



Validity of the pineapple crop model SIMPIÑA across the climatic gradient in Réunion Island



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ABSTRACT

Models used for designing cropping systems and for responding to cropping problems caused by climate variations must generate accurate predictions. Here, we describe the SIMPIÑA model, which simulates the development and growth of the 'Queen Victoria' pineapple cultivar and which accounts for stress resulting from nitrogen and water deficiencies. We present the calibration and the validation of SIMPIÑA with 15 independent data sets derived from experiments carried out on Réunion Island and covering wide ranges of climatic conditions and management practices. Comparison of simulations with data sets shows that the predictive accuracy of SIMPIÑA is very good, with relative RMSE values ranging from 0.06 to 0.19 for plant fresh biomass; such precision is sufficient for informing management decisions. Interestingly, there was no bias between observed and simulated values. A process-removal approach allowed us to determine how stress processes resulting from water or nitrogen deficiency influence the predictive capacity of the model across a broad range of climatic conditions. There was no clear trend for the effect of climate on model error in comparisons of the model with stress processes removed. When stress processes were partially removed from the model, fruit biomass error was particularly high when the effect of stress was removed from the radiation conversion efficiency and from biomass remobilization. Given its ability to correctly predict crop dynamics under contrasting conditions, SIMPIÑA appears to include the essential processes at the correct level of complexity.

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1. Introduction

Computer models are increasingly used by agronomists to design sustainable and innovative cropping systems for many different situations (Bergez et al., 2010; Loyce and Wery, 2006; Rossing et al., 1997). To predict crop performances, most crop models (e.g., CROPSYST (Stockle et al., 2003), DSSAT (Jones et al., 2003), APSIM (Keating et al., 2003), and STICS (Brisson et al., 1998)), are process-based and simulate soil–plant–environment interactions. In some cases, ad hoc models are developed to account for specific constraints on yield of particular crops or of production in particular contexts. In all cases, the predictive capacity of crop models is the core of their usefulness in agriculture. A crop model must be valid for many different situations to

be useful for the design of cropping systems (Vermeulen et al., 2013), or the study of climate change effects (Laderach et al., 2011).

The validity domain of a model depends partly on the quality and quantity of data (including their range) used for model parameterization and evaluation and on the level at which processes are described (Affholder et al., 2012). Model complexity is not a guarantee of validity (Boote et al., 1996; Sinclair and Seligman, 1996), and which processes are included depends on model objectives (Affholder et al., 2012). Recently, researchers proposed the use of model reduction approaches to evaluate the adequacy of a model's structure and to select the most appropriate level of complexity (Affholder et al., 2003; Cox et al., 2006; Crout et al., 2009, 2014; Kimmins et al., 2008). In addition to comparing observed and simulated outputs in order to assess the predictive capacity of a crop model, this approach attempts to elucidate the key processes that determine crop yield and the critical phases in the crop's development under various cultural practices and climatic conditions.

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In the current report, we describe and evaluate a model of pineapple production. Pineapple farms are high input systems that use large quantities of mainly nitrogen (N) fertilizers (Fournier, 2011), which can severely impact tropical environments. Water is also important at most stages of pineapple development (Combres, 1983), and irrigation is widely used. Optimizing the management of N fertilization and irrigation is thus important to pineapple farmers and to the environment. Such optimization requires an accurate, process-based model to simulate pineapple growth and development while accounting for differences and changes in mineral and water resources.

Pineapple ('Queen Victoria' cultivar) was the first fruit to be produced on Réunion Island, which is an island country located in the Indian Ocean, east of Madagascar. Pineapple is grown under a wide range of conditions on Réunion Island, where the elevation ranges from 50 m to 900 m a.s.l. and annual rainfall ranges from 500 mm to 5000 mm. Pineapple pests are nearly absent in the country, which makes it easier to assess the effects of water and N stresses on plant development and yield under different climatic conditions. Pineapple production on Réunion Island is thus very useful for investigating which processes and factors determine the validity of a crop model across a climatic gradient. An unusual feature of pineapple production on Réunion Island is that harvest occurs every month of the year because floral induction is controlled by the farmer.

Existing pineapple production models predict fruit development based on heat-units (Fleisch and Bartholomew, 1987; Fournier et al., 2010). A more comprehensive model was developed, the ALOHA-Pineapple model (Malezieux et al., 1994; Zhang, 1992; Zhang et al., 1997) based on the CERES-Maize model (Jones and Kiniry, 1986), which simulates the growth, development, and yield of the 'Smooth Cayenne' cultivar. However, this model was calibrated only in locations with low thermal variability and did not test low input scenarios.

In this paper, we present the SIMPIÑA model, which simulates the development and growth of the 'Queen Victoria' pineapple cultivar under various climatic conditions and N and water management practices on Réunion Island. The new model simulates water and nitrogen balances and estimates stress coefficients that affect pineapple growth and development. After developing the SIMPIÑA model based in part on published reports and on data derived from two experiments carried out in research station, we evaluated the accuracy of the model by comparing model outputs with data from 15 independent data sets covering a broad range of soil and climatic conditions. We then used a process removal approach to test how stress processes influence the predictive capacity of the model across a range of climatic conditions. Finally, we discuss whether the SIMPIÑA model has an appropriate level of complexity.

2. Materials and methods

2.1. Experimental data

The model was calibrated and tested with two independent data sets from Réunion Island. First, irrigation and fertilizer experiments were used to calibrate the model. Then, 15 independent data sets from different climatic zones (from 150 to 700 m a.s.l.) were used to test the model. All data sets used for calibrating and testing are presented in Table 1. In all experiments, temperature, rainfall, evapo-transpiration (ETP), and total radiation (Rg) were recorded with a Campbell ScientificTM meteorological station (Sheperd, UK), which was located beside the plot and at 1 m above the soil surface. When irrigation was applied, plots were drip irrigated under plastic mulch.

2.1.1. Calibration experiments with irrigation and fertilization

The calibration experiments with irrigation and fertilizer were conducted at the Bassin Plat Research Station on Réunion Island (see Table 1 for elevation and other background information). Plots used for irrigation and fertilizer experiments, which are described in the following paragraphs, were planted with 'Queen Victoria' pineapples in September 2011 on plastic mulch at a density of 88,000 plants ha⁻¹. Flowering was induced by applying ethephon (Ethrel, Bayer, SA) at 3 L ha⁻¹, 245 days after planting. In both experiments, one replicate corresponded to one ridge, with a specific sucker weight. The planted suckers weighed 275 g for one replicate, 225 g for two replicates, and 175 g for one replicate. Each month, eight pineapple plants were collected from each replicate and each treatment. Dry weight and fresh weight were determined for leaves, roots, stems, peduncles, inflorescences, fruits, and crowns. In addition, the number of fruitlets per fruit was determined. In both experiments, we measured 1920 plants and 960 fruits. Because control treatments (R) in irrigation and fertilizer experiments received the same amount of water and fertilizer (optimal irrigation and 300 kg of N ha⁻¹) and did not significantly differ between the two experiments (for plant weight at flowering induction, ANOVA $p=0.41$; for fruit biomass at harvest, ANOVA, $p=0.98$), we merged their data in the analyses.

Two irrigation treatments were tested in one calibration experiment: with drip irrigation (R), based on tensiometer readings and following technical recommendations (Fournier, 2011), and without irrigation (I0). The pineapples were planted with standard fertilization of 300 kg of N ha⁻¹ (i.e., 650 kg of urea) and 450 kg of potassium ha⁻¹ (i.e., 900 kg of sulfate) following technical recommendations (Fournier, 2011). Of the total fertilizer applied, 20% was applied in solid form before planting, and the remainder was applied as a solution at 7, 12, 16, 20, 23, 26, and 28 weeks after planting.

Three N fertilization treatments were tested in a second calibration experiment: 300 (R), 150 (N150), and 0 (N0) kg of N ha⁻¹. Of the total fertilizer applied, 20% was applied in solid form before planting, and the remainder was applied as a solution at 7, 12, 16, 20, 23, 26, and 28 weeks after planting. Each treatment was drip irrigated based on tensiometer readings and following technical recommendations (Fournier, 2011).

2.1.2. Model testing data sets

As noted earlier, 15 experiments were used for model testing. Experiments P1–P6 were used to determine the accuracy of vegetative growth predictions, and experiments F1–F9 were used to determine the accuracy of predictions of fruit biomass at harvest and date of harvest (Table 1). Pineapple plants were collected each month during the vegetative stage (during 6–8 months, depending on the year of planting and the elevation) in experiments P1–P6, which were managed identically following the conventional techniques used on Réunion Island, i.e. optimal irrigation and 300 kg of N ha⁻¹ (Fournier, 2011). A total of 594 plants were measured. Fruit biomass and date of harvest were determined in experiments F1–F9 (but experiments F3 and F4 were used only for date of harvest because fruit biomass data were not collected), which were managed with one of two levels of N fertilization. Some "F experiments" received a standard fertilization of 300 kg of N ha⁻¹, and others received only 150 kg of N ha⁻¹. A total of 712 fruits were measured on 1313 harvest dates.

2.2. Model description

2.2.1. Model structure

SIMPIÑA was developed using STELLA[®] (software environment from High Performance System[®], Lebanon, NH). Pineapple plant growth and fruit development at the field scale were simulated

Table 1
Data sets used for calibration and validation of the SIMPIÑA model.

Location (and use)	Data sets ^a	Fertilization (kg N ha ⁻¹)	Irrigation	Elevation (m)	Year	Density (plants ha ⁻¹)	Annual rainfall (mm)	Number of data
Bassin Plat (55° 29' 20.64" E, 21° 19' 21.62" S) (calibration)	R	300	Yes	150	2012	88,000	556	676
	I0	300	No	150	2012	88,000	556	344
	N150	150	Yes	150	2012	88,000	556	333
	N0	0	Yes	150	2012	88,000	556	322
Bassin Plat (55° 29' 20.64" E, 21° 19' 21.62" S) (validation)	P1	300	Yes	150	2007	55,000	1050	96
	P2	300	Yes	150	2007	110,000	1050	111
	P3	300	Yes	150	2008	55,000	776	83
	P4	300	Yes	150	2008	110,000	776	97
	P5	300	Yes	150	2009	55,000	770	95
Tampon (55° 32' 21.06" E, 21° 17' 3.59" S) (validation)	P6	300	No	650	2006	100,000	1871	112
Bassin Plat (55° 29' 20.64" E, 21° 19' 21.62" S) (validation)	F1	300	Yes	150	2007	98,000	1050	69
	F2	300	Yes	150	2010	66,000	766	131
	F3	150	Yes	150	2011	66,000	537	278
	F4	150	Yes	150	2012	66,000	556	323
Bérive (55° 31' 10.59" E, 21° 17' 10.21" S) (validation)	F5	300	No	550	2010	83,000	877	122
	F6	150	No	550	2010	83,000	877	124
Saint Benoit (55° 42' 12.86" E, 21° 05' 53.85" S) (validation)	F7	300	No	340	2010	63,000	4005	90
	F8	150	No	340	2010	63,000	4005	104
	F9	300	No	275	2009	88,000	3616	72

^a Notations in this column refer to treatments in the two calibration experiments (one concerning irrigation and the other concerning N fertilization) and to names of validation data sets.

as affected by daily changes in soil N and soil water. Biophysical processes were determined according to three process-based modules, i.e., plant growth, water balance, and N balance. Pineapple development was divided into four stages: planting to initiation of dry matter production; the initiation of dry matter production to floral induction (artificially induced by the farmer); floral induction to flowering; and flowering to harvest. Flowering and harvest processes were determined based on a sum of degree days (SDD(t)) using a different base temperature for each development stage. The growth of pineapple was based on radiation interception, conversion to dry biomass (DM), and partitioning of DM into compartments: roots, leaves, stem, peduncle, inflorescence, fruit, crown, and suckers. After flowering, DM partitioning depended on the demand of each organ. DM of each organ was converted to fresh biomass (FM) to simulate pineapple yield. Model parameters, variables, and equations are presented in Tables 2–4, respectively.

2.2.2. Pineapple growth and development module: SIMPIÑA-CROP

Pineapple fresh biomass (gFM) is simulated in three steps: (i) estimation of dry matter production by the leaves; (ii) dry matter partitioning between organs; and (iii) accumulation of water stock in each organ. Dry matter production was calculated according to Monteith's equation (Monteith, 1972) (Eq. 1).

Dry matter production was initiated after a number of days calculated (IGR) since planting. The light energy conversion efficiency (Eb) varies according to phenological stage. The quantity of dry matter produced was calculated based on the radiation intercepted by the pineapple (Eq. 2). The leaf area index (LAI(t)) was calculated with a constant specific leaf area multiplied by the foliar biomass newly produced at each time step. LAI(t) was reduced by senescence (Eq. 3). Initial foliar biomass is set to the dry sucker biomass at planting.

Biomass newly produced was allocated to roots, stem, and leaves from planting to floral induction, and to peduncle and inflorescence from floral induction to flowering, with specific allocation coefficients and without priority rules (Table 2). These coefficients were constant for roots, peduncle, and inflorescence whereas the biomass allocated to the stem and leaves varies with the sum of degree-days (Eqs. 4 and 5). At flowering, the biomass newly produced was allocated to fruit, crown, and sucker according to

their demand with a priority to fruit. The remaining daily biomass produced was partitioned into leaves and stem according to a coefficient of partitioning (psurplus). Fruit demand was calculated as the demand of a fruitlet multiplied by the number of fruitlets per fruit. As demonstrated by Malezieux (1988), the number of fruitlets was estimated from an asymptotic function of fresh vegetative biomass at floral induction. We assumed that no competition occurred between fruitlets in pineapple fruit, as suggested by the absence of a relationship between fruitlet biomass and number of fruitlets in a fruit (Prudent et al., 2012). Fruitlet demand was simulated by a potential sigmoidal growth curve as proposed for other fruits (Léchaud et al., 2005; Lescouret et al., 1998) (Eq. 6). We assumed a linear relationship between crown demand and fruit growth because crown removal has no effect on fruit growth (Chen and Paull, 2009) (Eq. 7). We assumed that the crown is not a source of carbohydrates for fruit growth. Sucker demand changed as a function of SDD(t) (Eq. 8). The harvest, which occurs when SDD(t) rises a threshold (SDD_m) that depends on planting density (Eq. 9).

The dry matter of each organ was converted to fresh matter by adding a volume of water, which depends on the dry biomass newly formed per organ and the specific water content per organ. Stem, leaves, and fruit water contents varied as a function of SDD(t) after planting for stem and leaves and after flowering for fruit (Eqs. 10–12).

2.2.3. Water balance module: SIMPIÑA-WATER

The SIMPIÑA-WATER water balance module simulates soil water content, drainage, and run-off. The soil was considered to be a water reservoir that is increased by rainfall and irrigation and decreased by crop evapotranspiration, drainage and run-off (Eq. 13). Total available soil water content for the crop (TAW) varied between soil water content at the field capacity and soil water content at the permanent wilting point (Eq. 14). TAW increased with root depth (Zr) (Eq. 15). The readily available soil water (RAW) in the root zone was that fraction of the total available soil water content that the crop can extract without suffering water stress (Eq. 16). Water inputs were defined as the sum of rainfall (Ra(t)) and irrigation (I(t)). The water balance calculated accounted for the following characteristics of pineapple systems: the design of pineapple leaf arrangement allows the canopy to retain a significant quantity of water in the leaf axils after rainfall. Once the

Table 2
SIMPIÑA model parameters.

Parameters	Unit	Description	Value	Source
<i>SIMPIÑA - CROP</i>				
$T_{bf}; T_{brec}$	°C	Base temperature for physiological development stage (from planting to flowering/from flowering to harvest)	8.34/9.24	Fournier et al. (2010); Lechaudel et al. (2010)
SDD _{fl}	°C d	Thermal time interval from floral induction to flowering	813	Fournier (pers. Com.)
$a_h; b_h$	°C d; °C d ha plant	Parameter of SDD _h as function of density	1298; 1.7	Lechaudel et al. (2010)
GR	Days	Time from planting to biomass production initiation	25	Calibrated
aGR	d	Growth delay parameter	3	Calibrated
Eb	g MJ ⁻¹	Light energy conversion efficiency (from planting to biomass production/from biomass production to floral induction/from floral induction to flowering;/from flowering to harvest stages).	0.8/1.6/1.6/2	Calibrated
TSDDEb	°C d	Threshold of sum of degree-day for Eb initiation	600	Calibrated
pEbW	%	Percentage of decrease in light energy conversion efficiency after water stress	50	Calibrated
pEbN	%	Percentage of decrease in light energy conversion efficiency after N stress	35	Calibrated
pREM	%	Percentage of potential biomass remobilization	10	Calibrated
LOSSsuckini	g gDM ⁻¹	Initial sucker rate decrease	0.02	Calibrated
Ea	–	Maximum interception efficiency	0.95	Varlet-Grancher et al. (1989)
Ec	–	Proportion of PAR intercepted	0.48	Gosse et al. (1986)
k	–	Extinction coefficient	0.3	Malézieux (1991)
SLA	m ² g ⁻¹	Specific leaf area	0.005	Observed
ksen	LAI ⁻¹	Senescence rate	0.001	Calibrated
ALro	–	Fraction of dry biomass allocated to roots	0.018	Observed
aALstem; bALstem;cALstem	–	Parameters of dry biomass allocated to stem as function of SDD(t)	2.92·10 ⁻⁶ ; 0.0193; 40	Observed
ALped	–	Fraction of dry biomass allocated to peduncle	0.15	Observed
ALinf	–	Fraction of dry biomass allocated to inflorescence	0.12	Observed
psurplus	%	Percentage of remaining assimilates allocated to leaves/stem	70/30	Calibrated
aNF; bNF	–	Parameter of fruitlet number as a function of FM _{fl}	–2224.41; 12.44	Malezieux (1988)
RGR	g g ⁻¹ °C d ⁻¹	Relative fruit growth rate	0.002524	Observed
maxDMfruitlet	gDM	Maximal dry fruitlet biomass	0.12; 4.05	Observed
Wcont	g g ⁻¹	Water content of crown/inflorescence/peduncle/roots/initial sucker planted/sucker	0.86/0.88/0.88/0.6/0.83/0.86	Observed
aWstem,bWstem,cWstem	–	Parameters of stem water content as function of SDD(t)	–1.82·10 ⁻⁸ ; 1.26·10 ⁻⁴ ; 0.66	Observed
iniWfruit	–	Initial fruit water content	0.86	Observed
aWfruit,bWfruit	–	Parameters of fruit water content as function of SDD(t)	–2.60·10 ⁻⁶ ; 1.30·10 ⁻³	Observed
minWleav,maxWleav	–	Minimal/Maximal leaf water content	0.8; 0.86	Observed
TSDDWleav	°C d	Threshold of sum of degree-day for Wleav (t)	2900	Calibrated
aDEM _{crown} ,bDEM _{crown}	–	Parameters of crown demand as a function of DMfruit (t)	0.14; 0.69	Observed
aDEM _{suck} ,bDEM _{suck}	–	Parameters of sucker demand as a function of SDD (t)	0.0148; 0.004	Observed
piniWfruit	%	Percentage decrease in initial fruit water content	5	Observed
pbWfruit	%	Percentage decrease in fruit water content parameter	2.5	Observed
pREM	–	Fraction of dry biomass potentially remobilized at step 't'	0.1	Calibrated
<i>SIMPIÑA - WATER</i>				
kR	–	Rainfall infiltration coefficients (before 60/between 60 and 120/after 120 days after planting)	0.4/0.5/0.8	Combres (1983)
LAI _{mid}	m ² m ⁻²	Threshold of LAI for rainfall interception	5	Calibrated
aLAI, bLAI, cLAI	–	Parameters of Rint as a function of LAI(t)	0.0559; –0.2028; 1.168	Calibrated
pTAW	%	Percentage of total soil water content readily available	50	Combres (1983)
kc	–	Crop coefficient	0.35	Allen et al. (1998)
pZr	–	Roots depth parameter	0.3	Calibrated
<i>SIMPIÑA - NITROGEN</i>				
kL	–	Leaching coefficient	0.1	Calibrated
Npot	g g ⁻¹ DM	Potential N content	0.013	Py et al. (1984)
Tstress	–	Threshold of daily stress	0.5	Calibrated
Tstresssum	–	Threshold of sum of stress	35	Calibrated

Table 3
Description of variables of the SIMPIÑA model.

Variables	Unit	Description
<i>SIMPIÑA - CROP</i>		
SDD(t)	°C d	Sum of degree-days at step (t)
SDD _{th}	°C d	Thermal time interval between flowering and harvest
SDD _r (t)	°C d	Sum of degree-days from flowering stage at step (t)
d	plant ha ⁻¹	Planting density
T(t)	°C d	Temperature at step (t)
ΔDM(t)	gDM plant ⁻¹	Dry biomass newly formed at step (t)
PARI(t)	MJ m ⁻²	Photosynthetically active radiation intercepted at step (t)
RG(t)	MJ m ⁻²	Total radiation at step 't'
LAI(t)	m ² m ⁻²	Total leaf area index at step (t)
kLAI(t)	m ² m ⁻²	Leaf area for rainfall interception (t)
DMsuckini(t)	gDM plant ⁻¹	Dry biomass of initial sucker planted at step (t)
ALleav(t)	–	Fraction of dry biomass allocated to leaves at step (t)
FM _{fi}	g plant ⁻¹	Fresh biomass at floral induction
NF	–	Number of fruitlets per fruit
DEMfruit(t)	gDM plant ⁻¹	Fruit demand at step (t)
DMfruitlet(t)	gDM plant ⁻¹	Dry biomass of fruitlet at step (t)
DMfruit(t)	gDM plant ⁻¹	Dry biomass of fruit at step (t)
DEMsuck(t)	gDM plant ⁻¹	Sucker demand at step (t)
DEMcrown(t)	gDM plant ⁻¹	Crown demand at step (t)
DMstem(t)	gDM plant ⁻¹	Stem dry biomass at step (t)
DMleav(t)	gDM plant ⁻¹	Leaf dry biomass at step (t)
Wleav(t)	g gFM ⁻¹	Leaf water content at step (t)
Wstem(t)	g gFM ⁻¹	Stem water content at step (t)
Wfruit(t)	g gFM ⁻¹	Fruit water content at step(t)
IGR	days	Time interval to initiation of dry matter production
<i>SIMPIÑA - WATER</i>		
SW(t)	mm	Soil water stock at step (t)
D(t)	mm	Drainage at step (t)
I(t)	m ⁻³	Irrigation at step (t)
R(t)	mm	Rainfall at step (t)
Rint(t)	mm	Rainfall intercepted in the leaf axils (t)
ET(t)	mm	Evapotranspiration at step (t)
TAW(t)	mm	Total available soil water content at step (t)
RAW(t)	mm	Readily available soil water content at step (t)
Fc	–	Field capacity
PWP	–	Permanent wilting point
Zr(t)	mm	Root depth at step (t)
MET(t)	mm	Maximal evapotranspiration at step (t)
ETo(t)	mm	Potential evapotranspiration at step (t)
Wstress(t)	–	Water stress at step (t)
Wstresssum(t)	–	Cumulative water stress at step (t)
<i>SIMPIÑA - NITROGEN</i>		
F(t)	kgN ha ⁻¹	Mineral N fertilized at step (t)
MINSOIL(t)	kgN ha ⁻¹	Soil mineral N at step (t)
S(t)	kgN ha ⁻¹	N mineralized from soil organic matter at step (t)
U(t)	kgN ha ⁻¹	Mineral N uptake at step (t)
L(t)	kgN ha ⁻¹	Mineral N leached at step (t)
SON	kgN ha ⁻¹	Soil organic N content
k2	–	Parameter of mineralization of soil organic nitrogen content
Nstress(t)	–	Water stress at step (t)
Nstresssum(t)	–	Cumulative water stress at step (t)

With t the time step of the model in days.

Table 4
Principal equations of the SIMPIÑA model.

No	Equation
1	ΔDM(t) = Eb. PARI(t)
2	PARI(t) = Ea. Ec. RG(t). (1 – exp(–K. LAI(t)))
3	LAI(t) = LAI(t – 1) + (SLA. DMleav(t)) – LAI(t – 1). ksen
4	ALstem(t) = aALstem. SDD(t) ² – bALstem. SDD(t) + cALstem
5	If (SDD _r (t) = 0) Then {ALleav(t) = 1 – (ALro + ALstem(t))} Else {ALleav(t) = 1 – (ALro + ALstem(t) + ALped + ALinf)}
6	DEMfruitlet(t) = RGR. DMfruitlet(t). (SDD(t) – SDD(t – 1)). (1 – (DMfruitlet(t)/maxDMfruitlet(t))). NF
7	demCROWN(t) = (aCROWN. biomsFRUIT(t) + bCROWN) – (aCROWN. biomsFRUIT(t – 1) + bCROWN)
8	If (SDD _r (t) = 0) Then {DemSUCK = (aSUCK. SDD(t) – aSUCK. SDD(t – 1))} Else {DemSUCK = 0}
9	SDD _{th} = a _h + (b _h . d)
10	Wstem(t) = aWstem. SDD(t) ² + bWstem. SDD(t) + cWstem
11	If (SDD(t) < TSDDWleav) Then {Wleav(t) = maxWleav – (maxWleav – minWleav)/TSDDWleav. (TSDDWleav – SDD(t))} Else {Wleav(t) = maxWleav}
12	If (SDD _r (t) = 1) Then {Wfruit(t) = iniWfruit + (aWfruit. SDD _r (t) + bWfruit)} Else {Wfruit(t) = aWfruit. SDD _r (t) + bWfruit}
13	SW(t) = SW(t – 1) + I – ET
14	TAW(t) = (Fc – PWP). Zr(t)
15	Zr(t) = pZr. FM(t) {with Zrmin < Zr(t) < Zrmax}
16	RAW(t) = pTAW. TAW(t)
17	Rint(t) = kLAI. R(t). kR
18	If (LAI(t) < LAI _{mid}) Then {kLAI = 1} Else {kLAI = aLAI. LAI(t) ² – bLAI. LAI(t) + cLAI}
19	MET(t) = kc. ETo(t)
20	ET(t) = MET(t). Wstress(t)
21	If (SW(t) < = RAW(t)) Then {Wstress(t) = SW(t)/RAW(t)} Else {Wstress(t) = 1}
22	If (SW(t) > RAW(t)) Then {D(t) = SW(t) – RAW(t)} Else {D(t) = 0}
23	MINSOIL(t) = MINSOIL(t – 1) + F(t) + S(t) – U(t) – L(t)
24	If (TAW > 0) Then {L(t) = MINSOIL(t). (1 – exp(–kL. (D(t)/TAW))} Else {L(t) = 0}
25	If (MINSOIL(t) < (ΔDM(t). Npot) Then {U(t) = MINSOIL(t)} Else {U(t) = (ΔDM(t). Npot)}
26	If (ΔDM(t). Npot = 0) Then {Nstress(t) = 1} Else {Nstress(t) = (U(t)/(ΔDM(t). Npot)}
27a	IGR = GR + (aGR. Wstresssum(t))
b	If (TIME < IGR & Wstress(t) < TWstress) Then {LOSSsuckini = 1} Else {LOSSsuckini = 0}
c	If (Wstress(t) or Nstress < TWstress) & (Wstresssum(t) or Nstresssum(t) > Tstresssum) Then {ΔDM(t) = Eb.pEbW. PARI(t) or ΔDM(t) = Eb.pEbN. PARI(t)} Else {ΔDM(t) = Eb. PARI(t)}
d	If (Wstresssum(t) > Tstresssum) Then {Wfruit(t) = iniWfruit. piniWfruit + (aWfruit. SDD _r (t) + bWfruit)} Else {Wfruit(t) = iniWfruit + (aWfruit. SDD _r (t) + bWfruit)}
e	If (Nstresssum(t) > Tstresssum) Then {Wfruit(t) = iniWfruit + (aWfruit. SDD _r (t) + bWfruit. pbWfruit)} Else {Wfruit(t) = iniWfruit + (aWfruit. SDD _r (t) + bWfruit)}
f	If (DEMfruit > ΔDM(t)) & (Wstresssum(t) or Nstresssum(t) > Tstresssum) Then {DEMfruit(t) = DMfruit(t – 1) + ΔDM(t) + pREM. (DMleav(t) + DMstem(t))} Else {DEMfruit(t) = DMfruit(t – 1) + ΔDM(t)}

plants grow and the canopy covers both mulch surface and the open areas, more rain water is captured by the plants and funneled to the plastic mulch (Eqs. 17 and 18). Moreover, the use of a plastic mulch reduced soil evaporation (Dusek et al., 2010). Thus, water input linked to rainfall was calculated from rainfall incorporated into the soil according to an infiltration coefficient, which varied from 0.4 at planting to 0.8 from 4 months after planting to harvest (Combres, 1983). Rainfall not incorporated into the soil corresponded to a volume of water run-off. Water outputs were defined by: evapotranspiration (ET(t)), which was based on: the reference evapotranspiration, a crop coefficient, *kc*; and a water stress coefficient, *Wstress*(t) (Eqs. 19 and 20). The water stress coefficient was calculated using the ratio between readily available soil content (RAW) and soil water content (Eq. 21). When the water content exceeded TAW, drainage occurred (Eq. 22).

2.2.4. N balance module: SIMPIÑA-NITROGEN

The N balance module was adapted from the model proposed by Dorel et al. (2008). It simulates at a daily step the mineral N dynamics in soil based on fertilization and soil organic matter mineralization as inputs and crop uptake and leaching as outputs (Eq. 23). Given the soil characteristics typical in pineapple production, we assumed that N volatilization and denitrification were negligible and could be ignored (Payet et al., 2009; Stevenson, 1994). We considered that only mineral fertilizers are applied and that N from fertilizers is transferred to soil mineral N at time of application. The quantity of mineral N produced by soil organic matter mineralization was a function of soil organic N content. The quantity of mineral N that is leached was calculated at a daily step using an adaptation of the equation of the NLEAP model designed by Schaffer et al. (1994) (Eq. 24). The potential plant N concentration at step *t* was calculated as a function of crop dry matter according to the curve of N dynamics related to dry biomass proposed for pineapple by (Py et al., 1984). Potential plant N concentration was used to determine the daily crop N demand. We assumed that crop N uptake is driven by crop dry matter production as simulated by the SIMPIÑA-CROP module (Eq. 25). The N stress coefficient was calculated as the ratio between N demand and N uptake (Eq. 26).

2.2.5. Effects of water and N stress in the SIMPIÑA-CROP module

Water and N stresses altered both pineapple growth and development. We used the daily stresses (*Wstress*(t) and *Nstress*(t)) and the sum of daily stress values between planting and time step *t* (*Wstresssum*(t) and *Nstresssum*(t)) to represent an effect of the accumulation of stresses during development. Stresses were considered to have effects only when they exceed a threshold (*Tstress* and *Tstresssum*). The following seven growth and development parameters were altered by water and N stresses:

- The parameter *aGR*, which was a function of *Wstresssum*(t), extends the interval between planting and beginning of growth as expressed in the variable *IGR* (Eq. 27a);
- The rate of initial sucker decrease (*LOSSsuckini*) was activated when *Wstress*(t) is < *TWstress* during *IGR* (Eq. 27b);
- The light energy conversion efficiency (*pEbW* and *pEbN*) was decreased when *Wstress*(t) or *Nstress*(t) was < *TWstress* from planting to floral induction and when *Wstresssum*(t) or *Nstresssum*(t) was > *Tstresssum* from floral induction to harvest. Because the effects of stresses on the value of *Eb* were not cumulative, the minimum *Eb* value calculated was used if the two stresses occur at the same time (Eq. 27c);
- *pinIWfruit* decreased the initial fruit water content (*iniWfruit*) when *Wstresssum*(t) > *Tstresssum* (Eq. 27d);
- *pbWfruit* decreases the bias parameter of fruit water content equation (*bWfruit*) when *Nstresssum*(t) > *Tstresssum* (Eq. 27e);

- To satisfy fruit demand, dry biomass may be remobilized first from leaves (*pREM*) and from stem if was is not sufficient. Remobilization is only activated when *Wstresssum*(t) or when *Nstresssum*(t) > *Tstresssum*. Consequently, the dry biomass of leaves and the stem could decreased after flowering (Eq. 27f).

2.2.6. Model calibration

Most parameters were based on published information (Table 2). *Eb*, *pZr*, *TSDD*, *TSDDWleav*, *ksen*, *GR*, *aGR*, *LOSSsuckini*, *pEbW*, *pEbN*, *pREM*, *psurplus*, *kL*, *Tstress*, and *Tstresssum* were estimated using an iterative procedure to minimize the root mean square error (RMSE) of the pineapple vegetative biomass and fruit biomass over treatments.

2.3. Model evaluation

2.3.1. Statistical analysis

We compared the observed and predicted values of plant weights during vegetative growth for data sets P1–P6, and of fruit biomass and date of harvest for data sets F1–F9. The accuracy of model predictions was evaluated through the relative root mean squared error (RRMSE) (Kobayashi and Us Salam, 2000), which is a common criterion to quantify the mean difference between simulation and measurements:

$$RRMSE = \frac{\sqrt{1/N \sum_{i=1}^N (y_i - \hat{y}_i)^2}}{\bar{y}}$$

where *y_i* is the observed value, *ŷ_i* the corresponding simulated value, *N* the number of observed data, and $\bar{y} = \sum_{i=1}^N y_i / N$ the mean of observed values.

2.3.2. Sensitivity analysis

We analyzed the sensitivity of the model to each parameter using climatic and management inputs of the control treatment (R). Sensitivity to model parameters was investigated for plant biomass at floral induction and for fruit biomass at harvest. The model was considered sensitive to a parameter when a 20% change in the parameter's value changed model output for vegetative or fruit biomass by >3%. This threshold was chosen according to expert and because it is an acceptable threshold for farmers to manage their crop.

2.3.3. Importance of water and N stress for the model's predictive capacity

For all data sets (calibration and validation experiments), we compared fruit biomass at harvest between the full SIMPIÑA model and other versions of the model in which stress processes were removed. The comparison of models allowed us to assess the relative importance of stress processes on the predictive capacity of the model over contrasting climatic and cultural conditions. Two methods were used for these comparisons.

In the first method, fruit biomass at harvest (*Y*) was simulated after total removal of stress processes from three model formulations: (i) the full model (M); (ii) the model without water stress processes (*M_{0W}*); and (iii) the model without N stress processes (*M_{0N}*) (Table 5). The percentage of deviation $((Y_M - Y_{M0}) \cdot 100) / Y_M$ between fruit biomass (*Y*) simulated by M and fruit biomass simulated by *M_{0W}* and *M_{0N}* was determined. To test whether the predictive capacity of the model was altered by climatic variables, we analyzed fruit biomass errors (%) as a function of temperature, total radiation, evapotranspiration, and rainfall.

In the second method, fruit biomass at harvest (*Y*) was simulated after partial removal of stress processes. This was accomplished by separately removing each parameter in the model affected by water stress and N stress (*aGR*, *LOSSsuckini*, *pEbW*, *pEbN*, *pinIWfruit*,

Table 5
Summary of stress parameters removed in reduced models from the SIMPIÑA model.

Model	Model parameter						
	aGR	LOSSsuckini	pEbW	pEbN	piniWfruit	pbWfruit	pREM
M	–	–	–	–	–	–	–
M0 _w	X	X	X	–	X	–	–
M0 _N	–	–	–	X	–	X	–
M1	X	–	–	–	–	–	–
M2	–	X	–	–	–	–	–
M3	–	–	X	–	–	–	–
M4	–	–	–	X	–	–	–
M5	–	–	–	–	X	–	–
M6	–	–	–	–	–	X	–
M7	–	–	–	–	–	–	X

The signs ‘–’ and ‘X’ indicate that the stress mechanism parameter was retained or removed, respectively. The value of remobilization parameter pREM is not null if N stress occurs in M0_w or if water stress occurs in M0_N.

pbWfruit, and pREM) in models M1 to M7 (Table 5). The percentage of deviation (fruit biomass errors) between fruit biomass simulated by model M (no processes removed) and models M1 to M7 (partial removed) was also compared for treatments sorted by level of N fertilizer and climatic area of production (dry, dry irrigable, humid).

3. Results

3.1. Model calibration

An iterative procedure was used to determine the values of GR, ksen, ALrem, TSSWleav, TSDDEb, kL, Tstress, Tstressum, Eb, aGR, pEbW, pEbN, and pREM (Table 2). Observed and simulated dynamics of pineapple plant biomass and fruit biomass were similar for

the three masses of suckers at planting and for the four water and N treatments (Fig. 1). Plant biomass and fruit biomass increased with sucker weight at planting, regardless of water and N treatments. Plant biomass and fruit biomass were lowest for I0 and F0 treatments. Relative RMSE values ranged from 0.06 to 0.15 for plant biomass and from 0.05 to 0.23 for fruit biomass.

3.2. Model evaluation

When evaluated with independent data collected under different weather conditions and planting densities, the model performed well in predicting the vegetative fresh biomass of the pineapple, with RMSE values ranging from 98 to 159 gFM plant⁻¹. The model had no bias, i.e., observed and simulated values

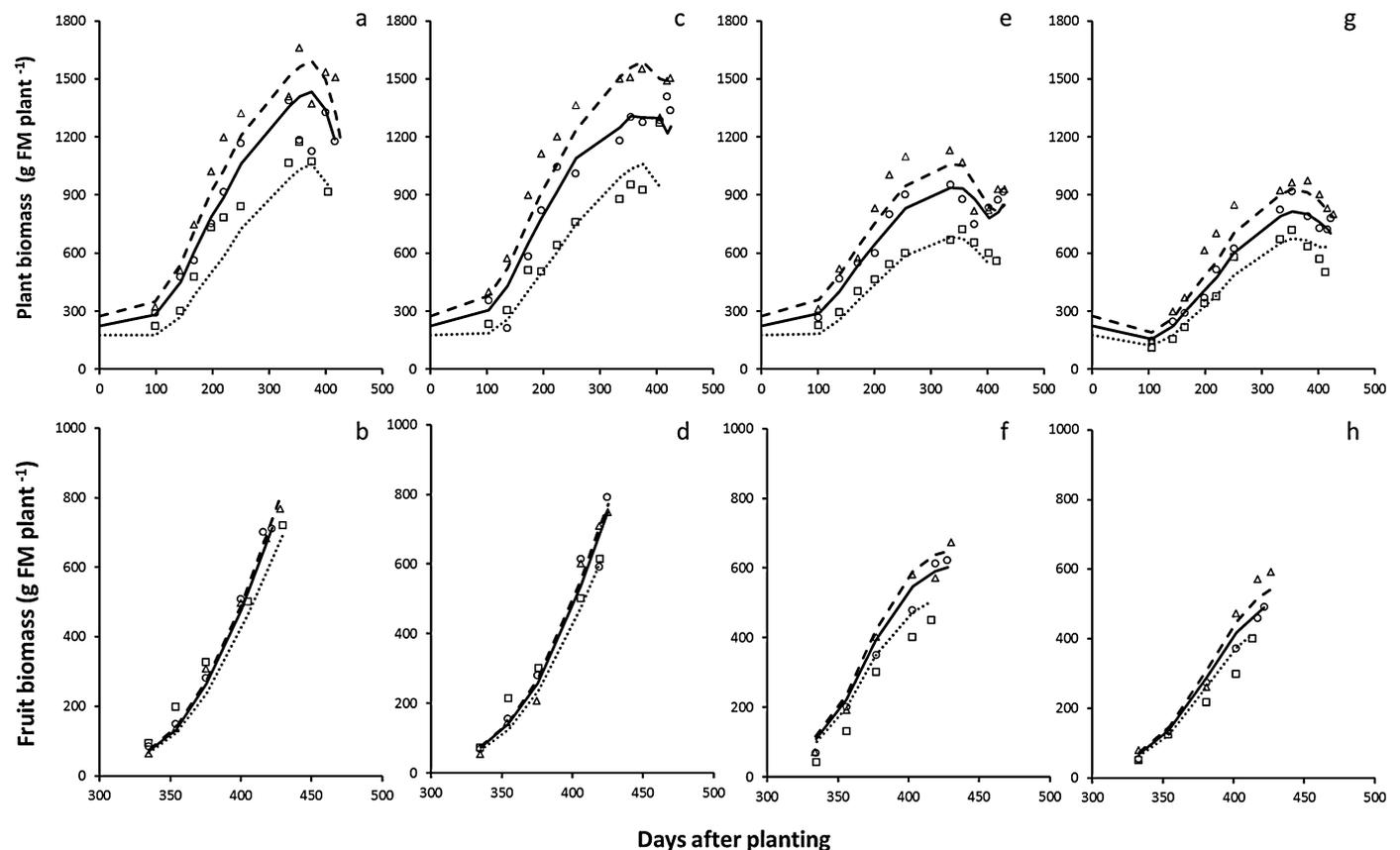


Fig. 1. Simulated and observed data for fresh pineapple plant biomass and pineapple fruit biomass in the calibration experiments as affected by sucker weight at planting and by two water and two N treatments. Observed data are symbols, and simulated data are lines. FM = fresh mass. Sucker weight at planting was 175 g (□, dotted line), 225 g (○, solid line), or 275 g (Δ, dashed line). The water and N treatments, which are summarized in Table 1, were R (a, b), N150 (c, d), N0 (e, f), and I0 (g, h).

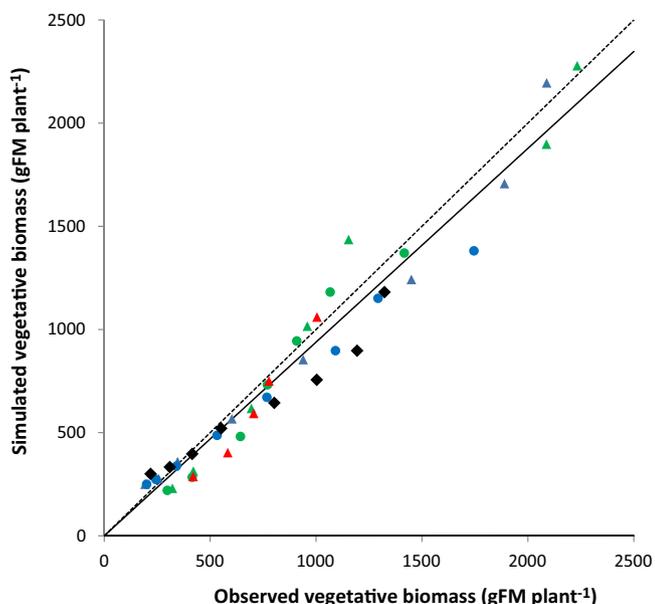


Fig. 2. Observed and simulated vegetative fresh biomass (gFM plant^{-1}) as affected by year (2006: black, 2007: blue, 2008: green, and 2009: red) and plant density ($55,000 \text{ plant ha}^{-1}$: Δ , $100,000 \text{ plant ha}^{-1}$: \diamond , and $110,000 \text{ plant ha}^{-1}$: \circ). The solid line shows the functional regression ($y = 0.94x$, $R^2 = 0.95$). The dotted line is the 1:1 line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

were highly correlated, with a slightly underestimation ($y = 0.94x$, $p < 2e - 16$, $R^2 = 0.95$) (Fig. 2). Fruit biomass at harvest and date of harvest were also accurately simulated by the SIMPIÑA model over a wide range of weather conditions and planting densities, with RMSE values of $22 \text{ gFM fruit}^{-1}$ for fruit biomass and 6 days for date to harvest (Fig. 3a and b).

3.2.1. Sensitivity analysis

Vegetative biomass at floral induction was sensitive to the parameters related to crop characteristics (crop coefficient, k_c), phenology (time from planting to biomass production initiation, GR; threshold of Eb initiation from planting to floral induction stage, TSDDEb), organ water content (TSSDWleav), and stress (threshold

of daily stress, Tstress; growth delay parameter, aGR; and initial sucker rate decrease, LOSSsuckini) (Fig. 4a). Fruit biomass at harvest was also sensitive to parameters related to biomass production (relative growth rate, RGR; extinction coefficient, k), phenology (base temperatures, T_{b_f} and $T_{b_{rec}}$; time from planting biomass production, GR; and sum of degree-day between floral induction to flowering, SDD_{ff}), water stock (parameter of fruit water content, aWfruit), and stress (threshold of daily stress, Tstress) (Fig. 4b).

3.2.2. Response of the model to removal of stress processes

Relative to the full model, the model without water stress processes ($M0_W$) had larger fruit biomass errors than the model without N stress processes ($M0_N$) (Fig. 5). There was no clear trend of the effect of climatic variables on error of $M0_W$ and $M0_N$ compared to the full model. Fruit biomass deviation was the same at low and high annual mean temperature. The effect of annual mean radiation on the errors was never monotonous with biggest errors at 18 and 20 MJ m^{-2} . Concerning ETP, the biggest errors were observed when ETP was < 3.5 and > 4 . Finally, the effect of annual mean rainfall showed no clear trend on fruit biomass deviation. Partial removal of stress processes indicated that fruit biomass error was particularly high when the effect of stress was removed from the radiation conversion efficiency (models M3 and M4) and from biomass remobilization (model M7) (Table 6). Fruit biomass error was negative for model M7. For model M6, only one deviation was observed for N0 treatment. In model M4, fruit biomass error was high for experiments with a low level of N fertilizer in dry and irrigable climatic areas and in humid climatic areas (N0 and F8).

4. Discussion

Comparison of observed and predicted data for the calibration experiments demonstrated that the SIMPIÑA model correctly accounted for the effects of sucker weight at planting and the fertilization and irrigation treatments. Selecting the initial sucker weight is an important management option because it affects the foliar area that in turn determines the initiation of biomass production. We also note that the extreme treatments in the calibration experiments (no irrigation and no N) were simulated with very low errors in fruit biomass (relative RMSE values were 0.12 and 0.14, respectively).

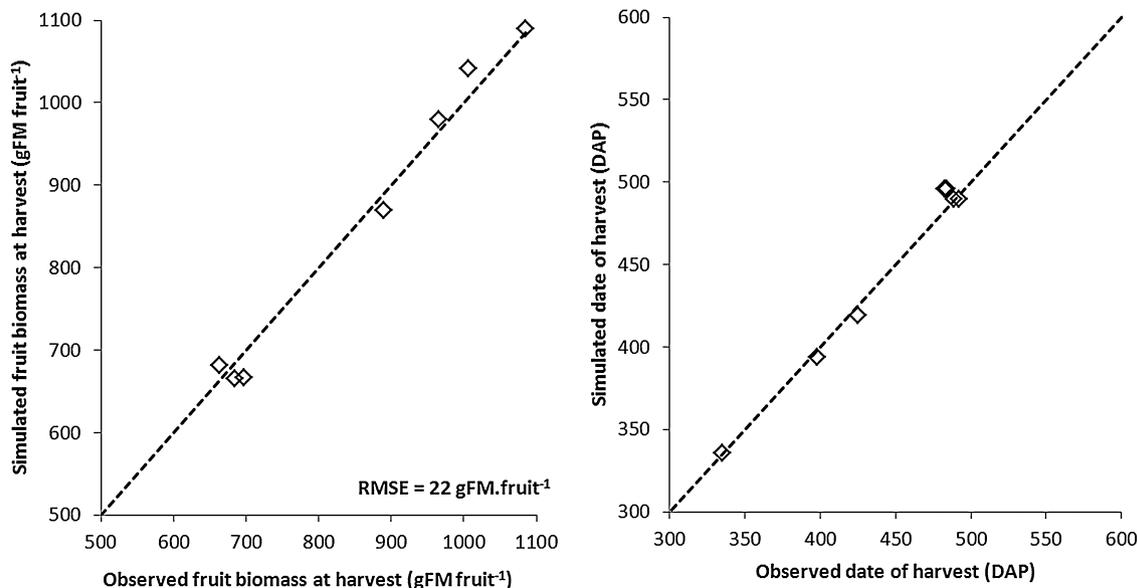


Fig. 3. Observed and simulated (a) pineapple fruit fresh biomass at harvest (gFM) and (b) date of harvest. DAP = day after planting. The dotted line is the 1:1 line.

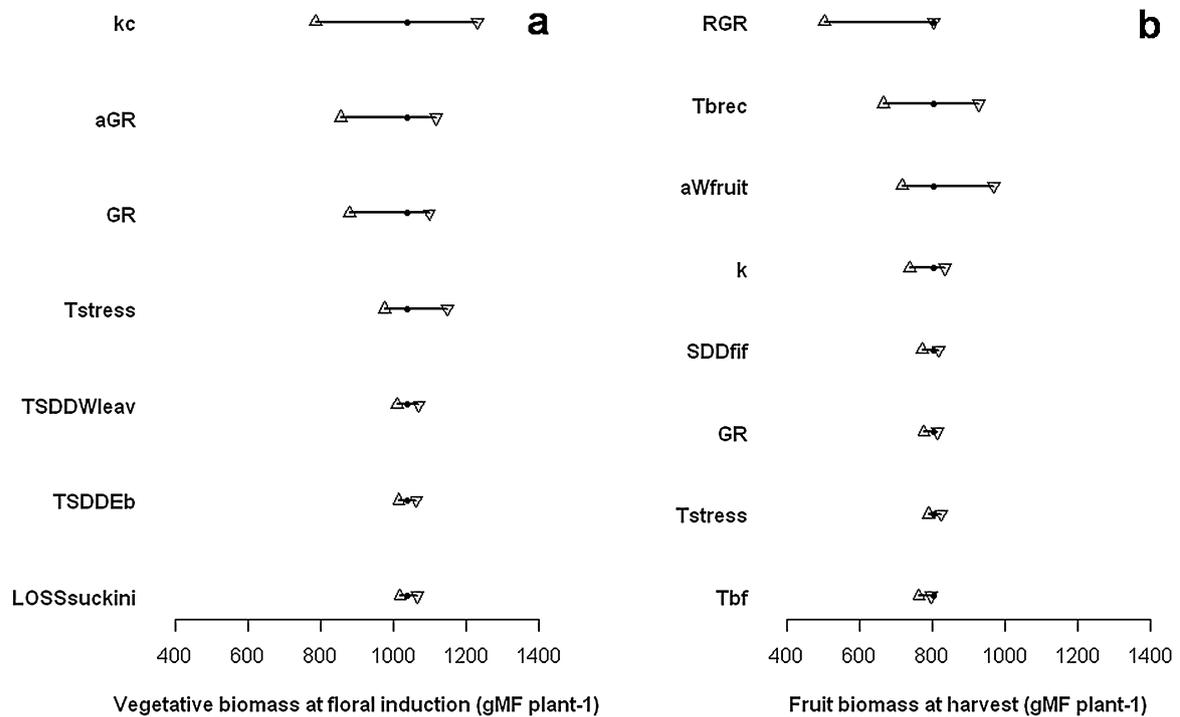


Fig. 4. Analysis of model sensitivity to parameters: mean (●) and values after -20% (△) and $+20\%$ (▽) variations in each model parameter of the (a) vegetative fresh biomass at floral induction and (b) fruit fresh biomass at harvest. Only parameters that showed variations $>3\%$ are presented.

In the validation simulations, there were good agreement between observations and simulations of vegetative plant biomass and fruit biomass at harvest under contrasting conditions of planting density, N fertilization, irrigation, and climate. The model accurately simulated the effect of planting densities, at a range observed in most production systems with others pineapple cultivars (De Souza et al., 2009; Malezieux, 1988), on pineapple growth and development. However, in order to valid the model for others cultivars, growth parameters would be adapted. Many parameters in literature are based on ‘Smooth Cayenne’ cultivar. As shown by Fournier et al. (2010), growth characteristics may differ between cultivar, i.e., number of leaves, the D leaf weight and the plant weight. Contrasted experiments with different cultivars and various fertilization and irrigation practices

under a large range of climatic conditions are required to estimate others cultivars growth parameters in the model. We note that the model accounts for the density effect not by using a correction factor but by estimating interplant competition for radiation and soil resources. Even though the validation data sets covered a broad range of climatic and management effects, there was no bias between simulations and observations. The model accurately simulated the effects of cultural practices, i.e., sucker weight at planting, planting density, and N and water stress across a broad climatic gradient. Furthermore, the overall prediction accuracy was good, with relative RMSE values equal to 0.13, 0.12, and 0.01 for vegetative biomass, fruit biomass, and date of harvest, respectively. Such accuracy is clearly sufficient to help farmers improve their management because cultural

Table 6
Summary of fruit deviation error after partial removal of stress processes in models M1 to M7.

Data sets	Fertilization (kg N ha ⁻¹)	Climatic area	Deviation error with water stress processes removed (%)				Deviation error with N stress processes removed (%)		Deviation error with all stress processes removed (%)
			M1	M2	M3	M5	M4	M6	
I0	300	Dry	40	41	104	12	0	0	-22
F5	300	Dry	19	23	69	13	0	0	-37
F6	150	Dry	14	23	62	10	0	0	-38
F1	300	Dry	0	0	0	0	0	0	0
F2	300	Dry	0	4	0	0	0	0	0
R	300	irrigable	3	6	49	0	0	0	-3
N150	150	irrigable	3	44	76	0	0	0	-35
N0	0	Dry	8	12	10	0	58	-2	-32
F9	300	irrigable	0	0	36	0	0	0	0
F7	300	Humid	0	0	0	0	2	0	-12
F8	150	Humid	0	0	0	0	57	0	-59

The stress parameters removed are listed in Table 5.

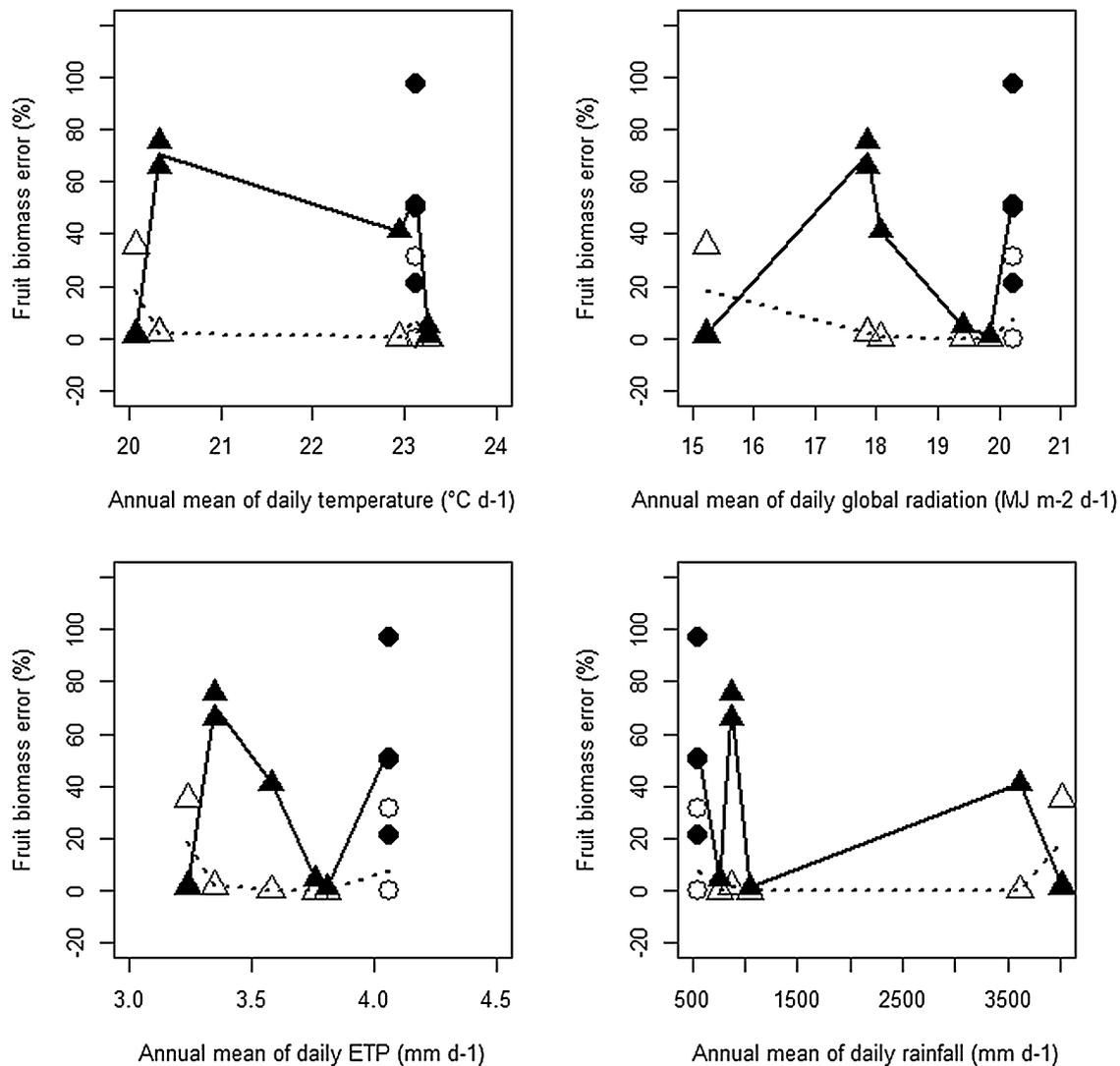


Fig. 5. Fruit biomass deviation (%) compared to the complete model (M0) for the model without water stress processes (model M0_w, black) and without N stress processes (model M0_N, white) as a function of annual mean of daily (a) temperature, (b) global radiation, (c) ETP, and (d) rainfall. Circles represent the calibration experiments and triangles represent the validation experiments. Solid and dotted lines represent the mean value of fruit biomass deviation compared to model M0 for model M0_w and M0_N, respectively.

practices tested in this study represents the range of existing cultural practices.

Vegetative plant biomass was most sensitive to *kc* (crop coefficient), showing that water plays a major role in vegetative biomass production (Combres, 1983; Malezieux, 1988; Py, 1960). The crop coefficient varied during the cropping cycle and generally had three values depending on phenological stage (an initial value, an intermediate value, and a final value): such values can be quite different in sugar cane and other crops (Allen et al., 1998). The crop coefficient for pineapple exhibits only low variation during the three phenological stages and when the crop is grown on plastic mulch, the values were 0.4, 0.2, and 0.2 for the three phenological stages respectively (Allen et al., 1998). Another study also reported minimal variation in *kc* value over pineapple developmental stages (Carr, 2012).

Surprisingly, vegetative plant biomass was also particularly sensitive to parameters related to the delay in the start of biomass production after planting (aGR and GR). This shows that this initial step after planting is crucial and influences the entire vegetative growth period, as previously observed for strawberry (Palha et al., 2011). The threshold at which stress is considered to alter growth (T_{stress}) also greatly influences the production of vegetative biomass. For

instance, the use of stress threshold coefficient strongly improved the prediction of banana crop growth in the SIMBA model (Ripoche et al., 2012). In a mango model, fruit biomass was less sensitive to RGR than to another parameter related to the early phase of fruit development, which was the initial fruit dry mass (Léchaudel et al., 2005). For several fruit species, the early phase of fruit growth is related to cell division and influences fruit mass at harvest (Bertin et al., 2002; Scorza et al., 1991). The extinction coefficient (*k*) also greatly affects fruit biomass in SIMPIÑA, showing that light interception is a major factor influencing biomass production. Overall, the sensitivity analysis in SIMPIÑA showed that biomass production relies on a variety of processes (light interception, stresses, fruit growth, and phenology) and is not dominated by a single process.

The removal of all stress processes from SIMPIÑA (in models M0_w and M0_N, Fig. 5) resulted in large errors in the simulation of fruit biomass relative to the full model (model M0). The variation in the effect of removal was greater with water stress processes (model M0_w) than N stress processes (model M0_N). This result may be explained by the greater diversity in rainfall than in N fertilization in the 11 situations used for model testing. In fact, the absence of mineral N fertilization has been used only recently by a few farmers who are testing organic production. Rainfall,

in contrast, varies greatly with the range in altitude on Réunion Island (from 0 to 900 m a.s.l.). However, there was no clear trend in fruit biomass error with climatic variables. This absence of trend when conditions diverge from those used in calibration suggests that stress can occur across the climatic gradient. It also suggests that cultural practices (irrigation and fertilization) can mitigate stress. Indeed, irrigation and fertilization were in interaction with stress processes thus the monotonous effect of climatic variables on the fruit biomass deviation was partially concealed.

By partially removing stress processes in the model, we attempted to increase our understanding of the effects of N and water stress processes on fruit biomass at harvest and to determine whether the model can be simplified. In half of the cases (Table 6), partial stress removal did not lead to error compared to the full model (model M0). This is in accordance with models M_{0W} and M_{0N} in that the effect of removal of water or N stress processes depended on the situation, suggesting that only certain processes are important and these differ depending on climatic area and cultural practices. Removing the effect of water stress on aGR (model M1) and on LOSSsuckini (model M2) clearly increased the error compared to model M0, especially under dry conditions. Although aGR and LOSSsuckini are both linked to the early phase of plant growth, the error was greater for M2, suggesting that water stress has a greater effect on loss of sucker weight than on the delay in the initiation of biomass production.

We also found that stress greatly affects the conversion of radiation into biomass, i.e., the removal of stress in models M3 and M4 results in high errors relative to model M0. Interestingly, the removal of stress effects on the remobilization of biomass (from leaves and stem to fruit) (model M7) led to negative errors compared to model M0. This means that for seven situations, predicted yield was lower with model M7 than with model M0. Even under conditions that seemed optimal, as in humid and dry irrigable areas, models lacking the reserve remobilization process underestimated fruit biomass. For the 'Smooth cayenne' cultivar, previous research found that foliar reserves constituted 60% of the carbon supply for fruit growth (Malezieux, 1988). This confirms the necessity of including the reserve remobilization process for fruit growth in the SIMPIÑA model. It is important to include all stress effects on model parameters in order to simulate a wide range of climatic conditions and cultural practices. Despite the absence of trends in the relationship between errors in fruit biomass predictions after removing stress processes and climatic conditions, especially rainfall, we note that brief stresses, like water stress on initial sucker weight, could greatly affect pineapple growth and development. Water stress could be an important source of yield loss when it occurs at a critical moment in crop development. Similar effects of water stress were observed at the early stages of foliar development of potato (Kashyap and Panda, 2003). In our case, we therefore infer that we have not included too many processes in the SIMPIÑA model and that model reduction does not seem possible, which is contrary to other studies in which model simplification was possible (Crout et al., 2009). Actually we had shown that the removal of stress processes resulted in large errors in the simulations relative to the full model. Thus stress processes might be necessary to simulate with accuracy the growth and development of pineapple under a large range of climatic conditions and cultural practices. Some simplifications might be acceptable for specific uses of the model but the validity range of the model would be limited and the model could not be used for pineapple system management on Réunion Island.

5. Conclusion

We showed that the SIMPIÑA model accurately simulates pineapple growth and development across a substantial climatic

gradient. The model evaluation showed that SIMPIÑA does not include needless processes. SIMPIÑA should allow pineapple growers to explore combinations of cultural practices (irrigation, fertilization, sucker masses at planting, planting density) under a diversity of conditions in order to optimize N and water resources while ensuring suitable yield.

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References

- Affholder, F., Scopel, E., Neto, J.M., Capillon, A., 2003. Diagnosis of the productivity gap using a crop model. Methodology and case study of small-scale maize production in central Brazil. *Agronomie* 23, 305–325.
- Affholder, F., Tiftonell, P., Corbeels, M., Roux, S., Motisi, N., Tixier, P., Wery, J., 2012. Ad hoc modeling in agronomy: what have we learned in the last 15 years? *Agron. J.* 104, 735–748.
- Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO – Food and Agriculture Organization of the United Nations, Rome, Italy.
- Bergez, J.E., Colbach, N., Crespo, O., Garcia, F., Jeuffroy, M.H., Justes, E., Loyce, C., Munier-Jolain, N., Sadok, W., 2010. Designing crop management systems by simulation. *Eur. J. Agron.* 32, 3–9.
- Bertin, N., Gautier, H., Roche, C., 2002. Number of cells in tomato fruit depending on fruit position and source–sink balance during plant development. *Plant Growth Regul.* 36, 105–112.
- Boote, K.J., Jones, J.W., Pickering, N.B., 1996. Potential uses and limitations of crop models. *Agron. J.* 88, 704–716.
- Brisson, N., Mary, B., Ripoche, D., Jeuffroy, M.H., Ruget, F., Nicoulaud, B., Gate, P., Devienne-Barret, F., Antonioletti, R., Duru, C., Richard, G., Beaudoin, N., Recous, S., Tayot, X., Plenet, D., Cellier, P., Machet, J.M., Meynard, J.M., Delecolle, R., 1998. STICS: a generic model for the simulation of crops and their water and nitrogen balances. I. Theory and parameterization applied to wheat and corn. *Agronomie* 18, 311–346.
- Carr, M.K., 2012. The water relations and irrigation requirements of Pineapple (*Ananas comosus* var. *comosus*): a review. *Exp. Agric.* 48, 488–501.
- Chen, N.J., Paull, R.E., 2009. Pineapple production for quality and postharvest handling. *Acta Hort.* 822, 253–260.
- Combres, J.C., 1983. Bilan énergétique et hydrique de l'ananas. Utilisation optimale des potentialités climatiques. Compte rendu d'activités. IRFA.
- Cox, G.M., Gibbons, J.M., Wood, A.T.A., Craigon, J., Ramsden, S.J., Crout, N.M.J., 2006. Towards the systematic simplification of mechanistic models. *Ecol. Model.* 198, 240–246.
- Crout, N.M.J., Craigon, J., Cox, G.M., Jao, Y., Tarsitano, D., Wood, A.T.A., Semenov, M., 2014. An objective approach to model reduction: application to the Sirius wheat model. *Agric. For. Meteorol.* 189–190, 211–219.
- Crout, N.M.J., Tarsitano, D., Wood, A.T., 2009. Is my model too complex? Evaluating model formulation using model reduction. *Environ. Model. Softw.* 24, 1–7.
- De Souza, O.P., Teodoro, R.E.F., De Melo, B., Torres, J.L.R., 2009. Fruit quality and productivity of pineapple under different planting densities and irrigation levels. *Pesqui. Agropecu. Bras.* 44, 471–477.
- Dorel, M., Achard, R., Tixier, P., 2008. SIMBA-N: modeling nitrogen dynamics in banana populations in wet tropical climate. Application to fertilization management in the Caribbean. *Eur. J. Agron.* 29, 38–45.
- Dusek, J., Ray, C., Alavi, G., Vogel, T., Sanda, M., 2010. Effect of plastic mulch on water flow and herbicide transport in soil cultivated with pineapple crop: a modeling study. *Agric. Water Manag.* 97, 1637–1645.
- Fleisch, H., Bartholomew, D.P., 1987. Development of heat unit model of pineapple (Smooth cayenne) fruit growth from field data. *Fruits* 42, 709–715.
- Fournier, P., 2011. La culture de l'ananas Victoria à la Réunion pour l'exportation. Recueil de bonnes pratiques. CIRAD, France.
- Fournier, P., Dubois, C., Benneveau, A., Soler, A., 2010. Growth indicators for different pineapple cultivars compared with the current standard 'Smooth Cayenne' in West Africa and Reunion Island: a first step toward modeling growth. *Agron. J.* 102, 1572–1577.
- Jones, C.A., Kiniry, J.R., 1986. CERES-Maize: A Simulation Model of Maize Growth and Development. Texas A&M University Press, College Station.

- Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. *Eur. J. Agron.* 18, 235–265.
- Kashyap, P.S., Panda, R.K., 2003. Effect of irrigation scheduling on potato crop parameters under water stressed conditions. *Agric. Water Manag.* 59, 49–66.
- Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. *Eur. J. Agron.* 18, 267–288.
- Kimmins, J.P., Blanco, J.A., Seely, B., Welham, C., Scoullar, K., 2008. Complexity in modelling forest ecosystems: how much is enough? *For. Ecol. Manag.* 256, 1646–1658.
- Kobayashi, K., Us Salam, M., 2000. Comparing simulated and measured values using squared deviation and its component. *Agron. J.* 92, 345–352.
- Laderach, P., Lundy, M., Jarvis, A., Ramirez, J., Portilla, E.P., Schepp, K., Eitzinger, A., 2011. Predicted impact of climate change on coffee supply chains. In: Filho, W.L. (Ed.), *Economic, Social and Political Elements of Climate Change*. pp. 703–723.
- Léchaudel, M., Génard, M., Lescourret, F., Urban, L., Jannoyer, M., 2005. Modeling effects of weather and source–sink relationships on mango fruit growth. *Tree Physiol.* 25, 583–597.
- Lechaudel, M., Damour, G., Fournier, P., Joas, J., Jahiel, M., 2010. How to Predict the Harvest Date of Tropical Fruit: from Simple Methods to Complex Models. *Acta Hort.* 880, 175–182.
- Lescourret, F., Habib, R., Génard, M., Agostini, D., Chadoeuf, J., 1998. Pollination and fruit growth models for studying the management of kiwifruit orchards. I. Models description. *Agric. Syst.* 56, 67–89.
- Loyce, C., Wery, J., 2006. Les outils de l'agronomie pour l'évaluation et la conception de systèmes de culture. *L'agronomie aujourd'hui*, pp. 77–95.
- Malezieux, E., 1988. Croissance et élaboration du rendement de l'ananas (*Ananas comosus* L. Merr.). INA-PG, Paris, France, pp. 241.
- Malézieux, E., 1991. Recherche de relations entre la biomasse aérienne, la surface foliaire et l'interception du rayonnement solaire chez l'ananas - Study of relationships between plant biomass, leaf area and solar radiation interception on pineapple. *Fruits, Paris* 46 (5), 523–532.
- Malezieux, E., Zhang, J., Sinclair, E.R., Bartholomew, D.P., 1994. Predicting pineapple harvest date in different environments, using a computer simulation model. *Agron. J.* 86, 609–617.
- Monteith, J.L., 1972. Solar radiation and productivity in tropical ecosystems. *J. Appl. Ecol.* 9, 747–766.
- Palha, M.G., Campo, J.L., Oliveira, P.B., 2011. Strawberry plant growth and dry matter partitioning as influenced by planting date and plant type in an autumn production system. *Acta Hort.* 926, 463–469.
- Payet, N., Findeling, A., Chopart, J.L., Feder, F., Nicolini, E., Saint Macary, H., Vauclin, M., 2009. Modelling the fate of nitrogen following pig slurry application on a tropical cropped acid soil on the island of Reunion (France). *Agric. Ecosyst. Environ.* 134, 218–233.
- Prudent, M., Wu Dai, Z., Génard, M., Bertin, N., Causse, M., Vivin, P., 2012. Fruit size in relation to competition for resources: a common model shared by two species and several genotypes grown under contrasted carbohydrate levels. In: 4th International Symposium on Plant Growth Modeling, Simulation, Visualization and Applications, 2012, Shanghai, China, 472, 472, 304–311.
- Py, C., 1960. Influence de la date de plantation et du poids des rejets sur la croissance des plants d'ananas en Guinée. *Fruits* 15, 451–453.
- Py, C., Lacoëuilhe, J.J., Teisson, C., 1984. *The Pineapple, Cultivation and Uses*. G.P. Maisonneuve et Larose, Paris, pp. 563.
- Ripoche, A., Achard, R., Laurens, A., Tixier, P., 2012. Modeling spatial partitioning of light and nitrogen resources in banana cover-cropping systems. *Eur. J. Agron.* 41, 81–91.
- Rossing, W.A.H., Meynard, J.M., vanIttersum, M.K., 1997. Model-based explorations to support development of sustainable farming systems: case studies from France and the Netherlands. *Eur. J. Agron.* 7, 271–283.
- Schaffer, M.J., Wylie, B.K., Follett, R.F., Bartling, P.N.S., 1994. Using climate weather data with the Nleap model to manage soil nitrogen. *Agric. For. Meteorol.* 69, 111–123.
- Scorza, R., May, L.G., Purnell, B., Upchurch, B., 1991. Differences in number and area of mesocarp cells between small-fruited and large-fruited peach cultivars. *J. Am. Soc. Hortic. Sci.* 116, 861–864.
- Sinclair, T.R., Seligman, N.G., 1996. Crop modeling: from infancy to maturity. *Agron. J.* 88, 698–704.
- Stevenson, F.J., 1994. *Humus Chemistry: Genesis, Composition, Reactions*, New York.
- Stockle, C.O., Donatelli, M., Nelson, R., 2003. CropSyst, a cropping systems simulation model. *Eur. J. Agron.* 18, 289–307.
- Varlet-Grancher, C., Gosse, G., Chartier, M., Sinoquet, H., Bonhomme, R., Allirand, J.-M., 1989. Mise au point: rayonnement solaire absorbé ou intercepté par un couvert végétal. *Agronomie* 9, 419–439, <http://dx.doi.org/10.1051/agro:19890501>.
- Vermeulen, S.J., Challinor, A.J., Thornton, P.K., Campbell, B.M., Eriyagama, N., Vervoort, J.M., Kinyangi, J., Jarvis, A., Laderach, P., Ramirez-Villegas, J., Nicklin, K.J., Hawkins, E., Smith, D.R., 2013. Addressing uncertainty in adaptation planning for agriculture. *Proc. Natl. Acad. Sci. U. S. A.* 110, 8357–8362.
- Zhang, J., 1992. Computer Simulation of Pineapple Growth, Development and Yield, Hawaiï, p. 279.
- Zhang, J., Bartholomew, D.P., Malézieux, E., 1997. ALOHA-Pineapple V.2.1: a computer model to predict the growth, development and yield of pineapple. *Acta Hort.* 425, 287–296.