Calibration and Validation of Complex and Simplified Tomato Growth Models for Control Purposes in the Southeast of Spain

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Abstract

The tomato crop growth models TOMSIM and TOMGRO have been calibrated and validated for total dry matter production and calibrated for fruit dry matter production in greenhouses located in Southeast of Spain. The parameter estimation was carried out in such a way that the models can be used to simulate the main dynamics of tomato crop growth with differences less than 10% in total dry matter estimation in both models; 2.4% for number of nodes and 6.4% for LAI in TOMGRO; 3.4% for truss appearance in TOMSIM. The dynamic of tomato crop growth is represented by both models in acceptable way. Based on the preliminary results these tomato crop growth models can be used for control purposes.

INTRODUCTION

In order to apply a three level hierarchical climate greenhouse control strategy in which the middle level is related to control of the crop development, where time scales are governed by physiological processes (Rodriguez et al., 2001), it is important to develop and validate reliable tomato growth models. In this control approach the computational time is important as the control is performed in real time (typical time basis of one minute due to the climate variable control). The models for simulating the dynamic of tomato growth have many state variables; e.g. TOMGRO v1.0 has 69, (Jones et al., 1991), TOMGRO v3.0 has 574 (Kenig and Jones, 1997), the tomato model by De Koning (1994) has more than 300 for a mature plant, TOMSIM reaches 34 for a crop growing by 100 days. The use of many state variables often involves problems with dimensionality or high computational cost. Therefore it is important to use reduced growth models aimed at decreasing the computational cost without affecting significantly the capability of the model to predict the dynamic of tomato growth and yield. On the other hand, a complex model is also required as a reference for accurately describing the dynamic of the growth. In this work the TOMGRO reduced model (Jones et al., 1999) with five state variables and TOMSIM (Heuvelink, 1996, 1999) have been implemented, calibrated and validated for total dry matter and calibrated for fruit dry weight, under the specific conditions (climate conditions, greenhouse structures, agronomical practices and greenhouse management strategies) of Almería (Spain). These models cited before are representative tomato crop growth models with differences in their underlying hypotheses, and it is important to test the adaptability of them. The main results of the parameters estimation and validation processes of these tomato growth models are shown in this paper.

MATERIALS AND METHODS

Experimental Data

Data from measurements for calibration and validation have been obtained using two experimental sets with plants of *Lycopersicon esculentum* ‘Ramy’, grown in Rockwool® substrate with recirculation of nutrient solution, at two plant densities, 3.04 m^{-2} and 4.02 m^{-2} . The experiments were carried out in a controlled climate greenhouse

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of plastic cover with a range of temperature between 11.5 °C and 35 °C, photosynthetic photon flux density (PPFD) between 50 and 850 μmol m^{-2} s^{-1} and without CO_2 artificial supply (range between 180 and 394 μmol mol^{-1}), which are typical conditions of an automated greenhouse in the Southeast of Spain. The tomato crop was planted when plants had an average of 10.8 true leaves. It was grown only with the main stem, pruning the secondary shoots, and flowers were pollinated with the aid of bumble-bees. Electrical conductivity and pH of nutrient solution were maintained within appropriate ranges. The greenhouse roof was whitened with calcium bicarbonate according to the growers practice. Data of temperature, photosynthetic active radiation (PAR) and CO_2 were measured with sensors located on the canopy and recorded each minute. In order to calibrate and validate the models, fresh and dry weight of stem, leaves and fruits and leaf area were measured periodically, ten times between 1 and 98 days after planting with a sample of three or six plants each time. Another different data set from a tomato crop grown during 262 days was used to test the model behaviours in a large crop cycle. The range of the climate variables in this experiment were: temperature between 9.8 °C and 42.0 °C, PPFD between 5 and 1600 μmol m^{-2} s^{-1} and CO_2 concentration between 290 and 1400 μmol mol^{-1}.

The Simplified and Complex Tomato Growth Models

The models tested in this paper are mechanistic ones based on photosynthesis: TOMGRO reduced state-variable (Jones et al., 1999) and TOMSIM aggregated model (Heuvelink, 1996; Heuvelink, 1999).

The simplified model used is TOMGRO with the following five state variables to be used for optimal control purposes (Jones, et al., 1999): number of nodes (N), leaf area index (LAI), fruit dry matter (W_F), above-ground biomass accumulation (W) and mature fruit biomass accumulation (W_M). The main equations corresponding to the dynamics of the number of nodes and leaf area index, which are functions of temperature. The dynamics of the total dry matter production and distribution in fruit and mature dry weight are dependent of photosynthesis and respiration processes, based on temperature, CO_2 concentration and PAR radiation. These equations are shown in Table 3.

The complex model used was the TOMSIM model (Heuvelink, 1996; Heuvelink, 1999), which estimates the dynamic of growth and development for tomato crop using the following state variables: leaf area index, total dry matter and fruit dry matter. The development and growth can be known in great detail: truss by truss, vegetative units and rate of flowering appearance which let us to model effects of climate variables on the tomato growth, very important for optimal climate control purposes. The model use a pool of assimilates and the distribution to organs of the plant is done according to strength of each sink. The equations in Table 4 represent the dynamic of this model. The constants and equations for photosynthesis were taken from Heuvelink (1996) for TOMSIM and from Jones et al., (1991) for TOMGRO.

Models were programmed in Simulink-Matlab and then were run in a computer for calibration and validation purposes. All variables in TOMGRO are calculated each minute. TOMSIM photosynthesis is calculated each minute but state variables are calculated once a day.

Calibration and Validation Procedures

In a first phase, two sets of data were used, one for calibration and the other for validation purposes with a short crop cycle. The first set (calibration) uses data of an experiment with plant density of 3.04 plants m^{-2} and the other (validation) of an experiment with 4.02 plants m^{-2}. The calibration process was made testing parameters to fit the state variables (Table 1 shows the parameters calibrated in TOMGRO). Mature fruit dry weight was not recorded. In order to estimate the fruit dry matter only the calibration process was carried out because only one data set was at hand. Constants were taken from Jones et al. (1999). In TOMSIM, the parameters listed in Table 2 are important to estimate photosynthesis and total dry matter (Bertin and Heuvelink, 1993;

Heuvelink, 1996). Specific leaf area (SLA) was not recorded; therefore LAI in TOMSIM is an input. An approach using potential truss growth rate was applied for fruit dry weight.

The values of the parameters of physiological processes (photosynthesis) and empirical parameters involved in both models (Tables 1 and 2), have been obtained using a direct sequential search to obtain approximate values using a least squares identification method. In a second step, a genetic algorithm has been used to refine them. The used error was the sum of error calculated in each sample time during the 98 days.

The study of the model formulation robustness based on the variation of the optimal obtained parameters has been performed with a sensitivity analysis, consisting on the calculation of the least squares for twenty values of the model parameters, in a variation interval of ±10% with respect to their optimal values. These analyses were made with all the parameters listed in Tables 1 and 2.

In a second phase, a data set of a large crop cycle has been used for validation purposes.

RESULTS

TOMGRO Reduced Model

The Fig. 1A-C show both simulation and measured data used for validation purposes. The simulation has a mean relative error of 2.4%, 6.4% and 8.8% for number of nodes, LAI and total dry weight respectively. The simulation graphs follow the growth dynamic in acceptable way. Fig. 1D shows the dynamic on fruit dry weight using calibration data. Using another data set for a large crop cycle with 262 days, different cultivar and substrate, the simulation and measures for total and fruit dry weight is illustrated in Fig. 3A-B, the difference is 10.3% for total dry weight and 21% for fruit dry weight, underestimating dry weight.

The values of parameters estimated for a short crop cycle, 98 days after transplanting, are given in Table 1. The parameters are compared with references used to estimate variables in other works. Fig. 4 shows the sensitivity of the parameters on the state variables, where it can be seen the important effect of δ and N_b on LAI in 4C and mean daytime temperature (*Tcrit*) above which there is abortion on fruit dry weight shown in Fig. 4D. Total dry weight is highly influenced by light use efficiency(α), light extinction coefficient (*CK*), CO_2 use efficiency (τ) and of course the coefficient of conversion to dry matter (*CE*).

TOMSIM Model

The obtained parameter values are shown in Table 2, being very similar or equal to those used in Heuvelink (1996), except for the respiration parameter (f).

Fig. 2A-B show the fit between the simulated and the measured data in the number of trusses and total dry weight. The absolute average error between simulated and measured data was 3.2% for truss appearance and 8.8% for total dry weight. Fig. 2D shows the simulation on fruit dry weight, and Fig. 4D shows the simulation for growth of 2nd, 3rd and 5th trusses. The response of this model to the large crop cycle data provides an error of 10% for total dry weight and 11% for fruit dry weight.

This model is sensitive to the effect of light use efficiency in absence of oxygen, the extinction coefficient for diffuse radiation as the Fig. 4B shows. The light scattering coefficient and the respiration coefficient have a little effect on estimations.

DISCUSSION

TOMGRO is simple but is acceptable for greenhouse control purposes, based on the preliminary results, with differences between predicted and measured values in a range between 8 and 10.3% in total dry weight. TOMSIM follows the dynamic of the growth with differences less than 10%. However, if the dynamic of trusses growth is required, TOMSIM is necessary because its characteristics on dynamic between vegetative units and fruits are very useful in order to apply different strategies to resource optimization.

Sensitivity analysis has been performed to the inputs of the models (Bertin and Heuvelink, 1993) to the estimated parameters. The inputs have usually been evaluated on main variables (dry matter or LAI) and internal parameters in relation to gross photosynthesis or respiration (Heuvelink, 1996; Nederhoff and Vegter, 1994). In this work the effect of some parameters on main state variables (i.e. total dry matter or LAI) is presented. It is evident the high influence of light use efficiency on total dry weight on both models (Fig. 4A-B). The light extinction coefficient has less effect but anyway important.

Although the validation is limited, based on these results we can conclude TOMGRO reduced and TOMSIM models for tomato crop growth can be used for applications in hierarchical greenhouse control architecture based on two aspects. First, their outputs present an acceptable behavior in all the modeled variables under the South-East Spain conditions, even though the error for large cycle is higher than 10% for TOMGRO, notice that the available sample data number is limited (only four measurements along the cycle). More experimental data are being obtained to complete the validation of the models. On the other hand, the running time is satisfactory in both models in order to obtain set point trajectories for control issues because the elapsed time for one simulation process of 98 days was 0.25 s for TOMGRO and 0.2 s in TOMSIM to estimate total dry matter, running both model implementations on a computer with microprocessor 2.1 GHz and 384 Mb of RAM.

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Tables

Table 1. Parameters estimated for reduced TOMGRO growth model.

Parameter	Description	Value	Range of estimation	Values reported by other authors	Variable
N_m	Max. rate of nodes	0.495	0.1 – 0.9	0.50 *	N
N_b	Param. in expolinear eq.	13	8 – 25	16 *	LAI
δ	Max. leaf area expantion	0.041	0.01 – 0.1	0.030	LAI
β	Param. in eq. expolinear	0.22	0.06 – 0.5	0.169 *	LAI
V_{max}*	Max. increase per node	6	2 – 12	8 *	Tdw
α**	Light efficiency	0.09	0.01 - 0.5	0.0645 **	Tdw
τ**	CO2 efficiency	0.12	0.01 – 0.5	0.0693 **	Tdw
CK**	Ext. coef. for radiation	0.61	0.3 – 0.9	0.58 **	Tdw
CE**	Coef. Conv. to dry matter	0.74	0.5 – 0.9	0.7 **	Tdw
T_{crit}*	Critic temperature	24	17 – 29	24.4*	Fdw
α_F	Partitioning to fruit	0.95	0.1 - 0.95	0.95*	Fdw
ν	Transition vegetative-fruit	0.24	0.05 – 0.9	0.20*	Fdw

*Jones et al., 1999; ** Jones et al., 1991

Table 2. Parameters estimated for TOMSIM.

Parameter	Description	Value	Range of estimation	Values reported by Heuvelink 1996	Variable
f	Respiration parameter	1.067	1-40	33	Tdw
CK^+	Extinction coef. for diffuse radiation	0.712	0.5-0.9	0.72	Tdw
Eo^+	Light efficiency	0.084	0.05-0.10	0.084	Tdw
σ^+	Scattering coefficient	0.14	0.08-0.30	0.15	Tdw

Tdw-Total dry weight ; Fdw-Fruit dry weight; + Heuvelink, 1996

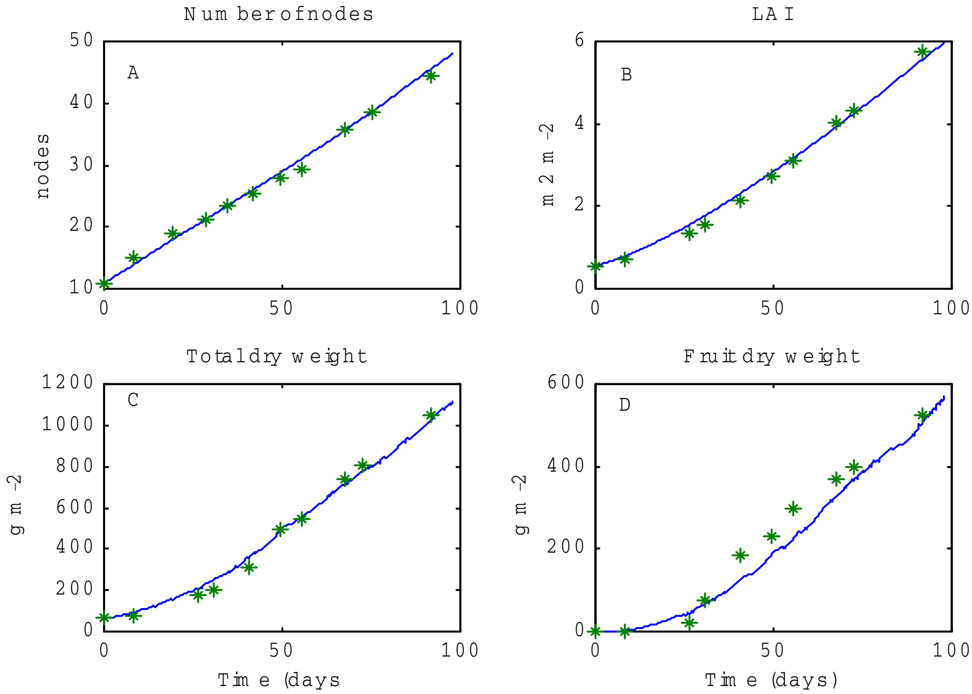
Table 3. Equations used in TOMGRO.

Equation		Description	Units
		α_F - max. partitioning new growth to fruit	d^{-1}
$\frac{dN}{dt} = N_m * f_N T$	(1)	β - coefficient in expolinear equation	$node^{-1}$
		δ - max. leaf area expansion per node	m^2 $node^{-1}$
		$\lambda(T_d)$ - temperature function to reduce leaf area	(-)
$\frac{d(LAI)}{dt} = \rho\delta\lambda(T_d)\frac{\exp[\beta(N-N_b)]}{1+\exp[\beta(N-N_b)]}*\frac{dN}{dt}$	(2)	ρ - plant density	plants m^{-2}
		p_1 - loss of leaf dry weight per node	g $node^{-1}$
		υ - transition coefficient	$node^{-1}$
		$f_N T$ - function to modify node development rate	(-)
$\frac{dW}{dt} = GR_{net} - p_1\rho(\frac{dN}{dt})$	(3)	$f_F(T_d)$ - function to modify partitioning to fruit vs average daily temperature	(-)
		$g(T_{dia})$ - function to reduce growth	(-)
		GR_{net} - net aboveground growth rate	g m^{-2} d^{-1}
$\frac{dW_F}{dt} = GR_{net}\alpha_F f_F(T_d)\left[1-e^{-\upsilon(N-N_{FF})}\right]g(T_{dia})$	(4)	LAI - leaf area index	m^2 m^{-2}
		N - number of nodes	(-)
		N_b - coefficient in equation (2)	node
$\frac{dW_M}{dt} = D_F(T_d)(W_F - W_M)$	(5)	N_{FF} - nodes per plant when first fruit appears	node
		N_m - maximum rate of nodes	node d^{-1}
		W - above ground dry weight	g m^{-2}
		W_F - fruit dry weight	g m^{-2}
		W_M - mature fruit dry weight	g m^{-2}
		$D_F(T_d)$ - Rate of development of fruit vs daily temperature	min^{-1}
		t - time	min

Table 4. Equations used in TOMSIM.

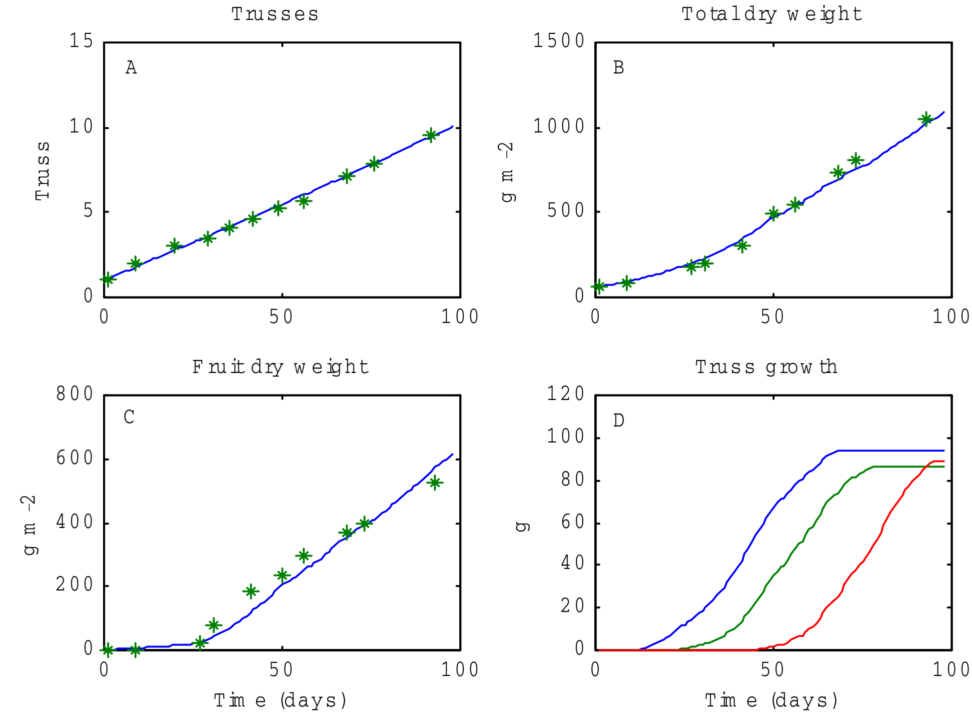
Equation		Description	Units
$FR = -a_1 + b_1\ln(T)$	(6)	a - parameter	g f.d.w. d^{-1}
		a_1 - parameter	truss d^{-1}
		b, b_1, c, d - parameters	(-)
$\frac{dW_{tm}}{dt} = C_f(P_{gc,d} - R_m)$	(7)	f - regression coefficient parameter	(-)
		t - time	d
		C_f - conversion efficiency	g dw g^{-1} CH_2O
$R_m = R'_m(1-e^{-f*RGR})$	(8)	$FDVR$ - fruit development rate of $N_f/2$ fruit on the truss	d^{-1}
		FR - flowering rate	truss d^{-1}
$TDVS_t = TDVS_{t-1} + FDVR_t$	(9)	N_f - Number of fruits per truss	(-)
		$P_{gc,d}$ - crop gross assimilation	gCH_2O m^{-2} d^{-1}
		PGR - potential growth rate of tr uss	g d^{-1}
$PGR_t = \frac{N_f ab(1+e^{-b(TDVS_t-c)})^{\frac{1}{1-d}}}{(d-1)(e^{b(TDVS_t-c)}+1)}$	(10)	$PFGR$ - potential fruit growth rate	g d^{-1}
		$PVGR$ - pot. growth of vegetative unit	g d^{-1}
		R_m - maintenance respiration rate	gCH_2O m^{-2} d^{-1}
$PVGR_{i,t} = 3.59e^{-0.168(T-19)}PFGR_{i,t}$	(11)	R'_m - max. maintenance respiration rate	gCH_2O m^{-2} d^{-1}
		RGR - relative growth rate	(-)
		TDVS - truss development stage, based on $N_f/2$ flower on the truss	(-)
		T - mean 24 h temperature	ºC
		W_{tm} - total dry matter in TOMSIM	g m^{-2}

Figures



_____ simulated * measured

Fig. 1. Measured and simulated variables using TOMGRO, (A) Number of nodes, (B) leaf area index, (C) total dry weight, (D) fruit dry weight.



_____ simulated * measured

Fig. 2. Simulated and measured variables using TOMSIM (A) number of trusses, (B) total dry weight, (C) fruit dry weight (D) growth simulation of trusses 2nd, 3rd and 5th.

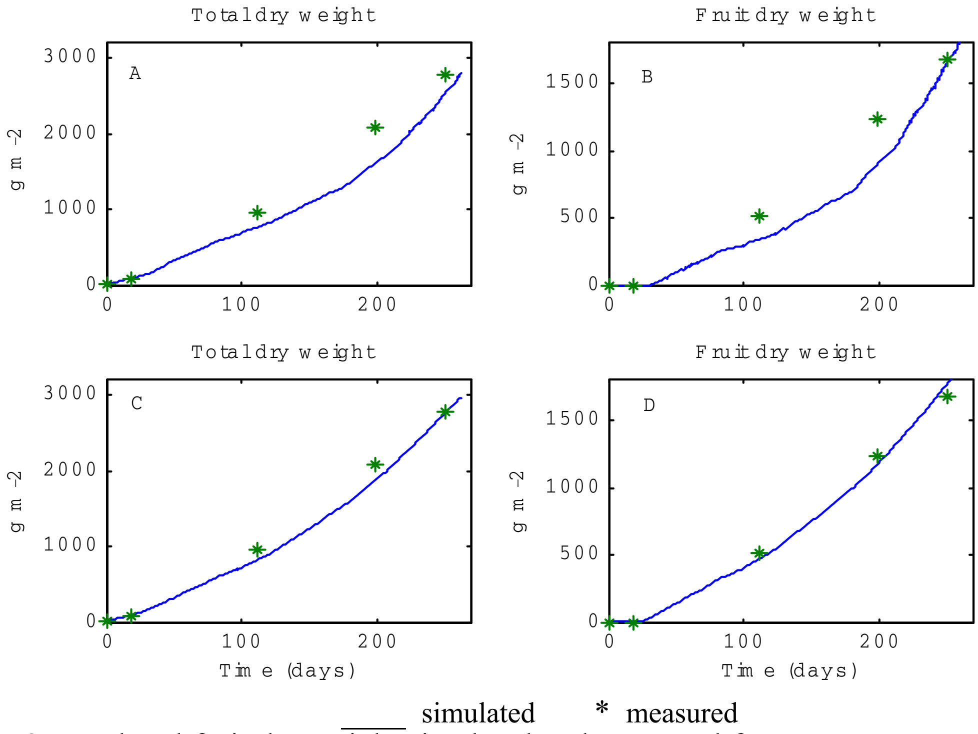


Fig. 3. Total and fruit dry weight simulated and measured for tomato crop grown during 262 days. (A) and (B): TOMGRO; (C) and (D): TOMSIM.

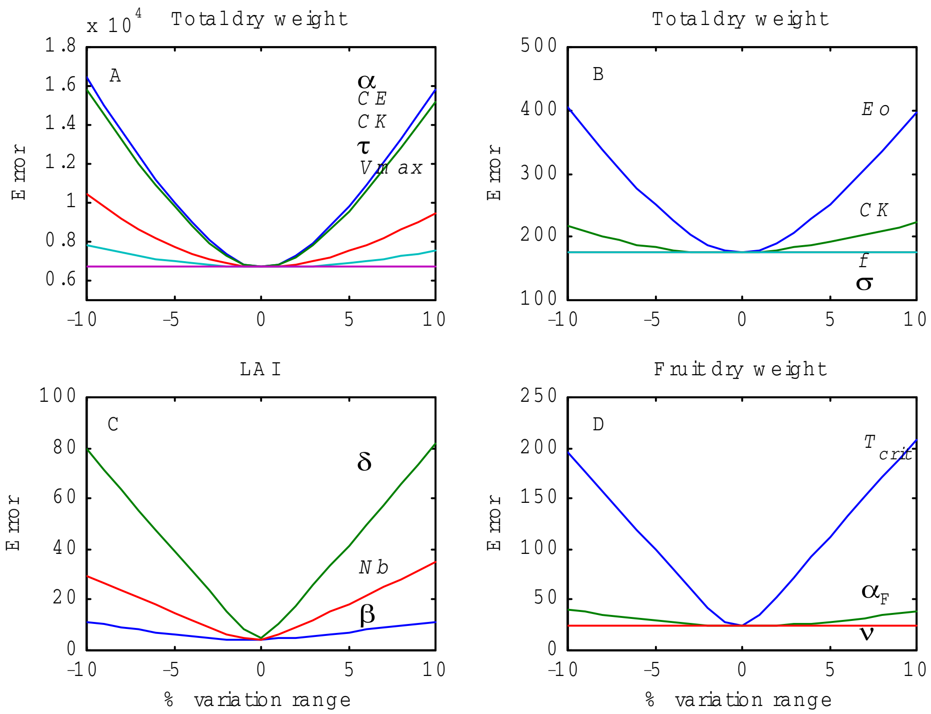


Fig. 4. Sensitivity of parameters. (A) for total dry weight in TOMGRO; (B) for total dry weight in TOMSIM; (C) for LAI in TOMGRO; (D) for fruit dry weight in TOMGRO.