Scientia Horticulturae 130 (2011) 874–886

Contents lists available at SciVerse ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

CCROP—Simulation model for container-grown nursery plant production

J.B. Million[a,*], J.T. Ritchie[b], T.H. Yeager[a], C.A. Larsen[a], C.D. Warner[c], J.P. Albano[d]

[a] Department of Environmental Horticulture, IFAS, University of Florida, Gainesville, FL 32611-0670, USA
[b] Department of Agricultural and Biological Engineering, IFAS, University of Florida, Gainesville, FL, USA
[c] Department of Astronomy, University of Florida, Gainesville, FL, USA
[d] U.S. Horticultural Research Laboratory, USDA-ARS, Ft. Pierce, FL, USA

ARTICLE INFO

Article history:
Received 9 November 2010
Received in revised form 20 July 2011
Accepted 22 August 2011

Keywords:
Decision-support tool
Irrigation
Nitrogen
Ornamental
Runoff

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 $\mathrm{kg\,ha^{-1}\,yr^{-1}}$, respectively, from the moderate fertilizer application rates of 1100 and 150 $\mathrm{kg\,ha^{-1}\,yr^{-1}}$ 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

---

* Corresponding author. Tel.: +1 352 538 1775; fax: +1 352 392 3870.
E-mail addresses: jmillion@ufl.edu (J.B. Million), ritchie@msu.edu (J.T. Ritchie), yeagert@ufl.edu (T.H. Yeager), calarsen@ufl.edu (C.A. Larsen), warner@astro.ufl.edu (C.D. Warner), joseph.albano@ars.usda.gov (J.P. Albano).

0304-4238/\$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.scienta.2011.08.030

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 ($\mathrm{cm}^2_{\mathrm{leaf}}\,\mathrm{cm}^{-2}_{\mathrm{ground}}$). The value of 0.6 °C $\mathrm{MJ}^{-1}\,\mathrm{m}^{-2}$ 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 $\mathrm{m}^{-2}\,\mathrm{d}^{-1}$) 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.