

Trial[d]	Ref.[c]	Plant date	Crop time		Shoot weight (g/plant)		Leaf area (cm^2/plant)	
			Days	DT[b]	Obs. (SD, N)[a]	Model (% diff)	Obs. (SD, N)	Model (% diff)
A	2007a	29 August 2003	140	95	24 (2, 60)	23 (−4)	ND	1710
B	2007b	25 March 2004	140	121	42 (2, 60)	45 (+7)	ND	3070
C	2010a	26 August 2004	119	110	29 (1, 60)	31 (+7)	ND	2270
D	2010b	12 March 2005	119	105	37 (5, 60)	36 (−3)	3140 (570, 16)	2530 (−19)
E	UP	12August 2005	203	119	30 (14, 7)	37 (+23)	2000 (410, 7)	2340 (+17)
F	UP	20 July 2006	202	136	41 (19, 8)	47 (+12)	2090 (570, 8)	3080 (+47)
G	UP	21 February 2007	121	113	53 (7, 30)	35 (−44)	3030 (340, 10)	2580 (−15)
H	2010a	7 November 2007	147	100	22 (3, 10)	20 (−9)	1820 (210, 10)	1420 (−22)
I	2009	4 April 2008	153	135	62 (12, 8)	63 (+2)	4530 (920, 8)	4760 (+5)
J	2011	9 April 2008	225	198	277 (58, 8)	288 (+4)	17,950 (4100, 8)	17,190 (−4)
K	2010a	2 April 2008	224	202	297 (39, 16)	252 (-15)	14,800 (1610, 16)	16,570 (+12)

[a] SD = standard deviation; *N* = no. of observations; ND = not determined.
[b] DT = development time, the relative number of days under optimal temperature conditions.
[c] Million et al. publications; UP = unpublished.
[d] Plants were grown in 2.8 L containers except Trials J and K for which plants were grown in 11.4 L containers.

gauges at the level of the top of the canopy for each runoff collection platform. Runoff volume was measured on a weekly basis and water samples analyzed for total N (Million et al., 2007b). Runoff and N loss were calculated on a per-container basis by dividing weekly totals by the number of containers on platform during the week of collection.

2.5.3. Trials used for model testing

Trial A evaluated the effect of container spacing on plant growth and runoff. Half of all containers were initially spaced at 32 per m^2 (approximately container-to-container in a square pattern) then spaced to 16 per m^2 (equivalent to removing every other container) 14 wk after planting. The other half was spaced at 16 containers per m^2 for the entire 20-wk trial.

Trial B evaluated the interactive effects of fertilizer and irrigation rates on plant growth and runoff. Treatments were a 2×2 factorial arrangement of two irrigation rates (1 or 2 cm d^{-1}) and two fertilizer rates (193 or 386 mmol N/container). Plants were spaced 13 wk after planting and were grown for 20 wk.

Trials C and D evaluated the effect of an ET-based schedule on plant growth and runoff. Treatments were a 2×2 factorial arrangement of two irrigation schedules and two fertilizer rates. Irrigation water was applied based on either a fixed irrigation rate of 1 cm d^{-1} or a variable rate proportional to the substrate water deficit (*SWD*) in containers. Substrate water deficit was determined by weighing eight containers at the end of the day. An estimate of daily ET was made by subtracting the container weight at the end of the day from the container weight measured after irrigation. The actual amount of irrigation water applied was adjusted by *CF* measured every 3 wk ($n = 16$). In Trial C, irrigation water was applied daily regardless of SWD; in Trial D, irrigation water was applied once SWD exceeded a threshold value of 1 cm per container (200 cm^3), equivalent to a managed-allowable deficit (MAD) of 30% (Welsh and Zajicek, 1993). Fertilizer rates evaluated were 193 and 386 mmol N/container for Trial C and 96 and 193 mmol N/container for Trial D. The 30% MAD irrigation schedule and a low fertilizer rate (96 mmol g N/container) were imposed in Trial D to test marginal levels of these two factors.

Trials E and F were conducted to evaluate growth and N uptake response to fertilizer rate. Fertilizer rates were 0, 48, 96, 193 and 386 mmol N/container for Trial E and 0, 96, 193, 289, 386, and 482 mmol N/container for Trial F. Four destructive harvests ($n = 7$ Trial E; $n = 8$ Trial F) were made at 6 wk intervals for shoot and root biomass, root and shoot N and leaf area. In Trial E container spacing was 32 containers per m^2 throughout the trial while in Trial F containers were initially spaced at 32 per m^2 then spaced at 16 containers per m^2 17 wk after planting.

Trial G evaluated the effect of two irrigation schedules on plant growth and runoff: fixed rate of 1 cm d^{-1} or a variable-rate as indicated by CCROP. In this trial *SWD* and *CF* were estimated by CCROP whereas in Trial D, SWD and *CF* were based on field measurements. Runoff was collected as in Trials A–D; however, due to errors in N analyses, N loss data are not available. Plants were fertilized with 257 mmol N/container and were spaced 10 wk after planting.

Trial H was included for additional plant growth data. Rooted cutting liners were planted in 2.8 L containers to produce transplants for Trial K. Fertilizer was applied at 193 mmol N/container.

Trials I and J evaluated the effect of pruning on subsequent plant growth. For Trial I, plants grown in 2.8 L containers were either pruned once 9 wk after planting or were left un-pruned. Pruning involved a horizontal cut to reduce plant height from 29 to 22 cm removing an average of 1–2 nodes on the main stems. Containers were spaced at 12 wk from 34 to 14 containers per m^2. Destructive harvests were made 6, 9, 17 and 21 wk after planting. Fertilizer rate was 243 mmol N/container. For Trial J, plants grown in 11.4 L containers were either pruned three times or left un-pruned. Plants were pruned three times by reducing height from 24 to 21 cm 9 wk after planting, from 38 to 37 cm 15 wk after planting, and 59 to 55 cm 23 wk after planting. Destructive harvests were made at each pruning and at the end of the 32-wk trial. Fertilizer rate was 1207 mmol N/container.

Trial K compared rooted cuttings versus 2.8 L grown plants (Trial H) as transplants for producing plants in 11.4 L containers. Fertilizer was incorporated at 1207 mmol N/container. Destructive harvests were made at 9, 12, 22 and 32 (rooted cutting treatment only) wk after planting. Plants grown from rooted cuttings were pruned three times (week 9, 16, and 22) while plants grown from 2.8 L transplants were pruned only once (week 12).

3. Results

3.1. Plant growth

The ability to simulate biomass accumulation is important for simulating plant nutrient uptake. Final shoot weight measurements for 11 trials along with model values are given in Table 2. For this evaluation we selected one treatment common to all trials with irrigation and fertilization: a fixed rate of irrigation (1 cm d^{-1}) and a medium-rate of fertilizer (193 mmol N/container). Model shoot weight values were within 1 SD of observed for 7 of 11 trials and within 2 SD for 10 of 11 trials. Model values were within 10% of measured values for 7 of 11 trials and within 23% of measured

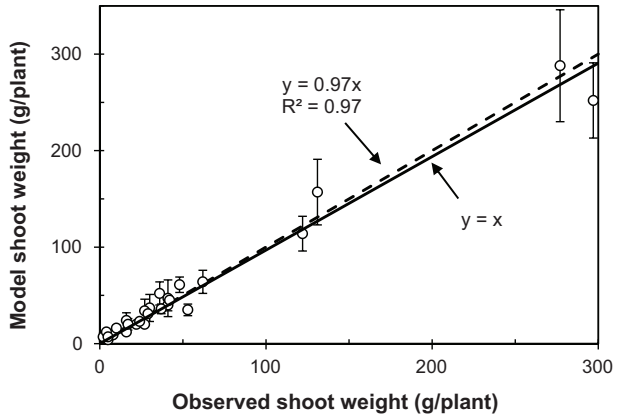

Fig. 5. Model versus observed shoot weight means for 11 trials with *V. odoratissimum*.

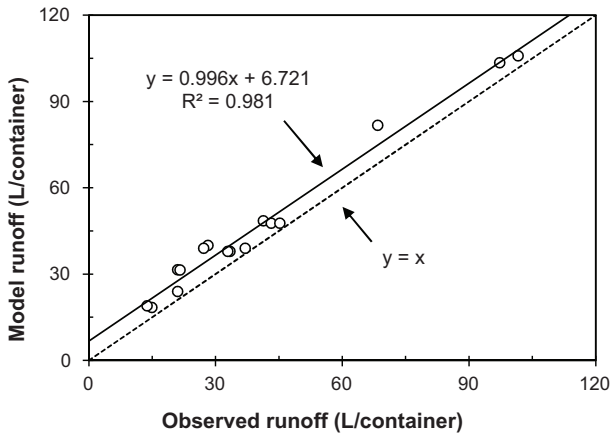

Fig. 7. Model versus observed runoff means for four trials with *V. odoratissimum*.

values for 10 of 11 trials. There was no clear bias in model outcomes (Fig. 5).

The ability to simulate differences in growth for different planting times (i.e. seasonal weather effects) is important. Crop days for each of the 11 trials are given in Table 2 along with cumulative development time. Average *DT* for four fall-planted trials (A, C, E and H) was 106 d while actual cropping time averaged 152 d. Lower *DT* values for fall-planted trials were a result of a higher frequency of suboptimal temperatures particularly towards the end of the trials. In contrast, the difference between actual crop days and DT was much less for spring-planted crops grown under more favorable temperatures in late spring and early summer. Lower DT is indicative of lower shoot weights for fall compared to spring-planted crops.

Simulating leaf area growth is important as leaf area directly affects rates of photosynthesis and ET. Leaf area is also used to estimate plant size, finish time and canopy capture of irrigation water and rain. Except for Trial F, CCROP did a reasonable job of simulating measured leaf area for the eight trials with LA measurements on finished plants (Table 2). Model estimates were within 1 SD of observed for 3 of 8 trials and within 2 SD for all eight. Model LA for Trial F was 47% greater than measured, indicating the model did a relatively poor job for this fertilizer rate trial. When model outcomes were plotted against observed values, no bias was observed (Fig. 6).

3.2. Runoff and N loss

Model runoff and N loss outcomes are compared with measured values in Table 3. Model runoff was within 1 SD for 9 of 16 treatment means and within 2 SD for 11 of 16 means in the five runoff trials. For the common treatment of 1 cm d^{-1} and 193 mmol N/container (257 mmol N/container Trial G), model runoff was 20, 12, 15, and 44 and 5% greater than measured for Trials A–D and G, respectively. The bias of the model in overestimating observed runoff is depicted in Fig. 7. The bias is likely due in part to a fraction of runoff being retained by and evaporating from the production surface instead of flowing into collectors. The woven, polypropylene groundcloth at a moderate slope of 1–3% and underlain by impervious plastic can retain 1.2 L m^{-2} of water if initially dry (unpublished data). If model runoff is decreased to account for 0.8 L m^{-2} d^{-1} water absorption by the runoff platforms, model runoff values would be 7, −2, 0, 30 and −4% greater than observed for the respective treatments described above. Model N loss was within 1 SD for 6 of 14 measured treatment means and within 2 SD for 10 of 14 treatment means. There was no consistent bias across all experimental treatments (Fig. 8).

The ability to simulate the relative effects of irrigation and N management practices on runoff and N loss is important for decisions regarding BMPs. For Trial A, a 66% increase (82 versus 49 L/container) in model runoff when containers were spaced at planting instead of later in the season agreed well with observed 67% increase (68 versus 41 L/container). The model was not as accurate in simulating the observed 35% increase (35.7 versus

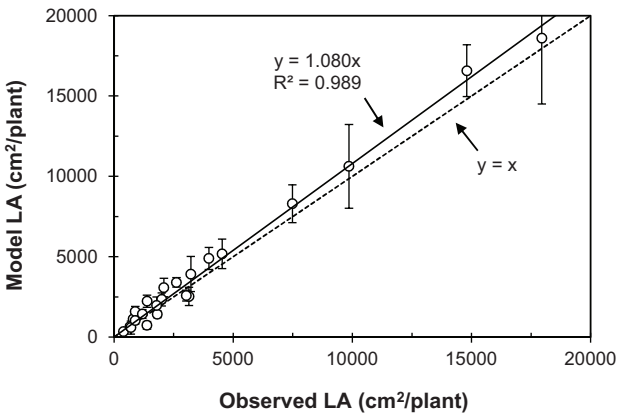

Fig. 6. Model versus observed leaf area (*LA*) means for eight trials with *V. odoratissimum*.

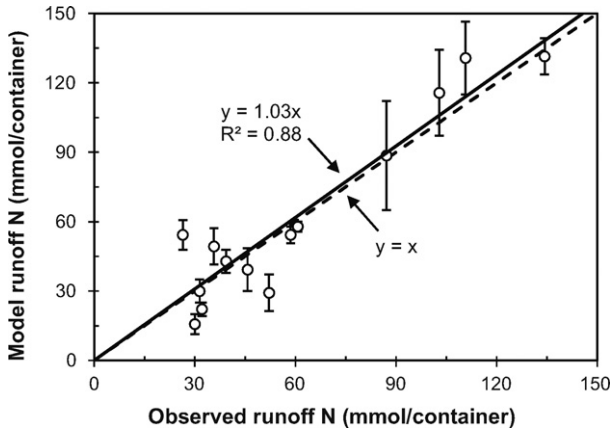

Fig. 8. Model versus observed N loss means for four runoff trials with *V. odoratissimum*.

Table 3
Observed versus model cumulative runoff (drainage plus un-intercepted rain and irrigation water) and plant shoot growth for four runoff trials with *V. odoratissimum* in 2.8 L containers. Irrigation applied as a fixed amount or an amount proportional to ET as determined by weighing.

Trial	Irrigation	N applied (mmol/container) [a]	Runoff (L/container)		Runoff N (mmol/container)		Shoot weight (g/plant)	
			Obs. (SD)[b]	Model (% diff)	Obs. (SD)	Model (% diff)	Obs (SD)	Model (% diff)
A	1 cm d^{-1} [c]	193	68 (5)	82 (+21)	35.7 (7.9)	49.3 (+38)	17 (2)	20 (+18)
	1 cm d^{-1} [d]	193	41 (5)	49 (+20)	26.4 (6.4)	54.3 (+105)	24 (2)	23 (−4)
B	1 cm d^{-1} [a]	193	43 (6)	48 (+12)	45.7 (9.3)	39.3 (−14)	42 (2)	46 (+10)
	1 cm d^{-1}	386	45 (4)	48 (+7)	110.7 (15.7)	130.7 (+18)	54 (1)	55 (+2)
	2 cm d^{-1}	193	102 (6)	106 (+4)	60.7 (2.1)	57.9 (−5)	38 (2)	36 (−5)
	2 cm d^{-1}	386	97 (10)	104 (+7)	134.3 (7.9)	131.4 (−2)	52 (2)	55 (+6)
C	1 cm d^{-1}	193	33 (5)	38 (+15)	39.3 (5.0)	42.9 (+9)	29 (1)	31 (+8)
	1 cm d^{-1}	386	33 (5)	38 (+15)	102.9 (18.6)	115.7 (+13)	32 (3)	35 (+9)
	ET	193	15 (4)	18 (+20)	31.4 (5.0)	30.0 (−5)	31 (1)	35 (+10)
	ET	386	14 (5)	19 (+36)	87.1 (23.6)	88.6 (+2)	33 (3)	35 (+6)
D	1 cm d^{-1}	129	28 (2)	40 (+43)	32.1 (2.9)	22.1 (−31)	36 (3)	22 (−39)
	1 cm d^{-1}	193	27 (2)	39 (+44)	58.6 (3.6)	54.3 (−7)	37 (5)	36 (−3)
	ET	129	21 (2)	32 (+48)	30.0 (4.3)	15.7 (−48)	33 (4)	26 (−21)
	ET	193	22 (3)	31 (+36)	52.1 (7.9)	29.3 (−44)	38 (2)	34 (−11)
G	1 cm d^{-1}	257	37 (4)	39 (+5)	ND	ND	53 (7)	35 (−34)
	ET	257	21 (2)	24 (+14)	ND	ND	46 (6)	27 (−31)

Total N = NO_3–N + total Kjehldahl N (minus NO_3–N).
[a] N applied as resin-coated, controlled-release 18N–2.6P–10K fertilizer (8–9 month release @21 °C).
[b] SD = standard deviation of 4 (runoff and runoff N) or 60 (shoot weight) observations; ND = not determined.
[c] container density was 16 per m^2 throughout the trial.
[d] container density was 32 per m^2 for first 14 wk then 16 per m^2 until end of trial (week 20).

26.4 mmol/container) in N loss when containers were spaced at planting; the model simulated a 10% decrease (49.3 versus 54.3 mmol/container). The primary reason for underestimating the increase in N loss was that the model underestimated the observed negative effect that spacing containers at planting had on biomass growth and N uptake. For Trial B, model results agreed well with the observed response that N loss more than doubled when the fertilizer rate doubled for each of two irrigation rates. For Trial C, ET-based irrigation when averaged over both rates for fertilizer reduced model runoff 51% (19 versus 38 L/container) compared to a fixed irrigation schedule, agreeing well with the observed reduction of 56% (15 versus 33 L/container). Similarly, model N loss was decreased 25% (59.3 versus 79.3 mmol/container) while actual N loss was decreased 17% (59.3 versus 71.1 mmol/container). In Trial D, ET-based irrigation averaged over both fertilizer rates reduced model runoff 20% (32 versus 40 L/container) while observed runoff was reduced 22% (22 versus 28 L/container). Similarly, model N loss was decreased 40% (22.6 versus 38.2 mmol/container) while observed N loss was decreased only 10% (41.1 versus 45.4 mmol/container). In Trial G, ET-based irrigation decreased model runoff 38% (24 versus 39 L/container) compared to a fixed irrigation schedule, agreeing well with the observed of 43% (21 versus 37 L/container).

3.3. Fertilizer response and N uptake

Measured and model growth and N uptake responses to N for multiple destructive harvests during Trial F are given in Fig. 9. For the high 5.4 g N/container fertilizer rate, model final shoot weight of 55 g/plant agreed well with the measured shoot weight of 51 g/plant. Model decreases in shoot weight were 10% (47 versus 55 g/plant) and 49% (27 versus 55 g/plant) when the 5.4 g N/container rate was decreased to 2.7 and 1.35 g N/container, respectively, agreeing well with measured decreases of 20% (41 versus 51 g/plant) and 54% (23 versus 51 g/plant), respectively. Model shoot N concentrations agreed fairly well with measured values. For the first harvest 11 wk after planting, model shoot N concentrations were generally higher than observed. Shoot growth at this point was minimal so that overestimation at this stage was not likely causing a significant overestimation of total N uptake. For the remaining harvests model N concentrations agreed well with measured values although simulated values were slightly higher than measured for the final harvest. Model values for shoot N content agreed well with measured values although for the 96 and 193 mmol N/container rates this was likely a consequence of slightly overestimating shoot weight and slightly underestimating shoot N concentration.

Similar N response results were observed for Trial E except that observed maximum N concentrations for the 386 mmol N/container rate were higher than in Trial F (2.0 versus 1.6 mmol g^{-1}). Model shoot N content was 24.3, 49.3, and 57.1 mmol/plant for the 96, 193, and 386 mmol N/container fertilizer rates, respectively, while respective measured values were 20.7, 30.7, and 51.4 mmol N/plant. Model overestimation of shoot N content for the 193 mmol N/container rate was primarily due to an overestimation of shoot weight (37 versus 30 g/plant) for this N rate.

In Trials B–D, two rates of fertilizer were compared under different irrigation treatments (Table 3). In Trial B, when the fertilizer rate was decreased from 386 to 193 mmol N/plant, model shoot weight was reduced 16% and 35% for the low and high fixed irrigation rates, respectively; respective observed decreases were 23% and 27%. When the fertilizer rate was decreased from 386 to 193 mmol N/plant in Trial C, model shoot weight was reduced 0% and 11% for the fixed and ET-based irrigation treatments, respectively; respective observed decreases were 6% and 10%. When the fertilizer rate was decreased from 193 to 96 mmol N/container in Trial D, model shoot weight was decreased 24% for the ET irrigation treatment and 39% for the fixed irrigation treatment while observed decreases were only 13% and 3%, respectively.

3.4. Pruning

Trials I and J evaluated the effects of pruning on plant growth (Fig. 10). In Trial I, plants grown in 2.8 L containers and pruned 9 wk after planting were compared to un-pruned plants. Pruning reduced plant height from 29 to 22 cm and *LA* from 720 to 450 cm^2. By the end of the trial (week 21), measured *LA* was 3330 and 4530 cm^2/plant, respectively, for pruned and un-pruned plants. CCROP-simulated final *LA* values were 4270 and 4760 cm^2/plant for pruned and un-pruned plants, respectively. Divergence of model *LA* from observed *LA* occurred during the latter stages of growth when

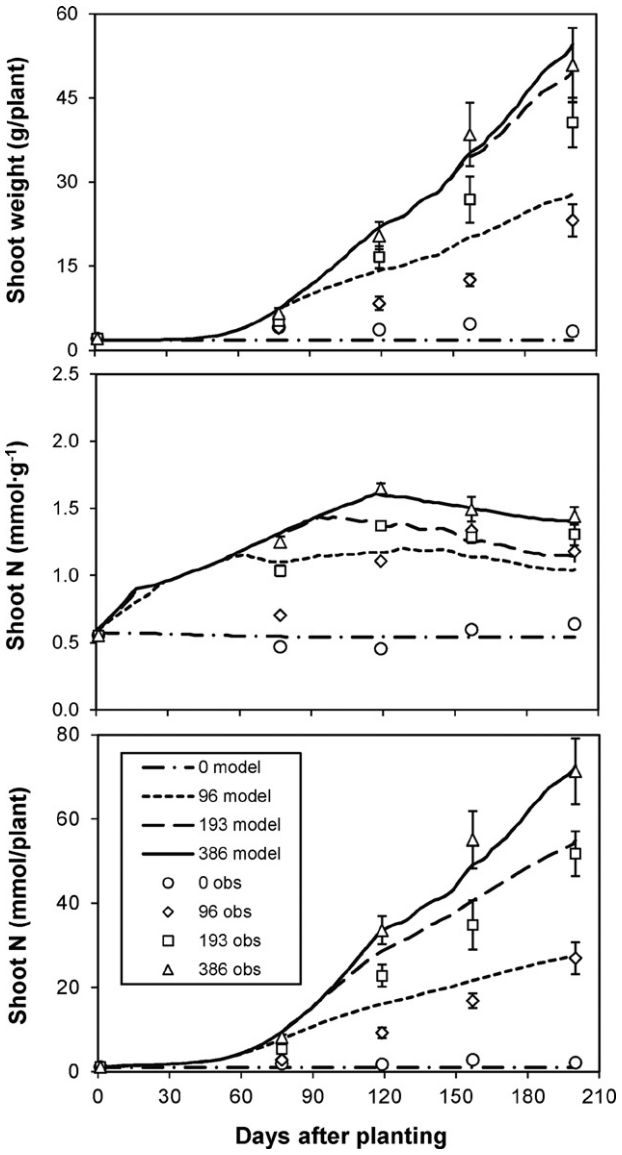

Fig. 9. Model versus observed response of *V. odoratissimum* to controlled-release fertilizer applied at 0, 96, 193, or 386 mmol N/container. Measured values represent the average of eight plants harvested four times during Trial F. Error bars represent 1 SE above and below the mean observed value.

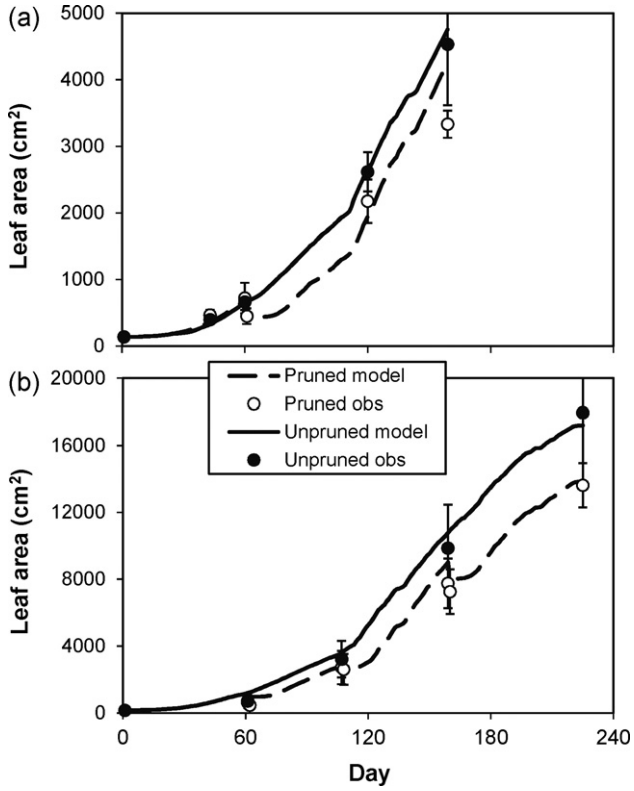

Fig. 10. Model versus observed leaf area response of *V. odoratissimum* grown in 2.8 L (a) and 11.4 L (b) containers to pruning. Means represent the average leaf area per plant of eight plants harvested at four intervals during the Trials I and J. Error bars represent 1 SE above and below observed means.

plants were grown past marketable size. In Trial J, simulated *LA* growth agreed well with measured *LA* growth for both pruned and un-pruned *V. odoratissimum* grown in 11.4 L containers.

4. Discussion

CCROP was developed to simulate how water, N, and plant growth processes are integrated in a container production system. Our primary goal was to accurately simulate plant growth. This is because an accurate simulation of biomass and leaf area growth is required to accurately simulate water and N processes. In this regard, we believe the model was shown to simulate biomass and leaf area growth reasonably well under a range of experimental conditions. One challenge we faced was simulating the onset of rapid growth following transplantation. Transplant quality can greatly affect the time for transplants to begin rapid growth. For example, a young, well-fertilized transplant may begin rapid growth sooner than an older transplant that has been held back without fertilizer. To account for variability in liner quality and other factors that might affect transplant vigor in real-time situations, the user can adjust or "calibrate" model plant size with field measurements. In order to better evaluate CCROP during model testing we did not make plant size adjustments based on observed size data.

One of the main reasons for developing CCROP was to simulate irrigation requirement and runoff. Accurate simulation of the water balance during production requires an accurate simulation of container ET. Model ET agreed well with measured ET monitored throughout the growing season for Trials C, D, and G (Fig. 11). It should be mentioned at this point how the ET functions used in CCROP differ from other ET models which use a crop coefficient

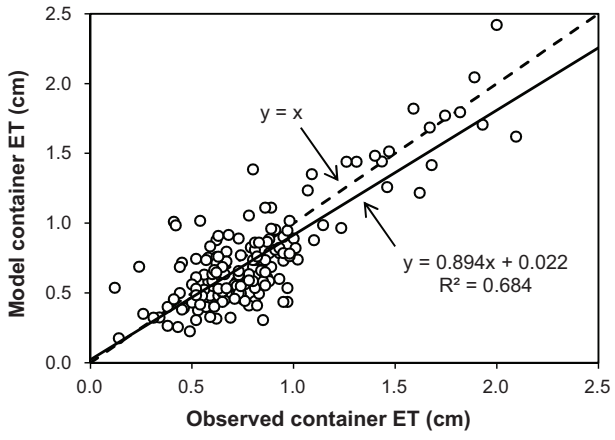

Fig. 11. Model versus observed evapotranspiration (ET) during Trial C, D, and G. ET was determined by weighing eight containers after irrigation and again at the end of the day.

(*Kc*) to estimate actual ET (*ETa*): $ETa = Kc \times ETo$. *Kc* values have been difficult to establish and use in container production because of the wide range of container size and container spacing used in nurseries. Partial cover exists for a significant time during production, especially with wide spacing, creating different environmental conditions for ET. Beeson (2010) used percent canopy closure to define a water needs index based on the projected canopy area of the plant. Beeson's percent canopy closure model uses an easily measurable quantity (plant width) to indirectly estimate the leaf area index effect on *ETa*. Pardossi et al. (2008) used plant height to model the effect of *LAI* on *ETa*, however, their equations are specific to the experimental conditions for that particular study. Schuch and Burger (1997) reported *Kc* values measured at various stages of growth but do not relate those values directly to plant size or *LAI*. Unlike these ET models, CCROP accounts for increased canopy temperatures when containers are spaced with incomplete plant cover as well as accounts for decreased ET when available water levels might be insufficient to meet transpiration demands. By considering these factors, CCROP can help overcome some of the reasons why the relationship between plant size and *Kc* can vary from one season to another even with the same production practices (Irmak, 2005).

We tested CCROP's ability to schedule irrigation in Trial G. For this trial, an earlier version of CCROP was used to determine daily irrigation amounts to apply based upon simulated water deficits in the container and *CF*. Very little runoff observed during a rapid growth phase in that trial (data not shown) along with reduced growth indicated we were underestimating ET for the ET irrigation treatment (Table 3). After modifying ET functions to account for greater observed ET during partial cover, model outcomes using the current version of the model more accurately simulated the observed water stress effect on growth in Trial G. Water stress resulting in reduced growth was also simulated in Trial D but unlike Trial G measured growth was not affected. This suggests that additional testing with marginal irrigation rates is needed to test and modify water stress functions. Regardless, the observed savings in irrigation water applied in Trial G with CCROP-based irrigation were accurately simulated by the current version of CCROP supporting our contention that CCROP can aid in real-time irrigation scheduling to minimize water use. Similarly, model outcomes for Trials C and D projected the considerable savings in water that were observed when irrigation was based upon measured substrate water deficit and the plant's irrigation capture factor.

Accurate simulation of runoff and associated N loss is important for evaluating effects of management practices on water and nutrient use efficiencies in the nursery. Model runoff outcomes for the five runoff trials (A–D and G) indicated that the model did a reasonable job of simulating the observed effects that irrigation, fertilizer and spacing treatments had on runoff and runoff N. Because the simulation of runoff and N loss integrates a wide range of related processes including N release from CRF, N uptake, drainage volume and drainage N concentration, which were not monitored, we cannot be confident that these individual processes were accurately simulated. Of these processes we believe the simulation of N release from CRF and plant N uptake to be relatively conservative functions compared to simulation of drainage. In this regard, irrigation capture factor has a considerable effect on drainage volume and thus drainage N concentration and N loss indicating that this factor deserves greater research attention than it has received. Even though model *CF* in Trial C and D agreed with *CF* values measured periodically during the two trials (data not shown), the high sensitivity of drainage to *CF* likely contributed to some of the differences described between model and observed runoff and N loss in runoff trials. Another source of variation in model testing that is difficult to account for is the timing of rainfall. CCROP integrates water balance functions on a daily basis whereas a given rainfall event may occur at different times of the day. For example, in our location summer rainfall occurs primarily in the afternoon due to convective storms so that this rainfall may effectively replace water lost through ET earlier in the day. The timing of rainfall at other times of the year tends to be more random and associated with frontal storms. CCROP does not account for these seasonal differences but the user can input a rain efficiency factor which can be used to evaluate how the timing of rainfall can affect the substrate water balance.

A constraint for evaluating model N loss outcomes is that N is a non-conservative element being susceptible to volatilization and other losses which can lead to low N recovery rates in N balance experiments (Cabrera, 2003; Ristvey et al., 2001). We are currently developing functions for phosphorus, a more conservative element in runoff studies. Drainage/runoff is difficult to collect continuously in field environments so that very little runoff information is available to develop and test model functions. Considering these constraints, we feel that current CCROP functions are sufficiently robust for the model to serve as a decision-making tool for typical container nursery production.

Growth response to marginal N fertilizer rates was tested in Trials D–F. When a high fertilizer N rate was used so that N supply was clearly not limiting, the model accurately simulated observed growth and N demand for trials E and F. When marginal fertilizer rates (<193 mmol N/container) were applied, model growth was reduced in all three trials, although in Trial D model growth reduction of 31% was much greater than the observed 8% reduction for the 129 mmol N/container rate. The ability to determine N response at marginally sufficient N rates is important for selecting N rates which minimize N inputs without reducing growth. For marginal N rates, a reduction in shoot N concentration may reduce plant quality (e.g., lighter green foliage) before it reduces plant growth. CCROP does not specifically assign quality based upon shoot N concentration but a comparison between model shoot N concentration and model optimum shoot concentration may indicate when quality may be reduced when growth is not.

Pruning is a difficult practice to simulate as growers differ greatly in the frequency and severity of their pruning schedules. In Trials I and J we followed minimal pruning practices pruning once for plants in 2.8 L containers and up to three times for plants grown in 11.4 L containers. Many growers refrain from pruning or prune lightly when sales are expected to be strong as little or no pruning results in fastest growth and shortest time to market. On the other hand growers are likely to prune more frequently or more severely to hold back plant growth when sales are expected to be slow. CCROP pruning functions address the observed delay in growth that occurs during the first pruning event designed to promote lateral branching from main stems. CCROP accurately simulated the observed effect that this pruning practice had on subsequent growth in Trials I and J. We do not have data to test whether pruning functions accurately simulate growth response to severe pruning that might be conducted to hold back growth. While model outcomes indicate an un-pruned plant will grow faster and finish earlier than a pruned plant, the model does not address the fact that the quality of an un-pruned plant may downgrade its marketability.

5. Conclusions

A simulation model can help growers and grower-advisers evaluate the impact that critical management practices have on plant growth and the efficient use of water and fertilizer in container nurseries. Unlike most models in the container industry which focus on a particular process such as ET, CCROP integrates a wide range of processes providing a unique opportunity for users to evaluate how plant growth, water and nutrient use might all be affected by management practices at a given container nursery.

Model testing showed that in most cases the model reasonably simulated treatment effects in a series of growth, runoff and pruning experiments. CCROP was also shown to reasonably simulate differences in growth and ET observed for crops planted at different times of the year. While there was no clear bias between model and measured outcomes for leaf area, biomass, and N loss, model runoff (L/container) was greater than measured in all cases. We attributed this bias in part to the retention and evaporation of runoff water moving away from containers into the runoff collector.

Several aspects of the model need further development and testing. Phosphorus is a nutrient with environmental implications (Gaiser et al., 2005) and P balance functions are needed. We also lack sufficient experimental data to adequately test water stress functions. Accurate simulation of water stress will be important as growers implement conservative irrigation practices such as deficit irrigation (Cameron et al., 2004) to maximize the opportunity to replace irrigation water with precipitation. Another weakness of the current model is that growth is limited during winter using temperature-dependent, sink-limited growth functions. CCROP does not address physiological dormancy induced with cool temperatures and broken with warm temperatures (Arora et al., 2003) so that growth can be erroneously simulated when short durations of warm temperatures occur during prolonged cold temperatures. We expect future versions of CCROP to simulate dormancy and P balance.

Model functions were developed primarily using observations with *V. odoratissimum*. We assembled the model in a modular format so it could be adapted to other species with growth habits somewhat similar to *V. odoratissimum* by changing certain species-specific coefficients. For example, we are testing growth functions for *Ilex vomitoria*, common name dwarf yaupon a slow-growing ornamental shrub with compact habit, small leaves, and drought tolerance.

A web-based program (http://www.bmptoolbox.org) has been developed to provide a user-friendly means of selecting inputs, executing CCROP, and viewing the output in graphical and tabular form. The corresponding author can be contacted to access this password-protected website. Program source code is also available on the website along with descriptions of input and output files. One set of tools allows users to select different levels of a certain factor (e.g., irrigation rate, fertilizer rate, location, plant date, etc.) and run virtual experiments keeping all other input management factors constant. We plan to add economic information to the biophysical information for improved decision-making capability including evaluations of profitability versus environmental risks (Confesor and Whittaker, 2007) as related to water and fertilizer management.

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