

# CONTAINER CROP MANAGEMENT TOOLS

## CCROP-MT V1.1

(<http://www.bmptoolbox.org>)

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## I. INTRODUCTION

Container Crop Management Tools (CCROP-MT) is a collection of web-based programs which serve as decision-making tools for container nursery management. The foundation of CCROP-MT is the plant growth model CCROP (Container Crop Resource Optimization Program) which simulates the growth and associated water and nutrient relationships of containerized ornamental plants. CCROP-MT serves as a web-based interface that allows the user to select inputs, execute CCROP simulations, and view output. This manual first describes CCROP and the processes it simulates. This is followed by a discussion of CCROP-MT and how it can be used as a decision-making tool.

## II. CCROP – The Model

CCROP (Container Crop Resource Optimization Program) is a plant growth simulation model that was developed using FORTRAN programming language. CCROP consists of a driver program and four subroutines: water, plant, nutrient, and output (Fig. 1). 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, weather and plant files and optionally from irrigation and supplemental solution fertilizer files. Output is written to text (.txt) files which contain either daily output data or summary output data.

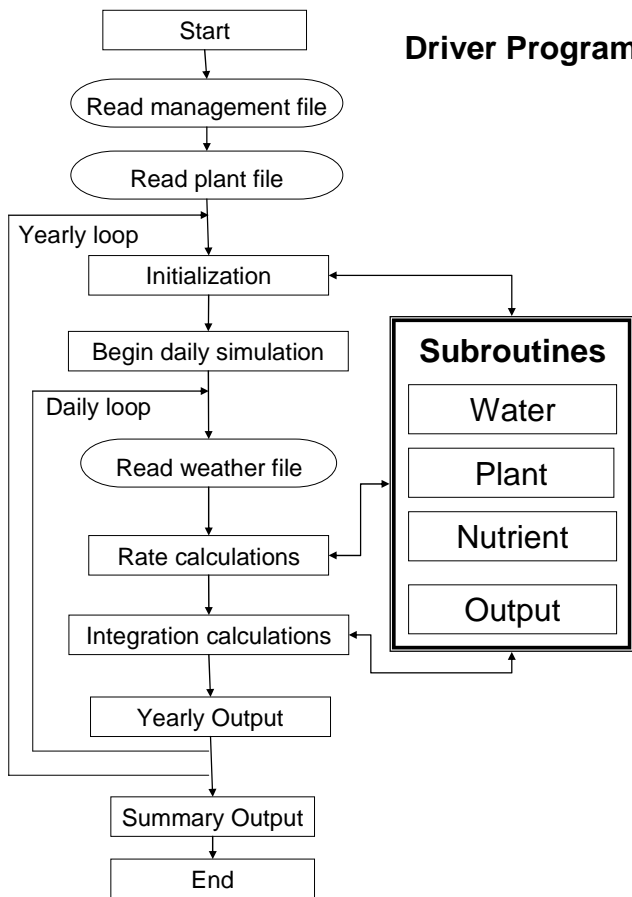


Fig. 1. Information flow in CCROP.

## A. CCROP - Input Files

Input files allow the user to specify conditions under which the simulation will be run. Each input file must be formatted exactly with respect to headers and rows. Format spacing within rows is not important for management and plant input files as long as there is a space between parameter values; however, format spacing within rows is critical for weather, irrigation and solution fertilizer input files. See appendix for examples of all input files (\* = run number).

### 1. Management file (\*\_P\_SPEC.txt)

The user specifies cultural practices in the management file. Parameters include dates for planting, moving, irrigation, supplemental fertilizer applications, pruning, and finishing. In cases where scheduling of practices is not based on fixed dates, options for scheduling are provided by selecting criteria which trigger a schedule change. For example, containers can be moved when a critical leaf area index is reached, irrigation can be scheduled based upon the managed allowable deficit concept and crops can be finished when a marketable size is reached.

A list of input variables in the management file are given in Table 1 and described below [*VARIABLE (type of variable)*].

*Integer* = non-decimal values  
*Real* = decimal values  
*Character* = letter characters (case sensitive)

Note: enter -99 for any variable that is not applicable

#### **\*Planting and move detail**

*PLT\_DOY* (*Integer*)

Plant date in Julian Day - assumed to be Day 1 of simulation

*START\_YR* (*Integer*)

First year to run simulation

*END\_YR* (*Integer*)

Last year to run simulation (simulation may actually end on following year)

*MOVE* (*Character*)

Enter 'FIXED' or 'LAI' to indicate basis for moving containers

FIXED = move containers after fixed number of days after planting

LAI = move containers when critical LAI is reached

*MOVE<sub>x</sub>* (*Integer x=1-3*)

Days after planting for x move. This is only applicable if *MOVE*='FIXED'.

Enter -99 if plants are never moved.

*MOVE\_LAI* (Real)

Threshold leaf area index to trigger container move. This is only applicable if *MOVE*=‘LAI’.

*NOM* (Integer)

Maximum number of moves for triggered move. This is only applicable if *MOVE*=‘LAI’.

### \*Transplant detail

*ILA* (Real)

Initial leaf area of transplant (**cm<sup>2</sup>**)

*IHT* (Real)

Height of transplant from substrate surface to uppermost foliage (**cm**)

*IWD* (Real)

Average canopy width of transplant (**cm**)

*TW\_Nact* (Real)

Nitrogen concentration in shoot (aboveground) tissue (**g N/g shoot**)

*RW\_Nact* (Real)

Nitrogen concentration in root tissue (**g N/g root**)

*TW\_Pact* (Real)

Nitrogen concentration in shoot (aboveground) tissue (**g P/g shoot**)

*RW\_Pact* (Real)

Nitrogen concentration in root tissue (**g P/g root**)

### \*Finish detail

*FINISH* (Character)

Enter ‘FIXED’ or ‘SIZE’ to indicate how to finish the crop

*HARVDAYS* (Integer)

Days after planting to finish crop. Only applicable if *FINISH*=‘FIXED’.

*HARV\_HT* (Real)

Height of plant when crop is finished (**cm**). Only applicable if *FINISH*=‘SIZE’.

### \*Size adjustment check dates

*CHK\_DAYx* (Integer) (x= 1, 2, or 3)

Days after planting for size adjustment.

This is designed to calibrate model with actual field value for real-time simulations.

*CHK\_HTx* (Real) (x= 1, 2, or 3)

On *CHK\_DAYx* plant height is assigned this value (**cm**)

*CHK\_Wx* (Real) (x= 1, 2, or 3)

On *CHK\_DAYx* plant width is assigned this value (**cm**)

### \*Container detail

*S\_VOL* (Real)

Substrate volume in container (**cm<sup>3</sup>**). This is fill volume not container volume.

*POTDIAM* (Real)

Top diameter of container (**cm**)

*PTAO* (Real)

Total production area allotted to each container at planting ( $\text{cm}^2$ ). This value is dependent upon plant spacing.

*PTAx (Real)* ( $x=1, 2, \text{ or } 3$ )

Total area allotted to each container after 1<sup>st</sup>, 2<sup>nd</sup>, and 3<sup>rd</sup> moves ( $\text{cm}^2$ )

### **\*Substrate water specs**

*SWLL (Real)*

Substrate water content at drained upper limit or container capacity. Container capacity condition is obtained by saturating the substrate in the container and allowing gravitational water (water not held by gravity) to drain from the container. Water content determined by oven-drying is reported on a volumetric basis ( $\text{cm}^3 \text{ water/cm}^3 \text{ substrate}$ )

*SWDUL (Real)*

Substrate water content at lower limit or permanent wilting point (-15 bar or -1.5 J/g). This condition can be met using a laboratory apparatus or can be estimated by sampling substrate in the root zone of a wilted plant. Water content determined by oven-drying is reported on a volumetric basis ( $\text{cm}^3 \text{ water/cm}^3 \text{ substrate}$ ).

*TP (Real)*

Total substrate porosity used in the calculation of pour volume for estimating nutrient leaching ( $\text{cm}^3 \text{ pores/cm}^3 \text{ substrate}$ ).

*PVLF (Real)*

Pour volume leaching factor used to describe the effect of drainage volume on drain N concentration (**unitless**).

### **\*Irrigation schedule**

*SCHED (Character)*

Enter 'FIXED' if irrigation scheduling is based on fixed irrigation rates  
Enter 'FILE' if irrigation scheduling is based upon an input irrigation file  
Enter 'MAD' if irrigation schedule is based upon recharging water lost through evapotranspiration and a managed allowable deficit.

*RAINCUT (Character)*

Enter 'NO' or 'YES' to indicate whether a rain cutoff sensor is used for 'FIXED' irrigation. If 'YES', then irrigation is not applied whenever 'yesterday's' rain exceeded 'today's' irrigation amount.

*IRRx (Integer)* ( $x=1, 2, \text{ or } 3$ )

Days after planting to change irrigation rate. Only applicable if SCHED='FIXED'.

*MAD (Real)*

Managed allowable deficit or the percent of available water that must be lost before irrigation is applied (%). Only applicable if SCHED='MAD'.

*MAD\_DIF (Real)*

For MAD irrigation, this is the threshold level to irrigate to when irrigating to less than container capacity. Threshold is a percent of available water (%) and therefore must be between MAD and 0% (container capacity).

*IRR\_NCONC (Real)*

Nitrogen concentration of the irrigation water ( $\text{ug}/\text{cm}^3$ ). See \*Supplemental solution fertilizer for inputting variable concentrations.

*IRR\_PCONC* (Real)

Phosphorus concentration of the irrigation water ( $\text{ug}/\text{cm}^3$ ). See \*Supplemental solution fertilizer for inputting variable concentrations.

### \*Fixed irrigation rates

*D\_IRR0* (Real)

Daily fixed irrigation rate at planting (cm). Only applicable if SCHED='FIXED'.

*D\_IRRx* (Real) (x =1, 2, or 3)

Daily irrigation rate associated with each IRRx (cm). Only applicable if SCHED='FIXED'.

### \*Input files

*WFNAME* (Character) (8 max characters)

Specifies filename of weather input file (weather filenames have .WTH extension).

*PFNAME* (Character) (8 max characters)

Specifies filename of plant input file (plant filenames have .WTH extension).

*IFNAME* (Character) (8 max characters)

Specifies filename of irrigation input file (weather filenames have .WTH extension).  
Only applicable if SCHED = 'FILE'.

*SFFNAME* (Character) (8 max characters)

Specifies filename of solution fertilizer input file (weather filenames have .sfm extension).  
Only applicable if SF = 'FILE'.

### \*Fertilizer detail

*FERT* (Real)

Fertilizer rate ( $\text{g}/\text{container}$ )

*PCT\_CRN* (Real)

Percent controlled-release nitrogen of fertilizer (%). PCT\_CRN should be equal to or less than PCT\_N.

*PCT\_N* (Real)

Percent total nitrogen of fertilizer (%)

*PCT\_P* (Real)

Percent total P of fertilizer (%)

*CRF\_DAYS* (Integer)

Longevity rating of controlled-release nitrogen fertilizer (day). This is based upon the manufacturer's rating which is typically the time it takes for 80-90% of controlled-release N to be released under laboratory conditions at constant temperatures, usually 21-25°C.

*APPL* (Character)

Enter 'INC' if fertilizer is incorporated into the substrate at planting  
Enter 'SURF' if fertilizer is surface-applied at planting

### \*Supplemental topdress fertilizer

*TDF* (Real)

Enter 'FIXED' for a fixed application day.



Enter 'TRIG' to trigger a supplemental fertilizer application when N release from fertilizer falls below a threshold value.

Enter 'NONE' or -99 if no supplemental topdress fertilizer is to be applied.

*TD\_DAYS (Integer)*

Days after planting to apply supplemental topdress fertilizer. Only applicable if TDF='FIXED'.

*TD\_TF (Real)*

Threshold factor to trigger a supplemental topdress fertilizer application. If N release from controlled-release fertilizer falls below this threshold percent (%) of plant N demand then a supplemental topdress fertilizer application is automatically applied. Only applicable if TDF='TRIG'.

*FERT2 (Real)*

Supplemental topdress fertilizer rate (g/container).

*PCT\_CRN2 (Real)*

Percent controlled-release nitrogen of fertilizer (%) in supplemental topdress fertilizer. PCT\_CRN2 should be equal to or less than PCT\_N2.

*PCT\_N2 (Real)*

Percent total nitrogen of supplemental topdress fertilizer (%).

*PCT\_P2 (Real)*

Percent total nitrogen of supplemental topdress fertilizer (%).

*CRF\_DAYS2 (Integer)*

Longevity rating of supplemental topdress controlled-release nitrogen fertilizer (day). This is based upon the manufacturer's rating which is typically the time it takes for 80-90% of controlled-release N to be released under laboratory conditions at constant temperatures, usually 21-25°C.

### **\*Supplemental solution fertilizer detail**

*SF (Character)*

Enter 'FIXED' for a fixed supplemental solution fertilizer application schedule.

Enter 'TRIG' to trigger a supplemental fertilizer application when N release from fertilizer falls below a threshold value.

Enter 'FILE' to input solution fertilizer schedule with a file.

Enter 'NONE' or -99 if no supplemental solution fertilizer is to be applied.

*SF\_START (Integer)*

Days after planting to start solution fertilizer applications. Only applicable if SF='FIXED'.

*SF\_END (Integer)*

Days after planting to end solution fertilizer applications. Only applicable if SF='FIXED'.

*SF\_INT (Integer)*

Interval between solution fertilizer applications (day).

*SF\_TF (Real)*

Threshold factor to trigger solution fertilizer applications. If N release from controlled-release fertilizer falls below this threshold percent (%) of plant N demand, then supplemental solution fertilizer applications are made according to SF\_INT and SF\_NCONC until the crop is finished. Only applicable if SF='TRIG'.

*SF\_NCONC* (Real)

Solution fertilizer nitrogen concentration ( $\text{ug}/\text{cm}^3$ )

*SF\_PCONC* (Real)

Solution fertilizer phosphorus concentration ( $\text{ug}/\text{cm}^3$ )

**\*Pruning detail**

*PRUNE* (Character)

Enter 'FIXED' for a fixed pruning schedule.

Enter 'TRIG' to trigger pruning at designated heights

Enter 'NONE' to not schedule pruning

*PRx* (Integer) (x=1, 2, or 3)

Days after planting for 1<sup>st</sup>, 2<sup>nd</sup>, or 3<sup>rd</sup> pruning (**day**). Only applicable if PRUNE='FIXED'.

*PR\_Hx* (Real) (x=1, 2, or 3)

Height of canopy from substrate after 1<sup>st</sup>, 2<sup>nd</sup>, or 3<sup>rd</sup> pruning (**cm**). Only applicable if PRUNE='FIXED'.

*PR\_Wx* (Real) (x=1, 2, or 3)

Width of canopy after 1<sup>st</sup>, 2<sup>nd</sup>, or 3<sup>rd</sup> pruning (**cm**). Only applicable if PRUNE='FIXED'.

*TPR* (Real) (x=1, 2, or 3)

Plant height to trigger 1<sup>st</sup>, 2<sup>nd</sup>, or 3<sup>rd</sup> pruning (**cm**). Only applicable if PRUNE='TRIG'.

*CUT* (Real)

Reduction in plant height for an automatically triggered pruning (**cm**). Only applicable if PRUNE='TRIG'.

*NOPMAX* (Integer)

Maximum number of prunes. Only applicable if PRUNE='TRIG'.

Table 1. Management file input variables for CCROP. Capitalized words in Units column are text options for the corresponding input variable.

Parameter	Description	Units
PLT_DOY	planting day of year	Julian Day
START_YR, END_YR	first and last years to run simulation	year
MOVE	criterion for moving containers	FIXED or LAI
MOVE1,2,3	days before 1 <sup>st</sup> , 2 <sup>nd</sup> , 3 <sup>rd</sup> moves	days after planting
MOVE_LAI	Leaf area index to trigger move	
NOM	maximum number of moves	
ILA	initial leaf area	cm <sup>2</sup>
IHT, IWD	Initial height and width	cm
IN_STATUS	N status of transplant	OPT, LOW, INPUT
TW_Nact and RW_Nact	N conc. in shoots and roots of transplant	g N/g tissue
TW_Pact and RW_Pact	P conc. in shoots and roots of transplant	g N/g tissue
FINISH	criterion for terminating season	FIXED or SIZE
HARVDAYS	finish after this number of days	days after planting
HARV_HT	finish when this height is reached	cm
S_VOL	volume of substrate in container	cm <sup>3</sup>
POT_DIAM	top diameter of container	cm
PTA0,1,2,3	area allotted containers at start and after 1 <sup>st</sup> , 2 <sup>nd</sup> , and 3 <sup>rd</sup> moves	cm <sup>2</sup>
SWLL	substrate water content at lower limit	cm <sup>3</sup> /cm <sup>3</sup>
SWDUL	substrate water content at drained upper limit	cm <sup>3</sup> /cm <sup>3</sup>
TP	total substrate porosity	cm <sup>3</sup> /cm <sup>3</sup>
PVLF	pour volume leaching factor	unitless
SCHED	irrigation schedule	FIXED, MAD, or FILE
RAINCUT	automatic rain cutoff for FIXED irrigation	YES or NO
IRRI, 23	days before 1 <sup>st</sup> , 2 <sup>nd</sup> , 3 <sup>rd</sup> changes in irrigation	days after planting
MAD	substrate water deficit to trigger irrigation	% of available water
MAD_DIF	target irrigation level for MAD irrigation when irrigating to less than SWDUL	% of available water
IRR_NCONC, IRR_PCONC	N and P concentration of irrigation water	ug/cm <sup>3</sup>
D_IRR0, D_IRRx	initial irrigation rate, rate after x change	cm/day
WFNAME	weather file name	
PFNAME	plant species file name	
IFNAME	irrigation file name (optional)	
SFFNAME	solution fertilizer file name (optional)	
FERT	fertilizer N rate	g/container
PCT_CRN	total N content of fertilizer	%
PCT_N	controlled-release N content of fertilizer	%
CRF_DAYS	longevity rating of fertilizer	day
APPL	fertilizer application method	INC or SURF
TDF	topdress fertilizer application schedule	FIXED, TRIG, NONE
TD_DAYS	day to apply topdress fertilizer	days after planting
TD_TF	topdress fertilizer application threshold factor	N release/N uptake
FERT2, PCT_N2,	topdress fertilizer specs (see above)	

PCT_CRN2, CRF_DAYS2		
SF	solution fertilization schedule	FIXED, TRIG, or FILE, NONE
SF_START, SF_END	day to start and stop solution fertilization	days after planting
SF_INT	time interval between solution fertilizer applications	day
SF_TF	threshold factor for triggering solution fertilizer applications (N release as percent of N demand)	%
SF_NCONC, SF_PCONC	solution fertilizer N and P concentration	ug/cm <sup>3</sup>
PRUNE	prune schedule	FIXED, TRIG, NONE
PR1,2,3	days to prune	days after planting
PR_H1,2,3	prune height	cm
PR_W1,2,3	prune width	cm
TPR1,2,3	plant height to trigger 1 <sup>st</sup> , 2 <sup>nd</sup> , and 3 <sup>rd</sup> prunes	cm
CUT	plant height to remove for triggered prune	cm
NOPMAX	maximum number of prunes	

## 2. Weather input file (WFNAME.wth)

A CCROP weather file is a text file which includes a heading followed by daily weather observations. The heading contains the altitude of the weather station which is used in evapotranspiration calculations. The input weather variables in the weather file are given in Table 4. Because solar radiation data is typically lacking in most historical weather data sets, a reasonable estimate can be made using the weather generator program WGENR (Grant, 2004; Fraisse, 2006). For real-time use, the weather file must be updated daily.

Table 4. Daily input variables in weather files read by CPM.

Input variable	Description	Units
YEAR	Year	
DOY	Day of year	
SRAD	Daily solar radiation	MJ
TMAX	Daily maximum temperature	°C
TMIN	Daily minimum temperature	°C
RAIN	Daily rainfall	mm

## 3. Plant input file (PFNAME.plt)

The plant input file contains parameter values specific to the plant species being grown. The plant filename for *Viburnum odoratissimum* is VIBUR\_OD.PLT which is designated in the management file. A list of the parameters in the plant input file is given in Table 2 and described below.

**\*Crop parameters**  
*CROPEC (Real)*

Coefficient used in calculating the aerodynamic component for plant evaporation.

See p.\*\*

Water subroutine:

```
AEROCOMP=(CROPEC*VPD**1.5)/LATHEAT
```

*CF\_MF and CF\_IF (Real)*

Relates container size to maximum (CF\_MAX) and inflection point (CF\_INF) for logistics equation for CF

See p.\*\*.

Driver program:

```
CF_INF=CF_IF*POTDIAM**0.5 !JR 3-9-10
```

```
CF_MAX=CF_MF*POTDIAM**0.75
```

*KINPUT (Real)*

Factor used to bias temperature due to solar radiation effect. Biased temperature is subsequently used in photosynthesis and development functions.

See p.\*\*.

Driver program:

```
BRAD=SOLAR*DRF*exp(-0.7*LAI)*(1-POT_TOPAREA/PTA)
```

```
TMAXB=TMAX+KINPUT*BRAD
```

*TDMIN, TDOPTMIN, TDOPTMAX and TDMAX (Real)*

These four values define lower limit (TDMIN), upper limit (TDMAX) and optimum (TDOPTMIN and TDOPTMAX) temperatures for determining potential rate of plant development.

Driver program:

```
DTSLOPEMIN=1/(TDOPTMIN-TDMIN)
```

```
DTSLOPEMAX=1/(TDMAX-TDOPTMAX)
```

```
RDTN1=min(DTSLOPEMIN*(TMAXB-TDMIN),1.)
```

```
RDTN2=min(DTSLOPEMIN*(TMIN-TDMIN),1.)
```

```
RDTX1=min(-DTSLOPEMAX*(TMAXB-TDMAX),1.)
```

```
RDTX2=min(-DTSLOPEMAX*(TMIN-TDMAX),1.)
```

```
RDT=max(min((RDTN1+RDTN2)*0.5,(RDTX1+RDTX2)*0.5),0.01)
```

*SW\_TF (Real)*

Substrate water threshold factor used determining when substrate water becomes limiting to plant evaporation

See p.\*\*.

Driver program:

```
WSUF=min(1.,1/SW_TF*A_SWavg_cm3/SWA_cm3)
```

## \*Leaf growth parameters

*RTPF (Real)*

Root partitioning factor for portioning growth between shoots and roots.

See p.\*\*.

Plant subroutine:

```
IF(d_PWSI.ge.d_PWSO) THEN
```

```
  d_TW=d_PWSO*(1-RTPF) !source-limited top growth
```

```
  d_RW=d_PWSO*RTPF !source-limited root growth
```

```
  IF(d_PWSI.eq.0) THEN !addresses floating point precision errors
```

```
    d_LA=0
```

```
  ELSE
```

```
    d_LA=d_LA*(d_PWSO/d_PWSI)
```

```
  ENDIF
```

```
ELSE
```

```
  d_TW=d_PWSI*(1-RTPF) !sink-limited top growth
```

```
d_RW=d_PWSI*RTPF+0.4*(d_PWSO-d_TW) !portion of extra source to roots
ENDIF
```

### *LG1, LG2 (Real)*

Leaf growth coefficients used in power function relating sink-limited leaf area growth to DT.

See p.\*\*.

[Plant subroutine:](#)

```
d_LA=LG1*LG2*DT1**(LG2-1)*RDT*min(WSUF,NSUF,PSUF)
```

### *LG3, LG4 (Real)*

Leaf growth coefficients used in quadratic function relating LA to biomass.

See p.\*\*.

[Plant subroutine:](#)

```
d_PWSI=2*LG3*LA+LG4)*d_LA
```

### *LG5 (Real)*

Used in function that reduces DT when actual LA is less than indicated by sink-limited LA-DT curve.

See p.\*\*.

[Plant subroutine:](#)

```
DT1=(LA-min(ILA,150.))/LG1)**LG5
```

### *TC1 (Real)*

Coefficient used to bias clear day radiation effect on temperature for source limited growth.

See p.\*\*.

[Driver program:](#)

```
PARB=min(SOLAR*0.5,CDR*0.5*TC1)
```

```
d_PWSO=RUE*PARB*TEMFACSO*(1-exp(-CINT*LAI))*min(WSUF,NSUF)*0.0001*PTA
```

### *RUE (Real)*

Factor related to the efficiency of converting captured solar radiation to plant biomass in source limited growth equation.

See p.\*\*.

[Plant subroutine:](#)

```
d_PWSO=RUE*PARB*TEMFACSO*(1-exp(-CINT*LAI))*0.0001*PTA
```

### *CINT (Real)*

Extinction coefficient used to describe the relationship between leaf area index and light capture by the plant canopy.

See p.\*\*.

[Plant subroutine:](#)

```
d_PWSO=RUE*PARB*TEMFACSO*(1-exp(-CINT*LAI))*0.0001*PTA
```

## **\*Nitrogen supply parameters**

### *NSUP\_MAX1, NUPMAX2, NSUP\_RF, NSUP\_C1, NSUP\_C2 (Real)*

Parameters relating substrate volume, substrate N concentration, and root weight to N supply for plant growth.

See p.\*\*.

[Plant subroutine:](#)

```
NSUPPLY=NSUP_MAX1*S_VOL**NSUP_MAX2*(1-exp(-NSUP_RF*RW))*  
(1-1/(1+(SUB_NCONC/NSUP_C1)**NSUP_C2))
```

### *NSUF\_C1, NSUF\_C2, NSUF\_TF (Real)*

Parameters relating relative N deficiency in shoots to N sufficiency.

See p.\*\*.

Plant subroutine:

```
TRELN=(TW_Nact-TW_Nmin)/(TW_Nopt-TW_Nmin)
IF(TRELN.LT.NSUF_TF) THEN
  NSUF=NSUF_C1*TRELN**NSUF_C2
ELSE
  NSUF=1.
```

### **\*Phosphorus supply parameters**

*PSUP\_MAX1, PUPMAX2, PSUP\_RF, PSUP\_C1, PSUP\_C2 (Real)*

Parameters relating substrate volume, substrate P concentration, and root weight to P supply for plant growth.

See p.\*\*.

Plant subroutine:

```
PSUPPLY=PSUP_MAX1*S_VOL**PSUP_MAX2*(1-exp(-PSUP_RF*RW))*
(1-1/(1+(SUB_PCONC/PSUP_C1)**PSUP_C2))
```

*PSUF\_C1, PSUF\_C2, PSUF\_TF (Real)*

Parameters relating relative P deficiency in shoots to P sufficiency.

See p.\*\*.

Plant subroutine:

```
TRELP=(TW_Pact-TW_Pmin)/(TW_Popt-TW_Pmin)
IF(TRELP.LT.PSUF_TF) THEN
  PSUF=PSUF_C1*TRELP**PSUF_C2
ELSE
  PSUF=1.
```

### **\*Nitrogen concentration parameters**

*TW\_Noptmax, TW\_Noptmin, DT\_Nmax, DT\_Nmin (Real)*

Parameters describing the two slopes (SLOPEN1 and SLOPEN2) used to calculate optimum N concentration in shoot biomass (TW\_Nopt) depending upon development time (DT). DT\_Nmin is noteworthy since it is the DT when optimal shoot N reaches a maximum.

See p.\*\*.

Plant subroutine:

```
SLOPEN1=(TW_Noptmax-TW_Noptmin)/DT_Nmin
SLOPEN2=(TW_Noptmax-TW_Noptmin)/(DT_Nmax-DT_Nmin)**2
IF(DT.LE.DT_Nmin) THEN
  TW_Nopt=TW_Noptmin+slopeN1*DT
ELSE
  TW_Nopt=TW_Noptmin+slopeN2*(DT-DT_Nmax)**2
ENDIF
NDEMAND=TW_Nopt*(d_TW)+RW_Nopt*(d_RW)
```

*TW\_Nmin (Real)*

Minimum N concentration in shoots for calculating relative deficiency factor.

See p.\*\*.

Plant subroutine:

```
TRELN=(TW_Nact-TW_Nmin)/(TW_Nopt-TW_Nmin)
```

*RW\_Nopt (Real)*

Optimal root N concentration for calculating NDEMAND in roots.

See p.\*\*.

Plant subroutine:

```
NDEMAND=TW_Nopt*(d_TW)+RW_Nopt*(d_RW)
```

### \*Phosphorus concentration parameters

*TW\_Poptmax, TW\_Poptmin, DT\_Pmax, DT\_Pmin* (Real)

Parameters describing the two slopes (SLOPEN1 and SLOPEN2) used to calculate optimum N concentration in shoot biomass (TW\_Popt) depending upon development time (DT). DT\_Pmin is noteworthy since it is the DT when optimal shoot P reaches a maximum.

See p.\*\*.

Plant subroutine:

```
SLOPEP1=(TW_Poptmax-TW_Poptmin)/DT_Pmin
SLOPEP2=(TW_Poptmax-TW_Poptmin)/(DT_Pmax-DT_Pmin)**2
IF(DT.LE.DT_Pmin) THEN
  TW_Popt=TW_Poptmin+slopeP1*DT
ELSE
  TW_Popt=TW_Poptmin+slopeP2*(DT-DT_Pmax)**2
ENDIF
PDEMAND=TW_Popt*(d_TW)+RW_Popt*(d_RW)
```

*TW\_Pmin* (Real)

Minimum P concentration in shoots for calculating relative deficiency factor.

See p.\*\*.

Plant subroutine:

```
TRELP=(TW_Pact-TW_Pmin)/(TW_Popt-TW_Pmin)
```

*RW\_Popt* (Real)

Optimal root P concentration for calculating PDEMAND in roots.

See p.\*\*.

Plant subroutine:

```
PDEMAND=TW_Popt*(d_TW)+RW_Popt*(d_RW)
```

### \*Size parameters

*HTC1,HTC2,WDC1,WDC2* (Real)

Parameters used in power function to relating changes in LA to changes in plant height and width.

See p.\*\*.

Plant subroutine:

```
HT=HT+HTC1*HTC2*LA**(HTC2-1)*d_LA
WIDTH=WIDTH+WDC1*WDC2*LA**(WDC2-1)*d_LA
```

*SZC1,SZC2* (Real)

Parameters used in power function to relate size adjustments to LA.

Plant subroutine:

```
LA=SZC1*SIZE**SZC2
```

### \*Photosynthesis temperature factors

*PHOTOTEMP1, PHOTOTEMP2, PHOTOTEMP3* (Real)

Coefficients used in the calculation of temperature factor affecting photosynthesis in source-limited growth functions.

See p.\*\*.

Plant subroutine:

```
TEMFACSO=PHOTOTEMP1-PHOTOTEMP2*(TBIAS-PHOTOTEMP3)**2
d_PWSO=RUE*PARB*TEMFACSO*(1-exp(-CINT*LAI))*min(WSUF,NSUF)*0.0001*PTA
```



**\*Pruning factors**

*PRTWFAC1, PRTWFAC2, PRLAFAC1, PRLAFAC2 (Real)*

Factors relating prune height reduction to reduction in shoot biomass and leaf area.

See p.\*\*.

Plant subroutine:

```
PRUNE_TW=TW*PRHT_RED*( PRTWF1*DT**(-PRTWF2)) !dwt of prunings
TW=TW*(1-PRHT_RED*( PRTWF1*DT**(-PRTWF2))) !new TW
LA=LA*(1-PRHT_RED*( PRLAF1*DT**(-PRLAF2))) !new LA
```

Table 2. Parameters in the plant input file.

Input variable	Description	Units
CROPEC	crop evaporative coefficient	MJ/kPa
CF_MF	relates container top area to maximum for logistic function estimating irrigation capture factor	
CF_IF	relates container top area to inflection point for logistic function estimating irrigation capture factor	
KINPUT	factor for biasing temperature due to solar radiation effect	
TDMIN, TDOPTMIN, TDOPTMAX, TDMAX	critical temperatures used in functions describing the influence of temperature on development	°C
RTPF	root partitioning factor	g root/g total
SW_TF	Substrate water threshold factor or fraction of available water below which water is limiting plant evaporation	
LGC1,LGC2	coefficients for power function relating sink-limited leaf area growth to DT	
LGC3,LGC4	coefficients relating biomass to sink-limited leaf area growth	
LGC5	coefficient used to reduce DT when actual LA is less than indicated by sink-limited growth functions.	
TC6	Coefficient used to bias clear day radiation effect for biased solar radiation	
RUE	radiation use efficiency	g/MJ
CINT	light extinction coefficient	
NSUP_MAX1, NSUP_MAX2	coefficients used to relate substrate volume to N supply maximum	g
NSUP_RF	root factor used to relate N supply to root growth	
NSUP_C1, NSUP_C2	parameters relating substrate N conc. to N supply	
NSUF_C1, NSUF_C2	factors for relating relative N conc in shoots to N sufficiency	
NSUF_TF	threshold factor for relating relative N conc in shoots to N sufficiency	
PSUP_MAX1, PSUP_MAX2	coefficients used to relate substrate volume to P supply maximum	
PSUP_RF	root factor used to relate P supply to root growth	
PSUP_C1, PSUP_C2	parameters relating substrate P conc. to P supply	
PSUF_C1, PSUF_C2	factors for relating relative P conc in shoots to N sufficiency	
PSUF_TF	threshold factor for relating relative P conc	

	in shoots to P sufficiency	
TW_Noptmax, TW_Noptmin; DT_Nmax, DT_Nmin	Parameters describing the two slopes (SLOPEN1 and SLOPEN2) used to calculate optimum N concentrations in shoot biomass depending upon development time (DT). DT_Nmin is noteworthy since it is the DT when optimal shoot N reaches a maximum.	g N/g shoot biomass; DT
TW_Nmin	minimum N conc. in shoot tissue for determining relative N sufficiency	g N/g tissue
RW_Nopt	optimum N concentration in roots	g N/g tissue
TW_Poptmax, TW_Poptmin; DT_Pmax, DT_Pmin	Parameters describing the two slopes (SLOPEP1 and SLOPEP2) used to calculate optimum P concentrations in shoot biomass depending upon development time (DT). DT_Pmin is noteworthy since it is the DT when optimal shoot P reaches a maximum.	g P/g shoot biomass; DT
TW_Pmin	minimum P conc. in shoot tissue for determining relative P sufficiency	g P/g tissue
RW_Popt	optimum P concentration in roots	g P/g tissue
HTC1, HTC2	coefficients for power function relating LA to plant height	
WDC1, WDC2	coefficients for power function relating LA to plant width	
SZC1, SZC2	coefficients for power function relating size to LA	
PHOTOTEMP1, PHOTOTEMP2, PHOTOTEMP3	factors for biasing temperature effect on photosynthesis in source growth function	
PRTWFAC1,2	pruning shoot factor that relates reduction in height to reduction in shoot biomass	
PRLAFAC1,2	pruning shoot factor that relates reduction in height to reduction in leaf area	

#### 4. Irrigation input file (IFNAME.irr) - Optional

Users may input daily irrigation rates via an irrigation input file. The DATE for the first line of data under heading must correspond to the plant day-of-year (PLT\_DOY) of the simulation using the irrigation file. There are only two variables in the irrigation input file (Table 3).

Table 3. Parameters in the irrigation input file (IFNAME.irr).

Input variable	Description	Units
DATE	date	YEARDOY
IRRIG	daily irrigation rate	cm

## 5. Solution fertilizer input file (SFFNAME.sfn) - Optional

This input file allows the user to input a daily record of solution fertilizer applications. The DATE for the first line of data under heading must correspond to the plant date (PLT\_DOY). There are only two variables in the irrigation input file (Table 4).

Table 3. Parameters in the solution fertilizer input file.

Input variable	Description	Units
DATE	date	YEARDOY
SF_NCONC	solution fertilizer N concentration	g/cm <sup>3</sup>
SF_PCONC	solution fertilizer P concentration	g/cm <sup>3</sup>

## B. CCROP - Driver and Subroutine Programs

This section is designed to give an overview of the driver and subroutine programs and the processes they simulate. Details of the individual processes are given in Section D.

### 1. Driver program (driver.for)

The driver program controls the simulation. The simulation is based upon a daily timeframe which means that input weather data and simulated processes (e.g. photosynthesis, evaporations, etc.) are all based upon daily averages. A general description of how the driver program controls the flow of information between subroutines in CCROP is given in Fig. 1 and in the following descriptions.

#### Initialization:

- Read management and plant input files
- Initialize parameters and set initial values
- Calculate area relationships
- Set substrate water content to container capacity

#### Begin daily simulation:

- Read in weather data
- Calculate PARB (biased solar radiation for photosynthesis function)
- Calculate bias temperatures for development and photosynthesis functions
- Calculate relative development time (RDT)
- Start daily simulation when start criteria are met
- Move containers, reset irrigation rates, prune or apply supplemental fertilizer if criteria are met
- Call variables from subroutine RATE calculations.

Note: Rate calculations do not rely on updated values from other subroutines

- Call variables from subroutine INTEGRATION calculations

Note: Integration calculations rely on updated values from other subroutines

- Calculate irrigation and rain capture factors

- Calculate available substrate N and P based upon loss in drainage, plant uptake, release from CRF, and input in irrigation water
- Call output from output subroutine
- End daily simulation loop
- End crop simulation when harvest criteria are met
- Re-initialize parameters for next year's run (yearly loop)
- Output summary data after final year
- End simulation

## **2. Water Subroutine**

### Initialization:

- Initialize parameters and set to initial values
- Calculate available water content

### Rate calculations:

- Calculate potential plant and substrate evaporation

### Integration calculations:

- Calculate irrigation to be applied
- Calculate irrigation and rain entering container
- Calculate drainage from container and runoff
- Determine actual substrate evaporation
- Determine actual plant evaporation and water sufficiency
- Calculate evapotranspiration
- Calculate new substrate water content (SW)
- Calculate water related parameters on area basis and container basis
- Calculate running totals on area basis and container basis

## **3. Plant subroutine (plant.for)**

### Initialization:

- Initialize parameters and set to initial values
- Calculate shoot and root biomass based on initial leaf area
- Calculate slope constants for optimum shoot N and P concentrations
- Assign initial N and P concentrations to transplant

### Rate calculations:

- Adjust plant size if scheduled and adjust shoot weight and LA accordingly
- Prune plant if scheduled and adjust size, leaf area, and biomass

### Integration calculations:

- Calculate optimum N and P concentrations in plant tissues
- Determine N and P sufficiency in shoot tissue
- Calculate sink-limited growth potential
- Calculate source-limited growth potential
- Calculate actual growth based upon whether growth is sink-limited or source-limited

- Calculate N supply in substrate based upon substrate volume, substrate N conc. and root biomass
- Calculate N demand based upon biomass growth and optimal tissue N concentration
- Calculate plant N uptake based upon whether N supply meets N demand
- Update biomass, N concentration, leaf area and size
- Calculate prune delay

#### **4. Nutrient subroutine (nutrient.for)**

##### Initialization:

- Initialize parameters and set to initial values
- Calculate N and P applied with fertilizer

##### Rate calculations:

- Calculate parameters for N and P release functions
- Start topdress fertilizer application if scheduled
- Start solution fertilizer application if scheduled
- Determine N and P release from CRF applications

##### Integration calculations:

- Calculate N and P in drainage, un-intercepted water and runoff
- Update running totals on container basis and area basis
- Determine need for supplemental topdress or solution fertilizer if scheduled

#### **5. Output subroutine (output.for)**

##### Initialization:

- Open output files and print headers

##### Rate calculations:

- none

##### Integration calculations:

- Write daily output files
- Write summary output

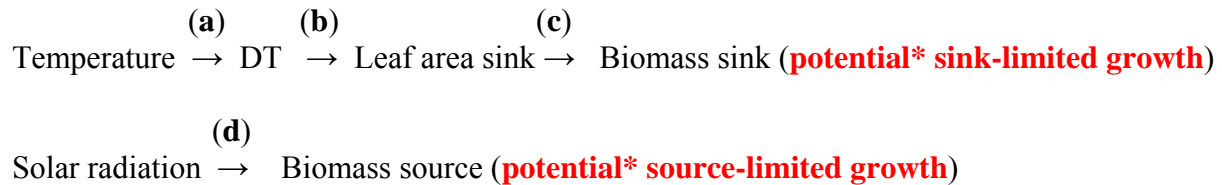
## **C. CCROP - Processes and Functions**

This section will describe the functions used by CCROP to simulate dynamic processes involved with estimating growth and water and nutrient relationships during containerized plant production.

### **1. Plant growth and development**

The simulation of plant growth and development relies on functions which estimate potential sink-limited growth (largely temperature dependent) with source-limited growth (largely solar radiation dependent). Potential sink-limited growth is controlled by development

time (DT) which is a function of temperature. Potential source-limited growth is controlled by photosynthesis. A description of these sink and source limited growth functions is given below.



\*Actual biomass growth is the lesser of sink-limited and source-limited biomass growth (e).

### (a) DT functions

Cumulative development time (DT) and relative daily time (RDT) which is the daily incremental change in DT are used to control sink-limited growth. Figure 2 depicts how four temperature points are used to define the relationship between DT and temperature. If temperatures are optimal (between TDOPTMIN and TDOPTMAX) RDT = 1 day. When temperatures fall below or rise above these optimum values, RDT <1.0 and growth potential will be less than optimal. When temperatures fall below minimum or rise above maximum values (TDMIN and TDMAX) then RDT approaches zero or no growth. The following discussion details how RDT is calculated.

The first two equations calculate slopes used to describe the RDT response to temperature (Fig. 2).

$$DTSLOPEMIN = 1 / (TDOPTMIN - TDMIN)$$

$$DTSLOPEMAX = 1 / (TDMAX - TDOPTMAX)$$

DTSLOPEMIN = slope describing RDT response to temperature

DTSLOPEMAX = slope describing RDT response to temperature

The following equations calculate RDT based upon temperature parameters TMIN and the biased temperature TMAXB:

$$RDTN1 = \min(DTSLOPEMIN * (TMAXB - TDMIN), 1.)$$

$$RDTN2 = \min(DTSLOPEMIN * (TMIN - TDMIN), 1.)$$

$$RDTX1 = \min(-DTSLOPEMAX * (TMAXB - TDMAX), 1.)$$

$$RDTX2 = \min(-DTSLOPEMAX * (TMIN - TDMAX), 1.)$$

$$RDT = \max(\min((RDTN1 + RDTN2) * 0.5, (RDTX1 + RDTX2) * 0.5), 0.01)$$

$$DT = DT + RDT$$

RDTN1 and RDTN2 = RDT relative to minimum critical temperatures (day)

RDTX1 and RDTX2 = RDT relative to maximum critical temperatures (day)

RDT = incremental daily increase in DT (day)

DT = development time (day)

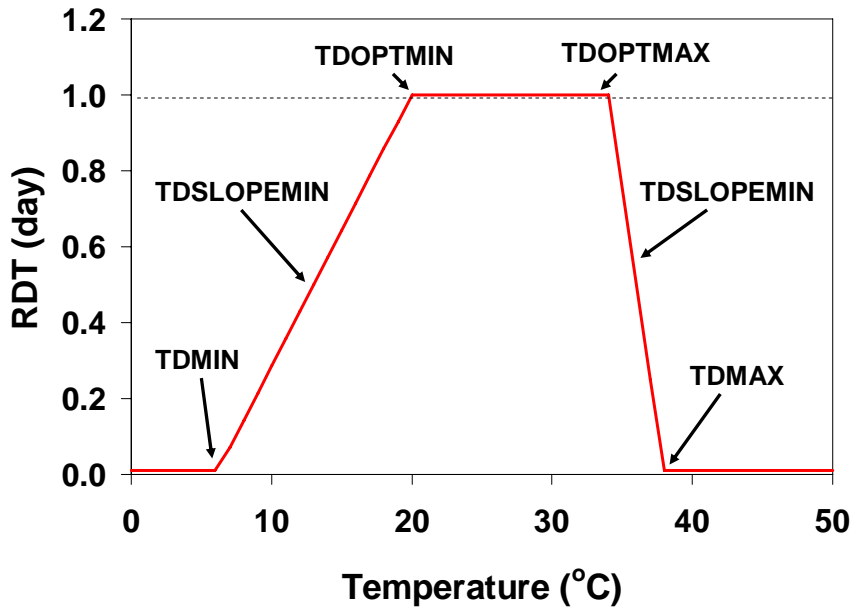


Fig. 2. Four critical temperatures used to define the response of relative development time to temperature.

### (b) Sink-limited growth functions

A power function is used to relate sink-limited leaf area growth to development time (DT). (Fig. 3). The derivative of the function is used to calculate daily leaf area growth based upon RDT:

$$d\_LA = LGC1 * LGC2 * DT1^{LGC2-1} * RDT * \min(WSUF, NSUF, PSUF)$$

$d\_LA$  = daily incremental change in LA

$LGC1, LGC2$  = plant specific coefficients for power function

$DT1$  = development time modified for actual LA (day)

$RDT$  = daily incremental change in DT (day)

$NSUF, WSUF, PSUF$  = water, nitrogen, and phosphorus sufficiency factors (0-1)

where  $LGC1$  and  $LGC2$  are 0.045 and 2.5, respectively. The power function suggests that growth proceeds exponentially but in most cases growth becomes limited by photosynthesis (source) so that actual LA growth will be less than potential as indicated in Fig 3. As such DT is modified based on actual LA so that the derivative function is based upon actual LA instead of potential LA. The modified DT ( $DT1$ ) to accomplish this is calculated with:

$$DT1 = ((LA - \min(ILA, 150.)) / LGC1) ** LGC5$$

$DT1$  = development time modified for actual LA (day)

$LA, ILA$  = leaf area and initial leaf area ( $cm^2$ )

$LGC1, LGC5$  = plant specific coefficients



where LGC5 is 0.39 for *V. odoratissimum*.

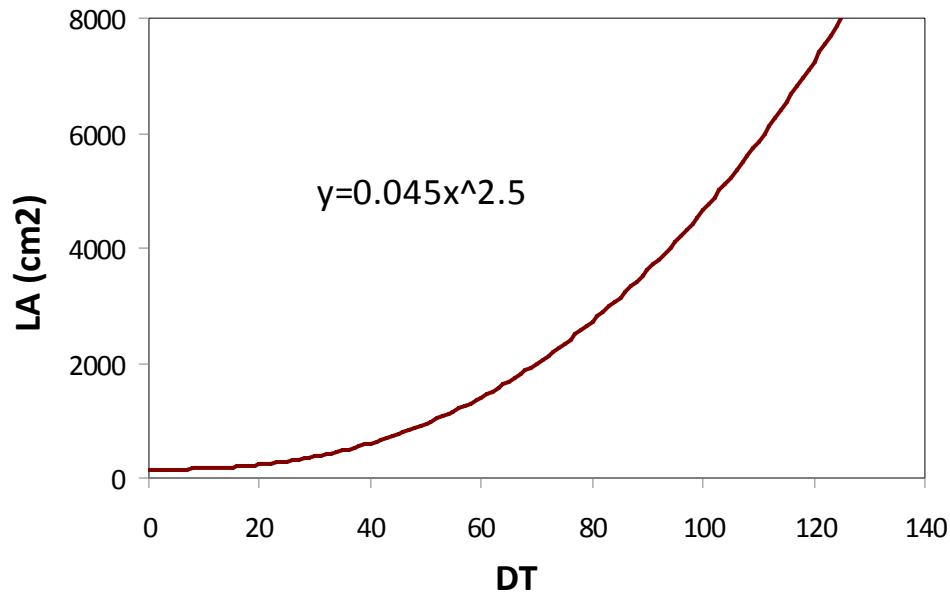


Fig. 3. Relationship between development time (DT) and potential sink-limited leaf area growth LA for *V. odoratissimum*.

If nitrogen or water are limiting (WSUF, NSUF, or PSUF <1), then potential growth is further limited by multiply by these factors.

**(c) Conversion of sink-limited leaf area growth to equivalent sink-limited biomass growth**

Once d\_LA is determined, a calculation is needed to convert potential leaf area growth to equivalent biomass growth so that sink versus source amounts can be compared directly (Fig. 4).

$$d\_PWSI = (2 * LGC3 * LA + LGC4) * d\_LA$$

d\_PWSI=sink-limited biomass growth (g)

LGC3, LGC4=plant specific leaf growth coefficients

LA= leaf area (cm<sup>2</sup>)

d\_LA=sink-limited leaf area growth (cm<sup>2</sup>)

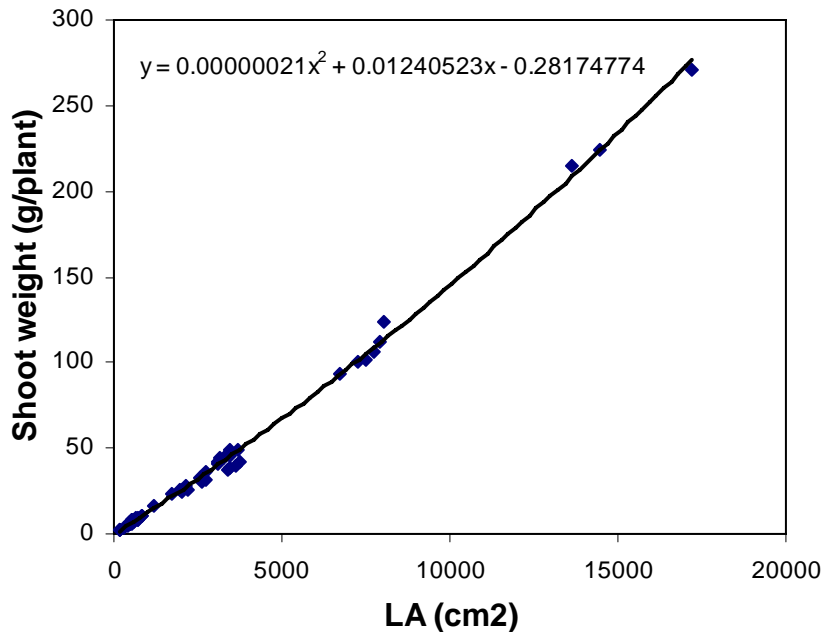


Fig. 4. Quadratic relationship relating leaf area (LA) to equivalent shoot biomass. The derivative of quadratic is used to estimate daily incremental biomass gain from daily incremental leaf area growth.

**(d) Source-limited growth functions**

Source-limited growth functions describe the photosynthetic capacity of the plant to produce the biomass necessary for growth. Radiation and temperature are the weather factors that affect source-limited growth functions. Plant-specific factors include temperature sensitivity, light extinction coefficient, and radiation use efficiency.

Temperature effect on photosynthesis is simulated with the following function (Fig.5):

$$TEMFACSO = PHOTOTEMP1 - PHOTOTEMP2 * (TBIAS - PHOTOTEMP3) ** 2$$

TEMFACSO=temperature factor for source-limited growth

PHOTOTEMP1,2,3=plant specific coefficients

TBIAS=biased temperature mean (°C)(see\*\*\*)

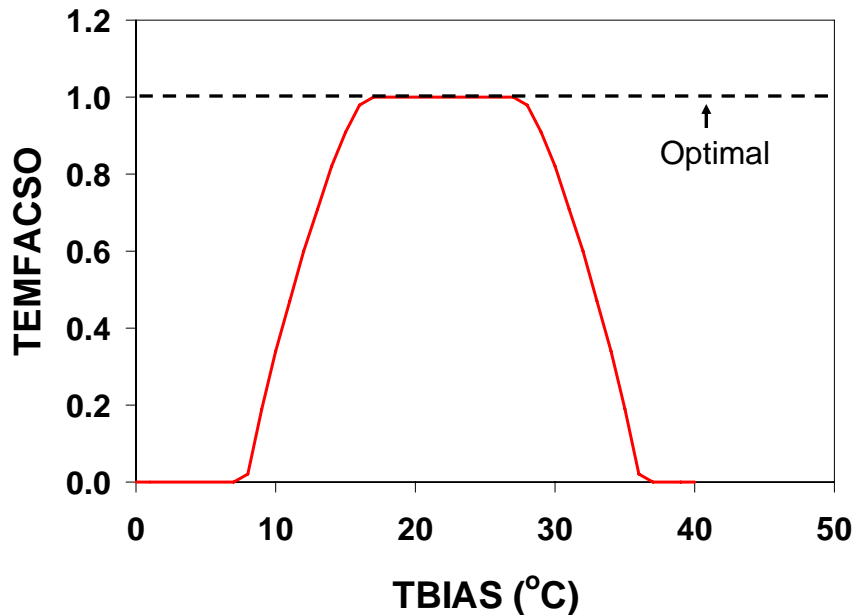


Fig. 5. Temperature factor for source-limited growth function. Temperature bias (TBIAS) is the average of daily minimum temperature and daily maximum temperature biased for solar radiation heating effect on exposed containers.

Source-limited growth rate is described by the following equation:

$$d\_PWSO = RUE * PARB * TEMFACSO * (1 - \exp(-CINT * LAI)) * \min(WSUF, NSUF, PSUF) * 0.0001 * PTA$$

**d\_PWSO**=daily incremental change in source-limited growth (g)

**RUE**=plant specific radiation use efficiency (g/MJ)

**PARB**=biased photosynthetically active radiation (MJ/m<sup>2</sup>)(see \*\*)

**TEMFACSO**=temperature factor (0-1)

**CINT**=light extinction coefficient is a measure of the canopy's capacity for capturing light and is related to canopy architecture, leaf size, and leaf inclination

**LAI**=leaf area index

**PTA**=total area allotted to each container (cm<sup>2</sup>)

**NSUF, WSUF, PSUF**= water, N, and P sufficiency factors (0-1)

Source-limited growth (d\_PWSO) is largely a function of solar radiation (PARB) and LAI (Fig. 8). As LAI approaches 3 to 4, essentially all light is captured and d\_PWSO reaches a maximum.

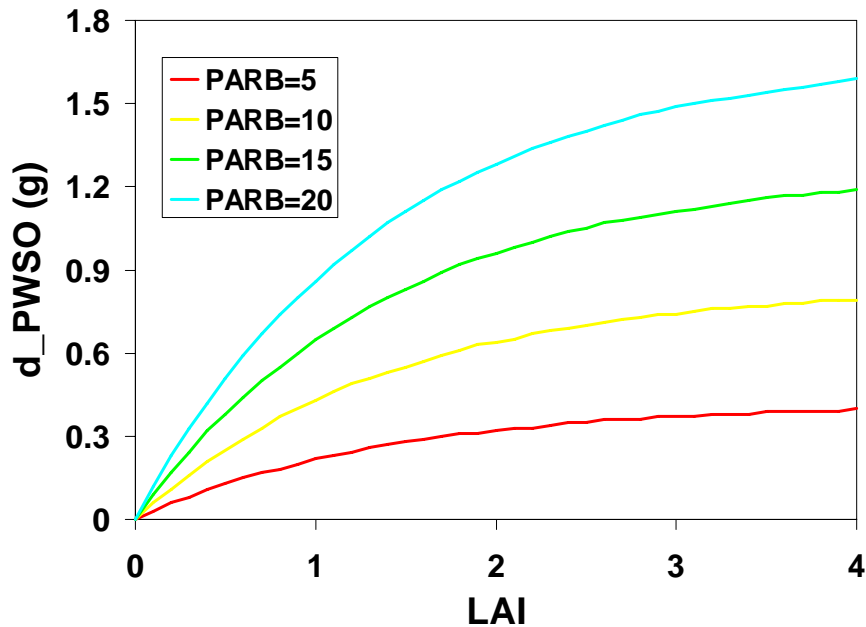


Fig. 6. Effect of LAI on source-limited growth ( $d_{PWSO}$ ) at four biased photosynthetically active radiation (PARB) levels.

#### (e) Actual growth – source versus sink

Now that potential sink and source-limited growth have been calculated, whichever is smallest will determine how much growth will take place any given day.

```

IF(d_PWSI.ge.d_PWSO) THEN
  d_TW=d_PWSO*(1-RTPF)
  d_RW=d_PWSO*RTPF
  d_LA=d_LA*(d_PWSO/d_PWSI)
ELSE
  d_TW=d_PWSI*(1-RTPF)
  d_RW=d_PWSI*RTPF+0.4*(d_PWSO-d_TW)
ENDIF

```

$d_{PWSI}$ =daily potential sink-limited growth (g)  
 $d_{PWSO}$ =daily potential source-limited growth (g)  
 $d_{TW}$ =daily shoot growth (g)  
 $d_{RW}$ =daily root growth (g)  
RTPF=root partitioning factor (g root/g plant)

In the first case where source is limiting,  $d_{PWSO}$  is simply partitioned into shoot and root tissue according to RTPF. In the second case where potential sink growth is limiting, a fraction (0.4) of the extra potential source growth is added to the roots and the rest is assumed lost through respiration or other means.

Once daily incremental growth is determined, cumulative growth is updated:

```
TW=TW+d_TW
RW=RW+d_RW
```

```
TW=shoot biomass (g)
RW=root biomass (g)
d_TW=incremental shoot growth (g)
d_RW=incremental root growth (g)
```

## 2. N and P demand, supply and uptake

In CCROP, plant uptake of N depends on whether the supply of N from the substrate is limiting or the N demand of the plant is limiting. The following discussion describes how CCROP simulates these processes and how negative feedback algorithms reduce growth under N deficiency conditions. Code for phosphorus (P) is identical to N

### (a) Plant N demand:

Plant N demand is the product of biomass growth (described above) and optimal N concentration. Optimal N concentration is a function DT and plant specific N concentration parameters (Fig. 9):

```
SLOPEN1=(TW_Noptmax-TW_Noptmin)/DT_Nmin
SLOPEN2=(TW_Noptmax-TW_Noptmin)/(DT_Nmax-DT_Nmin)**2

IF(DT.LE.DT_Nmin) THEN
  TW_Nopt=TW_Noptmin+slopeN1*DT
ELSE
  TW_Nopt=TW_Noptmin+slopeN2*(DT-DT_Nmax)**2
ENDIF
```

```
SLOPEN1=rate of change in optimal shoot N conc when DT<DT_Nmin
SLOPEN2=rate of change in optimal shoot N conc when DT=>DT_Nmin
TW_Noptmax=maximum optimal N conc in shoots (g N/g shoot)
TW_Noptmin=minimum optimal N conc in shoots (g N/g shoot)
DT_Nmin=DT when optimal N conc in shoots is at a maximum (day)
DT_Nmax=DT defining SLOPEN2
```

Optimal tissue N concentration increases during early stages of growth as new leaf growth occurs then declines as the proportion of woody tissue to leaf tissue increases with continued biomass growth. Optimum N relationships are plant specific and are determined with N fertilizer experiments where destructive harvests are made periodically during the season and biomass and N conc are determined. Once optimum N concentration values are calculated for shoot and root tissues, then plant demand for N is the product of incremental biomass growth and optimum N concentration plus any deficit carried over from ‘yesterday’:

```
NDEMAND=(TW*(TW_Nopt-TW_Nact))+RW*(RW_Nopt-RW_Nact))+
TW_Nopt*d_TW+RW_Nopt*d_RW
```

```
NDEMAND=N demand of whole plant (g)
TW=shoot biomass (g)
```

TW\_Nopt=optimum N conc in shoot (g/g)  
 TW\_Nact=actual N conc in shoot (g/g)  
 RW=root biomass (g)  
 RW\_Nopt=optimum N conc in root (g/g)  
 RW\_Nact=actual N conc in root (g/g)  
 d\_TW=daily incremental change in shoot biomass (g)  
 d\_RW=daily incremental change in root biomass (g)

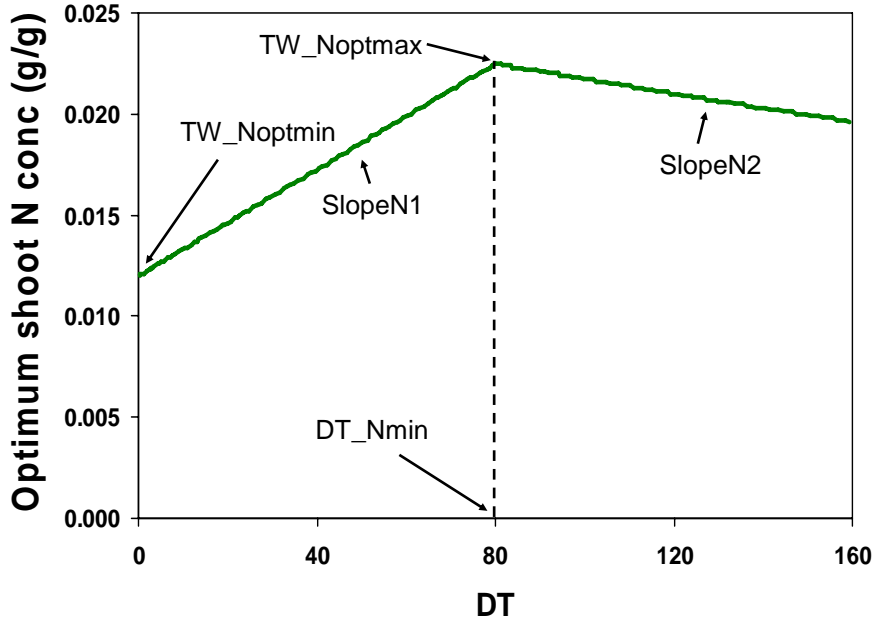


Fig. 7. Optimal N concentration in shoot (TW\_Nopt) and root (RW\_Nopt) tissues as a function of DT.

**(b) N supply:**

N supply for plant uptake is a function of available N in substrate, substrate volume, and root biomass (Fig. 8):

$$\begin{aligned}
 \text{SUB\_NCONC} &= \text{SUB\_N} / \text{SWDUL\_cm3} * 10^{**6} \\
 \text{NSUPPLY} &= \text{NSUP\_MAX1} * \text{S\_VOL} * \text{NSUP\_MAX2} * (1 - \exp(-\text{NSUP\_RF} * \text{RW})) * \\
 &\quad (1 - 1 / (1 + (\text{SUB\_NCONC} / \text{NSUP\_C1}) ** \text{NSUP\_C2}))
 \end{aligned}$$

SUB\_NCONC=N conc in substrate (ug/cm<sup>3</sup>)  
 SUB\_N=available N in substrate (g)  
 SWDUL\_cm3=water content at drained-upper limit (cm<sup>3</sup>)  
 NSUPPLY=N supply for plant uptake (g)  
 NSUP\_MAX1 and NSUP\_MAX2=N supply coefficients  
 NSUP\_RF=N supply root factor  
 RW=root biomass (g)  
 NSUP\_C1 and NSUP\_C2=N supply coefficients

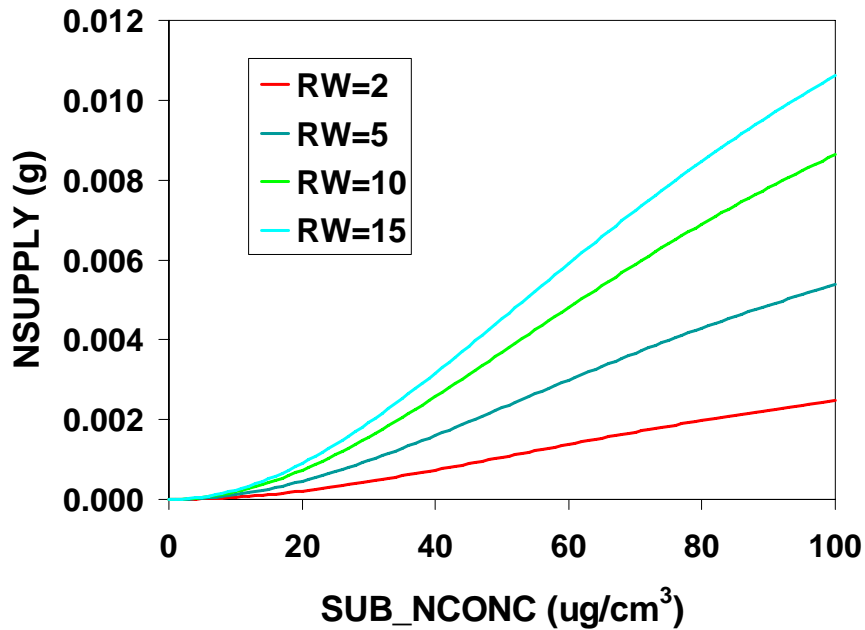


Fig. 8. N supply for plant uptake as a function of substrate N concentration (SUB\_NCONC) and root biomass (RW).

**(c) N uptake:**

Plant N uptake is the lesser of plant N demand and substrate N supply. Nitrogen taken up by the plant then is distributed to shoot and root tissues based upon ratio of optimum N conc in shoot and root tissue:

```

NUPTAKE=min(NDEMAND,NSUPPLY)
N_PLT=N_PLT+NUPTAKE
RW_Nact=N_PLT/(TW*(TW_Nopt/RW_Nopt)+ RW)
N_ROOT=RW*RW_Nact
N_TOP=N_PLT-N_ROOT
TW_Nact=N_TOP/TW

```

- NUPTAKE**=N taken up by plant (g)
- NDEMAND**=N demand of whole plant (g)
- NSUPPLY**=substrate N available for plant uptake (g)
- NPLT**=N content of plant (g)
- RW\_Nact**=root N concentration (g/g)
- TW**=shoot biomass (g)
- TW\_No**pt=optimum N conc in shoot (g/g)
- RW\_No**pt=optimum N conc in root (g/g)
- RW**=root biomass (g)
- N\_ROOT**=N content of roots (g)
- N\_TOP**=N content of shoots (g)
- TW\_Nact**=shoot N concentration (g/g)

**(d) N sufficiency:**

N sufficiency in the plant is based upon the deviation of actual shoot N concentration from optimum shoot N concentration (Fig. 11):

$$\text{TRELN} = (\text{TW\_Nact} - \text{TW\_Nmin}) / (\text{TW\_Nopt} - \text{TW\_Nmin})$$

TRELN=relative N sufficiency in shoot (0-1)

TW\_Nact=shoot N concentration (g/g)

TW\_Nmin=minimum shoot N conc (g/g)

TW\_Nopt=optimum shoot N conc (g/g)

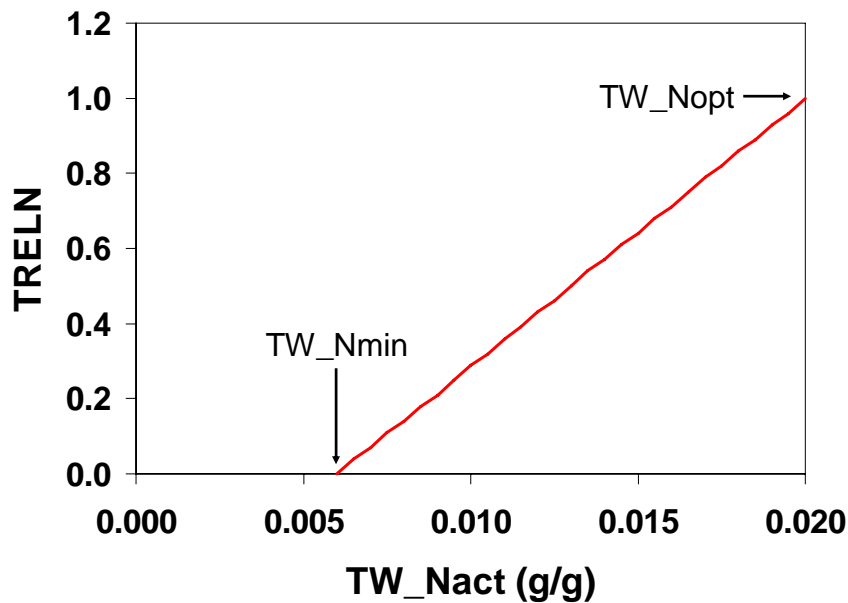


Fig. 9. Relative N sufficiency (TRELN) as a function of shoot N concentration (TW\_Nact) when in this example TW\_Nmin=0.006 and TW\_Nopt=0.02 g/g.

An N sufficiency factor that is used to negatively feedback on plant growth if N concentration in plant tissue reaches a critical level is calculated with the following (Fig. 10):

```
IF (TRELN.LT.NSUF_TF) THEN
  NSUF=NSUF_C1*TRELN**NSUF_C2
ELSE
  NSUF=1.
ENDIF
```

TRELN=relative N sufficiency factor

NSUF=N sufficiency factor (0-1)

NSUF\_TF=N sufficiency threshold factor

NSUF\_C1 and NSUFC2=N sufficiency coefficients



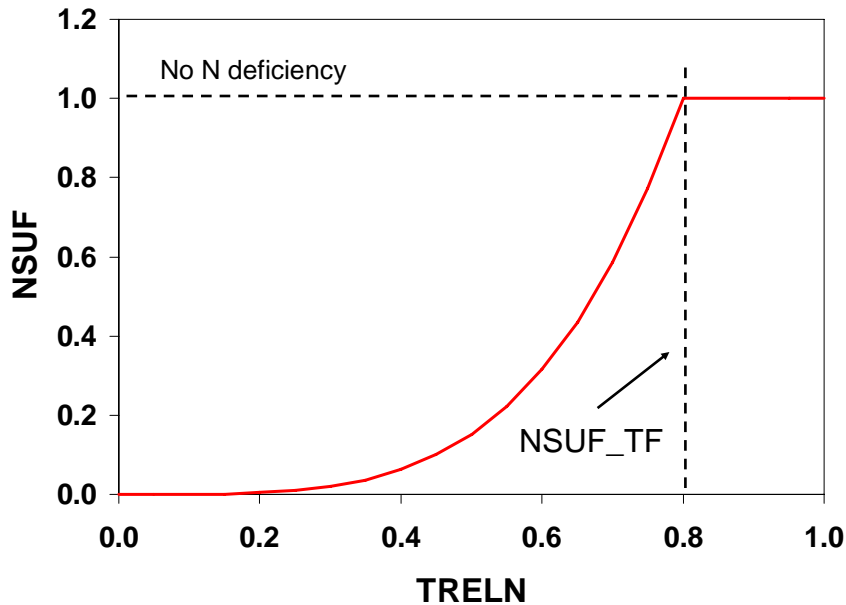


Fig. 10. N sufficiency factor (NSUF) used to reduce plant growth under conditions of N deficiency as a function of relative N sufficiency in shoots (TRELN).

The N sufficiency threshold factor allows shoot N conc to fall below optimum shoot N conc before N deficiency (NSUF<1) is observed. NSUF is subsequently used as a potential modifier of sink and source-limited growth functions.

### 3. Evaporation and water sufficiency

Evaporation processes for both substrate (evaporation) and plant (transpiration) are discussed in this section. Potential evaporation describes the maximum potential rate of evaporation from plant or substrates. Actual evaporation is less than potential evaporation if water availability in substrate is limiting. Because plant transpiration equations are based on total area but plants must obtain water from containers occupying only a fraction of the production area, additional calculations are needed to convert evaporation rates on a per-container basis.

#### (a) Potential evaporation

Potential evaporation calculations are based upon Penman equations developed for humid climates in which vapor pressure deficit is estimated from temperature (Fig. 11).

```

LATHEAT=( 25.01-TBIAS/42.3)
GAMMA=0.0674*PRESS
DELTA=2503*EXP(17.27*TBIAS/(TBIAS+237.3))/(TBIAS+237.3)**2
RADCOM=DELTA/(DELTA+GAMMA)*SOLAR*0.6/LATHEAT
RADCOM_CDR=DELTA/(DELTA+GAMMA)*CDR*0.6/LATHEAT
TDAY=TMAX*0.75+TMIN*0.25
VPD=0.6108*EXP(17.27*BTMEAN/(BTMEAN+237.3))-0.6108*EXP(17.27*TMIN/
(TMIN+237.3))

```

$$\text{AEROCOMP} = (\text{CROPEC} * \text{VPD} ** 1.5) / \text{LATHEAT}$$

$$\text{AEROCOMS} = (4.0 * \text{VPD} ** 1.5) / \text{LATHEAT}$$

Potential plant and substrate evaporation depend on leaf cover (LAI) so that ESO decreases as LAI increases.

$$\text{EPO} = (\text{RADCOM} + \text{AEROCOMP}) * (1. - \text{EXP}(-0.7 * \text{LAI}))$$

$$\text{ESO} = (\text{RADCOM} + \text{AEROCOMS}) * \text{EXP}(-0.6 * \text{LAI})$$

$$\text{ETO} = (\text{RADCOM} + \text{AEROCOMP})$$

$$\text{ESO\_cm3} = \text{ESO} * \text{POT\_TOPAREA}$$

$$\text{EPO\_cm3} = \text{EPO} * \text{PTA}$$

$$\text{ETO\_cm3} = \text{ETO} * \text{PTA}$$

**LATHEAT**=latent heat of evaporation (

**TBIAS**=average biased daily temperature (see \*\*)

**GAMMA**=subcalculation

**PRESS**=atmospheric pressure

**DELTA**=subcalculation

**RADCOM**=radiation component

**SOLAR**=solar radiation (MJ)

**VPD**=vapor pressure deficit

**TDAY**=daily temperature mean biased toward TMAX (see \*\*)

**TMIN**=minimum daily temperature (°C)

**AEROCOMP**=aerodynamic component for plant evaporation

**AEROCOMS**=aerodynamic component for substrate evaporation

**CROPEC**=crop evaporation coefficient

**EPO**=potential plant evaporation (cm)

**ESO**=potential substrate evaporation (cm)

**ETO**=potential substrate evapotranspiration (cm)

**POT\_TOPAREA**= area of container top (cm<sup>2</sup>)

**LAI**=leaf area index (cm<sup>2</sup> /cm<sup>2</sup>)

**ESO\_cm3**=potential substrate evaporation (cm<sup>3</sup>/container)

**EPO\_cm3**=potential plant evaporation (cm<sup>3</sup>/container)

**ETO\_cm3**=potential plant evapotranspiration (cm<sup>3</sup>/container)

**POT\_TOPAREA**=top area of container (cm<sup>2</sup>)

**PTA**=production area allotted each container (cm<sup>2</sup>)

### (b) Actual evaporation

Actual substrate and plant evaporation rates are less than potential rates if water is limiting. The following algorithms are used to determine if water is limiting and adjust evaporation rates accordingly.

#### Actual substrate evaporation:

Actual substrate evaporation (ES\_cm3) is less than potential when substrate water content is limiting. To determine if water is limiting, substrate water content as a fraction of DUL is calculated after subtracting one-half of potential plant evaporation. This fraction is used in a negative exponential function to estimate substrate-limited evaporation. This amount is

compared to potential substrate evaporation (ESO\_cm3); the lesser of these two is considered ES\_cm3. The 1.5 in the equation below is a constant with units of cm/day which is multiplied by POT\_TOPAREA to convert to cm<sup>3</sup> (Fig. 15).

$$ES\_cm3 = \min(1.5 * POT\_TOPAREA * (\max((SW\_cm3 - 0.5 * EPO\_cm3), 0.)) / SWDUL\_cm3)^{2.5}, ESO\_cm3)$$

- ES\_cm3=actual substrate evaporation (cm<sup>3</sup>)
- POT\_TOPAREA=container top area (cm<sup>3</sup>)
- SW\_cm3=substrate water content (cm<sup>3</sup>)
- EPO\_cm3=potential plant evaporation (cm<sup>3</sup>)
- SWDUL\_cm3=substrate water content at drained-upper limit (cm<sup>3</sup>)
- ESO\_cm3=potential substrate evaporation (cm<sup>3</sup>)

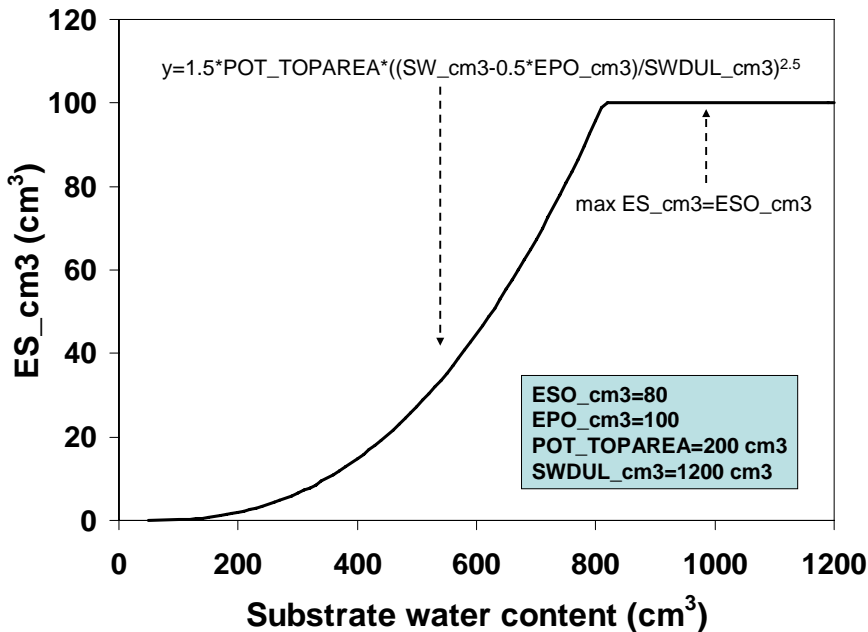


Fig 11. Actual substrate evaporation (ES\_cm3) is a function of substrate water content (SW\_cm3), potential plant evaporation (EPO\_cm3), potential substrate evaporation (ESO\_cm3), substrate water content at drained upper limit (SWDUL\_cm3) and container top area (POT\_TOPAREA).

Actual plant evaporation, actual evapotranspiration and water sufficiency:

Actual plant evaporation (EP\_cm3) is reduced if average available substrate water content accounting for ET (A\_SWavg\_cm3) < 50% (assuming substrate water threshold factor = 0.5) of substrate available water-holding capacity (SWA\_cm3). In this case, a water sufficiency factor (WSUF) is calculated which reduces EP\_cm3 and ET\_cm3. WSUF is also used to reduce growth.

$A\_SWavg\_cm3 = \max(SW\_cm3 - 0.5 * (ES\_cm3 + EP\_cm3) - SWLL\_cm3, 0.)$   
 $WSUF = \min(1., 1 / SW\_TF * A\_SWavg\_cm3 / SWA\_cm3)$   
 $EP\_cm3 = EP\_cm3 * WSUF$   
 $ET\_cm3 = ES\_cm3 + EP\_cm3$

$A\_SWavg\_cm3$  = average available substrate water (cm<sup>3</sup>)  
 $SW\_cm3$  = substrate water content (cm<sup>3</sup>)  
 $ES\_cm3$  = substrate evaporation (cm<sup>3</sup>)  
 $EP\_cm3$  = actual plant evaporation (cm<sup>3</sup>)  
 $SWLL\_cm3$  = substrate water content at lower limit (cm<sup>3</sup>)  
 $WSUF$  = water sufficiency factor (0-1)  
 $SW\_TF$  = substrate water threshold factor (0-1)  
 $SWA\_cm3$  = substrate available water capacity (cm<sup>3</sup>)  
 $ET\_cm3$  = evapotranspiration (cm<sup>3</sup>)

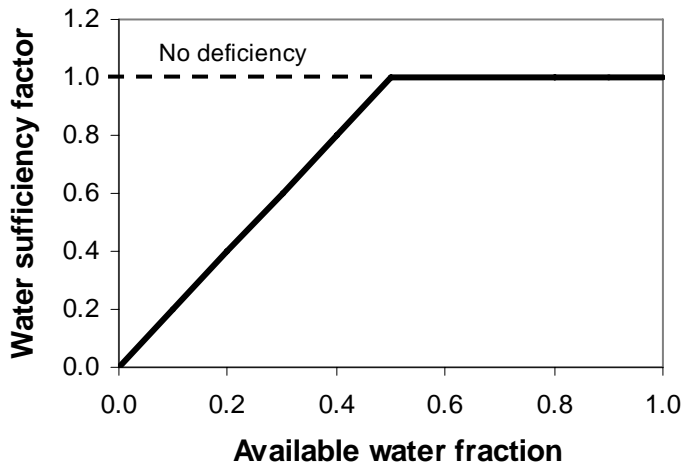


Fig. 12. Relationship available water fraction (average available substrate water/available substrate water holding capacity) and water sufficiency factor. For this example, the substrate water threshold factor (SW\_TF) is 0.5.

#### 4. N and P release from controlled-release fertilizer

Controlled-release fertilizers (CRF) are commonly used for container horticulture. Nitrogen release from CRF is simulated with a 2-phase approach defined by the day of maximum release rate and the period of time before (upslope) and after (downslope) the day of maximum release rate (Fig. 13). A CRF with a greater longevity rating will take a longer time to reach maximum release and the maximum release rate will be lower than a CRF with a shorter release rating (Fig. 19). Temperature is the primary environmental factor affecting N release from CRF. The effect of temperature can be explained by its direct influence on both water vapor pressure and membrane permeability, processes which control the movement of water into and out of the CRF granule. Vapor pressure, which is exponentially related to temperature, is used

by CCROP to elicit the temperature effect on nutrient release (Fig. 13). With this in mind, the following equations model N and P release from a CRF. The first three equations calculate the temperature effect:

```
VP=0.611*exp(17.27*TBIAS/(TBIAS+237.3))
CRF_TFAC=0.5225+0.2109*VP
FERTDAYS=CRF_DAYS*1/CRF_TFAC
```

VP=vapor pressure (kPa)  
TBIAS= radiation-biased daily temperature mean (oC)  
CRF\_TFAC=temperature factor  
CRF\_DAYS=CRF longevity (day)  
FERTDAYS=temperature-modified CRF longevity (day)

This second set of equations computes constants used in nutrient release functions and then computes the nutrient release rate.

```
REL_DAYS=REL_DAYS+1
PEAKDAYS=0.2947*FERTDAYS
PEAKRATE=0.35/PEAKDAYS
UPCOEFF=0.175/PEAKDAYS**2
DNCOEFF=(0.625-PEAKRATE*(FERTDAYS-PEAKDAYS))/(FERTDAYS-PEAKDAYS)**2
FINALDAYS=PEAKDAYS-PEAKRATE/(2*DNCOEFF)

IF(REL_DAYS.LT. PEAKDAYS) THEN
    RELEASERATE=2*UPCOEFF*REL_DAYS
ELSE
    RELEASERATE=PEAKRATE+2*DNCOEFF*(REL_DAYS-PEAKDAYS)
ENDIF
```

REL\_DAYS=days after application (day)  
PEAKDAYS=days to maximum release rate (day)  
FERTDAYS=temperature-modified CRF longevity (day)  
PEAKRATE=maximum release rate (g/g CRF)  
UPCOEFF=coefficient describing upslope of N release  
DNCOEFF=coefficient describing downslope of N release  
FINALDAYS=days to 100% release  
RELEASERATE= nutrient release rate (g/g CRF)

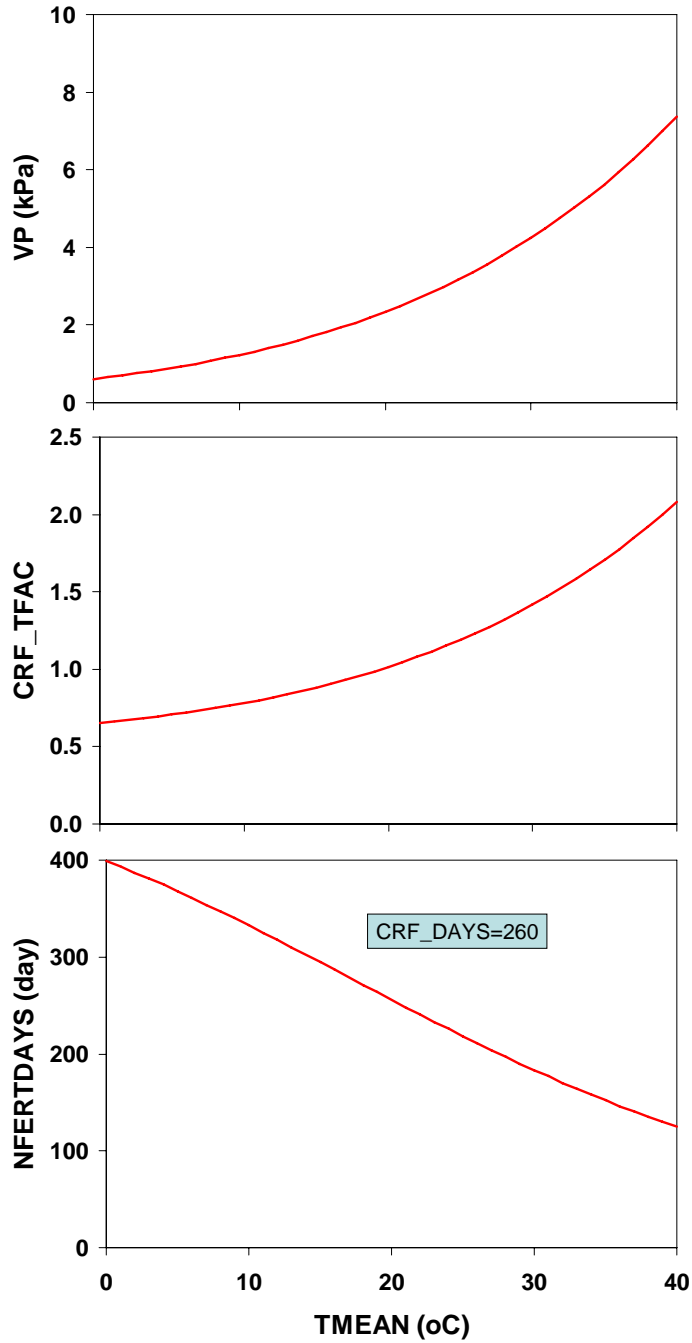


Fig 13. Effect of average daily temperature (TMEAN) on vapor pressure (VP), CRF temperature factor (CRF\_TFAC), and ultimately CRF longevity (NFERTDAYS).

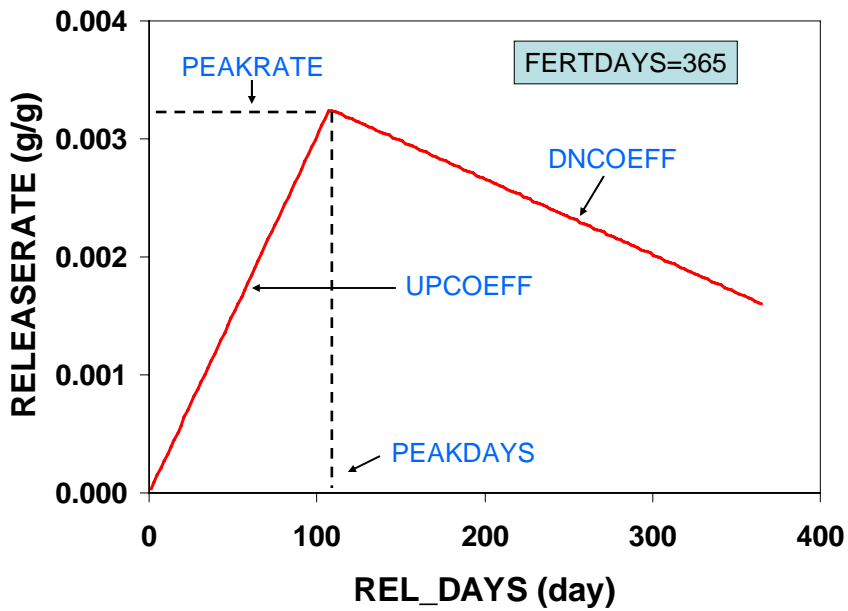


Fig 14. Two-phase approach for modeling nutrient release from controlled-release fertilizer. Fractional release rate (RELEASERATE) increases to a maximum rate at PEAKDAYS and decreases thereafter.

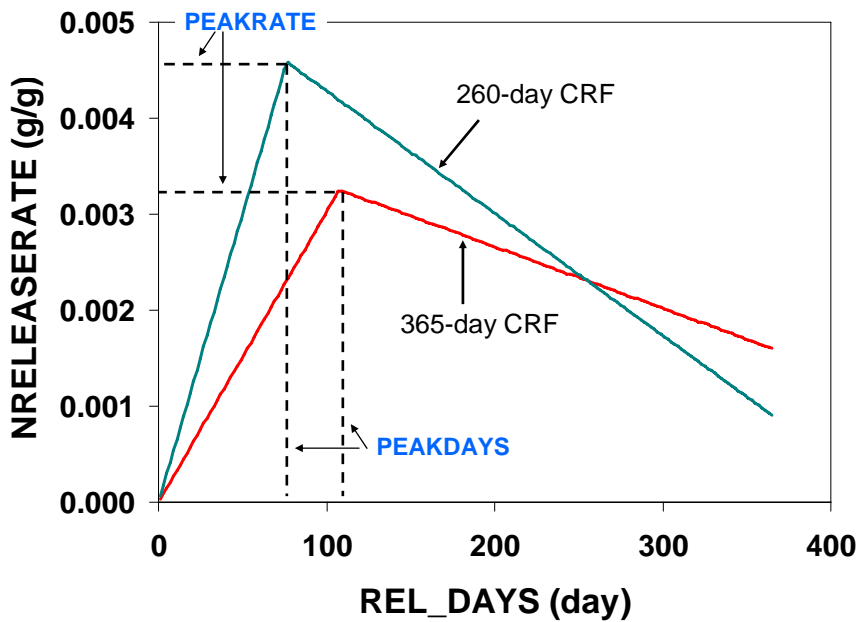


Fig 15. Fractional release rate (RELEASERATE) for two CRFs with different longevities. The 365-day CRF takes longer to reach maximum release and the maximum N release rate is lower than the 260-day CRF.

The release rates are multiplied by the amount of controlled-release fertilizer applied (note: not balance left in container):

```
NRELEASE=CRF_N*RELEASERATE
NRELEASE2=CRF_N2*RELEASERATE2
```

```
PRELEASE=CRF_P*RELEASERATE
PRELEASE2=CRF_P2*RELEASERATE2
```

```
NRELEASE= N released from CRF (g/container)
CRF_N= controlled release N applied (g/container)
RELEASERATE= nutrient release rate (g/g CRF)
NRELEASE2= N released from supplemental CRF (g/container)
CRF_N2= supplemental controlled release N applied (g/container)
RELEASERATE2= nutrient release rate (g/g CRF)
PRELEASE= P released from CRF (g/container)
CRF_P= controlled release P applied (g/container)
PRELEASE2= P released from supplemental CRF (g/container)
CRF_P2= supplemental controlled release P applied (g/container)
```

## 5. Supplemental fertilizer

Supplemental fertilizer is fertilizer applied after planting and therefore is in addition to startup fertilizer. Supplemental fertilizer is typically applied when the startup fertilizer becomes inadequate for meeting the plant nutrient requirements. Supplemental fertilizer may be applied as a granular product typically onto the surface of the substrate (topdress fertilizer) or in solution by injecting liquid fertilizer concentrate into the irrigation water (solution fertilizer). While a supplemental topdress application is typically effective for an extended period of time, solution fertilizer is commonly re-applied at regular intervals since it is readily soluble (i.e., leachable) and there is a practical limit to the fertilizer concentration that can be safely applied. Both topdress and solution fertilizer applications can be scheduled by entering a fixed date or by triggering an application when N release from start-up controlled-release fertilizer falls below a threshold percentage of plant N demand. Triggered applications are only allowed after the first 30 days. For solution fertilization, a third option of inputting applications is via an input file.

### (a) Supplemental topdress fertilizer

For fixed and triggered topdress applications, the application is initiated by setting release day to 0. The contribution of any readily available fertilizer N is added to the substrate N pool. The equations below just show how the topdress application is scheduled. Once applied, N release from topdress fertilizer (NRELEASE2) uses the same functions as N release from startup CRF (NRELEASE) described previously.

```
IF (TDF.eq. 'FIXED' .and. DAY.eq. TD_DAY) THEN
REL_DAYS2=0
```



```

SUB_N=SUB_N+FERT_N2-CRF_N2
SUB_P=SUB_P+FERT_P2-CRF_P2
ENDIF

IF(TDF.eq.'TRIG') THEN
  TD_UPFAC=NDEMAND*TD_TF*.01
  IF(NRELEASE.lt.TD_UPFAC.and.DAY.gt.30.and.SUB_N.lt.NDEMAND.and.
    REL_DAYS2.eq.-99) THEN
    REL_DAYS2=0
    SUB_N=SUB_N+FERT_N2-CRF_N2
    SUB_P=SUB_P+FERT_P2-CRF_P2
  ENDIF
ENDIF

```

TDF=topdress fertilizer schedule

DAY=days after planting (day)

TD\_DAYS=number of days after planting to apply supplemental topdress fertilizer (day)

REL\_DAYS2=number of days after supplemental topdress application (day)

SUB\_N=substrate N (g)

SUB\_P=substrate P (g)

FERT\_N2=supplemental fertilizer N applied (g/container)

CRF\_N2=supplemental controlled-release N applied (g/container)

TD\_UPFAC=topdress uptake factor (g)

NDEMAND=N plant demand (g)

TD\_TF=topdress threshold factor (%)

NRELEASE=N release (g)

### (b) Supplemental solution fertilizer

Supplemental solution fertilizer is applied via irrigation water. Supplemental solution fertilizer can be applied on an irregular schedule at variable N concentrations by inputting the application schedule in an input file (SCHED='FILE'). Otherwise, supplemental fertilizer applications are scheduled to start on a fixed date (or a triggered date), reapplied at a constant time interval and at a constant N concentration. For fixed scheduling, a stop date can be input while for triggered applications the applications at the indicated interval are continued until the crop is finished. The following code shows how these different schedules are implemented.

```

IF(SF.eq.'FILE') THEN
  READ(4,42)SF_NCONC
  FORMAT(8X,F6.0)
ENDIF

IF(SF.eq.'TRIG') THEN
  SF_START=0
  SF_UPFAC=NDEMAND*SF_TF*.01
ENDIF

IF(SF.eq.'TRIG'.and.SF_START.eq.0) THEN
  IF(NRELEASE.lt.SF_UPFAC.and.DAY.gt.30.and.SUB_N.lt.NDEMAND) THEN
    SF_START=DAY+1
  ENDIF
ENDIF

```

```

IF(SF.ne.'NONE'.and.DAY.eq.SF_START.and.DAY.lt.SF_END)THEN
  IRR_NCONC=SF_NCONC
  IRR_PCONC=SF_PCONC
  SF_START=SF_START+SF_INT
ELSEIF(SF.eq.'FILE')THEN
  IRR_NCONC=SF_NCONC
  IRR_PCONC=SF_PCONC
ELSE
  IRR_NCONC=H2O_NCONC
  IRR_PCONC=H2O_PCONC
ENDIF

```

SF=solution fertilizer schedule  
SF\_NCONC=solution fertilizer N concentration (ug/cm<sup>3</sup>)  
SF\_PCONC=solution fertilizer P concentration (ug/cm<sup>3</sup>)  
SF\_START=day of solution fertilizer application (day)  
SF\_UPFAC=threshold N to trigger solution fertilization (g)  
NDEMAND=N plant demand (g)  
SF\_TF=solution fertilizer threshold factor (%)  
NRELEASE=N release (g)  
DAY=days after planting (day)  
SUB\_N=substrate N (g)  
SF\_END=days after planting to end solution fertilizer applications (day)  
IRR\_NCONC=N concentration of irrigation water (ug/cm<sup>3</sup>)  
IRR\_PCONC=P concentration of irrigation water (ug/cm<sup>3</sup>)  
SF\_INT=interval between solution fertilizer applications (day)  
H2O\_NCONC=N concentration of irrigation water source (g)  
H2O\_PCONC=P concentration of irrigation water source (g)

## 6. Water, N and P balance

Water, nitrogen and phosphorus dynamics in container production involve balancing inputs and outputs (Fig. 16). Inputs of rain and irrigation water must be balanced by outputs of evaporation water loss and water lost through drainage or un-intercepted irrigation and rainfall. Nitrogen inputs from fertilizer or irrigation water must be balanced by outputs of plant N uptake and N lost in un-intercepted irrigation and drainage water. Runoff in CCROP is the sum of un-intercepted irrigation/rain and container drainage.

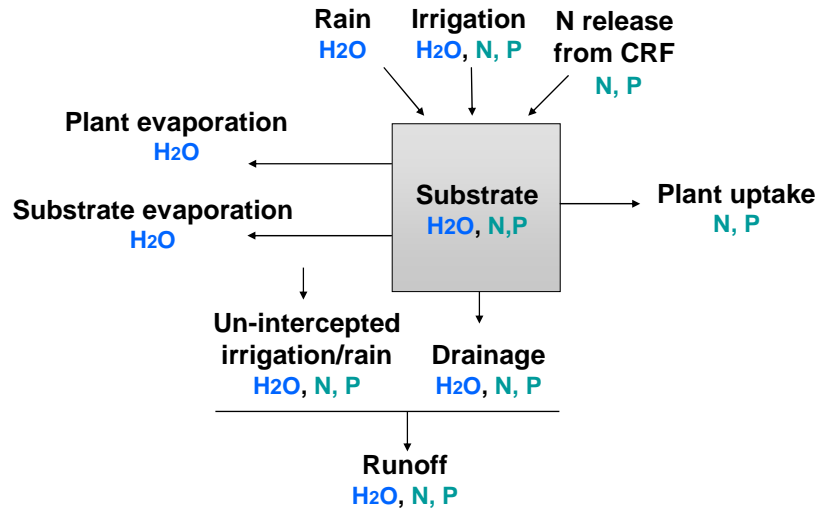


Fig. 16. Simulating water and nitrogen dynamics in container crop production involves balancing inputs and outputs.

### (a) Irrigation

CCROP uses three different types of irrigation scheduling to input irrigation water: FILE, FIXED, or MAD. A complete log of daily irrigation can be inputted with an irrigation file. A fixed irrigation schedule is based upon applying the same amount of irrigation water everyday. With CCROP the fixed amount can be changed up to three times. With a fixed schedule, a rain cutoff sensor can be simulated which stops irrigation if ‘yesterday’s’ rain exceeded the fixed amount of irrigation to apply. A third irrigation scheduling option is managed allowable deficit irrigation (MAD) which applies an amount of water that is proportional to the water deficit in the container substrate. In the management input file the user inputs a MAD value which is the percent of available water that must be lost from the container substrate before irrigation is applied. Once available water content falls below the threshold indicated by MAD then irrigation is based upon the amount of water needed to bring the substrate water content up to drained upper limit (container capacity). For deficit irrigation (irrigation designed to apply less than what would be required to reach drained upper limit), the target substrate water content is calculated using MAD\_DIF input from the management file. Like MAD, MAD\_DIF is based on a percent reduction in available water and by definition is:  $0\% < \text{MAD\_DIF} < \text{MAD}$ . MAD irrigation scheduling also considers the plant’s capacity for [capturing irrigation water](#) into the container. The following equations indicate how these scheduling options work. For both file and fixed options, irrigation is entered as a depth of water which is subsequently converted to volume per container; for MAD scheduling, the amount of water to apply is based upon a volume so the conversion is not needed.

```

IF(SCHED.eq. 'FILE') THEN
  IRRIG_cm3=IRRIG*POT_TOPAREA

ELSEIF(SCHED.eq. 'FIXED') THEN
  IF(RAINCUT.eq. 'YES'.and.Y_RAIN_cm.lt.D_IRR) THEN
    IRRIG_cm3=D_IRR*POT_TOPAREA
  ELSEIF(RAINCUT.eq. 'YES'.and.Y_RAIN_cm.ge.D_IRR) THEN

```

```

    IRRIG_cm3=0.0
ELSE
    IRRIG_cm3=D_IRR*POT_TOPAREA
ENDIF

MAD_TF=1-MAD*0.01
MAD_SW_cm3=MAD_TF*SWA_cm3
SW_DIF_cm3=SWDUL_cm3-(MAD_DIF*0.01*SWA_cm3)

ELSEIF(SCHED.eq.'MAD') THEN
    IF(A_SW_cm3.lt.MAD_SW_cm3) THEN
        IRRIG_cm3=(SW_DIF_cm3-SW_cm3)/CF_IRR
    ELSEIF(0.5*(A_SW_cm3-EPO_MAD_cm3).lt.SW_TF*SWA_cm3) THEN
        IRRIG_cm3=max((SW_DIF_cm3-SW_cm3)/CF_IRR,0.)
    ELSE
        IRRIG_cm3=0.0
    ENDIF
ENDIF

```

SCHED=type of schedule to base irrigation on

IRRIG\_cm3=irrigation water (cm<sup>3</sup>)

IRRIG=irrigation water (cm)

POT\_TOPAREA=top area of container (cm<sup>2</sup>)

RAINCUT=cuts off irrigation if yesterday's rain exceeds today's fixed irrigation amount

Y\_RAIN=yesterday's irrigation (cm)

D\_IRR=irrigation water for fixed irrigation schedule (cm)

MAD\_TF=substrate water threshold factor (fraction of available water)

MAD=managed allowable deficit to trigger irrigation (% of available water)

MAD\_SW\_cm3=substrate water content at MAD (cm<sup>3</sup>)

SWA\_cm3=available substrate water capacity (cm<sup>3</sup>)

SW\_DIF\_cm3=substrate water content after MAD irrigation (cm<sup>3</sup>)

SWDUL\_cm3=substrate water content at drained-upper limit (cm<sup>3</sup>)

A\_SW\_cm3=available substrate water (cm<sup>3</sup>)

SW\_cm3=substrate water (cm<sup>3</sup>)

CF\_IRR=irrigation capture factor

EPO\_MAD\_cm3=potential evapotranspiration for clear day conditions (cm<sup>3</sup>)

SW\_TF= fraction of available water below which water limits growth

There is also code in CCROP that is designed to work with CCROP-MT so that irrigation can be managed on a real-time basis. With the real-time option, irrigation is based upon MAD scheduling but the user can change the actual amount of irrigation water applied if different than MAD. The way CCROP accomplishes this is to create an input irrigation file based upon MAD output. By doing this the user can amend the input file with CCROP-MT to reflect actual irrigation but the model can still offer a MAD-recommended irrigation rate for 'today'.

### (b) Irrigation capture factor

The irrigation capture factor (CF\_IRR) describes the effect that the plant canopy has on the amounts of overhead irrigation and rainfall that reach the container substrate. A rain capture factor CF\_RAIN is assumed to be the same as CF\_IRR until further research warrants a change.

CF\_IRR is the amount of irrigation water that enters the container with a plant relative to the amount of irrigation water that would enter the container without a plant. The potential for the canopy to channel water into the container increases as the size of the plant canopy increases. CF is modeled using a logistics function with plant size index. CF maximum and inflection point for the logistics equation are based upon container diameter. CF\_IRR is limited by the space between containers as described by AREA\_RATIO, the ratio of area allotted each container to the top area of the container CCROP assumes that some water will fall between containers even with a dense canopy so irrigation enhancement is limited to 90% of the area ratio. Until additional research is conducted the capacity of the canopy to capture rain is assumed to be the same as its capacity to capture irrigation. The following equations calculate the CF\_IRR, the irrigation capture factor:

```

AREA_RATIO=PTA/POT_TOPAREA
CF_INF=CF_IF*POTDIAM**0.5    !JR 3-9-10
CF_MAX=CF_MF*POTDIAM**0.75
CF_IRR=max(1.,CF_MAX-(CF_MAX-0.75)/(1+(SIZE/CF_INF)**4)) !

IF(CF_IRR.gt.0.9*AREA_RATIO+0.1) THEN    !JR and JM 1-26-10
  CF_IRR=0.9*AREA_RATIO+0.1
ENDIF

```

**AREA\_RATIO**=ratio of area allotted each container to top area of container  
**PTA**=area allotted each container (cm<sup>2</sup>)  
**POT\_TOPAREA**=top area of container (cm<sup>2</sup>)  
**CF\_INF**=inflection point  
**CF\_IF**=inflection point factor  
**CF\_MAX**=maximum CF  
**CF\_MF**=maximum CF factor  
**CF\_IRR**=irrigation capture factor  
**SIZE**=plant size index = (height+width)/2

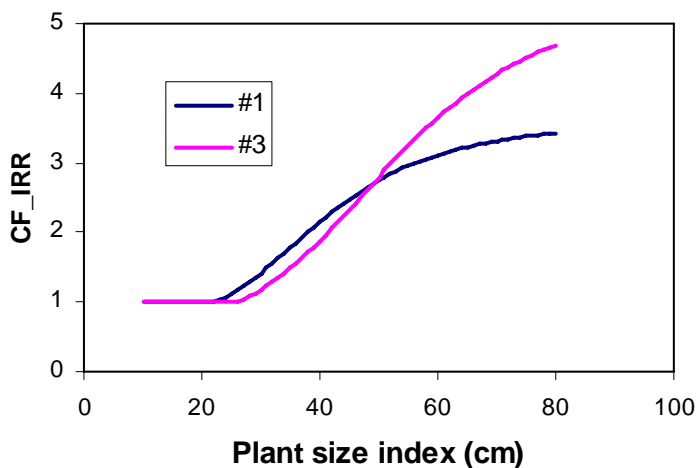


Fig. 17. Irrigation capture factor (CF\_IRR) describes the ability of the plant to capture water that would otherwise fall outside the container. CF is the amount of water entering the container

substrate with a plant relative to the amount of water entering the container without a plant. CF values in graph are maximum values and may be limited by container spacing (i.e., area allotted each container).

### (c) Drainage and runoff

Drainage refers to water that drains out the bottom of containers and occurs when water entering the container exceeds the capacity of the substrate to retain it. Runoff is the sum of drainage plus un-intercepted water falling between containers. The following equations calculate drainage, un-intercepted water, and runoff and reset substrate water content accordingly. The first series calculates drainage when rainfall is not effective (i.e., occurs after irrigation but before significant ET).

```

POT_IRRIG_cm3=IRRIG_cm3*CF_IRR
TOTAL_IRRIG_cm3=IRRIG_cm3*AREA_RATIO
THRU_IRR_cm3=TOTAL_IRRIG_cm3-POT_IRRIG_cm3

POT_RAIN1_cm3=(1-RAIN_EF)*RAIN_cm*POT_TOPAREA*CF_RAIN
SW_cm3=SW_cm3+POT_IRRIG_cm3+POT_RAIN1_cm3
IF(SW_cm3.gt.SWDUL_cm3)THEN           !case where drainage occurs
    POT_DRAIN1_cm3=SW_cm3-SWDUL_cm3
    SW_cm3=SWDUL_cm3
ENDIF

POT_RAIN2_cm3=(RAIN_EF)*RAIN_cm*POT_TOPAREA*CF_RAIN
SW_cm3=SW_cm3-ET_cm3+POT_RAIN2_cm3
IF(SW_cm3.gt.SWDUL_cm3)THEN
    POT_DRAIN2_cm3=SW_cm3-SWDUL_cm3
    SW_cm3=SWDUL_cm3
ENDIF

TOTAL_RAIN_cm3=RAIN_cm*PTA
POT_RAIN_cm3=POT_RAIN1_cm3+POT_RAIN2_cm3
THRU_cm3=TOTAL_RAIN_cm3-POT_RAIN_cm3+Total_IRRIG_cm3-POT_IRRIG_cm3
POT_DRAIN_cm3=POT_DRAIN1_cm3+POT_DRAIN2_cm3
RUNOFF_cm3=POT_DRAIN_cm3+THRU_cm3

POT_IRRIG_cm3=irrigation entering container (cm3)
IRRIG_cm3=irrigation water if no plant effect on capture (cm3)
CF_IRR=irrigation capture factor
TOTAL_IRRIG_cm3=irrigation in area allotted container (cm3)
AREA_RATIO=ratio of area allotted each container to top area of container
THRU_IRR_cm3=irrigation water falling between containers (cm3)
POT_RAIN1_cm3=ineffective rain (cm)
RAIN_EF=fraction of rain that effectively offsets ET
RAIN_cm=rain (cm)
POT_TOPAREA=top area of container (cm2)
CF_RAIN=rain capture factor
SW_cm3=substrate water content (cm2)
SWDUL_cm3=substrate drained-upper limit (cm3)

```

POT\_DRAIN1\_cm3=drainage with ineffective rain (cm<sup>3</sup>)  
 POT\_RAIN2\_cm3=effective rain (cm<sup>3</sup>)  
 ET\_cm3=actual evapotranspiration (cm<sup>3</sup>)  
 POT\_DRAIN2\_cm3=drainage from effective rain (cm<sup>3</sup>)  
 TOTAL\_RAIN\_cm3=rain falling in area allotted container (cm<sup>3</sup>)  
 PTA=area allotted each container (cm<sup>2</sup>)  
 POT\_RAIN\_cm3=total rain entering container (cm<sup>3</sup>)  
 THRU\_cm3=amount of rain and irrigation water falling between containers (cm<sup>3</sup>)  
 POT\_DRAIN\_cm3=total drainage from container (cm<sup>3</sup>)  
 RUNOFF\_cm3=runoff (cm<sup>3</sup>)

#### (d) N and P leaching

N and P leaching is the movement of N and P out of the container substrate via drainage water. While drainage typically accounts for most of the N in runoff, if irrigation water contains appreciable N then N in un-intercepted irrigation can also contribute to runoff N. The amount of available N and P (SUB\_N and SUB\_P) that is subject to leaching is dependent upon N and P release from controlled-release N fertilizer, N and P applied in irrigation water, N and P removed by plant uptake or N and P leached in drainage water (Fig. 16). Equations for the processes affecting SUB\_N are given below; **SUB\_P equations (not given) are similar.**

#### Initial fertilizer N

Substrate N (SUB\_N) has an initial value that is dependent upon the initial fertilizer application and the fraction of fertilizer that is controlled-release N.

$FERT\_N = FERT * PCT\_N * 0.01$   
 $CRF\_N = FERT * PCT\_CRN * 0.01$   
 $SUB\_N = FERT\_N - CRF\_N$

FERT\_N=fertilizer N applied (g)  
 FERT=fertilizer applied (g)  
 PCT\_N=percent N in fertilizer (%)  
 CRF\_N=controlled-release N applied (g)  
 PCT\_CRN=percent controlled-release N in fertilizer (%)  
 SUB\_N=substrate available N (g)

#### N additions to substrate N

Inputs to the available pool of N in the substrate include N release from CRF and inputs from irrigation water.

$NRELEASE = CRF\_N * RELEASERATE$   
 $NRELEASE2 = CRF\_N2 * RELEASERATE2$   
 $POT\_IRR\_N = IRR\_NCONC * POT\_IRRIG\_cm3 * 0.000001$

NRELEASE=N release from CRF (g)  
 CRF\_N=controlled-release N applied (g)  
 RELEASERATE=rate of N release from CRF (g N/g CRF)(see \*\*)  
 NRELEASE2=N release from supplemental CRF (g)

CRF\_N2=supplemental controlled-release N applied (g)  
 RELEASERATE2=rate of N release from supplemental CRF (g N/g CRF)  
 POT\_IRRIG\_N=irrigation N added to container (g)  
 IRR\_NCONC=concentration of N in irrigation water  
 POT\_IRRIG\_cm3=irrigation into container (g)

### Nitrogen leaching and runoff N

N leaching is a product of drainage volume and concentration of N in drainage water (Fig. 18). N concentration in drainage water is estimated by calculating a maximum drain N concentration value and multiplying this by an N leaching factor. The N leaching factor is dependent upon a leach coefficient and drainage volume so that as drainage volume increases the leaching factor decreases exponentially (Fig 19). The leach coefficient, which is input in the plant management input file, describes the relative decrease in drainage N concentration as drainage volume increases. Additions of N in un-intercepted irrigation water are added to drain N to get runoff N. N concentration of runoff water is back calculated knowing runoff volume.

```

DRPV=POT_DRAIN_cm3 / ( TP_cm3-SWLL_cm3 )
NCONC_MAX=SUB_N / ( TP_cm3-SWLL_cm3 )
NLF=0.5*exp( -PVLf*DRPV )
DRAIN_N=NLF*NCONC_MAX*POT_DRAIN_cm3
DRAIN_NCONC=max( DRAIN_N/POT_DRAIN_cm3 , 0. )
THRU_N=THRU_IRR_cm3*IRR_NCONC*0.000001
RUNOFF_N=DRAIN_N+THRU_N
  IF (RUNOFF_cm3.gt.0) THEN
    R_OFF_NCONC=DRAIN_N/RUNOFF_cm3
  ELSE
    R_OFF_NCONC=0
  ENDIF
  
```

DRPV=drainage pore volume  
 POT\_DRAIN\_cm3=drainage volume (cm<sup>3</sup>)  
 TP\_cm3=total substrate porosity (cm<sup>3</sup>)  
 SWLL\_cm3=water content at lower limit (cm<sup>3</sup>)  
 NCONC\_MAX=maximum conc of N in drainage water (ug/cm<sup>3</sup>)  
 SUB\_N=available substrate N (g)  
 NLF=nitrogen leaching factor (unitless)  
 PVLf=pour volume leaching factor (unitless)  
 DRPV=leach pour volume (unitless)  
 DRAIN\_N=drainage N (g)  
 DRAIN\_NCONC=N concentration in drainage water (ug/cm<sup>3</sup>)  
 THRU\_N=N in un-intercepted irrigation water (g)  
 THRU\_IRR\_cm3=un-intercepted irrigation water falling between containers (cm<sup>3</sup>)  
 IRR\_NCONC=N conc of irrigation water  
 RUNOFF\_cm3=runoff volume (cm<sup>3</sup>)  
 RUNOFFN=runoff N (g)  
 R\_OFF\_NCONC=conc of N in runoff water (ug/cm<sup>3</sup>)



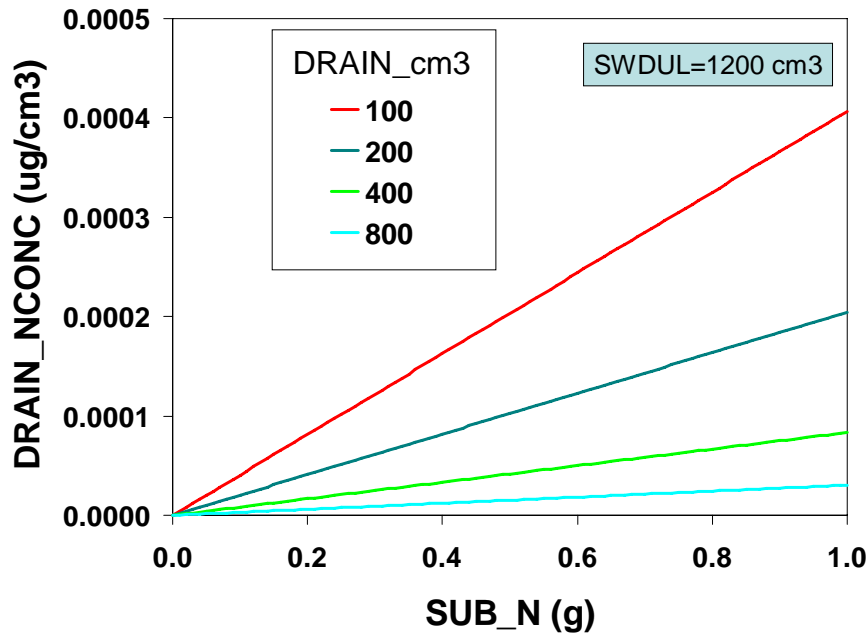


Fig. 18. Nitrogen concentration of drainage water (DRAIN\_NCONC) is a function of substrate N (SUB\_N) and drainage volume (DRAIN\_cm3).

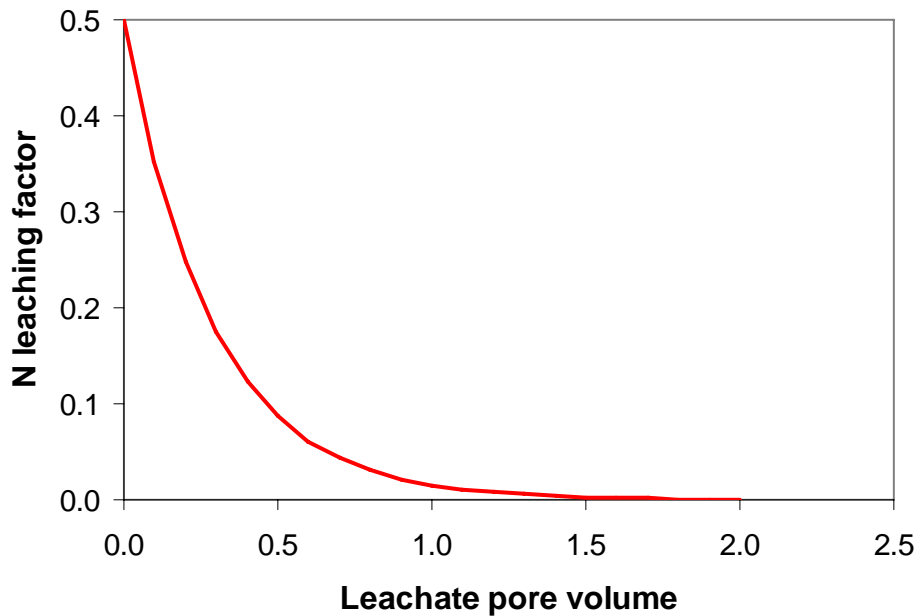


Fig. 19. Nitrogen leaching factor (NLF) is a function of substrate N (SUB\_N) and drainage volume (DRAIN\_cm3). NLF is multiplied by the maximum drainage N concentration to determine drainage N concentration.

**(e) Substrate N balance**

N balance is calculated as an integration equation in the driver program.

```
SUB_N=SUB_N-DRAIN_N+NRELEASE+NRELEASE2-NUPTAKE+POT_IRR_N
```

SUB\_N=substrate N (g)

DRAIN\_N=drainage N (g)

NRELEASE=N release from CRF (g)

NRELEASE2=N release from supplemental CRF (g)

NUPTAKE=N taken up by plant (g)

POT\_IRRIG\_N=irrigation N added to container (g)

## 7. Pruning and plant size

### (a) Pruning

Pruning is the removal of a portion of the shoot in order to promote branching and improve plant uniformity and quality. Removal of biomass and associated leaf area is dependent upon the severity of the pruning. Research has shown that the proportion of leaf area to shoot biomass is greater near the top of the canopy than at the bottom of the canopy where woody stem growth is greater. CCROP assumes that pruning will remove primarily the outermost shoot growth so that terminal buds are removed without excessive loss of shoot biomass. Pruning is scheduled either by inputting a fixed schedule or by selecting plant heights to trigger pruning events. If a fixed pruning schedule is selected then the user must input the number of days after planting to prune along with the height and width of the plant after pruning (see management input file). If a triggered pruning schedule is selected then the user inputs the plant height(s) to trigger a pruning event and the desired reduction in height from the pruning. Whether a fixed or triggered pruning schedule is selected, plant specific factors relating pruning height reduction to biomass and leaf area reduction are used to adjust shoot biomass and leaf area. N content of shoots is also adjusted to account for N in pruned plant tissue). A delay in growth after pruning is simulated by initiating a development day period during which the prune delay effect (PR\_DELAY) decreases rapidly as the period ends. The length of the prune delay period increases as the severity of the prune increases (Fig. 20).

```
IF (PRUNE.eq. 'FIXED' .and. DAY.eq. PR) THEN
  DT_PR=DT
  IF (DT.lt.80) THEN
    PR_DELAY=0.
  ELSE
    PR_DELAY=1. !minimal delay for larger plants
  ENDIF
  PRHT_RED=(HT-PR_H)/HT
  HT=PR_H
  WIDTH=PR_W
  PRUNE_TW=TW*PRHT_RED*(PRTWF1*DT**(-PRTWF2))
  PRUNE_LA=LA*PRHT_RED*(PRLAF1*DT**(-PRLAF2))
  PRUNE_N=PRUNE_TW*1.2*TW_Nact
  PRUNE_P=PRUNE_TW*1.2*TW_Pact
  TW=TW-PRUNE_TW
  LA=LA-PRUNE_LA
  N_TOP=N_TOP-PRUNE_N
  N_PLT=N_PLT-PRUNE_N
  P_TOP=P_TOP-PRUNE_P
```

P\_PLT=P\_PLT-PRUNE\_P

```
IF (PR_DELAY.lt.1.2) THEN
  PR_DELAY=0.328*PRHT_RED*exp(-0.2277)*(DT-DT_PR)**3
  d_LA=min(d_LA*PR_DELAY,d_LA)
ENDIF
```

PR =number of days after planting to prune (day)  
DT\_PR=prune DT used as starting point for prune delay period (day)  
DT =development days (day)  
PR\_DELAY=fractional delay (0-1) in leaf area growth due to pruning  
PRHT\_RED=fractional height reduction due to pruning  
HT=height of canopy (cm)  
PR\_H=height after pruning (cm)  
WIDTH=width of canopy (cm)  
PR\_W=width of canopy after pruning (cm)  
PRUNE\_TW=biomass of prunings (g)  
TW=shoot biomass (g)  
PRTWF1,2=prune shoot biomass factors  
PRUNE\_LA=LA of prunings (g)  
LA=leaf area (cm<sup>2</sup>)  
PRLAF1,2=prune leaf area factors  
PRUNE\_N=N content of prunings (g)  
PRUNE\_P=P content of prunings (g)  
TW\_Nact=N concentration in shoot (g/g)  
TW\_Pact=P concentration in shoot (g/g)  
N\_TOP=N content of shoots (g)  
N\_PLT=N content of whole plant (g)  
P\_TOP=P content of shoots (g)  
P\_PLT=P content of whole plant (g)  
d\_LA=daily incremental change in leaf area (cm<sup>2</sup>)

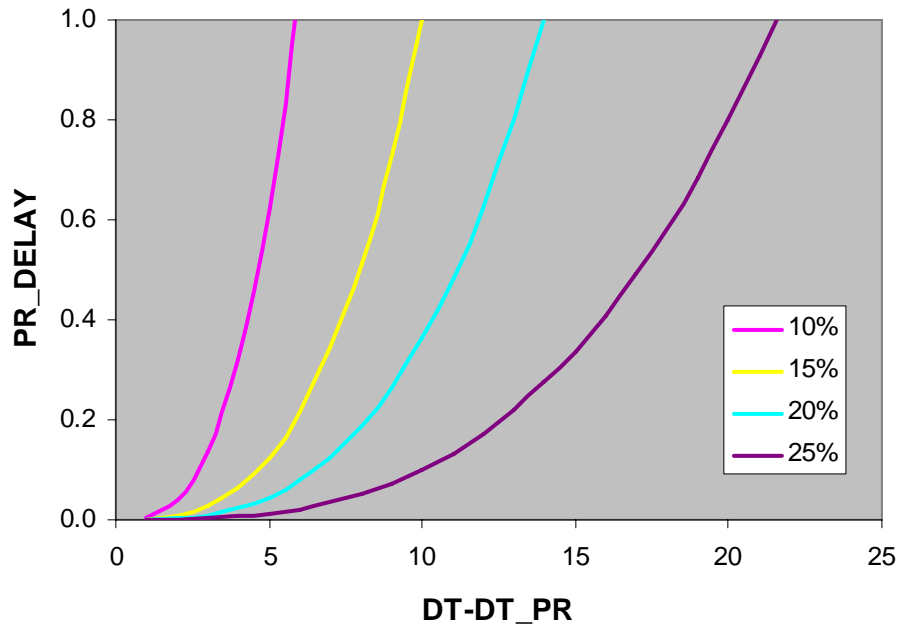


Fig. 20. Effect of prune height reduction on length of prune delay period. DT-PR represents the number of development days after pruning. For example, a 20% prune height reduction has a 14-day prune delay period (i.e., PR\_DELAY=1 after 14 days).

### (b) Size relationships

Size refers to the height and width of the plant canopy. Plant height is the distance from the substrate surface to the uppermost foliage. Plant width is the average of two perpendicular width measurements with the first measurement the widest. Simulating size is important because height and/or width are used to describe the marketable product as it conforms to industry grades and standards.

Plant height and width are estimated with power functions:

$$\begin{aligned}
 HT &= HT + HTC1 * HTC2 * LA^{**} (HTC2 - 1) * d\_LA \\
 WIDTH &= WIDTH + WDC1 * WDC2 * LA^{**} (WDC2 - 1) * d\_LA \\
 SIZE &= (HT + WIDTH) / 2
 \end{aligned}$$

HT=plant height (cm)  
 HTC1, HTC2 = height coefficients  
 LA=leaf area (cm<sup>2</sup>)  
 d\_LA=daily incremental change in leaf area (cm<sup>2</sup>)  
 WIDTH=average plant width (cm<sup>2</sup>)  
 WDC1, WDC2 =width coefficients  
 SIZE=size index (cm)

Plant height and width can be adjusted if values are known to be different. This could be the case when working up experimental data or for calibrating real-time simulations with values measured in the field. If size is corrected, TW and LA are likewise adjusted along:

$$LA = SZC1 * SIZE ** SZC2$$

$$TW = LGC3 * LA ** 2 + LGC4 * LA - 0.2817$$

LA= leaf area (cm<sup>2</sup>)

SZC1,SZC2= size coefficients for power function

TW= shoot weight (g)

LGC3,LGC4= coefficients for quadratic function relating LA to shoot weight

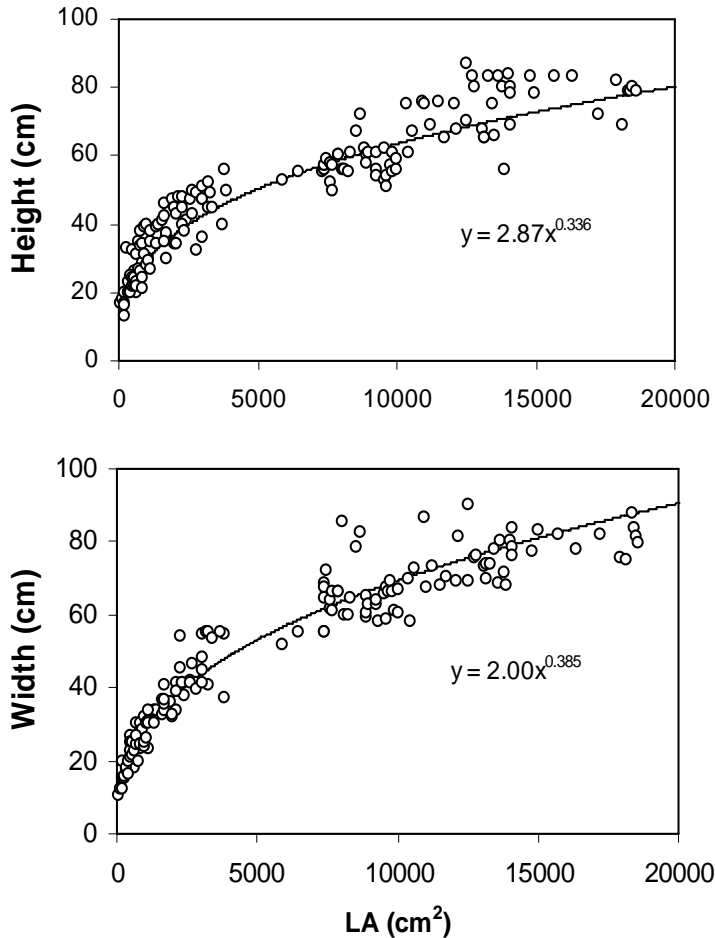


Fig. 20. Power functions relating LA to plant height and width.

## 8. Temperature and radiation functions

Several different temperature functions are used for modifying processes simulated by CCROP. The purpose of this section is to describe these functions and to indicate which processes are affected by them.

### (a) Average temperature (TMEAN)

```
TMEAN=max((TMAX*0.5+TMIN*0.5),0.1)  evaporation
```

**(b) Temperature mean biased toward daily maximum (TDAY)**

```
TDAY=TMAX*0.75+TMIN*0.25  photosynthesis, evaporation
```

**(c) Biased photosynthetically active radiation (PARB)**

The following series of equations estimate the effect of the sun's angle and incoming solar radiation on the amount of solar radiation affecting the temperature and potential photosynthetic rate of the plant canopy. The angle of the sun (declination) which depends on location and time of year affects the length of the light path that solar radiation must travel through the atmosphere to reach the plant. As the sun's angle becomes more obtuse, e.g. during the transition from fall to winter, extraterrestrial solar radiation becomes attenuated to a greater extent.

The heating effect of solar radiation on plant canopy can be estimated in part by estimating the degree of cloudiness. Cloudiness is estimated by calculating what the clear day solar radiation level should be and comparing that to observed solar radiation. This fractional clear day radiation value is then used to estimate the heating effect of solar radiation on temperature affecting photosynthesis.

```
LAT=LAT*0.01745
SINLAT=SIN(LAT)
COSLAT=COS(LAT)
PRESS=(101.0-0.0107*ALT)/101.0

ESCOR=1-0.016733*COS(0.0172*(DOY-1))
OM=0.017202*(DOY-3.244)
THETA=OM+0.03344*SIN(OM)*(1-0.15*SIN(OM))-1.3526
SINDEC=0.3978*SIN(THETA)
COSDEC=(1-SINDEC**2)**0.5
SINF=SINDEC*SINLAT
COSF=COSDEC*COSLAT
HRANG=ACOS(-SINF/COSF)
ETR=37.21/ESCOR**2*(HRANG*SINF+COSF*SIN(HRANG))
H2=SINF+COSF*COS(HRANG/2.)
AIRMASS=PRESS*(-16.886*H2**3+36.137*H2**2-27.462*H2+8.7412)
TARCD=0.87-0.0025*TMIN
CDR=ETR*TARCD**AIRMASS
FCDR=min(SOLAR/CDR,1.)
DRF=max(1.33*(FCDR-0.25),0.0)
PARB=min(SOLAR*0.5,CDR*0.5*TC1)
```

```
LAT=latitude (radians)
SINLAT=sine of latitude (radians)
COSLAT=cosine of latitude (radians)
PRESS=atmospheric pressure relative to sea level (kPa)
ALT=altitude(m)
ESCOR=earth sun distance correction (m)
DOY=julian day of year
OM=optical air mass
THETA=optical air mass subcalculation
```

SINDEC=sine of declination  
 COSDEC=cosine of declination  
 SINFC=sine subcalculation  
 COSFC=cosine subcalculation  
 HRANG=hour angle of the sun (radians)  
 ETR=extraterrestrial solar radiation (MJ/m<sup>2</sup>)  
 H2=subcalculation  
 AIRMASS=optical air mass density  
 TARCD=clear day transmissivity of air  
 TMIN=daily minimum temperature (°C)  
 CDR=clear day solar radiation (MJ/m<sup>2</sup>)  
 FCDR=fraction of clear day solar radiation  
 SOLAR=solar radiation (MJ/m<sup>2</sup>)  
 DRF=direct radiation fraction  
 PARB=biased photosynthetically active radiation  
 TC1=plant specific temperature coefficient

#### (d) Biased temperature maximum (TMAXB)

BRAD=SOLAR\*DRF\*exp(-0.7\*LAI)\*(1-POT\_TOPAREA/PTA)  
 TMAXB=TMAX+KINPUT\*BRAD      **photosynthesis and development**

BRAD=biased solar radiation for canopy (MJ/m<sup>2</sup>)  
 SOLAR=solar radiation (MJ/m<sup>2</sup>)  
 DRF=direct radiation fraction  
 LAI=leaf area index  
 POT\_TOPAREA=top area of container (cm<sup>2</sup>)  
 PTA=total area allotted each container (cm<sup>2</sup>)  
 TMAXB=daily maximum temperature biased for radiation heating affect (°C)  
 TMAX=daily maximum temperature (°C)  
 KINPUT=plant specific coefficient (unitless)

#### (e) Average temperature biased for radiation heating effect (TBIAS)

TBIAS=(TMIN+TMAXB)/2      **photosynthesis**

TBIAS=average temperature biased for radiational heating (°C)  
 TMIN=daily minimum temperature (°C)  
 TMAXB=daily maximum temperature biased for radiation heating affect (°C)

## C. CCROP - Output Files

Output files in CCROP are text (.txt) files which contain either daily or summary output. Daily output files contain a line of output for each day of the simulation while summary output files contain only one line containing the cumulative totals for each yearly simulation run. A discussion of daily and summary output files follows. \*=run number. Due to space limitations, headings of output columns are not always the variable name. Variable names are highlighted in blue.

### 1. Daily output files

**(a) General (\*\_dailyoutput.txt)**

YR = year planted (year)  
DOY = day of year (julian day of year)  
DAY = days after planting (day)  
LA = leaf area per plant (cm<sup>2</sup>)  
LAI = leaf area index (cm<sup>2</sup>/cm<sup>2</sup>)  
TW = plant top dry weight (g)  
RW = plant root dry weight (g)  
DT = development time (day)  
SRad = SOLAR = solar radiation (MJ/m<sup>2</sup>/day)  
TMIN = daily temperature minimum (°C)  
TMAX = daily temperature maximum (°C)  
Ra = RAIN\_cm = rainfall in production area (cm)  
Ir = IRRIG\_cm = irrigation in production area (cm)  
EF = IRR\_EF = irrigation enhancement factor (unitless)  
P\_Ra = POT\_RAIN\_cm = rain entering container (cm)  
P\_Ir = POT\_IRRIG\_cm = irrigation entering pot (cm)  
Sw = SW\_cm = water content in container at start of day (cm)  
P\_Dr = POT\_DRAIN\_cm = drainage from container (cm)  
Ro = RUNOFF\_cm = runoff in production area (cm)  
P\_Et = POT\_ET\_cm = evapotranspiration from container (cm)  
Ht = HT = plant height (cm)  
Et = ET\_cm = evapotranspiration from production area (cm)  
P\_Ar = PTA = production area allotted to each container (cm<sup>2</sup>)

\*\*\*Note: Difference between P\_Ra and Ra and the difference between P\_Ir and Ir is due to the capture factor, CF

**(b) Plant (\*\_Nplantoutput.txt)**

YR = year planted (year)  
DOY = day of year (julian day of year)  
DAY = days after planting (day)  
d\_TW = daily incremental change in shoot biomass (g)  
d\_RW = daily incremental change in root biomass (g)  
RW = root biomass (g)  
TW = top biomass (g)  
N\_TOP = N content of tops (g)  
N\_ROOT = N content of roots (g)  
Tact = TW\_Nact = actual N concentration in shoot biomass (%)  
Ract = RW\_Nact = actual N concentration in root biomass (%)  
TW\_Nopt = optimal N concentration in shoot biomass (%)  
RW\_Nopt = optimal N concentration in root biomass (%)  
NDemand = NDEMAND = N demand of plant (g)  
NUptake = NUPTAKE = N taken up by plant (g)  
NSupply = NSUPPLY = substrate N available for plant uptake (g)  
NSUF = nitrogen sufficiency factor (0-1)



WSUF = water sufficiency factor (0-1)  
NupCum = NUPTAKE\_CUM = cumulative N uptake

**(c) N release (\*\_NReloutput.txt)**

YR = year planted  
DOY = day of year  
DAY = days after planting  
TMean = TMEAN = average daily temperature (oC)  
VP = vapor pressure (kPa)  
TFac = CRF\_TFAC = temperature factor for modifying N release from CRF (unitless)  
Rate = RELEASERATE = daily fractional release rate for CRF (g/g)  
NRel = NRELEASE = N released from CRF (g/container)  
CumNRel = CUMNRELEASE = cumulative N released from CRF (g/container)  
CRF\_N = CRF\_N\_BAL = CRF N remaining (g/container)  
NDemand = NDEMAND = N demand of plant (g)  
FD = FERTDAYS = temperature corrected CRF longevity (day)  
AvT = AVGTEMP = running average of mean daily temperatures (oC)  
AvFD = AVGFD = running average of NFD (day)  
NRel2 = NRELEASE2 = N release from supplemental CRF application (g)  
CRF\_N2 = CRF\_N\_BAL2 = supplemental CRF N remaining (g/container)  
AvT2 = AVGTEMP2 = running avg. of mean temp for supplemental CRF application  
FD2 = AVGFD2 = temperature corrected longevity of supplemental CRF  
SUB\_N = SUB\_N = available N in substrate (g/container)  
RD2 = REL\_DAYS2 = no. of days after applying supplemental CRF

**(d) Runoff (\*\_Nleachoutput.txt)**

YR = year planted (year)  
DOY = day of year (julian day of year)  
DAY = days after planting (day)  
SubN = SUB\_N = available N in substrate (g/container)  
DrCm3 = POT\_DRAIN\_cm3 = volume of drainage (cm<sup>3</sup>/container)  
DrNconc = DRAIN\_NCONC = N concentration in drainage water (g/cm<sup>3</sup>)  
DrainN = DRAIN\_N = N content of drainage water (g/container)  
NRelease = NRELEASE = N released from CRF (g/container)  
NUptake = NUPTAKE = N taken up by whole plant (g/plant)  
CumDr = DRAIN\_CUM\_cm3 = cumulative volume of drainage (cm<sup>3</sup>/container)  
CumDrN = CUMDRAIN\_N = cumulative N lost in drainage (g/container)  
ROcm3 = RUNOFF\_cm3 = runoff volume (cm<sup>3</sup>/container)  
RO\_Nconc = R\_OFF\_NCONC = N concentration of runoff (g/cm<sup>3</sup>)  
Ro\_N = RUNOFF\_N = N in runoff (g/container)  
CumRoN = CUMRUNOFF\_N = cumulative N in runoff (g/container)  
THRU\_N = N in irrigation water falling between containers (g/container)  
IrN = POT\_IRR\_N = N supplied in irrigation water (g/container)  
CumIrN = POT\_IRR\_N\_CUM = cumulative N supplied in irrigation water (g/container)

Note: for Dr\_Nconc and RO\_Nconc, g/cm<sup>3</sup> \* 1,000,000 = mg/L = ppm

**(e) Plant (\*\_Pplantoutput.txt)**

YR = year planted (year)  
DOY = day of year (julian day of year0)  
DAY = days after planting (day)  
d\_TW = daily incremental change in shoot biomass (g)  
d\_RW = daily incremental change in root biomass (g)  
RW = root biomass (g)  
TW = top biomass (g)  
P\_TOP = P content of tops (g)  
P\_ROOT = P content of roots (g)  
Tact = TW\_Pact = actual P concentration in shoot biomass (%)  
Ract = RW\_Pact = actual P concentration in root biomass (%)  
TW\_Popt = optimal P concentration in shoot biomass (%)  
RW\_Popt = optimal P concentration in root biomass (%)  
PDemand = PDEMAND = P demand of plant (g)  
PUptake = PUPTAKE = P taken up by plant (g)  
PSupply = PSUPPLY = substrate P available for plant uptake (g)  
PSUF = nitrogen sufficiency factor (0-1)  
WSUF = water sufficiency factor (0-1)  
PupCum = PUPTAKE\_CUM = cumulative P uptake

**(f) P release (\*\_PReloutput.txt)**

YR = year planted  
DOY = day of year  
DAY = days after planting  
TMean = TMEAN = average daily temperature (oC)  
VP = vapor pressure (kPa)  
TFac = CRF\_TFAC = temperature factor for modifying P release from CRF (unitless)  
Rate = RELEASERATE = daily fractional release rate for CRF (g/g)  
PRel = PRELEASE = P released from CRF (g/container)  
CumPRel = CUMPRELEASE = cumulative P released from CRF (g/container)  
CRF\_P = CRF\_P\_BAL = CRF P remaining (g/container)  
PDemand = PDEMAND = P demand of plant (g)  
FD = FERTDAYS = temperature-corrected CRF longevity rating (day)  
AvT = AVGTEMP = running average of mean daily temperatures (oC)  
AvFD = AVGFDD = running average of FERTDAYS (day)  
PRel2 = PRELEASE2 = P release from supplemental CRF application (g)  
CRF\_P2 = CRF\_P\_BAL2 = supplemental CRF P remaining (g/container)  
AvT2 = AVGTEMP2 = running avg. of mean temp for supplemental CRF application  
FD2 = AVGFDD2 = temperature-corrected longevity rating of supplemental CRF (day)  
SUB\_P = SUB\_P = available P in substrate (g/container)  
RD2 = REL\_DAYS2 = no. of days after applying supplemental CRF

**(g) Runoff P (\*\_Pleachoutput.txt)**

YR = year planted (year)

DOY = day of year (julian day of year)  
 DAY = days after planting (day)  
 SubP = SUB\_P = available N in substrate (g/container)  
 DrCm3 = POT\_DRAIN\_cm3 = volume of drainage (cm<sup>3</sup>/container)  
 DrPconc = DRAIN\_PCONC = P concentration in drainage water (g/cm<sup>3</sup>)  
 DrainP = DRAIN\_P = P content of drainage water (g/container)  
 PRelease = PRELEASE = P released from CRF (g/container)  
 PUptake = PUPTAKE = P taken up by whole plant (g/plant)  
 CumDr = DRAIN\_CUM\_cm3 = cumulative volume of drainage (cm<sup>3</sup>/container)  
 CumDrP = CUMDRAIN\_P = cumulative P lost in drainage (g/container)  
 ROcm3 = RUNOFF\_cm3 = runoff volume (cm<sup>3</sup>/container)  
 RO\_Pconc = R\_OFF\_PCONC = P concentration of runoff (g/cm<sup>3</sup>)  
 Ro\_P = RUNOFF\_P = P in runoff (g/container)  
 CumRoP = CUMRUNOFF\_P = cumulative P in runoff (g/container)  
 THRU\_N = P in irrigation water falling between containers (g/container)  
 IrP = POT\_IRR\_P = P supplied in irrigation water (g/container)  
 CumIrP = POT\_IRR\_P\_CUM = cumulative P supplied in irrigation water (g/container)

Note: for Dr\_Nconc and RO\_Nconc, g/cm<sup>3</sup> \* 1,000,000 = mg/L = ppm

#### (h) Temperature (\*\_tempoutput.txt)

YR = year finished  
 DOY = day of year finished  
 DAY = number of days from plant to finish  
 TMIN = minimum daily temperature (oC)  
 TMAX = maximum daily temperature (oC)  
 TMAXB = maximum dialy temp. biased for solar radiation effect (oC)  
 SRAD = SOLAR = daily solar radiation (MJ/m<sup>2</sup>)  
 FCDR = fractional clear day radiation (unitless)  
 DRF = direct radiation fraction (unitless)  
 RDT = relative development time (day)  
 DT = cumulative development time (day)  
 TEMF = TEMPFACSO = temperature factor for adjusting photosynthesis  
 RW = root weight (g)  
 TW = shoot weight (g)  
 LA = leaf area (cm<sup>2</sup>)  
 LAI = leaf area index (cm<sup>2</sup>/cm<sup>2</sup>)

## 2. Summary output files

Summary files are written on a container basis for efficiency studies or on an area basis for environmental studies. For area basis output, multiply cm by 10 to get equivalent L/m<sup>2</sup>. For example 20 cm of water is equivalent to 400 L/m<sup>2</sup>.

#### (a) Container basis (\*\_summaryoutput.txt)

YR = year finished  
 DOY = day of year finished

**DAY** = number of days to finish  
**Rain** = **RAIN\_CUM\_cm3** = cumulative rain (L/container)  
**Irrig** = **IRRIG\_CUM\_cm3** = cumulative irrigation water applied (L/container)  
**ET** = **ET\_CUM\_cm3** = cumulative ET (L/container)  
**Drain** = **DRAIN\_CUM\_cm3** = cumulative drainage volume (L/container)  
**Runoff** = **RUNOFF\_CUM\_cm3** = cumulative runoff volume (L/container)  
**Nloss** = **CUMRUNOFF\_N** = cumulative N loss in runoff (g/container)  
**NConc** = **CUMRUNOFF\_N\*1000000/ RUNOFF\_CUM\_cm3** = N concentration in runoff (mg/L)  
**HT** = final height (cm)  
**TW** = final shoot biomass (g/plant)  
**P\_Area** = **AVG\_PTA** = average area allotted to a container (cm<sup>3</sup>)  
**NUpCum**=**NUPTAKE\_CUM**= cumulative N uptake (g/plant)  
**Ploss** = **CUMRUNOFF\_P** = cumulative P loss in runoff (g/container)  
**PConc** = **CUMRUNOFF\_P\*1000000/ RUNOFF\_CUM\_cm3** = P concentration in runoff (mg/L)  
**PUpCum**=**PUPTAKE\_CUM**= cumulative P uptake (g/plant)

**(b) Area basis (\*\_summaryarea.txt)**

**YR** = year finished (year)  
**DOY** = day of year finished (julian day of year)  
**DAY** = number of days from plant to finish (day)  
**Rain** = **RAIN\_CUM\_cm** = cumulative rainfall (cm)  
**Irr** = **IRR\_CUM\_cm** = cumulative irrigation water applied (cm)  
**ET** = **ET\_CUM\_cm** = cumulative evapotranspiration (cm)  
**Drain** = **DRAIN\_CUM\_cm** = cumulative drainage (cm)  
**Roff** = **RUNOFF\_CUM\_cm** = cumulative runoff (cm)  
**NLoad** = **NLOAD\_CUM** = cumulative N load (g/m<sup>2</sup>)  
**PLoad** = **PLOAD\_CUM** = cumulative P load (g/m<sup>2</sup>)

### III. CCROP-MT – Management Tools

CCROP Management Tools are web-based programs designed to help the user run CCROP simulations and view output. An account can be set up to save and manage simulation runs. The website is <http://www.bmptoolbox.org>.

#### A. My Account

##### 1. Manage Saved Runs

The user must open an account in order to save simulation runs. If logged into the account, the user will be prompted to name the simulation run. If no name is given, the file will not be saved. A list of saved runs can be accessed by going to ‘My Account’ and clicking ‘Manage Saved Runs’. The following is an example of the listing that will appear.

ID	RUN NAME	TYPE	EDIT	DELETE	DEFAULT
20	Example_A	grower	[edit]	<input type="checkbox"/>	<input type="checkbox"/>
21	Example_B	irr	[edit]	<input type="checkbox"/>	<input type="checkbox"/>
23	Example_C	fert	[edit]	<input type="checkbox"/>	<input type="checkbox"/>
33	Example_E	location	[edit]	<input type="checkbox"/>	<input type="checkbox"/>
51	Holly_Mar	irr	[edit]	<input type="checkbox"/>	<input type="checkbox"/>
52	Holly_July	irr	[edit]	<input type="checkbox"/>	<input type="checkbox"/>
53	Fig10	grower	[edit]	<input type="checkbox"/>	<input type="checkbox"/>
54	Fig10_3gal	grower	[edit]	<input type="checkbox"/>	<input type="checkbox"/>
55	Example_D	realtime	[edit]	<input type="checkbox"/>	<input type="checkbox"/>

Several options are available:

- 1) Clicking the run name provides output only - you will not be able to edit inputs and rerun
- 2) Clicking [edit] provides you with the inputs for the saved run – you will need to resubmit to see output.
- 3) Selecting Delete allows you to delete a saved run.
- 4) Selecting Default allows you to use the input values of the saved run as default input values for other runs of the same type tool (e.g. GROWER, IRR, LOCATION, REALTIME, etc.).

## 2. Uploading input files

Technical users may wish to upload their own input files. Files that may be uploaded include: weather (\*.WTH), irrigation (\*.IRR), solution fertilizer (\*.SFN), and plant spec (\*.PLT). Files uploaded will be stored under the user's account. It is very important to follow the formatting rules indicated. To help with this, examples can be copied and pasted to serve as templates for creating the input files needed. Once uploaded, these files will be saved under the account name and will be available to the user.

## 3. Automate runs

When using the Real-time Irrigation Scheduling Tool to automatically control irrigation, the user can use 'Automate runs' to select a time that the saved run will be automatically resubmitted on a daily basis. Additional details of automatic irrigation control will be discussed in the Real-time Irrigation Tool section below.

## B. Output

There are four types of output:

1) **Daily Time Plots** (Grower and Technical Tools only). You can choose to see output for individual years or the mean of all years. Individual plots can be saved by right clicking the plot and selecting 'Save image as'. Plots are time-stamped with the current version of CCROP.

2) **Summary Charts**. Charts give mean, median, min, and max values for the range of years the simulation was run. Individual plots can be saved by right clicking the plot and selecting 'Save image as'. Plots are time-stamped with the current version of CCROP.

3) **Summary Tables**. Tables include data for each simulation year as well as simple statistics. Tables can be downloaded by clicking the yellow 'Download' icon.

4) **View Output Files**. Output files and some input files can be accessed in text file format. These text files can be saved and imported into a spreadsheet file as needed.

By clicking '**Generate Reports**' in output tabs, the user can select which output to print out in a report.

## C. CCROP Tools

1. **Tool overview** Several tools are available depending upon the user's objective.

**Grower Tool** - Simulation is based on one set of inputs. User-selected inputs are limited to factors that have more critical impact (e.g. plant date, location, fertilizer, irrigation). Output is detailed and includes daily time-plots.

**Comparison Tools** - Simulations compare several levels of a given factor (e.g. location, plant date, fertilizer rate, irrigation) keeping all other inputs constant. Output is more limited than for Grower Tool.

**Real-time Irrigation Tool** – Simulation is designed to assist the user in day-to-day irrigation scheduling.

**Technical Tool** – For technical users, allows all CCROP inputs to be accessed. All output variables may be viewed. Inputs are metric.

## 2. Grower Tool

### A. Select container size.

1. **Trade #1**: container diameter = 16 cm (6.3 inch); substrate volume = 2400 cm<sup>3</sup>
2. **Trade #3**: container diameter = 28 cm (11 inch); substrate volume = 10,000 cm<sup>3</sup>

### B. Select location nearest your nursery

Location determines the weather input file that will be used. Two types of historical weather files are available:

1. **FAWN**- downloaded daily from the Florida Automated Weather Network – 35 locations. FAWN weather stations have variable years of weather data which limit the number of yearly simulation runs. Details of each weather station can be viewed by mousing over the respective station on the map.

2. **Long-term historical** (>30 yrs) – 9 locations. These long-term data sets typically contain weather data from the 1960s to early 2000s. These are weather files are not updated.

### C. Select plant start date

The date selected will be the start day and year. The start day (e.g March 3) will be the same for all years the simulation was run. If the start year was not changed, simulations will be run for each year in the weather data set.

### D. Select end year

The year selected will be the last year to run the simulation.

### E. On what basis do you want to finish the crop? Criteria for finishing yearly simulations

1. **Finish the crop after a fixed number of weeks**
2. **Finish the crop when the following plant height is reached**

### F. Spacing arrangement Determines the area allotted each container.

1. **Square spacing**
2. **Triangular spacing**

**G. Container move schedule** Determines if and when containers will be spaced. Tool does not permit more than one move.

1. **Don't move** Same spacing will remain throughout simulation
2. **Move containers after fixed number of weeks** Enter weeks after planting to move.
3. **Move based on model recommendation** Containers will be moved when LAI reaches 4.

**H. Container spacing after move** Enter new spacing if containers are to be moved.

### **I. Select irrigation schedule**

1. **Fixed daily rate** Same irrigation amount will be applied each day. If rain shutoff sensor is selected, irrigation will not be applied if 'yesterday's rain exceeded irrigation amount. Up to three changes in the fixed irrigation rate can be input.
2. **Model recommended rate** Irrigation applied is based upon resupplying the container substrate with water lost through evapotranspiration. The default managed allowable deficit (MAD) for the Grower Tool is 10% which means no water will be applied if the water deficit in the container substrate is less than 10% of the available water-holding capacity of the substrate. The irrigation rate takes into consideration the capture factor, CF, which describes the ability of the plant to capture water that would otherwise fall between containers.

### **J. Fertilizer detail**

1. **Fertilizer rate** Entered one of two ways. Selecting either way automatically calculates the equivalent rate in the other units.
  - a) lb N per cubic yard (typical industry rate), or
  - b) g fertilizer per container
2. **Enter percent total N** The percent of N in fertilizer.
3. **Enter percent controlled-release N** The percent of controlled-release N in fertilizer which may be less than percent total N.
4. **Enter the longevity of the fertilizer** The longevity rating of the fertilizer in months is converted to days in CCROP by multiplying months by 30.5.

### **K. Defaults Not modifiable by Grower Tool**

1. Initial Leaf area=150 cm<sup>2</sup>, initial ht=14 cm width=12 cm;
2. Initial N and P concentration are optimal
3. SWLL=0.25, SWDUL=0.5, TP=0.75 PVLf=3.5
4. No supplemental topdress fertilizer
5. No supplemental solution fertilizer
6. Plants are pruned 4 cm (1.6 inch) when plant height reaches 27 cm (10.6 inch). For trade #3 containers a second pruning is made when plant height reaches 42 cm (16.5 inch).



**3. Comparison Tools** These tools compare two or more levels of a given factor keeping all other inputs constant.

1. **Fertilizer** Compares up to four different fertilizer rates
2. **Irrigation** Compares fixed irrigation schedules with MAD (ET-based) schedule.
3. **Fertilizer and irrigation** Evaluates the interaction of two different fertilizer rates and two different irrigation schedules.
4. **Plant date** Compares two or more planting dates
5. **Location** Compares two or more locations

**4. Real-time Irrigation Tool**

**5. Technical Tool**