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Full Length Research Paper

Evaluation of WARM model for simulating some rice varieties in Northern Delta

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The present research study was carried out to simulate rice yield by using WARM simulation model. Research on rice cropping systems carried out in Egypt has to face the great climate changes, and the linked abundance of cultivated varieties, characteristic of the high latitudes-temperate areas where rice is traditionally grown. Therefore, dynamic simulation models can provide a useful tool for system analysis needed to improve the knowledge, the agronomic management and crop monitoring. WARM (Water Accounting Rice Model) simulates yield of paddy rice (*Oryza sativa* L.), based on temperature-driven development and radiation-driven crop growth. It also simulates; biomass partitioning, floodwater effect on temperature, spikelet sterility, floodwater and chemicals management, and soil hydrology. Biomass estimates from WARM were evaluated. The test-area was Sakah, Kafrelsheikh (Egypt). Data collected from 2003 to 2012 from rice crop grown under flooded and non-limiting conditions were split into a calibration (to estimate WARM model parameters) and an evaluation sets. Plants were sampled during the life cycle from rice plots of two rice cultivars Sakha 101 and Giza 177, maintained at potential production, to determine some important crop variables and parameters such as aboveground biomass (AGB), leaf area index (LAI), potential yield, specific leaf area, and the date of the main phenological stages. Results show that the model was able to simulate rice growth for both varieties. The assessment of model performances has shown average of relative root mean square error (RRMSE) calculated on AGB curves was above 50% for the calibration and 30% for evaluation sets. The modeling efficiency (EF) is always positive and the coefficient of determination (CD) is always very close to 1. Indeed, intercept and slope were always close to their optima and (R^2) was always higher than 0.90. The indices of agreement calculated for the evaluation datasets were better than the corresponding ones computed at the end of the calibration, indirectly proving the robustness of the modeling approach. WARM's robustness and accuracy, combined with the low requirements in terms of inputs and the implementation of modules for reproducing biophysical processes strongly influencing the year-to-year yield variation, make the model suitable for forecasting rice yields on regional, national and international scales.

Keywords: WARM, *Oryza sativa* L., simulation model, flooded conditions, yield forecast, climate change

1. INTRODUCTION

Rice (*Oryza sativa* L.), the staple food of about one-half of the world population, providing 35–60% of the dietary calories consumed by 3 billion people, is arguably among the most important crops worldwide. Although total rice production has more than doubled since 1965, problems about food security still persist and need to be managed based on early and reliable forecasting activities. (Cassman *et al.*, 1997), so that it appears crucial to increase rice production through an increase in yield from rice-cultivated land because an expansion of irrigated areas probably will not be realizable (Mae, 1997).

Rice is one of the major field crops in Egypt. It occupies about 0.65 million hectares, produces approximately 6 million metric tons of rough rice annually (RRTC, 2005) and contributes about 20% to the per capita cereal consumption. The country ranks as one of the highest in the world in terms of productivity per unit area.

Modern rice-culture, facing both food and environmental security, requires sustainable and environmentally sound management analysis, both at farm and regional scale, integrating our knowledge of pedoclimatic conditions, crop production physiology, and agro techniques for analyzing agro-ecosystem. Dynamic simulation models could provide the technical support for analyzing system for better planning, management, and monitoring.

Crop modelling has had a lot of appeal over the years, driven as much by the community's expectations as by the targets identified by modelers (Day, 2001). Since the 1980s, crop modellers have been pointing their attention on rice productions (e.g. Bachelet and Gay, 1993; Mahmood, 1998; Confalonieri and Bocchi, 2005; Confalonieri *et al.*, 2006a). Egypt is the largest rice producer, with more than half of the total production. In Egypt, the crop is typically grown in flooded fields, also to achieve thermal regulation. This and other typical features of rice systems (e.g. weed and disease management, nutrient cycles) make it a challenge to simulate rice growth via a generic crop simulator.

WARM (Confalonieri *et al.*, 2006b) is a novel model for paddy rice simulations developed by an interdisciplinary network of scientists working in different fields of rice research and modelling (<http://mars.jrc.it/mars/Projects/WARM>). Compared to the rice models already available (e.g. CERES-Rice, Singh *et al.*, 1993; ORYZA, Kropff *et al.*, 1994; CRISP, Anastacio *et al.*, 1999), WARM takes into account some relevant processes influencing the final yield usually not considered (i.e. micrometeorological peculiarities of paddy fields, diseases, hydrology of paddy soils, cold-shocks induced spikelet sterility) and reproduces the biophysical processes with a consistent level of complexity. That is, the same variable is never affected by processes modelled in a very detailed way and others which are reproduced using rough

approaches. Moreover, the number of input parameters is very low and none of the parameters is without a biophysical meaning (i.e. impossible to measure or estimate from measurements), thus facilitating model parameterization and use. Moreover, all parameters describing cultivar morphological and physiological features have a biophysical meaning and can be directly measured or derived from measured data. The peculiarity of a rice-based cropping system was analyzed and led to specific modules for the simulation of the floodwater effect on the vertical thermal profile (Confalonieri *et al.*, 2005), the simulation of blast disease, the simulation of the typical hydrology of paddy soils and the simulation of the yield losses due to cold shocks during the pre-flowering period. The model has proven to be suitable and robust for small-scale simulations, where information for parameterizing and feeding models is characterized by a high degree of uncertainty (Wit *et al.*, 2005).

Therefore, the objective of this work was to calibrate and evaluate WARM model for Japonica type early (JE) and Japonica type medium-late (JM) varieties, to enable us to forecast yield and to assess the likely impact of climate change on grain yield and yield variability.

2. MATERIALS AND METHODS

2.1. Experimental data

This research was carried out in Milan University, Italy during the year 2013 to simulate rice yield through the WARM simulation model developed by the crop modeller Prof. Roberto Confalonieri (Department of Crop Science, Section of Agronomy, University of Milan).

The data of the WARM simulation model were collected from the experimental results carried out in the Rice Research experimental farm at Sakha Research station and published in the Rice Annual report from 2003 up to 2012 as well as the data of phenology and physiology characters recorded for variety registration of Giza 177 and Sakha 101. Daily meteorological data between 2003 and 2012 (rain fall, maximum and minimum air temperature and global solar radiation) were collected from Kafrelsheikh automatic weather stations related to weather central lab-Agriculture Research Center (ARC), the soils were sub-acid, with medium-low cation exchange capacity (CEC). Plant samples were dried in oven until constant weight to determine the dry matter weight of aboveground biomass (AGB) which will be always expressed as dry matter in this text, leaf area index (LAI) was obtained by measuring the area of leaves with a leaf area meter and specific leaf area (SLA) by dividing leaves area by leaves weight. For all experiments the soils were characterized by medium

Table 1. Datasets used for model calibration and validation. * Aboveground biomass; ** leaf area index

Experimental site	Latitude N	Longitude E	Soil texture	Sowing date	Variety	Variety group	Measured variables	Nitrogen treatment
Sakha, Kafrelsheikh, Egypt	31°57'	30° 57'	clay	15 May	Giza 177	JE	AGB*, LAI**	As recommended
				15 May	Sakha 101	JM	Potential yield	

Table 2: Approaches to the simulation of crop growth and development implemented by WARM.

Process	WARM
-Development	-Thermal time accumulation, possibly accounting for photoperiod
-Daily biomass accumulation	-Net photosynthesis, based on radiation use efficiency
-Factors limiting biomass accumulation	-Air temperature, saturation of the enzymatic chains, senescence, diseases
-Leaf area development	-Derived from leaf biomass and a daily calculated specific leaf area (the latter derived from development stage and two input parameters: specific leaf area at emergence and at mid-tillering)
-Floodwater effect on temperatures	-Mechanistic micrometeorological approach (resolution of surface energy balance equations)
-Extreme weather events' effects	-Effect of cold shock causing yield losses due to spikelet sterility

nutrients availability, the harvest index (HI) and the phenological stages of emergence, flowering and maturity [respectively codes 10, 65 and 89 of the **B**iologische **B**undesanstalt, **B**undessortenamt and **C**hemical industry (**BBCH**) scale for rice] were determined (Lancashire *et al.*, 1991).

In all experiments, the plots were kept weed free and plant protection was applied as necessary to avoid the presence of pests and diseases. The sowing date was 15 May (the day 136 of year), rice was direct-seeded and the field was flooded. In the experiments, where different N levels were applied, the plots fertilized with the amount of N were considered for this study was conducted under non-limiting conditions.

Chemical and physical soil analyses were performed at the beginning of each experiment to determine texture and organic matter. In all trials, crop samples were taken during the growing season to determine AGB. Harvest index (HI) was computed at harvest time. Plant N concentration (PNC) was measured in samples taken at the same dates when AGB was determined.

2.2. Crop growth simulation

In this study, the WARM approach for the simulation of rice growth under potential conditions was evaluated.

In the following section, a description of the main WARM peculiarities is given. Table (2) shows the main approaches for crop growth and development implemented in WARM.

For crop development, the thermal time accumulated between a base temperature and a cut-off temperature is computed. The accumulated thermal time can be optionally corrected with a factor accounting for photoperiod. Base and cut-off temperatures can be set to different values for the periods sowing – emergence and emergence – physiological maturity.

Similar to SUCROS-derived models, development stages are standardized by converting growing degree-days (GDDs) into a numerical code (DVS) from 0.00 to 2.00 (respectively, emergence and physiological maturity, with DVS = 1.00 corresponding to flowering), useful for synchronizing the simulation of different processes. There variables are obtained as follows (Eqs. (1, 2),

Table (3): WARM parameters (C: calibrated parameters; L: literature; E: local experience; M: measured; D: WARM default parameter). JM: Japonica-type varieties (medium maturity); JE: japonica-type (early maturity) varieties. GDD: growing degree days. AGB: aboveground biomass.

Parameter	Units	Value		Description	Determination
		JM	JE		
<i>Development</i>					
TbaseDem	°C	25	25	Base temperature for development before emergence	E, L
TmaxDem	°C	38	38	Maximum temperature for development before emergence	E
GDDemTbase D	°C-days	170	145	GDDs from sowing to emergence	M
	°C	25	25	Base temperature for development before emergence	L
TmaxD	°C	38	38	Maximum temperature for development before emergence	L
	°C-days			GDDs from emergence to flowering	
GDDem-fl	°C-days	3130	2540	GDDs from flowering to maturity	M
GDDfl-mat	°C-days	695	740	GDDs from maturity to harvest	M
GDDmat-harv		195	200		
<i>Growth</i>					
RUE ^a	gMJ ⁻¹			Radiation use efficiency	L
K	-	2.6	2.3	Extinction coefficient for solar radiation	C
TbaseG	°C	0.50	0.50	Base temperature for growth	E, C
ToptGa	°C	12	12	Optimum temperature for growth	E, C
TmaxG	°C	28	28	Maximum temperature for growth	E
LAini	m ² m ⁻²	30	30		
SLAini	m ² kg ⁻¹			Initial leaf area index	
SLAtill	m ² kg ⁻¹	0.02	0.02	Specific leaf area at emergence	D, C
RipL0a	-	29	29	Specific leaf area end tillering	M
LeafLife	°C-days	18	18	AGB partition to leaves at emergence	M
ApexHeight	Cm	0.8	0.8	Leaf duration	C
Kc	-	700	710	Maximum panicle height	C
		100	105	Crop coefficient at full canopy	E
		1.05	1.05		L

^a Relevant parameters from the sensitivity analysis (Confalonieri *et al.*, 2006b).

respectively, for the periods emergence-flowering and flowering-physiological maturity (Confalonieri *et al.*, 2009):

$$DVS = \frac{(GDDcum - GDDem)}{GDDfl} \quad (1)$$

$$DVS = 1 + \frac{(GDDcum - GDDem - GDDfl)}{GDDmat} \quad (2)$$

Where: $GDDcum$ (°C-day) = the cumulated GDDs, $GDDem$ (°C-day) = the GDDs required to reach emergence, $GDDfl$ (°C-day) = the GDDs required to reach flowering, $GDDmat$ (°C-day) = the GDDs required to reach physiological maturity.

2.3. WARM: a novel model for rice simulation

Temperature is one of the most important driving variables for simulation of crop growth and development. In paddy rice systems, this meteorological variable is greatly influenced by the presence of floodwater. In WARM, the micrometeorological model TRIS proposed by Confalonieri *et al.* (2005) is adopted to take into account the floodwater effect on the vertical thermal profile. TRIS generates hourly and daily temperatures for both the water body and the air layers above the air-water interface (18 layers of 0.1m each). In particular, the temperatures generated by TRIS at the meristematic apex height are used for simulating the

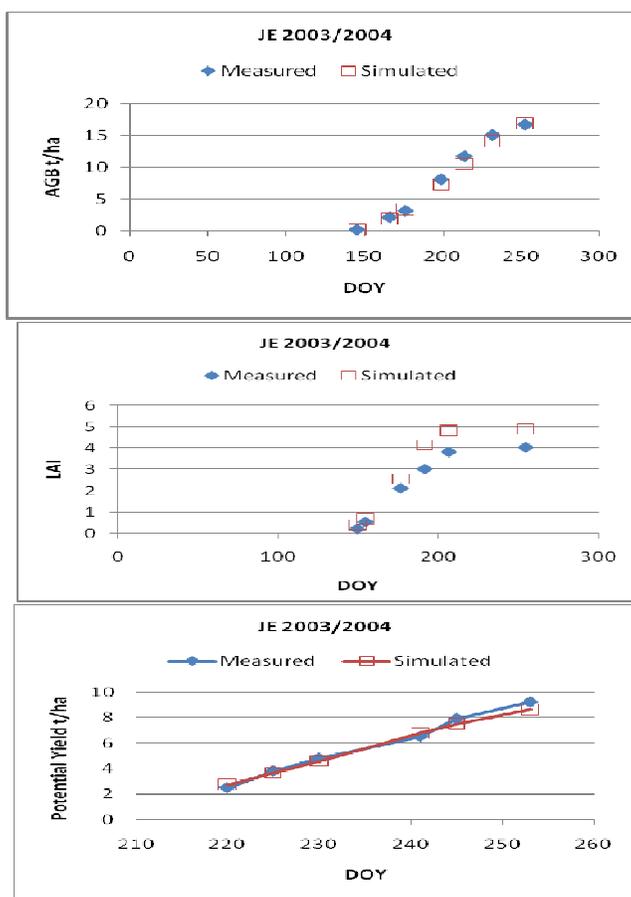


Figure (1) Measured and simulated AGB, LAI and Potential Yield (t/ha) values after Calibration. JE: Japonica early (Giza 177), DOY (Days of Year)

processes related to plant development and spikelet sterility. Average canopy temperature is used for simulating thermal limitation to photosynthesis and leaves aging.

For the simulation of *AGB* accumulation and partitioning, and *LAI* development, the GAIA model (Confalonieri, 2005) is used. The net photosynthesis rate is simulated using a *RUE*-based approach accounting for the effect of temperature limitations, saturation of the enzymatic chains, and senescence phenomena on radiation use efficiency (Confalonieri *et al.*, 2006b). *AGB* accumulated each day is assigned to leaves using a parabolic function which assumes the maximum value (input parameter *RipL0*) at emergence and zero at flowering. *AGB* partitioning to panicles starts at the panicle initiation stage (*PI*) and is assumed as maximum at the beginning of the ripening phase, when all the daily accumulated *AGB* is partitioned to panicles. Stems biomass is computed by subtracting panicles and leaves biomasses from total *AGB*.

2.4. Model parameterization and validation

WARM model version 1.9.6 (9 August 2007) was used. Options were set to avoid limitations due to water and nutrients stresses, pests and diseases. Under such potential conditions, the parameterization was mostly based on previous research, field measurements, and reference values from the user guide supplied with the models. For some parameters, a calibration work was performed on a sub-set of *AGB* data and varied between Japonica-type, medium-late maturity varieties (JM) and Japonica early maturity -type varieties (JE).

WARM parameters mostly affecting the *AGB* at physiological maturity. Such relevant parameters were either calibrated or determined from direct field measurements. All other parameters were left to default. Information about parameters and their sources of information are shown in Table (3).

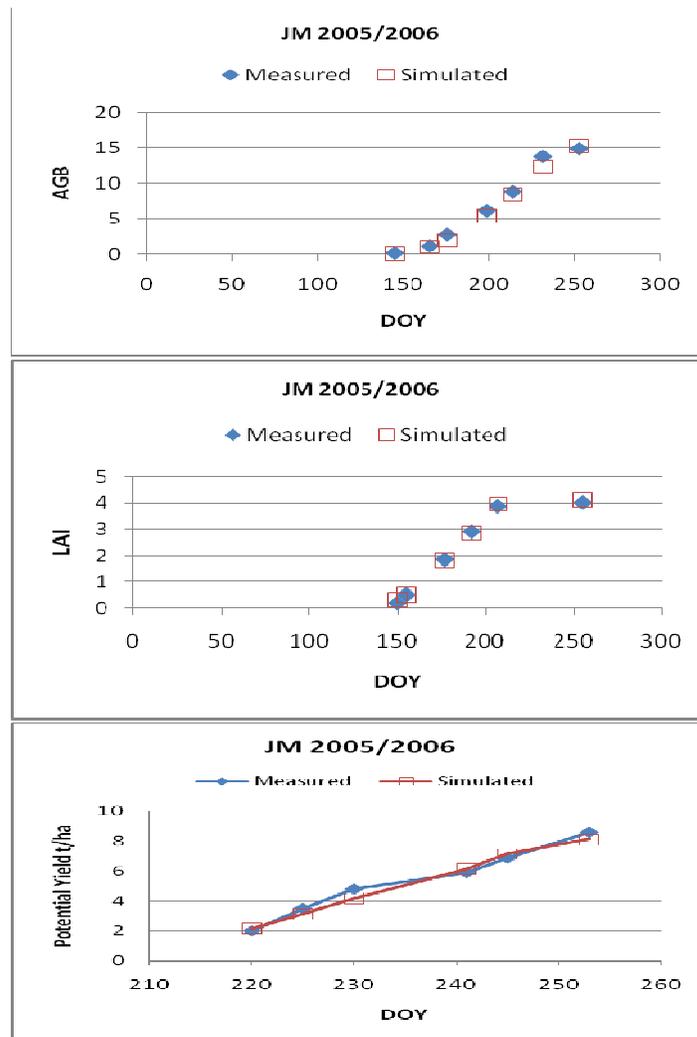


Figure (2). Measured and simulated AGB, LAI and Potential Yield (t/ha) values after Calibration. JM: Japonica medium –late (Sakha 101), DOY (Days of Year)

Maximum radiation use efficiency (maximum *RUE*) was set for WARM to the values measured by Boschetti *et al.* (2006) on the same varieties. These values, higher than those published for rice and other C3 species from some authors (e.g. Kiniry *et al.*, 1989) and were similar with those reported by Campbell *et al.* (2001). Specific leaf area (*SLA*) values were derived by Boschetti *et al.* (2006) for the same groups of varieties.

The agreement between observed and predicted values was expressed by using the indices proposed by Loague and Green (1991): the 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, $-\infty/+\infty$, optimum = 1, if positive, indicates that the model is

a better predictor than the average of measured values), the coefficient of residual mass (CRM, 0–1, optimum = 0, if positive indicates model underestimation) and the parameters of the linear regression equation between observed and predicted values.

3. RESULTS AND DISCUSSION

The main purpose of this study was to evaluate the adequacy of the WARM model for simulating rice crop in Egypt, to help us to forecast yield and to assess the likely impact of climate change on grain yield and yield

variability. The data used, collected under optimal conditions for water and nitrogen availability, were split into two independent datasets for the calibration and evaluation activities.

3.1. Calibration of crop model parameters

Warm parameter values (development and growth parameters) with the source of information or after calibration are shown in Table (3). Base and optimum temperatures are in the range of those reported, respectively, by Siéet *et al.* (1998) and Casanova *et al.* (1998). Maximum temperatures are coherent with those used by Mall and Aggarwal (2002) for the CERES-Rice and ORYZA1 models.

For radiation use efficiency (RUE) measured values were derived from Bouman *et al.* (2006) and Boschetti *et al.* (2006) for the same group of varieties. The value of 0.5 for Extinction coefficient for solar radiation(k) is consistent with that reported by (Dingkuhn *et al.*, 1999). The values of Specific leaf area at emergence(SLAini) and Specific leaf area end tillering (SLAtill) are within the range of those measured by Dingkuhn *et al.* (1998) and by Boschetti *et al.* (2006). *SLAtill* and *Leaf Life* (Leaf duration) were calibrated to allow the model to reproduce measured leaf area index curves.

Air temperature is in fact one of the most important driving variables in crop models and, in paddy fields, it is strongly influenced by floodwater. Nishiyama (1995) indicated water warming as effective up to several centimeters above the water surface. Other authors (Dingkuhn *et al.*, 1995) underlined that, in paddy fields. In fact, the meristematic apex is exposed to water temperature until the panicle initiation stage; then, internodes elongation lifts the apex out of the water surface (Dingkuhn *et al.*, 1995). Such effects are accounted for by WARM through the specialized micrometeorological module TRIS.

There was general agreement between observed and simulated aboveground biomass (AGB t/ha), leaf area index (LAI m^2/m^2) and potential yield (t/ha) values after calibration for both varieties as shown in Figures(1,2) and Table (4).

In general, WARM presents a reasonable accuracy in simulating aboveground biomass accumulation and leaf area index for both varieties Giza 177 and Sakha 101, respectively. This is confirmed by the fitting indices as shown in Table (4) where the coefficient of residual mass is negative for the two datasets. While the relative root mean square error values obtained for both varieties are above 20%, the others, though presenting satisfying results, are slightly higher. The same considerations are valid for the modeling efficiency. In general, the regression parameters

are satisfactory: slope values are close to one for all simulations.

Simulated values of aboveground biomass for both varieties present a good agreement with measured ones in almost all the situations, with the modeling efficiency constantly above 0.9. The agreement between observed and simulated leaf area index values is usually lower. This is probably due both to the difficulty of simulating the balance between emission and death of green leaf area index units before flowering and to the higher errors in leaf area index measurements compared with above ground biomass ones. (Confalonieri *et al.*, 2009).

Although the daily aboveground biomass accumulation rate depends on absorbed radiation and therefore on green leaf area index state, the not completely satisfactory simulation of green leaf area index before flowering does not significantly affect aboveground biomass accumulation, because in that phase the canopy is practically closed and the interception of radiation can be considered complete as mentioned by (Confalonieri *et al.*, 2009).

Calibrated values for these parameters are within the range of values found in the literature and allowed the model to reproduce measured data in a satisfactory way, especially the aboveground biomass curves.

The predicted potential yields for both varieties were similar to observed yields after calibration. Since, the statistical analysis showed a reasonable agreement between observed and predicted potential yield, with indices of agreement RRMSE values ranging between 33% and 39% for Giza 177 and Sakha 101, respectively and EF and CD was always close to one, Table (4).

3.3. Evaluation of crop model parameters

Figures (3,4) and Table (4) show the results of the crop parameter test. Despite a general slight overestimation, for both varieties, WARM satisfactorily simulates above ground biomass values, also during the evaluation. As already discussed for the calibration phase, the best values of fitting indices were calculated for the medium- late variety.

Measured aboveground biomass values are accurately reproduced by the model. In all cases, R^2 is higher than 0.98 for both varieties. The modeling efficiency for the simulation of leaf area index reached a value of 0.85 and 0.91 for Giza 177 and Sakha 101, respectively. Index of agreement between predicted and observed values fluctuated from 0.90 to 0.98 (a value of 1.0 indicating excellent agreement), respectively with most values equal or better than 0.95.

Simulated values of potential yield for both varieties present a good agreement with measured ones after evaluation, with the modeling efficiency (EF) constantly above 0.90. While, the RRMSE was 30% and 65% for Giza 177 and Sakha 101, respectively. (CD), (CRM) and R^2 for both varieties are closer to their optimum.

Table (4) Indices of agreement between observed and simulated aboveground biomass (AGB; t/ ha), leaf area index (LAI; m²/ m²) and Potential Yield (t/ha) values.

Activity	Variety group	Year	Variable	RRMS %	EF	CRM	CD	Slope	Intercept (t/ha)	R ²
Calibration	JE (Giza 177)	2003 2004	AGB	57	0.99	0.05	1.07	1.03	0.13	0.99
			LAI	64	0.75	-0.27	0.58	0.80	-0.04	0.99
			Potential yield	33	0.98	0.02	1.18	1.08	-0.33	0.99
	JM (Sakha101)	2005 2006	AGB	20	0.98	0.07	1.01	1.00	0.43	0.99
			LAI	7	1.00	-0.02	0.97	0.99	0.00	1.00
			Potential yield	39	0.97	0.03	1.00	0.99	0.19	0.97
Evaluation	JE (Giza 177)	2009 2010	AGB	10	0.97	-0.08	1.03	1.01	-0.76	0.98
			LAI	49	0.85	-0.18	0.85	0.94	-0.31	0.96
			Potential yield	30	0.98	0.00	1.32	1.15	-0.86	1.00
	JM (Sakha101)	2011 2012	AGB	69	0.98	0.08	1.03	1.02	0.52	1.00
			LAI	35	0.91	-0.02	0.80	0.87	0.31	0.94
			Potential yield	65	0.93	-0.03	1.40	1.16	-1.06	0.95

(RRMSE) Relative Root Mean Square Error (%; 0 to +∞, optimum = 0).

(EF) Modelling Efficiency (–, –∞ to 1, optimum = 1).

(CRM) Coefficient of Residual Mass (–, –∞ to 1, optimum = 0).

(CD) coefficient of determination (minimum = 0, optimum = 1).

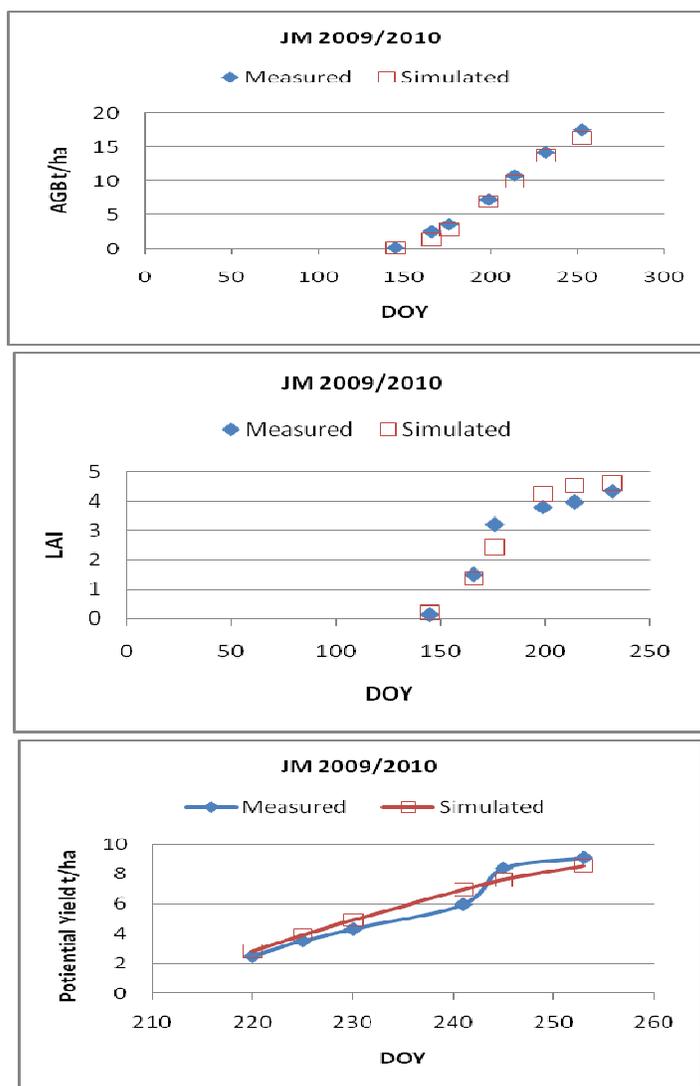


Figure (3) Measured and simulated AGB, LAI and Potential Yield (t/ha) values after Evaluation. JM: Japonica medium –late (Sakha 101), DOY (Days of Year)

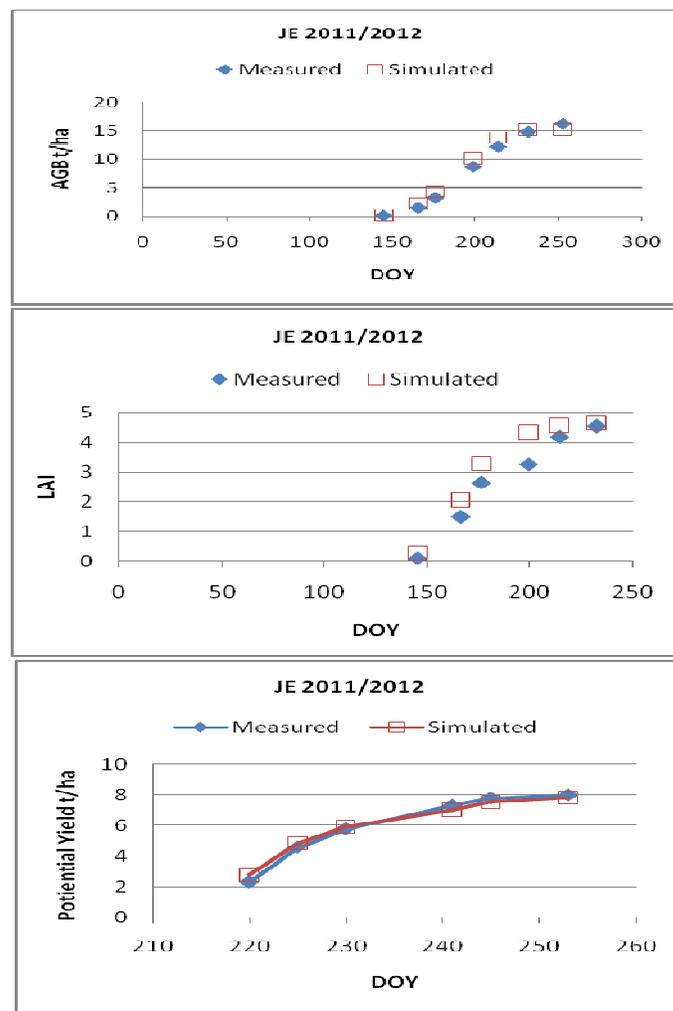


Figure (4) Measured and simulated AGB, LAI and Potential Yield (t/ha) values after Evaluation. JE: Japonica early (Giza 177), DOY (Days of Year)

It is important to underline that WARM performances in evaluation are better than the calibration ones: average values of relative root mean square error (RRMSE), modeling efficiency (EF), and coefficient of residual mass (CRM) and R^2 for the evaluation datasets are closer to their optimum.

During the evaluation, the model presented the same level of accuracy discussed for the calibration dataset. The fitting indices calculated for the JE variety are better than those calculated for the other variety group. Also during the evaluation, the model has shown to be able to reproduce growth and development of different varieties under different conditions.

The WARM approach to growth modelling can be considered more representative of paddy rice systems and more parsimonious with respect to parameter needs. The approach used to simulate air temperature is an example of the closer representation of the real system. The

different processes influencing crop growth were implemented in WARM by maintaining a certain balance among the model compartments as cited by (Confalonieri *et al.*, 2009).

4. CONCLUSIONS

The aim of this work was to calibrate and evaluate the WARM model for simulating rice crop in Egypt to forecast yield, and to assess the likely impact of climate change on rice yield.

After calibration and evaluation, model performances are very similar and the simulation of floodwater effect on temperature did not lead to incoherent model behaviors. These results show that the model is robust and able to reproduce yield variability within years and locations.

This is the first time a model explicitly accounting for the micrometeorological peculiarities of paddy rice has been evaluated. The WARM model can be considered suitable for investigating the interactions between weather and crop productivity in a changing climate.

WARM, after this parameterization, is able to simulate accurately the growth of both rice cultivars types (Giza 177 and Sakha 101). The exploration of different meteorological conditions allows excluding that the presented parameters sets include errors due to particular meteorological situations. Therefore, the two parameters sets calibrated for Japonica early and medium-late varieties may be used for large-scale simulations of rice growth in Egypt for carrying out operational rice yield forecasts on regional, national and international scales, aiming at managing food security problems.

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