COMPARISON OF WOFOST, CROPSYST AND WARM FOR SIMULATING RICE GROWTH (JAPONICA TYPE – SHORT CYCLE VARIETIES)

CONFRONTO TRA WOFOST, CROPSYST E WARM PER LA SIMULAZIONE DELLA CRESCITA DEL RISO (VARIETÀ JAPONICA PRECOCI)

Roberto Confalonieri[1,*], Davide Gusberti[2], Marco Acutis[2]

[1] *Institute for the Protection and Security of the Citizen, Joint Research Centre of the European Commission, AGRIFISH Unit, MARS-STAT Sector, TP 268 - 21020 Ispra (VA), Italy*
[2] *Department of Crop Science, University of Milano, Via Celoria 2, 20133 Milano, Italy*
** Corresponding author: Tel. +39-0332-789872, E-mail: roberto.confalonieri@jrc.it, Fax: +39-0332-789029*

Received 31/10/2006 - Accepted 1/12/2006

Abstract
Rice is one of the most important crops worldwide and during the last 15 years crop modellers have pointed their attention on this crop. In this paper, three models are compared for the simulation of rice (Japonica type – short cycle varieties) growth under potential conditions for water, nutrients, pests and diseases. The three models simulate crop growth using different approaches: WOFOST is based on the photosynthesis approach, CropSyst and WARM respectively on the concepts of transpiration and radiation use efficiency. Each of these approaches represents crop growth with a different level of detail and has different requirements in terms of data needs. Data used for models calibration and validation were collected in northern Italy between 1990 and 1996. The three models showed similar accuracy in reproducing crop behavior, both during calibration and validation. Relative root mean square errors ranged from 6.9% to 22.6%, from 9.9% to 18.0%, and from 10.6% to 17.5% respectively for WOFOST, CropSyst and WARM. Similar levels of reliability were reached in spite of the different modelling approaches and levels of detail in the description of the processes related to biomass accumulation – partitioning and leaf area index simulation. The WARM model appeared the easiest to be used because of the lower number of parameters describing cultivars morphology and physiology and because of the absence of parameters purely empirical.

Keywords: *Oryza sativa* L., crop model, parameterization, radiation use efficiency, partitioning.

Riassunto
Il riso è una delle più importanti colture al mondo e negli ultimi 15 anni i modellisti hanno puntato la loro attenzione su questa specie. In questo articolo vengono confrontate le performance di tre modelli utilizzati per simulare la crescita di questa coltura (varietà Japonica precoci) in condizioni ottimali per quanto riguarda la disponibilità di acqua e nutrienti e per quanto riguarda infestanti, parassiti e malattie. I tre modelli utilizzati per questo studio simulano l'accumulo di biomassa utilizzando approcci diversi: WOFOST riproduce le varie fasi della fotosintesi con un notevole livello di dettaglio, mentre CropSyst e WARM si basano, rispettivamente, sui concetti di efficienza d'uso dell'acqua traspirata e della radiazione intercettata. Questi tre approcci rappresentano la crescita della pianta con diversi livelli di dettaglio e sono caratterizzati da notevoli differenze in termini di richieste di dati per effettuare le simulazioni. I dati utilizzati per la calibrazione e la validazione dei modelli sono stati raccolti nel nord Italia tra il 1990 e il 1996. L'RRMSE ha assunto valori compresi tra 6.9% e 22.6 %, tra 9.9% e 18.0% e tra 10.6% e 17.5% rispettivamente per WOFOST, CropSyst e WARM. I tre modelli hanno dimostrato livelli di accuratezza molto simili nel riprodurre i valori osservati, sia in fase di calibrazione che di validazione. Questo risultato è interessante, soprattutto alla luce sia dei concetti completamente diversi che stanno alla base della modellizzazione dell'accumulo di biomassa sia al diverso livello di dettaglio nella descrizione dei processi coinvolti con l'accumulo di biomassa, la ripartizione degli assimilati e l'evoluzione della superficie fogliare. WARM è apparso il modello più facile da utilizzare per via del numero ridotto di parametri che descrivono la morfologia e la fisiologia della pianta e per via dell'assenza di parametri puramente empirici.

Parole chiave: Oryza sativa *L., modello di crescita, parametrizzazione, efficienza d'uso della radiazione, ripartizione.*

Introduction
Since the beginning of the nineties, crop modellers are pointing their attention on rice productions because of the worldwide importance of this crop as staple food. It is now possible to find in the Literature many examples of crop models explicitly dedicated to rice or "adapted" for rice simulations. In most cases, they differ for the algorithms implemented, for the production levels considered (potential, water and nitrogen limited, diseases limited), for the attention dedicated to the management options, to the user's interface, for the possibility of running simulations at large scale, etc. (van Ittersum *et al.*, 2003). Considering crop growth, it is possible to distinguish three major groups of mechanistic/process-based models, according to the approach used for the daily accumulation of biomass under potential conditions (temperature and radiation are the only factors limiting

growth). The first group includes the family of models based on gross assimilation of CO_2 and on maintenance and growth respiration to get the final net carbon assimilation. These first simulation tools and their descendants are known as the "School of de Wit" crop models (van Ittersum *et al.*, 2003) by the name of the pioneer scientist who founded the first modelling team in Wageningen, The Netherlands, during the 1960s. Examples of this type of models are SUCROS (van Keulen *et al.*, 1982) and the derived WOFOST (van Keulen and Wolf, 1986) and ORYZA (Kropff *et al.*, 1994). This approach, although conceptually sound and undoubtedly powerful for drawing attention to gaps in understanding and for analyzing processes at plant components level (Confalonieri and Bechini, 2004), is very demanding for what concerns the parameterization. Moreover, for predictive purposes, it has not been yet demonstrated to be more reliable than some simpler approaches (Spitters, 1990).
The other approaches for the daily accumulation of biomass are based on the concept of net photosynthesis: biomass is considered proportional to one (or both) of the two main driving factors involved in the photosynthetic carbon fixation: intercepted radiation (second major group of models) and transpired water (third one).
The first equation for the estimation of aboveground biomass (AGB) based on the intercepted radiation was proposed by Warren Wilson (1967) and is universally known as the Monteith equation (Monteith, 1977) by the name of the scientist whose work gave credibility to this approach. The core of this approach is the concept of radiation use efficiency (RUE): a parameter used to derive the AGB accumulated each day from intercepted solar radiation. Examples of the RUE-based models are the CERES-family models (Uehara and Tsuji, 1993) and STICS (Brisson *et al.*, 2003).
The approach based on transpiration use efficiency (TUE) was originally proposed by Bierhuizen and Slatyer (1965) and improved by Tanner and Sinclair (1983). Practically this approach computes AGB by multiplying a biomass/transpiration parameter (theoretically species- or variety-specific) for potentially transpired water and dividing the results for daily mean vapour pressure deficit (VPD). An evident problem of the just mentioned equation is that the division for VPD estimates infinite growth at near zero VPD values. This is why the most known model adopting this approach, CropSyst (Stöckle *et al.*, 2003), computes each day also a second daily-AGB using the RUE approach. When the RUE-base AGB is lower than the TUE-base one, the first is used.
In this work, three models were compared for the simulation of paddy rice biomass in northern Italy under potential growing conditions. Each model calculates AGB accumulation using on of the three approaches mentioned before: WOFOST (van Keulen and Wolf, 1986) is representative of the photosynthesis approach, CropSyst (Stöckle *et al.*, 2003) can be considered representative of the TUE-based approach in northern Italy conditions (Confalonieri *et al.*, 2006) and WARM (Confalonieri *et al.*, 2005a) is representative of the RUE-based models. Data related to CropSyst simulations refer to the work of Confalonieri and Bocchi (2005).

Materials and methods

Experimental data

Experimental data, collected in northern Italy between 1990 and 1996, are described by Confalonieri and Bocchi (2005; experiments number 1, 2 and 3 in Table 1 of the article, referring to the datasets collected at Gudo Visconti in 1990, Vercelli in 1990, Castello d'Agogna in 1995 and Castello d'Agogna in 1996). For all the experiments, data from plots maintained at potential production level (van Ittersum and Rabbinge, 1997) were used.

Simulation models

WOFOST

WOFOST (Van Keulen and Wolf, 1986; Boogaard *et al.*, 1998) belongs to the family of models derived by SUCROS (Van Keulen *et al.*, 1982) and described by Bouman *et al.* (1996) and, more recently, by Van Ittersum *et al.* (2003).
WOFOST adopts the SUCROS approach for simulating potential production. Crop development can be simulated as a simple function of temperature, either related to photoperiod or due to both thermal and photoperiodic conditions. Gross CO_2 assimilation, maintenance and growth respiration are simulated. The first is derived on a daily basis using a Gaussian integration on the instantaneous CO_2 assimilation rates computed at three moments of the day for three depths in the canopy basing on the photosynthesis light response curves for individual leaves. Fluxes of direct and diffuse photosynthetically active radiation (PAR) are derived from the diffuse radiation and the Lambert – Beer's law is used for computing the light distribution in the canopy. Extinction coefficient for solar radiation can be customized according to the canopy architecture of the simulated variety. Maintenance respiration is assumed to be proportional to the dry weight of the plants organs, considering that different organs have different respiration/weight ratios. For the growth respiration, leaves, stems, roots and storage organs are differently described according to their chemical composition. Total dry matter production is partitioned among the different crop organs according to partitioning coefficients, changing according to the development stage. Before the close-canopy stage, leaf area is considered growing exponentially as a function of temperature. When the canopy closes, leaf area index (LAI) is derived by the leaf weight using a development-dependent specific leaf area (SLA). Leaves senescence is considered.

CROPSYST

CropSyst (Stöckle *et al.*, 2003) is a process-based, multiyear, multi-crop, daily time step cropping systems simulation model. Crop development is simulated as a function of thermal time accumulated between a base temperature and a maximum temperature. Crop growth is simulated for the whole canopy by calculating unstressed biomass growth based on potential transpiration and on intercepted radiation. The minimum between daily transpiration- and radiation-based biomasses is selected and successively shortened by considering water and nitrogen limitations. Temperature limitations are explicitly considered in the radiation-dependent growth. Daily LAI expansion is calculated from total AGB, daily accumulated AGB, a constant SLA and an empiric parameter called stem leaf partition coefficient (SLP). Root depth is simulated as a function of leaf area development, and reaches its maximum when the plant flowers. Further details about the algorithms implemented in CropSyst were described by Stöckle *et al.* (2003).

WARM

WARM simulates crop development computing the thermal time accumulated between a base temperature and a cutoff temperature; optionally the obtained value can be corrected with a factor accounting for photoperiod. Base and cutoff temperatures can be set to different values for the periods sowing – emergence and emergence – harvest. Growing degrees days (GDDs) are converted into a decimal code (assuming values from 0.00 to 2.00) to standardize development stages (phenophases are also explicitly determined). Decimal codes are obtained, respectively for the period emergence-flowering and flowering-physiological maturity, with the following equations:

$$\mathrm{DVS} = \frac{(\mathrm{GDD_{cum}} - \mathrm{GDD_{em}})}{\mathrm{GDD_{flo}}} \tag{1}$$

$$\mathrm{DVS} = \frac{1 + (\mathrm{GDD_{cum}} - \mathrm{GDD_{em}} - \mathrm{GDD_{flo}})}{\mathrm{GDD_{mat}}} \tag{2}$$

where DVS is the development stage code, GDD_{cum} (°C-days) are the cumulated GDDs, GDD_{em} (°C-days) are the GDDs necessary to reach emergence and GDD_{flo} (°C-days) are the GDDs necessary to reach flowering and GDD_{mat} (°C-days) are the GDDs necessary to reach physiological maturity. Using the decimal code (like for the SUCROS-derived models), 0.00 correspond to emergence, 1.00 to flowering, 2.00 to physiological maturity.
For the simulation of the processes related to AGB accumulation, partitioning and LAI estimation, the GAIA model (Confalonieri, 2005) has been used. Net photosynthesis is simulated using a RUE-based approach (Eq. 3):

$$AGB = RUE \cdot 0.5 \cdot Rad \cdot \left(1 - e^{-k \cdot LAI}\right) \cdot T_{\lim} \tag{3}$$

where AGB (kg m^{-2} day^{-1}) is the daily accumulated aboveground biomass, RUE (kg MJ^{-1}) is the ratio of aboveground biomass accumulated to intercepted PAR, Rad (MJ m^{-2} day^{-1}) is the daily global solar radiation (with 0.5 × Rad being an estimate for PAR), $(1-e^{-k \times LAI})$ is the fraction of PAR intercepted by the canopy, k is the extinction coefficient for PAR and T_{lim} is a factor accounting for temperature limitation to growth. The beta function proposed by Yin *et al.* (1995) for simulating development is used to account for temperature limitations to photosynthesis:

$$\left[\left(\frac{T_{avg} - T_b}{T_{opt} - T_b}\right) \cdot \left(\frac{T_{\max} - T_{avg}}{T_{\max} - T_{opt}}\right)^{\frac{T_{\max} - T_{opt}}{T_{opt} - T_{\min}}}\right]^C \tag{4}$$

where T_{avg} (°C) is the mean daily air temperature; T_b (°C), T_{opt} (°C) and T_{max} (°C) are respectively the minimum, optimum and maximum daily mean temperature for growth; C is an empiric parameter set to 1.8 to make the beta distribution function assume the value of 0.5 when T_{avg} is the average of T_b and T_{opt}.
RUE varies according to irradiance level, development, diseases, nitrogen (N) concentration and cold injuries. In this work, carried out at potential production level, reductions to RUE due to diseases, N concentration and cold injuries were not taken into account. A daily factor accounting for the saturation of the enzymatic chains involved with photosynthesis (Rad_F; kg MJ^{-1}) is calculated using an empiric function derived by Choudhury (2001):

$$Rad\_F = \begin{cases} 0 & Rad < 25\ MJ\ m^{-2}\ d^{-1} \\ RUE_{\max} - \left(-0.04 \cdot RUE_{\max} \cdot Rad + 2 \cdot RUE_{\max}\right) & Rad \geq 25\ MJ\ m^{-2}\ d^{-1} \end{cases} \tag{5}$$

A second daily factor (DVS_F; kg MJ^{-1}) considers the effect of senescence on RUE. The empiric function describing the influence of DVS on RUE is derived by Campbell *et al.* (2001):

$$DVS\_F = \begin{cases} 0 & DVS < 1 \\ RUE_{\max} - \left(-0.25 \cdot RUE_{\max} \cdot DVS + 1.25 \cdot RUE_{\max}\right) & DVS \geq 1 \end{cases} \tag{6}$$

where DVS (-) is the development stage code, RUE_{max} (kg MJ^{-1}) is the RUE value not limited by water, nutrients, pest, diseases, senescence, excess of radiation, temperature, damages.
Actual daily RUE is obtained subtracting Rad_F and DVS_F from RUE_{max}.
AGB accumulated each day is partitioned to leaves using a parabolic function which assumes the maximum value (input parameter; RipL0 [-]) at emergence and zero at flowering (Eq. 7):

$$LeavesAGB_{day} = \begin{cases} AGB_{day} \cdot \left(-RipL0 \cdot DVS^2 + RipL0\right) & DVS < 1 \\ 0 & DVS \geq 1 \end{cases} \tag{7}$$

where $LeavesAGB_{day}$ (kg m^{-2} day^{-1}) is the AGB daily partitioned to leaves and AGB_{day} (kg m^{-2} day^{-1}) is the AGB accumulated in the day. This approach for partitioning (based on a single parameter, RipL0) is considered a robust compromise between the SUCROS one (van Keulen *et al.*, 1982), considered very difficult to be reasonably parameterized for large scale simulations and other, considered excessively empiric and insufficiently linked to reality (e.g. the CropSyst approach).
AGB partitioning to panicles starts at the panicle initiation stage (PI) and it is assumed as maximum (all the daily accumulated AGB is partitioned to panicles) at the beginning of the ripening phase. Like for the allocation of AGB to leaves, a parabolic function is used (Eq. 8):

$$PanicleAGB_{day} = \begin{cases} 0 & DVS < 0.6 \\ AGB_{day} \cdot \left(-1.9 \cdot DVS^2 + 5.4 \cdot DVS - 2.9\right) & 0.6 \le DVS \le 1.5 \\ 1 & DVS > 1.5 \end{cases} \quad (8)$$

where $PanicleAGB_{day}$ (kg m^{-2} day^{-1}) is the AGB daily partitioned to panicles. DVS = 0.6 represents the panicle initiation.

Stems biomass is simply derived by subtracting panicles and leaves biomasses to total AGB.

A daily factor accounting for spikelet sterility due to cold shocks during the period between PI and heading is calculated using Eq. 9, which the Authors derived by the detailed investigation of Kakizaki and Kido (1938) reported by Nishiyama (1995):

$$SterilityF = \begin{cases} \sum_{h=1}^{24}\left(T_{thresh} - T_h\right) \cdot \left[\frac{1}{\gamma \cdot \sqrt{2 \cdot \pi}} \cdot e^{-\left(\frac{(DVS - DVS11)^2}{2 \cdot \gamma^2}\right)} \cdot \delta\right] & 0.6 \le DVS \le 0.9 \\ 0 & otherwise \end{cases} \quad (9)$$

where T_{thresh} (°C) is the threshold temperature below which cold-induced sterility damages are caused, T_h (°C) are the hourly temperatures, DVS11 is the DVS of the eleventh day before heading (DVS code = 0.8). γ and δ are coefficients used to distinguish between varieties sensitive for few or many days around the eleventh before heading, which correspond to the middle of the period PI – heading (Nishiyama, 1995). The integral of SterilityF is used to reduce $PanicleAGB_{day}$.

The height of the meristematic apex (the part of the plant most sensitive to temperatures) is derived with a beta function which assumes zero at the PI and the maximum (input parameter) at the heading stage.

The height of the meristematic apex is used everywhere in WARM (therefore also for sterility computation) for getting the correct temperatures (at the meristematic apex height) from the TRIS micrometeorological model proposed by Confalonieri *et al.* (2005b). In this way, TRIS allows GAIA to simulate biomass accumulation, spikelet sterility, etc. taking into account the floodwater effect on vertical thermal profile.

Leaf area index (LAI; m^2 m^{-2}) is computed multiplying the leaves biomass for a specific leaf area (SLA, m^2 kg^{-1}) variable according to the development stage (Eq. 10).

$$SLA = \begin{cases} \frac{SLA_{till} - SLA_{ini}}{0.35^2} \cdot DVS^2 + SLA_{ini} & DVS \le 0.35 \\ SLA_{till} & DVS > 0.35 \end{cases} \quad (10)$$

where SLA_{till} (m^2 kg^{-1}) is the SLA at the mid tillering stage (DVS = 0.35) and SLA_{ini} (m^2 kg^{-1}) is the SLA at emergence.

Each day, leaf senescence is calculated by subtracting the dead LAI to the total LAI. The dead LAI is obtained by killing the LAI accumulated in the day in the past individuated by subtracting the LeafLife (input parameter; °C-day) to the current DVS (a correspondence between DVS and days is maintained).

Model parameterization and validation

The versions of the three models used for this work are the 3.02.23 (January 8, 2002) for CropSyst, the 1.7 (Control Centre, March 2002) for WOFOST, and the 1.7.2 (January 31, 2006) for WARM.

For all the models, options for avoiding limitations due to water and nutrients stresses, pests and diseases were used.

In this work, all the data sets refer to the group of rice varieties defined Japonica-Early by Confalonieri and Bocchi (2005). Data from the experiments carried out at Gudo Visconti in 1990 and at Castello d'Agogna in 1995 were used for calibration of crop parameters, data from those carried out at Vercelli in 1990 and at Castello d'Agogna in 1996 for validation.

CropSyst parameterization has been described by Confalonieri and Bocchi (2005). A preliminary sensitivity analysis of WOFOST and WARM using the method of Morris (Confalonieri *et al.*, 2006) allowed individuating the parameters with the highest influence on model output (AGB in this case). Some of these parameters have been calibrated and others determined from field experiments. The others have been left to their default value (Tables1 and 2).

The agreement between observed and estimated values was expressed by using the indices proposed by Loague and Green (1991): the percent relative root mean squared error (RRMSE, minimum and optimum=0%), the coefficient of determination (CD, minimum=0, optimum=1, indicates whether the model reproduces the trend of measured values or not), the modelling efficiency (EF, $-\infty \div 1$, optimum=1, if positive, indicates that the model is a better estimator than the average of measured values), the coefficient of residual mass (CRM, $-\infty \div \infty$, optimum=0, if positive indicates model underestimation) and the parameters of the linear regression equation between observed and estimated values.

Results and discussion

Experimental results

Maximum daily temperature is usually lower than T_{cutoff} in the considered Region and meteorological data collected during the experiments confirm it. The average number of days in which minimum daily temperature was lower than a T_{base} equal to 12°C during the rice cycle is 20 (maximum: 28 days in 1996 at Castello d'Agogna; minimum: 17 days in 1990 at Vercelli).

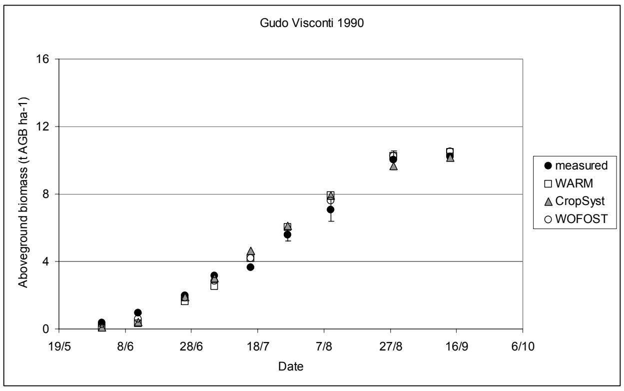

Fig 1a - Time course of measured and simulated aboveground biomass values (calibration data set).
Fig 1a - *Andamento nel tempo dei valori misurati e simulati di biomassa (dataset utilizzato per la calibrazione)*

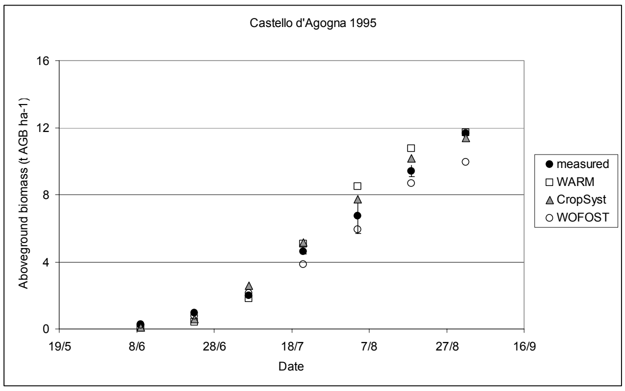

Fig 1b - Time course of measured and simulated aboveground biomass values (calibration data set).
Fig 1b - *Andamento nel tempo dei valori misurati e simulati di biomassa (dataset utilizzato per la calibrazione)*

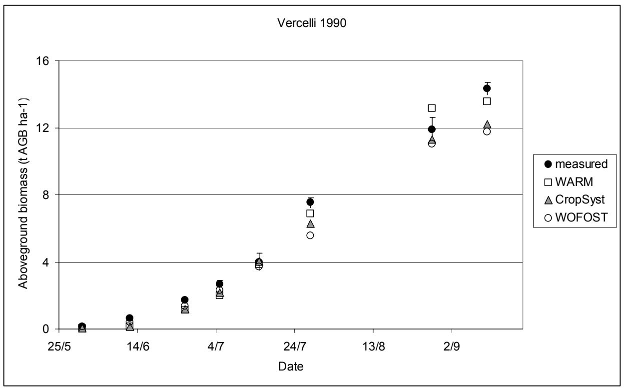

Fig 2a - Time course of measured and simulated aboveground biomass values (validation data set).
Fig 2a - *Andamento nel tempo dei valori misurati e simulati di biomassa (dataset utilizzato per la validazione)*

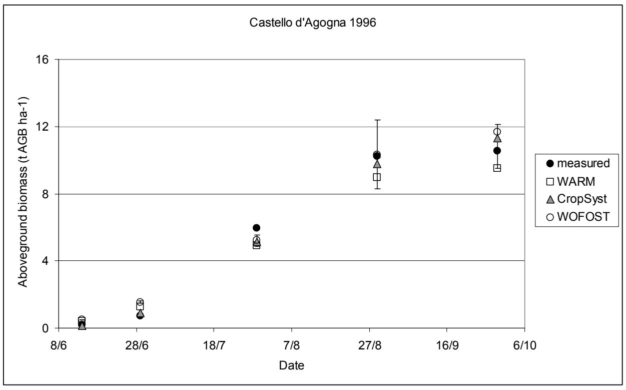

Fig 2b - Time course of measured and simulated aboveground biomass values (validation data set).
Fig 2b - *Andamento nel tempo dei valori misurati e simulati di biomassa (dataset utilizzato per la validazione)*

Tab. 1 - WARM parameters for Japonica – type, short cycle rice varieties (C: calibrated parameters; L: literature; E: local experience; M: measured; D: WARM default parameter)
Tab. 1 - *Parametri colturali di WARM per le varietà Japonica precoci (C: parametri calibrati; L: letteratura; E: valori proposti da esperti locali; M: misurati; D: parametri di default di WARM)*

Parameter	**Units**	**Value**	**Description**	**Determination**
Development				
TbaseDem	°C	11	base T for devel. before emergence	E, L
TmaxDem	°C	42	max. T for devel. before emergence	E
GDDem	°C-days	70	GDDs from sowing to emergence	M
TbaseD	°C	12	base T for devel. before emergence	L
TmaxD	°C	42	max. T for devel. before emergence	L
GDDem-fl	°C-days	850	GDDs from emergence to flowering	M
GDDfl-mat	°C-days	500	GDDs from flowering to maturity	M
Growth				
RUE	g MJ^{-1}	2.6	radiation use efficiency	C
k	-	0.5	extinction coeff. for solar radiation	C
TbaseG	°C	11.5	base T for growth	E, C
ToptG	°C	29	optimum T for growth	E, C
TmaxG	°C	35	maximum T for growth	E
LAIini	m^2 m^{-2}	0.01	initial leaf area index	D
SLAini	m^2 kg^{-1}	28	specific leaf area at emergence	M
SLAtill	m^2 kg^{-1}	18	specific leaf area end tillering	M
RipL0	-	0.75	AGB partition to leaves at emerg.	C
LeafLife	°C-days	500	leaf duration	C
ApexHeight	cm	80	maximum panicle height	E
kc	-	1.05	kc full canopy	L

Tab. 2a - WOFOST parameters for Japonica – type, short cycle rice varieties (C: calibrated parameters; L: literature; E: local experience; M: measured; D: from Van Diepen *et al.*, 1988); parameters involved with development and growth

Tab. 2a *- Parametri colturali di WOFOST per le varietà Japonica precoci (C: parametri calibrati; L: letteratura; E: valori proposti da esperti locali; M: misurati; D: da van Diepen et al., 1988); parametri coinvolti con sviluppo e crescita*

Parameter	Units	Value	Description	Determination
Development				
TBASEM	°C	10	lower threshold T for emergence	E, L
TEFFMX	°C	35	max. eff. T for emergence	E
TSUMEM	°C-days	90	T sum from sowing to emergence	M
IDSL	-	0	pre-anthesis development based on T (=0), daylenght (=1), both (=2)	-
TSUM1	°C-days	770	T sum from emergence to anthesis	M
TSUM2	°C-days	400	T sum from anthesis to maturity	M
DTSMTB	°C ; °C-days	00 ; 00 11 ; 00 30 ; 19 42 ; 00	daily increase in T sum as a function of av. T	L
DVSI	-	0	development stage start simulation	-
DVSEND	-	2.3	development stage at harvest	E
Growth				
LAIEM	ha ha^{-1}	0.1	leaf area index at emergence	D
RGRLAI	ha ha^{-1} °C^{-1} day^{-1}	0.012	maximum relative increase in LAI	C
SLATB	- ; ha kg^{-1}	0.00 ; 0.00285 0.13 ; 0.00295 0.24 ; 0.00260 0.28 ; 0.00230 0.31 ; 0.00200 0.57 ; 0.00190 0.67 ; 0.00180 2.01 ; 0.00170	specific leaf area as a function of development stage	M
SPA	ha kg^{-1}	0	specific pod area	D
SSATB	ha kg^{-1}	0.0 ; 0.0003 0.9 ; 0.0003 2.0 ; 0.0000	specific stem area as a function of development stage	D
SPAN	days	38	life span of leaves growing at 35 °C	E
TBASE	°C	8	lower threshold T for ageing of leaves	
KDIFTB	-	0.00 ; 0.40 0.65 ; 0.40 1.00 ; 0.60 2.00 ; 0.60	extinction coefficient for diffuse visible light as a function of development stage	D
EFFTB	kg ha^{-1} hr^{-1} J^{-1} m^{2} s	10 ; 0.54 40 ; 0.36	light-use efficiency single leaf as function of daily mean T	D
AMAXTB	- ; kg ha^{-1} hr^{-1}	0 ; 33 2 ; 33	max. leaf CO2 assimilation rate as function of development stage	C
TMPFTB	°C ; -	00 ; 0.00 11 ; 0.00 14 ; 0.07 23 ; 0.90 27 ; 1.00 33 ; 1.00 45 ; 0.30	reduction factor of AMAX as function of average T	E, L
TMNFTB	°C ; -	0 ; 0 3 ; 1	reduction factor of gross assimilation rate as function of low min. T	D

Data of AGB accumulation are shown in Figure 1.a, 1.b, 2.a, 2.b. Average AGB at maturity was 11.7 t AGB ha^{-1} while average yield was 7 t ha^{-1}: these values are comparable with what is usually obtained in the region as referred by the national rice institute in annual relations. The highest AGB production (14.3 t ha^{-1}) was obtained in 1990 at Vercelli in a soil with high soil organic matter, while for the other locations AGB was from 10.2 to 11.6 t ha^{-1}. Based on all available data, harvest index was 0.6 for Loto: this value is typical for this variety of small size and high potential yield.

Models results

Calibrated parameters for CropSyst are described and discussed by Confalonieri and Bocchi (2005). Calibrated parameters for WARM and WOFOST are shown in Tables 1, 2.a, 2.b, 2.c. For both WARM and WOFOST cardinal temperatures are within the range of those reported by Yin and Kropff (1996), Casanova *et al.* (1998), Sié *et al.* (1998). The WARM parameters SLA_{ini} and SLA_{till} are consistent with those from Dingkuhn *et al.* (1998), like the corresponding SLATB parameters of WOFOST. WARM RUE is coherent with that reported by Horie and Sakuratani (1985). WOFOST partitioning coefficient and other parameters of the two models which were cali-

Tab. 2b - WOFOST parameters for Japonica – type, short cycle rice varieties (C: calibrated parameters; L: literature; E: local experience; M: measured; D: from Van Diepen *et al.*, 1988); parameters involved with partitioning of assimilates

Tab. 2b - *Parametri colturali di WOFOST per le varietà Japonica precoci (C: parametri calibrati; L: letteratura; E: valori proposti da esperti locali; M: misurati; D: da van Diepen et al., 1988); parametri coinvolti con la ripartizione degli assimilati*

Parameter	Units	Value	Description	Determination
Partitioning-related parameters				
CVL	kg kg^{-1}	0.750	efficiency of conversion into leaves	C
CVO	kg kg^{-1}	0.684	efficiency of conversion into st. org.	
CVR	kg kg^{-1}	0.754	efficiency of conversion into roots	D
CVS	kg kg^{-1}	0.242	efficiency of conversion into stems	C
Q10	-	2	rel. incr. in respiration rate per 10 °C	D
RML	kg CH_2O kg^{-1} day^{-1}	0.020	rel. maint. resp. rate leaves	D
RMO	kg CH_2O kg^{-1} day^{-1}	0.003	rel. maint. resp. rate st. org.	D
RMR	kg CH_2O kg^{-1} day^{-1}	0.010	rel. maint. resp. rate roots	D
RMS	kg CH_2O kg^{-1} day^{-1}	0.015	rel. maint. resp. rate stems	D
RFSETB	- ; -	0 ; 1 2 ; 1	red. factor for senescence as function of development stage	D
FRTB	- ; kg kg^{-1}	0.00 ; 0.50 0.43 ; 0.25 1.00 ; 0.00 2.00 ; 0.00	fraction of total dry matter to roots as a function of development stage	D
FLTB	- ; kg kg^{-1}	0.000 ; 0.950 0.120 ; 0.900 0.240 ; 0.250 0.275 ; 0.418 0.350 ; 0.626 0.435 ; 0.617 0.530 ; 0.540 0.625 ; 0.350 0.720 ; 0.300 0.820 ; 0.100 1.000 ; 0.000 2.000 ; 0.000	fraction of aboveground biomass to leaves as a function of development stage	C
FSTB	- ; kg kg^{-1}	0.000 ; 0.050 0.120 ; 0.100 0.240 ; 0.750 0.275 ; 0.582 0.350 ; 0.374 0.435 ; 0.383 0.530 ; 0.460 0.625 ; 0.650 0.720 ; 0.700 0.820 ; 0.700 1.000 ; 0.328 1.335 ; 0.000 2.000 ; 0.000	fraction of aboveground biomass to stems as a function of development stage	C
FOTB	- ; kg kg^{-1}	0.000 ; 0.000 0.720 ; 0.000 0.820 ; 0.200 1.000 ; 0.672 1.335 ; 1.000 1.220 ; 1.000 2.000 ; 1.000	fraction of aboveground biomass to storage organs as a function of development stage	D

brated are reasonably similar to those found in the Literature.
Results of models calibration are shown in Figures 1.a, 1.b and in Table 3.
It is possible to notice a good agreement between measured and simulated AGB values, both from the graphs and from the fitting indices. In particular, for the dataset of Gudo Visconti – 1990, measured and simulated AGB curves are practically overlapped: relative root mean square error (RRMSE) falls between 6 and 11%, modeling efficiency (describing the agreement between observed and simulated trends; EF) is higher or equal to 0.98, coefficient of residual mass (CRM) is very close to zero, and regression parameters are close to their optimum values. For the dataset of Castello d'Agogna – 1995, it is possible to notice a constant underestimation in the data simulated by WOFOST after the first three samplings (beginning of stem elongation phase). This is underlined by the values of RRMSE and CRM, which reflect the worse performance of WOFOST with respect to the Gudo Visconti dataset, although the indices assume also in this case values which can be considered satisfactory. For the same dataset, WARM overestimates AGB for the sampling number five and six (beginning of flowering and ripening stages), although the final biomass is correctly simulated.During the validation, calibrated parameters allowed the three models to reproduce measured AGB values with sufficient accuracy, thus revealing a satisfactory level of robustness (Figure 2.a and 2.b). This is generally confirmed by all the indices of agreement shown in Table 3. In particular, for the dataset of Vercelli – 1990, WARM reproduces accurately the

Tab. 2c - WOFOST parameters for Japonica – type, short cycle rice varieties (C: calibrated parameters; L: literature; E: local experience; M: measured; D: from Van Diepen *et al.*, 1988); other parameters

Tab 2c - *Parametri colturali di WOFOST per le varietà Japonica precoci (C: parametri calibrati; L: letteratura; E: valori proposti da esperti locali; M: misurati; D: da van Diepen et al., 1988); altri parametri*

Parameter	Units	Value	Description	Determination
Other parameters				
PERDL	-	0.3	max. relative death rate of leaves due to water stress	D
RDRRTB	- ; kg kg^{-1} day^{-1}	0.0000 ; 0.00 1.5000 ; 0.00 1.5001 ; 0.02 2.0000 ; 0.02	relative death rate of roots as a function of development stage	D
RDRSTB	- ; kg kg^{-1} day^{-1}	0.0000 ; 0.00 1.5000 ; 0.00 1.5001 ; 0.02 2.0000 ; 0.02	relative death rate of stems as a function of development stage	D
CFET	-	1	correction factor transpiration rate	D
DEPNR	-	3.5	crop group n. for soil water depletion	D
IAIRDU	-	1	air ducts in roots present (=1) or not (=0)	D
RDI	cm	0	initial rooting depth	D
RRI	cm day^{-1}	1.2	maximum daily increase in rooting depth	D
RDMCR	cm	80	maximum rooting depth	D

Tab. 3 - Indices of agreement between measured and simulated aboveground biomass values (t AGB ha^{-1})

Tab. 3 - *Indici di fitting tra dati di biomassa misurati e simulati (t AGB ha^{-1})*

	Data set	model	RRMSE (%)	EF	CRM	CD	Slope	Intercept (t AGB ha^{-1})	R^2
Calibration	Gudo 90	WARM	10.63	0.98	-0.01	0.83	0.91	0.38	0.99
		CropSyst	11.10	0.98	-0.02	0.94	0.96	0.09	0.98
		WOFOST	6.87	0.99	-0.02	0.89	0.94	0.18	1.00
	Agogna 95	WARM	17.49	0.95	-0.08	0.79	0.88	0.25	0.98
		CropSyst	11.73	0.98	-0.06	0.93	0.96	-0.08	0.99
		WOFOST	16.21	0.96	0.11	1.29	1.15	-0.08	1.00
Validation	Vercelli 90	WARM	12.53	0.98	0.05	0.92	0.95	0.50	0.99
		CropSyst	17.96	0.96	0.13	1.19	1.10	0.24	0.99
		WOFOST	22.57	0.94	0.15	1.31	1.16	0.12	0.99
	Agogna 96	WARM	16.44	0.96	0.09	1.37	1.18	-0.39	0.99
		CropSyst	9.87	0.99	0.01	0.97	0.98	0.18	0.99
		WOFOST	13.10	0.97	-0.06	0.98	0.98	-0.22	0.98

course of measured data, with only a slight overestimation for the August 28 sampling, however characterized by the highest error (see the error bars – 95 % confidence interval for the mean) within the dataset. CropSyst and WOFOST show, for the Vercelli dataset, the similar underestimating behavior after the beginning of the stem elongation phase. This is true especially for the July 7 and September 11, the latter corresponding to harvest. Although the last two samplings of the Castello d'Agogna – 2006 dataset (end of August and of September) are characterized by quite large errors, some uncertainties were noticed in the simulation results from WARM and WOFOST.

All the models compared in this study performed satisfactorily both during calibration and validation, none of them appearing significantly more accurate than the others. For this reason, nothing like "this model works better then the others" will be the result of this comparative study. It is interesting to underline that similar levels of reliability have been shown by three different approaches for the simulation of (i) daily AGB accumulation, (ii) allocation of AGB into the different plant organs and (iii) calculation of leaf area index and light interception. For biomass accumulation under potential conditions, this reflects the almost stechiometric relation between water, CO_2 and intercepted radiation in photosynthesis. In fact, transpired water (correlated to water uptaken by the crop) is the main factor driving AGB accumulation in CropSyst, assimilation of CO_2 and intercepted radiation are the corresponding factors for WOFOST and WARM. Therefore, the different approaches for biomass accumulation like for partitioning and LAI simulation do not appear, in the explored conditions, to lead to a discrimination of the three models based on their different ability in reproducing observed data. The three approaches (and therefore the three models) are different in terms of the empiricism degree and data requirements. WOFOST is very suitable for reproducing and studying processes with fine detail, for depicting the state-of-the-art of crop physiology, and for teaching purposes. This model is however hard to handle and parameterize because of the high requirement as number of parameters to describe plant morpho-physiological features (see Table 2.a, 2.b, 2.c) and input data. Such complexity is not always translated in a higher level of accuracy, as shown by this study. CropSyst and WARM requires quite reduced sets of crop parameters and input data and, in spite of a higher level of simplification, they proved fairly accurate in reproducing observations. With respect to WARM, CropSyst shows a degree of empiricism which is maybe too high in the algorithms involved with the simulation of LAI (see Eq. 7 in Stöckle *et al.*, 2003), a fundamental aspect because of its direct relation to light interception.

In general, WARM appears to be the most easy model to parameterize out of those investigated: (i) fewer parameters are needed, (ii) less empirical parameters are present and (iii) potential RUE is easier to estimate from field experiments than VPD-corrected TUE and maximum CO_2 assimilation rates. Moreover, the parameters involved with AGB partitioning (RipL0) and LAI computation (SLA at emergence and at mid tillering) can be easily derived from field experiments.

Conclusions

This study suggests that the performances of the different approaches used by the three models for the simulation of crop growth are comparable. The main differences among the models under test should be individuated considering an enlarged concept of performance, which includes not only the capability of reproducing time courses of biomass samples collected in field experiments. The effort required for model parameterization (usually inversely correlated to the number of parameters), the presence of parameters which can not be measured (purely empirical), and the explanatory capability should be taken into account, certainly in relation to the specific needs of the modeling work and the application scale. This enlarged concept of performance varies according to the different situations and user's needs. According to such criteria, a first distinction can be done between WOFOST and the other two models. The first is very accurate in describing the plant behavior but highly demanding in terms of data for parameterization and feeding. CropSyst and WARM can work with quite reduced data sets, thus encouraging large scale applications. With respect to CropSyst, WARM has only parameters which can be easily derived from field experiments, thus allowing more reliable parameterizations. For the estimation of rice productions at regional scale, WARM can be considered a satisfactory compromise between the detail required for a realistic modelling of crop behavior and the actual availability of spatially distributed knowledge.

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