Crop Monitoring as an
E-agricultural tool in
Developing Countries

# EVALUATION REPORT ON RICE SIMULATION AT FIELD LEVEL

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# EXECUTIVE SUMMARY

This report presents the results of the evaluation of the performances of the models WARM, WOFOST and CropSyst for rice growth and development simulation at field level in the Jiangsu province. For both calibration and validation purposes, data of rice aboveground biomass and green leaf area index collected at nine different sites in 2011 and 2012 were used. The observations datasets were split in two parts, taking into account different sowing techniques (transplanting and direct sowing). Evaluation metrics showed good performances for the three models for aboveground biomass simulation for both the sowing techniques and for all the combinations site × year, whereas the reproduction of measured trend of green leaf area index resulted less accurate for the datasets where rice was directly sown. An improved transplanting algorithm allowed the three models to achieve good performances in reproducing aboveground biomass and green area index measurements in the transplanted datasets.

# 1. **Introduction**

Crop growth models present a variable number of parameters which drive crop development and growth. Model calibration consists in the modification of the values of these parameters in order to allow the model to reproduce the behavior of specific species or cultivars, thus obtaining a good agreement between simulated and measured variables (e.g., biomass, leaf area index) under specific conditions. The effectiveness of the calibration process can be evaluated by analyzing the performance of a model via evaluation indices (e.g., Fox, 1981; Loague and Green, 1991). A large set of indices are available in literature, able to evaluate model behavior under different perspectives: e.g., accuracy, correlation, robustness and complexity. The impact of the calibration process should be tested against independent (validation) datasets. The number of parameters or variables to be calibrated should be kept to the minimum, following the principle that it is better to measure or use reference data than simultaneously calibrate several parameters.

In this work, a calibration of WARM (Confalonieri et al., 2009), WOFOST (van Keulen and Wolf, 1986) and CropSyst (Stöckle et al., 2003) models was manually performed, according to the “trial and error” method, without the use of automatic optimization algorithms. Only the most relevant parameters of the three models were calibrated (Confalonieri et al., 2013), according to outcomes of the sensitivity analysis study already performed within the E-AGRI project (see E-AGRI report D32.1).

# 2. Materials and methods

## 2.1. Field level calibration and validation of the models WARM, WOFOST and CropSyst for rice simulation in Jiangsu

### 2.1.1. The observation datasets

The data used for the calibration and validation of the three models were collected in the Jianghuai plain at nine sites during the years 2011-2012 (see report D31.1).

The experiments with directly sown rice were separated from the ones in which rice was transplanted, because the algorithms used for direct-sown and transplanted rice are different, and available transplanting algorithms have not been evaluated as extensively as those for direct-sowing. Moreover, CropSyst and WOFOST, being generic crop simulators, do not have – in their original versions – options for simulating transplanting. In some experimental sites, the sowing method and the rice varieties adopted were different in the two experimental years, therefore the datasets characterized by the same sowing method and rice varieties in both years were used for models calibration, whereas the others were used for validation. Table 1 shows the experiments chosen for calibration, the rice variety and the type of sowing: the same variety (i.e., Huaidao 5) was used in the three direct sowing experiments. Table 1 also shows that rice was artificially transplanted at site SD1, whereas mechanical transplanting was used at site SD8. This is a new agro-management technology developed in Jiangsu province, characterized by a very high density of seedlings in the seedbed aimed at increasing – in relative terms – the remaining field surface. Table 2 presents the same information related to the validation datasets.

*Table 1 Jiangsu datasets selected for calibration*

| Site code | Cultivation method | Rice variety | Rice type |
|---|---|---|---|
| **SD3** | Direct sowing | Huaidao 5 | Late-maturing *Japonica* rice |
| **SD5** | Direct sowing | Huaidao 5 | Late-maturing *Japonica* rice |
| **SD6** | Direct sowing | Huaidao 5 | Late-maturing *Japonica* rice |
| **SD1** | Mechanical transplanting | Yangjing 4227 | Early-maturing *Japonica* rice |
| **SD8** | Artificial transplanting | Y Liangyou | Late-maturing *Indica* rice |

*Table 2 Jiangsu datasets selected for validation*

| Site code | Year | Cultivation method | Rice variety | Rice type |
|---|---|---|---|---|
| **SD4** | 2011<br>2012 | Direct sowing | Huaidao 5 | Late-maturing *Japonica* rice |
| **SD2** | 2011 | Direct sowing | Zhendao 88 | Medium-maturing *Japonica* rice |
| **SD9** | 2012 | Direct sowing | Xudao 3 | Late-maturing *Japonica* rice |
| **SD7** | 2011<br>2012 | Artificial transplanting | C Liangyou | Late-maturing *Indica* rice |
| **SD9** | 2011 | Mechanical transplanting | Huaidao 5 | Late-maturing *Japonica* rice |
| **SD2** | 2012 | Mechanical transplanting | Huaidao 5 | Late-maturing *Japonica* rice |

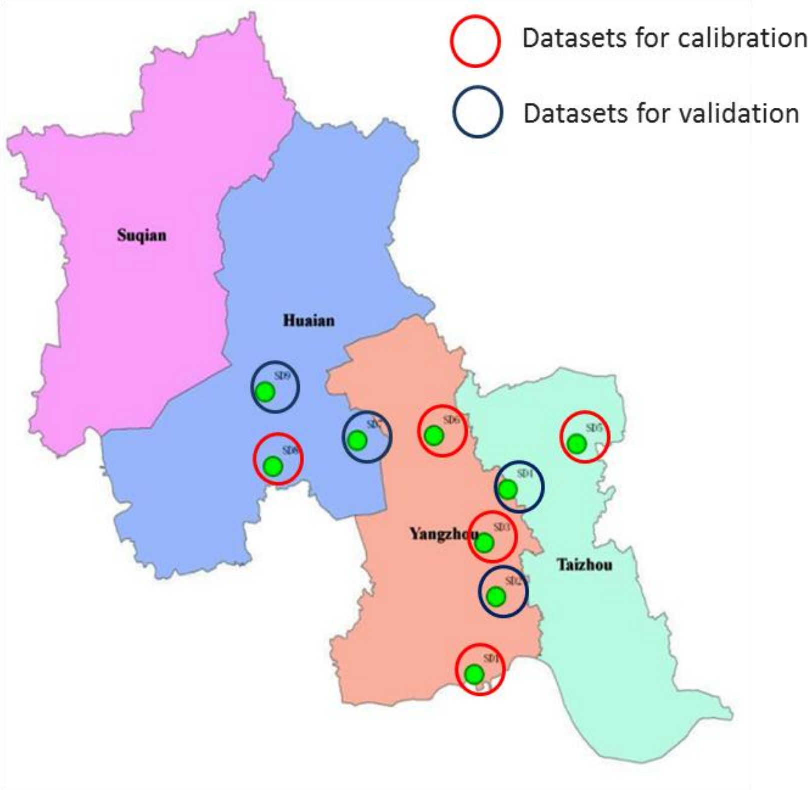


Figure *1* shows the distribution of the selected sites. Sites chosen for calibration are representative of the wide range of environmental and meteorological conditions experimented by rice crop in Jiangsu. These experimental sites are spread in the rice cultivation area and they are not grouped in a specific region.

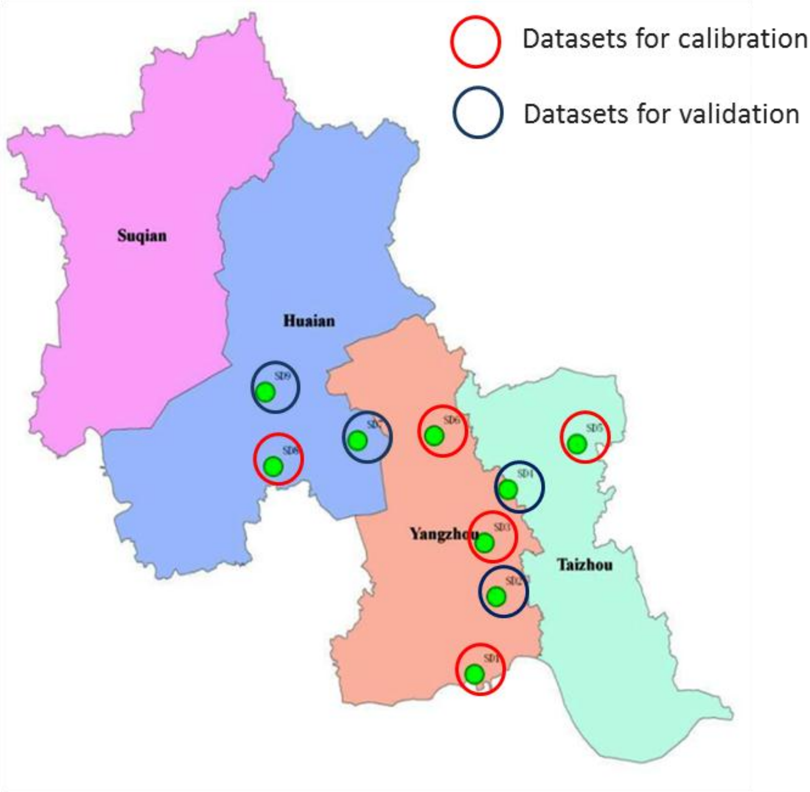


*Figure 1 Distribution of calibration and validation datasets in the study region*

Before the model calibration, an analysis of rice Above Ground Biomass (AGB) and Green leaf Area Index (GAI) observations was performed.

All datasets in 2011 showed a steep accumulation rate of AGB in the last part of the growing season. As an example, in Figure 2 this anomalous linear increase in SD3 between flowering (i.e., the fifth point in the graph) and maturity (i.e., the last point) is shown.

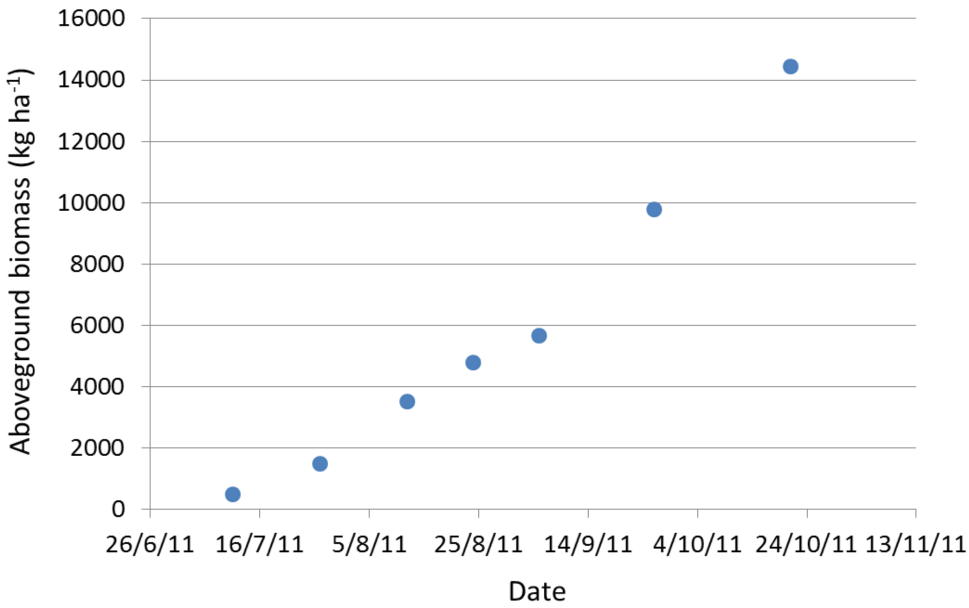


*Figure 2 Total aboveground biomass measured at SD3 in 2011*

This trend is due to an unexpected accumulation of biomass and partitioning to the different organs during the reproductive phase (see

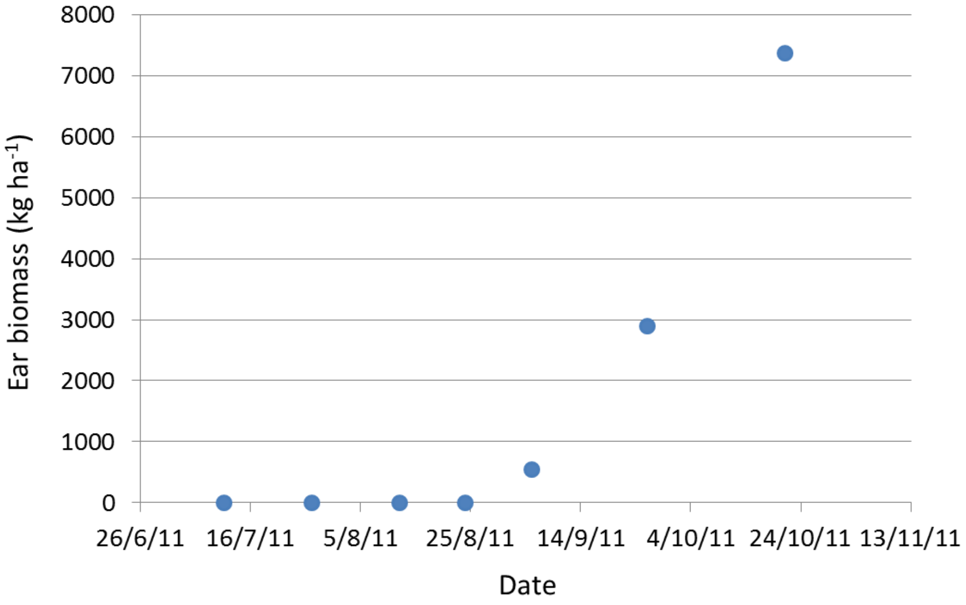


Figure 3 and Figure 4). Grain filling presents a linear increasing trend during the last 25 days before physiological maturity, even though the value of harvest index in all datasets is about 0.5, which is typical of rice crop. Moreover, biomass accumulation in stems presented an unexpected increase during the first 20 days after flowering. In this phases, in fact, the plant start allocating most of the photosynthates to storage organs, and decidedly decreasing the translocation to leaves and stems, that are even interested by re-translocation processes (they are defined as source in this phase).

Given (i) these considerations and (ii) the theoretical formulation of the three models, some uncertainties in the correct reproduction of observations in the last part of the growing period was expected.

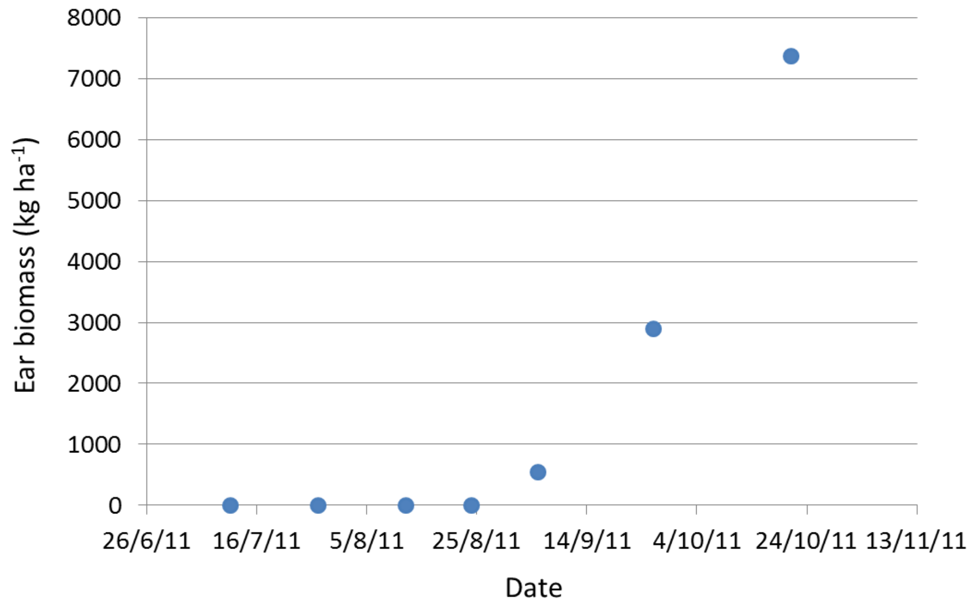


*Figure 3 Ear biomass observed at site SD3 in 2011*

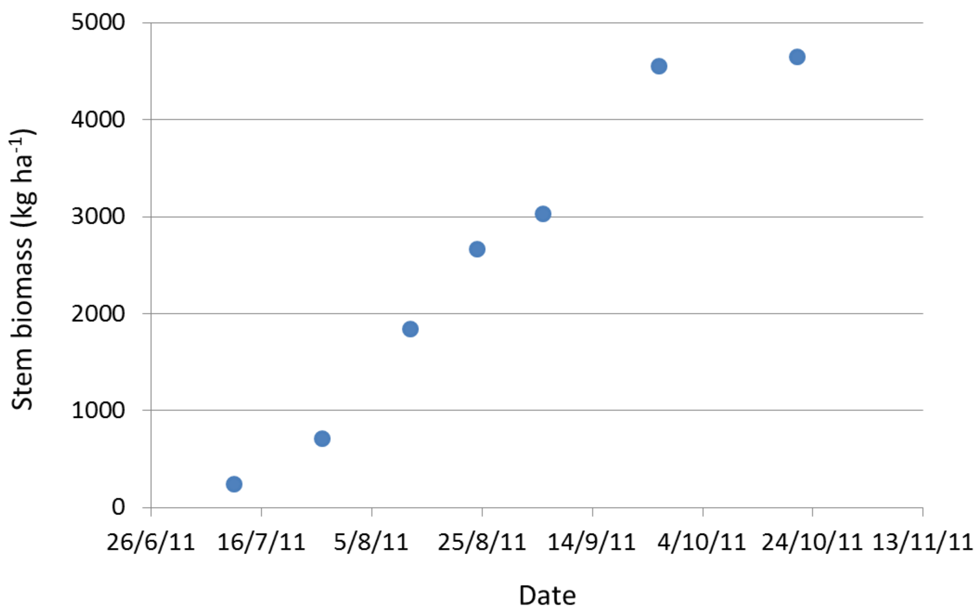


*Figure 4 Stem biomass observed at site SD3 in 2011*

In 2012, the unexpected trend in AGB values was not observed in all datasets, as shown in Figure 5. As an example, at site SD3 the same rice variety was sown in 2011 and 2012 in the same growing period. In 2012 the crop showed a higher accumulation of biomass during the period before flowering compared to the 2011 dataset (see Figure 2). The AGB accumulated in the period from flowering to maturity prior to grain-filling was about 4 t ha$^{-1}$, whereas in 2011 it was 8 t ha$^{-1}$.

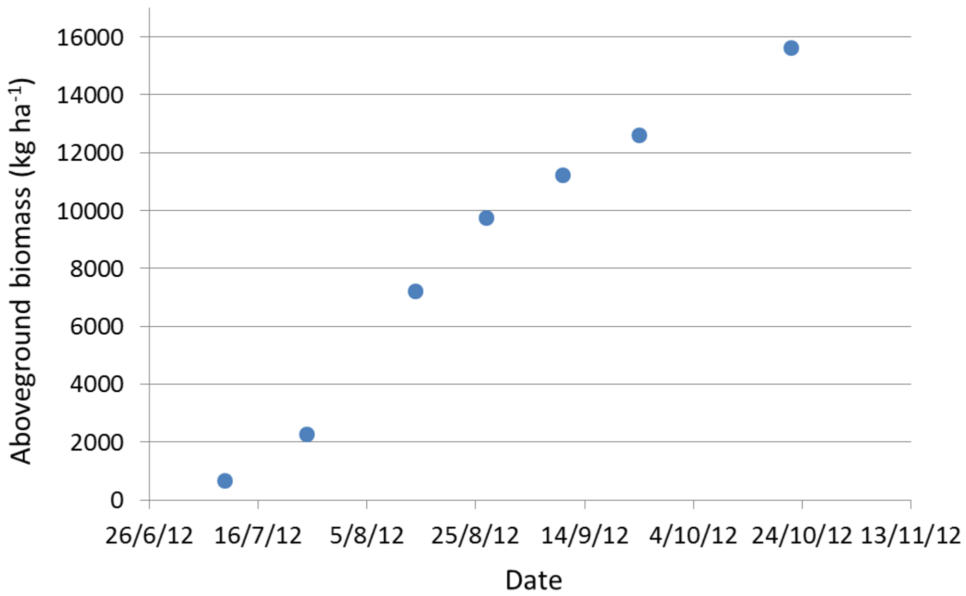


*Figure 5 Total aboveground biomass observed at SD3 in 2012*

The average final value of AGB was similar both in 2011 and 2012: it was 16 t ha$^{-1}$ in directly sown datsasets and 14 t ha$^{-1}$ in transplanted datasets.

On the other hand, GAI measurements were almost the same for transplanted datasets in the two years, but they were markedly different in the directly sowing datasets. The observed trend of GAI can be approximated by a bell-shaped curve with the peak reached around the heading stage, after which leaves senescence begins. The average value of this peak was 5-6 m$^2$ m$^{-2}$ for transplanted crops in 2011-2012 and also for directly sown rice in 2011, whereas in 2012 GAI reached the value of 10 m$^2$ m$^{-2}$ in all the experiments. Figure 6 shows the comparison between the trend of GAI during rice growing season of 2011 and 2012 at site SD6.

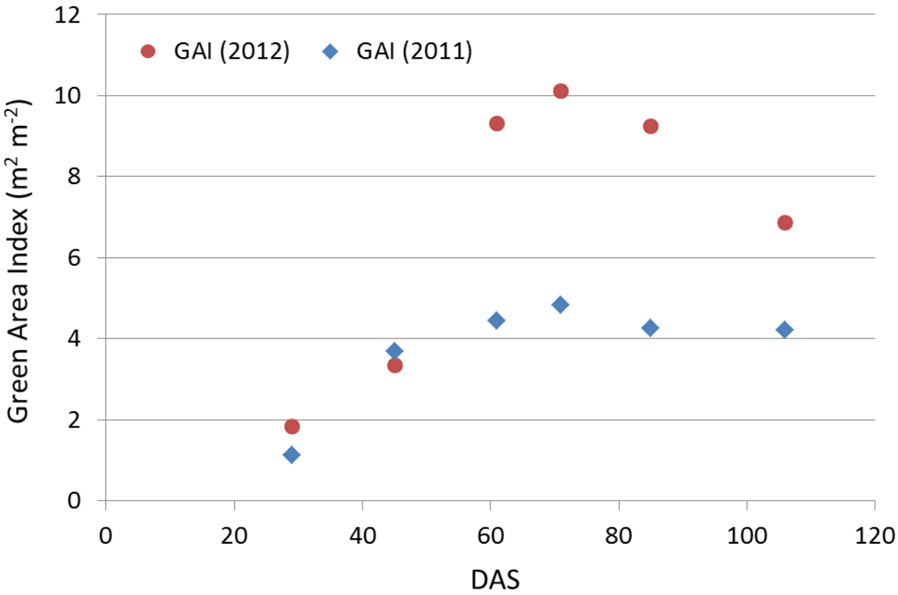


*Figure 6 Comparison between Green Area Index observed at site SD6 in 2011 and 2012 (DAS: days after sowing)*

### 2.1.2. The meteorological datasets

Given the proximity of meteorological stations to the experimental fields, six meteorological datasets were supplied. All of them were characterized by very low values of global solar radiation, given the rice growing period and the latitudes at which experiments were performed (i.e., about 32°N). In particular, the maximum value is rarely above 20 MJ $m^{-2}$ during summer. Figure 7 shows the comparison between the radiation data observed at site SD3 and the ones retrieved from the Era-Interim reanalysis database of the European Centre for Medium-Range Weather Forecasts (ECMWF) with 25×25 km grid resolution. ECMWF values are almost always higher than the meteorological datasets coming from the experimental sites. Moreover, Figure 7 points out that in some periods, the same low observation value is recorded for several consecutive days. The good agreement between ECMWF and measured average air temperature (Figure 8) data further suggested possible problems in measuring or processing of radiation data.
Given the similarities of air temperature data, it was agreed to use ECMWF data for model calibration and validation.

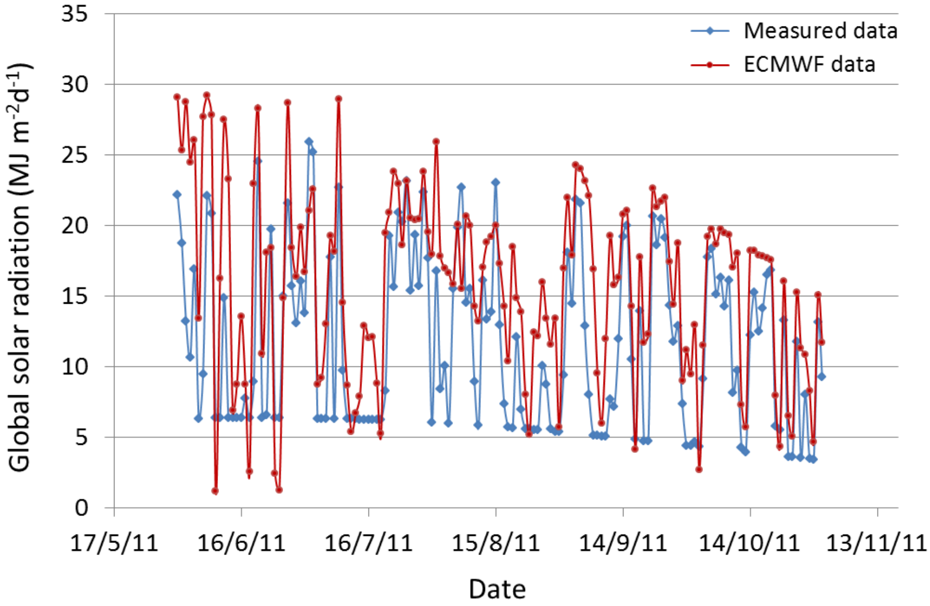


*Figure 7 Comparison of daily global solar radiation measured at site SD3 site and retrieved from the ECMWF Era Interim archive*

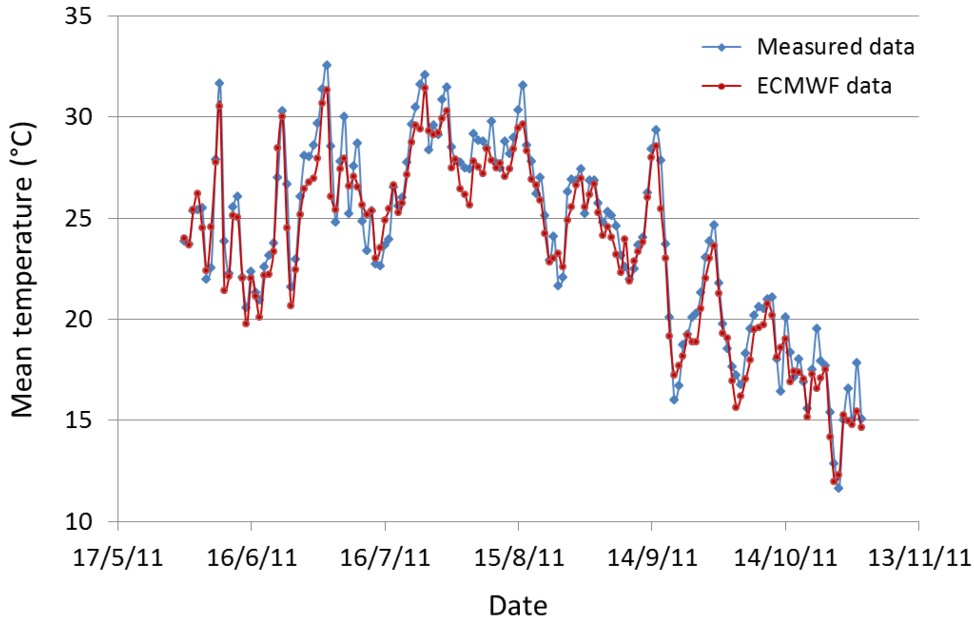


*Figure 8 Comparison of daily mean air temperature measured at site SD3 site and retrieved from the ECMWF Era Interim archive*

Once decided to use ECMWF meteorological data as models inputs, the meteorological data used by the crop growth models to simulate potential rice development and growth (i.e., temperature and global solar radiation) in 2011 and 2012 were compared. It emerged that rice growing season (i.e., from June to October) in 2012 was warmer than 2011 in all the sites. Daily mean air temperature, averaged during the rice growing period in 2012, was about 1°C higher than in 2011, thus determining an increased thermal time accumulated by the crop from sowing to maturity stage. Moreover, average global solar radiation was about 2 MJ $m^{-2}$ $d^{-1}$ higher in 2012 than in 2011.

# 3. Results and Discussion

## 3.1. Calibration and validation of the models WARM, WOFOST and CropSyst for rice simulation in Jiangsu

The complete lists of the calibrated parameter values for WARM, WOFOST, and CropSyst are detailed in Appendix A, B, and C, respectively.

The first calibrated parameters are those affecting plant development. The obtained results were similar both in direct sowing and transplanting datasets, so the same discussion applies to both cultivation methods. In order to simulate crop development, the thermal time accumulated between a base temperature and a cut-off temperature was computed by models. Base and cut-off temperatures were set to the same value, derived from literature, in the three models. Growing degree days needed to reach flowering and maturity stages were calibrated separately for each model to achieve agreement between measured and simulated data. According to the observed trend in the meteorological data (see 2.1.1), models simulated a shorter crop cycle in 2012 compared to 2011, whereas experimental datasets showed longer plant cycle in 2012. For this reason, it was not possible to find parameter values allowing a satisfactory crop development simulation both in 2011 and 2012, and in some sites the difference between measured and simulated dates of maturity reached 15-20 days. The same results were obtained in the validation datasets.

Once parameters involved with crop development were calibrated, the parameters involved with biomass accumulation were considered. A specific effort was put in the calibration of the parameters showing a high relevance in explaining output variability, according to the sensitivity analysis performed in this project (see E-AGRI report D32.1). The discussion of the results for crop growth simulation for both direct-sown and transplanted rice is presented in the following sections.

### 3.1.1. Results obtained with direct sowing datasets

Since the observation sites chosen for parameter calibration are located at similar latitudes and there are no significant differences in the meteorological data, the simulated AGB and

GAI trends are similar for all the models in all the datasets. For this reason, only the results obtained in site SD5 are shown as example.

AGB data simulated by WARM, WOFOST and CropSyst (continuous lines) are shown in Figure 9, Figure 10 and Figure 11, respectively, compared with data collected at different stages of rice growth (rhombi). All the models showed a good performance in reproducing AGB measured data in 2011, exclusive of the last observation because of the anomalous trend discussed in paragraph 2.1.1. For 2012, the simulation of AGB was very close to the measurements.

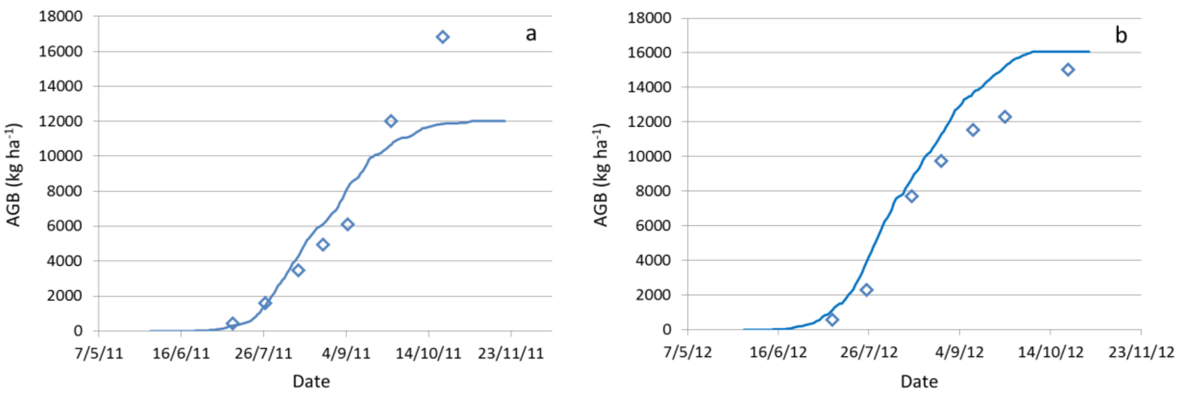


*Figure 9 Comparison between simulated (blue line) and measured (blue diamonds) aboveground biomass in 2011 (a) and 2012 (b). Site SD5, WARM model*

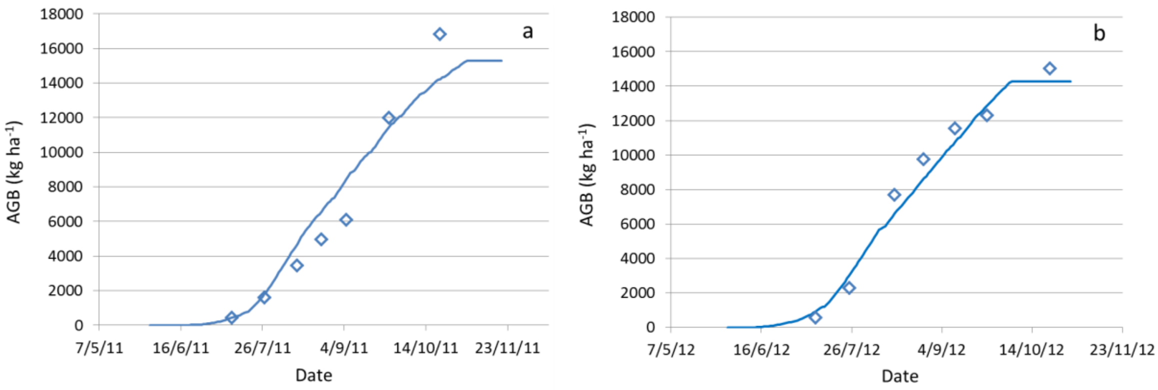


*Figure 10 Comparison between simulated (blue line) and measured (blue diamonds) aboveground biomass in 2011 (a) and 2012 (b). Site SD5, WOFOST model*

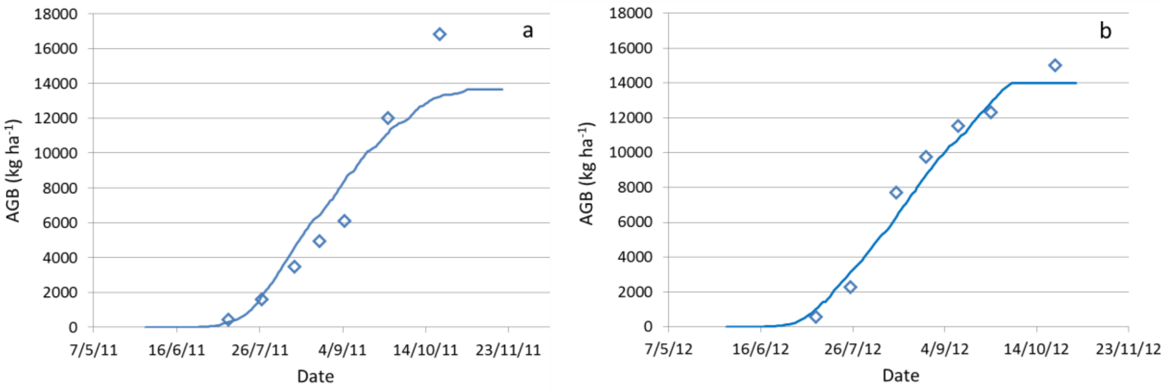


*Figure 11 Comparison between simulated (blue line) and measured (blue diamonds) aboveground biomass in 2011 (a) and 2012 (b). Site SD5, CropSyst model*

GAI trends simulated by WARM, WOFOST and CropSyst are shown in Figure 12, Figure 13 and Figure 14, respectively. Parameters were calibrated aiming at finding a single parameter set capable to minimize the errors between simulated and measured data both in 2011 and 2012. Given that the observed peak of GAI in 2012 was double compared to 2011 one (see 2.1.1), in general the three models showed a good ability to reproduce the data collected, with a slight overestimation of GAI values in 2011 and an underestimation in 2012.

WOFOST and CropSyst models were not able to reproduce the variability of the observed data collected in the two cropping seasons. They simulated the same GAI trend in 2011 and 2011, with a peak of 8 $m^2m^{-2}$ near the flowering phase, whereas WARM performed decidedly better, with a simulated peak of GAI of 6 $m^2m^{-2}$ in 2011 and 9 $m^2m^{-2}$ in 2012.

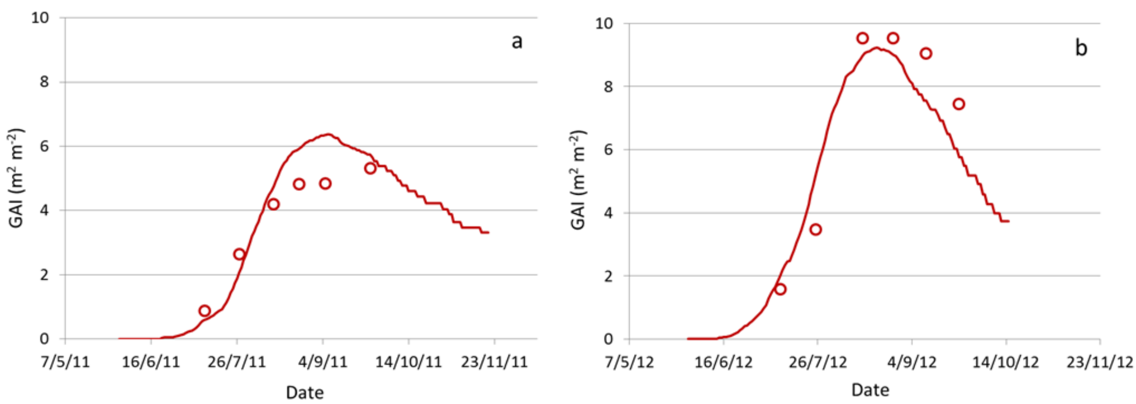


*Figure 12 Comparison between simulated (red line) and measured (red circles) green leaf area index in 2011 (a) and 2012 (b). Site SD5, WARM model*

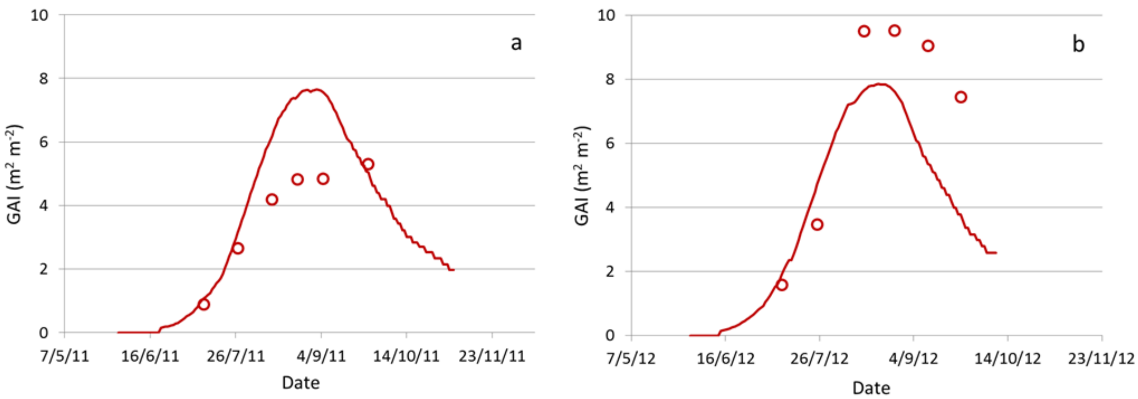


*Figure 13 Comparison between simulated (red line) and measured (red circles) green leaf area index in 2011 (a) and 2012 (b). Site SD5, WOFOST model*

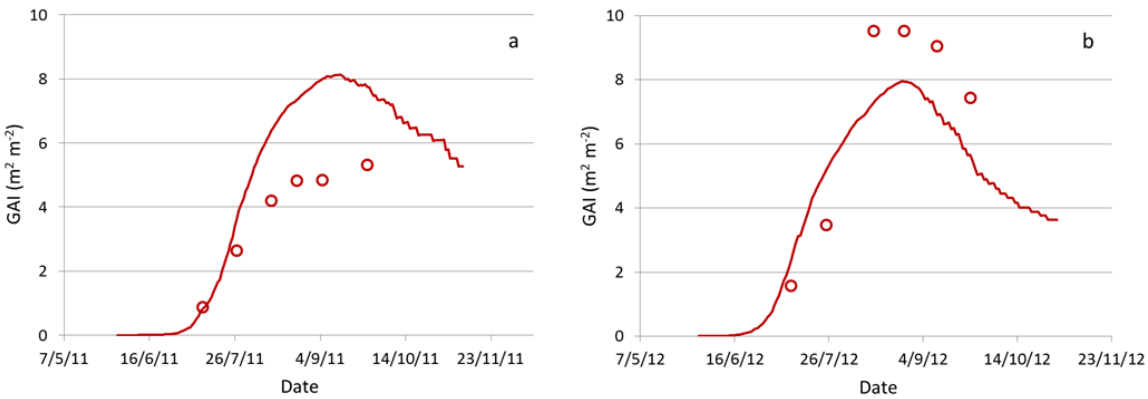


*Figure 14 Comparison between simulated (red line) and measured (red circles) green leaf area index in 2011 (a) and 2012 (b). Site SD5, CropSyst model*

The values of some of the most commonly used evaluation metrics computed for the three models are presented in

*Table 3* (WARM),

Table 4 (WOFOST) and Table 5 (CropSyst). These indices of agreement between measured and simulated data provide different quantitative information about model performances, by comparing measured and simulated values. These indices are (i) the relative root mean squared error (RRMSE; Loague and Green, 1991; minimum and optimum = 0%; maximum = + ∞), (ii) the modeling efficiency (EF; Nash and Sutcliffe, 1970; - ∞ ÷ 1, optimum =1, if positive, indicates that the model is a better predictor than the average of measured values), and (iii) the coefficient of residual mass (CRM; Loague and Green, 1991; 0-1, optimum = 0, if positive indicates model underestimation). These tables also show the values of the parameters of the regression line between measured and simulated data.

The good performances of the three models in reproducing measured AGB data was confirmed by the values of the fitting indices: mean RRMSE was about 24%, 19% and 22% for WARM, WOFOST and CropSyst respectively, which were comparable to those observed in literature. WOFOST was the model that better simulated AGB in both the years, whereas WARM resulted less accurate in reproducing AGB trend in the last part of the 2011 season (RRMSE close to 31%). The other indices presented values close to the optimum ones, thus further indicating an overall good performance of the three models.

As emerged from Figure 12, WARM showed the best performances in reproducing GAI measured data: the value of RRMSE was about 27%. Even if this value is apparently worse than the RRMSE value referred to AGB, GAI measurements are usually characterized by a higher degree of uncertainty. Moreover, the simulation of the balance between emission and death of GAI units around flowering is usually one of the processes reproduced by models with the poorest reliability. The low performances of the other two models in reproducing GAI trends in 2011 and 2012 was confirmed by fitting indices values: average RRMSE for WOFOST and CropSyst was about 45%, strongly affected by the marked underestimation of GAI in 2011; the modelling efficiency was negative, which means that averaged measured values are better predictors then models. Mean CRM was negative in 2011 and positive in 2012, thus proving the tendency of models to overestimate and underestimate GAI in 2011 and 2012, respectively.

*Table 3 Regression indices and indices of agreement between measured and simulated AGB and GAI values referred to WARM model calibrated on direct sowing datasets*

| Variable | Activity | Exp | RRMSE (%) | EF | CRM | Slope | Intercept | $R^2$ |
|---|---|---|---|---|---|---|---|---|
| | | | ***Year 2011*** | | | | | |
| **AGB** | Calibration | SD3 | 26.66 | 0.89 | -0.07 | 1.05 | -0.73 | 0.90 |
| | | SD5 | 33.72 | 0.84 | 0.05 | 1.26 | -1.28 | 0.88 |
| | | SD6 | 30.19 | 0.85 | 0.05 | 1.16 | -0.60 | 0.87 |
| | Validation | SD2 | 28.12 | 0.88 | -0.10 | 1.10 | -1.26 | 0.90 |
| | | SD4 | 37.11 | 0.82 | 0.05 | 1.28 | -1.40 | 0.86 |
| | | ***Mean*** | 31.16 | 0.85 | 0.00 | 1.17 | -1.06 | 0.88 |
| **LAI** | Calibration | SD3 | 31.09 | 0.37 | -0.20 | 0.63 | 0.84 | 0.95 |
| | | SD5 | 22.75 | 0.69 | -0.12 | 0.70 | 0.80 | 0.95 |
| | | SD6 | 39.08 | -0.43 | -0.15 | 0.47 | 1.72 | 0.73 |
| | Validation | SD2 | 48.78 | -0.58 | -0.40 | 0.59 | 0.54 | 0.94 |
| | | SD4 | 24.11 | 0.65 | -0.12 | 0.69 | 0.87 | 0.91 |
| | | ***Mean*** | 33.16 | 0.14 | -0.20 | 0.62 | 0.95 | 0.90 |
| | | | ***Year 2012*** | | | | | |
| **AGB** | Calibration | SD3 | 22.03 | 0.86 | -0.20 | 0.96 | -1.28 | 0.97 |
| | | SD5 | 20.49 | 0.88 | -0.19 | 0.93 | -0.83 | 0.99 |
| | | SD6 | 8.43 | 0.98 | 0.01 | 1.08 | -0.60 | 0.99 |
| | Validation | SD2 | 11.07 | 0.97 | -0.05 | 1.02 | -0.59 | 0.97 |
| | | SD9 | 19.97 | 0.88 | -0.17 | 0.99 | -1.39 | 0.97 |
| | | ***Mean*** | 16.40 | 0.91 | -0.12 | 0.99 | -0.94 | 0.98 |
| **LAI** | Calibration | SD3 | 24.00 | 0.71 | 0.08 | 1.17 | -0.51 | 0.75 |
| | | SD5 | 17.83 | 0.85 | 0.05 | 1.20 | -0.94 | 0.89 |
| | | SD6 | 18.11 | 0.85 | 0.13 | 1.22 | -0.42 | 0.96 |
| | Validation | SD2 | 19.42 | 0.82 | 0.13 | 1.27 | -0.67 | 0.95 |
| | | SD9 | 22.78 | 0.74 | 0.10 | 1.33 | -1.42 | 0.85 |
| | | ***Mean*** | 20.43 | 0.80 | 0.10 | 1.24 | -0.79 | 0.88 |
| ***Mean (AGB, 2011-2012)*** | | | **23.78** | **0.88** | **-0.06** | **1.08** | **-1.00** | **0.93** |
| ***Mean (GAI, 2011-2012)*** | | | **26.80** | **0.47** | **-0.05** | **0.93** | **0.08** | **0.89** |

*Table 4 Regression indices and indices of agreement between measured and simulated AGB and GAI values referred to WOFOST model calibrated on direct sowing datasets*

| Variable | Activity | Exp | RRMSE (%) | EF | CRM | Slope | Intercept | $R^2$ |
|---|---|---|---|---|---|---|---|---|
| | | | | ***Year 2011*** | | | | |
| **AGB** | Calibration | SD3 | 24.27 | 0.91 | -0.17 | 0.97 | -0.76 | 0.95 |
| | | SD5 | 23.90 | 0.92 | -0.05 | 1.15 | -1.34 | 0.94 |
| | | SD6 | 20.41 | 0.93 | -0.04 | 1.05 | -0.60 | 0.94 |
| | Validation | SD2 | 25.40 | 0.90 | -0.16 | 1.06 | -1.35 | 0.94 |
| | | SD4 | 27.26 | 0.90 | -0.04 | 1.18 | -1.47 | 0.93 |
| | | ***Mean*** | 24.25 | 0.91 | -0.09 | 1.08 | -1.10 | 0.94 |
| **LAI** | Calibration | SD3 | 51.67 | -0.75 | -0.41 | 0.56 | 0.74 | 0.87 |
| | | SD5 | 46.62 | -0.29 | -0.34 | 0.59 | 0.78 | 0.79 |
| | | SD6 | 51.19 | -1.46 | -0.35 | 0.46 | 1.45 | 0.78 |
| | Validation | SD2 | 69.08 | -2.16 | -0.60 | 0.54 | 0.41 | 0.90 |
| | | SD4 | 45.56 | -0.27 | -0.31 | 0.57 | 0.97 | 0.72 |
| | | ***Mean*** | 52.82 | -0.99 | -0.40 | 0.54 | 0.87 | 0.81 |
| | | | | ***Year 2012*** | | | | |
| **AGB** | Calibration | SD3 | 10.40 | 0.97 | 0.03 | 1.12 | -0.66 | 0.98 |
| | | SD5 | 9.56 | 0.97 | 0.03 | 1.06 | -0.23 | 0.98 |
| | | SD6 | 17.52 | 0.92 | 0.14 | 1.14 | 0.14 | 0.99 |
| | Validation | SD2 | 16.17 | 0.93 | 0.11 | 1.14 | -0.10 | 0.98 |
| | | SD9 | 10.48 | 0.97 | 0.03 | 1.09 | -0.49 | 0.98 |
| | | ***Mean*** | 12.83 | 0.95 | 0.07 | 1.11 | -0.27 | 0.98 |
| **LAI** | Calibration | SD3 | 39.39 | 0.21 | 0.26 | 1.16 | 0.93 | 0.56 |
| | | SD5 | 36.05 | 0.39 | 0.24 | 1.26 | 0.24 | 0.68 |
| | | SD6 | 31.76 | 0.53 | 0.25 | 1.36 | -0.19 | 0.88 |
| | Validation | SD2 | 33.04 | 0.49 | 0.24 | 1.34 | -0.09 | 0.81 |
| | | SD9 | 40.97 | 0.17 | 0.29 | 1.31 | 0.47 | 0.61 |
| | | ***Mean*** | 36.24 | 0.36 | 0.25 | 1.29 | 0.27 | 0.71 |
| | | ***Mean (AGB, 2011-2012)*** | **18.54** | **0.93** | **-0.01** | **1.10** | **-0.69** | **0.96** |
| | | ***Mean (GAI, 2011-2012)*** | **44.53** | **-0.31** | **-0.07** | **0.91** | **0.57** | **0.76** |

*Table 5 Regression indices and indices of agreement between measured and simulated AGB and GAI values referred to CropSyst model calibrated on direct sowing datasets*

| Variable | Activity | Exp | RRMSE (%) | EF | CRM | Slope | Intercept | $R^2$ |
|---|---|---|---|---|---|---|---|---|
| | | | ***Year 2011*** | | | | | |
| **AGB** | Calibration | SD3 | 24.99 | 0.90 | -0.14 | 1.00 | -0.78 | 0.93 |
| | | SD5 | 27.89 | 0.89 | -0.02 | 1.19 | -1.37 | 0.92 |
| | | SD6 | 24.62 | 0.90 | 0.00 | 1.10 | -0.65 | 0.91 |
| | Validation | SD2 | 27.24 | 0.88 | -0.16 | 1.06 | -1.38 | 0.93 |
| | | SD4 | 31.14 | 0.87 | -0.01 | 1.21 | -1.48 | 0.90 |
| | | ***Mean*** | 27.18 | 0.89 | -0.07 | 1.11 | -1.13 | 0.92 |
| **LAI** | Calibration | SD3 | 69.51 | -2.17 | -0.60 | 0.52 | 0.57 | 0.96 |
| | | SD5 | 57.24 | -0.94 | -0.50 | 0.59 | 0.42 | 0.99 |
| | | SD6 | 65.24 | -2.99 | -0.49 | 0.42 | 1.41 | 0.80 |
| | Validation | SD2 | 94.82 | -4.96 | -0.87 | 0.50 | 0.18 | 0.94 |
| | | SD4 | 56.75 | -0.96 | -0.48 | 0.58 | 0.51 | 0.95 |
| | | ***Mean*** | 68.71 | -2.40 | -0.59 | 0.52 | 0.62 | 0.93 |
| | | | ***Year 2012*** | | | | | |
| **AGB** | Calibration | SD3 | 14.06 | 0.94 | 0.07 | 1.16 | -0.68 | 0.97 |
| | | SD5 | 10.59 | 0.97 | 0.04 | 1.08 | -0.31 | 0.98 |
| | | SD6 | 21.70 | 0.87 | 0.18 | 1.21 | 0.05 | 0.99 |
| | Validation | SD2 | 19.16 | 0.90 | 0.13 | 1.18 | -0.17 | 0.97 |
| | | SD9 | 15.44 | 0.93 | 0.09 | 1.16 | -0.46 | 0.97 |
| | | ***Mean*** | 16.19 | 0.92 | 0.10 | 1.16 | -0.27 | 0.98 |
| **LAI** | Calibration | SD3 | 26.60 | 0.64 | 0.14 | 1.60 | -2.51 | 0.87 |
| | | SD5 | 26.31 | 0.68 | 0.13 | 1.60 | -2.69 | 0.88 |
| | | SD6 | 23.38 | 0.75 | 0.15 | 1.35 | -1.06 | 0.91 |
| | Validation | SD2 | 23.18 | 0.75 | 0.13 | 1.48 | -1.88 | 0.92 |
| | | SD9 | 29.82 | 0.56 | 0.20 | 1.79 | -3.21 | 0.93 |
| | | ***Mean*** | 25.86 | 0.68 | 0.15 | 1.56 | -2.27 | 0.90 |
| ***Mean (AGB, 2011-2012)*** | | | **21.68** | **0.91** | **0.02** | **1.13** | **-0.70** | **0.95** |
| ***Mean (GAI, 2011-2012)*** | | | **47.28** | **-0.86** | **-0.22** | **1.04** | **-0.83** | **0.92** |

The robustness indicator ($I_R$; Confalonieri et al., 2010), which represents a measure of the capability of the models to maintain the same degree of accuracy across different experimental conditions, was computed for the three models. This index calculates the ratio of the standard deviation of modelling efficiency of all datasets in the two years and the standard deviation of the values of a Synthetic AgroMeteorological indicator (SAM, -1 to +1) taking into account reference evapotranspiration and precipitation in the same datasets. $I_R$ ranges from 0 (optimum) to $+\infty$.

Table 6 shows the values of $I_R$ for the three models. WOFOST and CropSyst obtained very good value of $I_R$ for AGB, whereas WARM achieved the best value for this indicator for GAI simulations. Values of $I_R$ for WOFOST and CropSyst referred to GAI confirmed the difficulty of these models to maintain high performances in the two different experimental years.

*Table 6 Robustness index values for AGB and GAI relative to the directly sowing datasets (*σ: standard deviation)*

| Variable | Model | σEF* | σSAM | Robustness |
|---|---|---|---|---|
| **AGB** | WARM | 0.052 | 0.146 | 0.355 |
| | WOFOST | 0.029 | 0.146 | 0.197 |
| | CropSyst | 0.031 | 0.146 | 0.215 |
| **GAI** | WARM | 0.532 | 0.146 | 3.649 |
| | WOFOST | 0.900 | 0.146 | 6.178 |
| | CropSyst | 1.968 | 0.146 | 13.50 |

The complexity of the models was evaluated with the Akaike's information Criterion (AIC; Akaike, 1974). AIC is a quantitative measure of the complexity of a model taking into account also the level of accuracy of the model itself. This index explicitly includes a penalty directly proportional to the number of model parameters. It therefore assigns a good score to the models that guarantee good performances of accuracy and at the same time require few inputs. In order to calculate AIC, the model output considered was AGB and the number of parameters needed for the simulation of crop development and potential growth were 16 for WARM, 20 for Cropsyst and 34 for WOFOST.

WARM achieved the best value of AIC (55.86), thus proving a high capability in reproducing crop growth with a lower number of parameters compared to the other two models. WOFOST was confirmed as the most complex model, with an AIC value of 92.47. In fact, even if it was characterized by a higher level of accuracy than the other two models for AGB simulation, it requires a decidedly higher number of parameters. AIC computed for the CropSyst model was 63.53, which represents a slight worse result with respect to the WARM one.

### 3.1.2. Results obtained with transplanting datasets

Results obtained using only 2011 experimental data for model calibration (version 1.0 of this report) revealed that improvements were necessary in the transplanting algorithm implemented for the three models (Kropff et al., 1994). We found a problem in the formalization of the stress suffered by the crop during the transplanting-shock period, related to its impact on the crop development stage. Actually both crop development and growth is greatly reduced in the days after the transplanting event, and the plant restart to grow only after the transplanting shock has elapsed. We solved this issue using the same methodology implemented in the Agricultural Production system SIMulator (APSIM; Keating et al., 2003) system. Moreover initial LAI values were set according to the seedbed densities in order to have an initial value of LAI after transplanting in line with actual sowing density. These changes forced us to perform a new calibration of the three models in 2011 and 2012 datasets.

With old parameterizations (version 1.0 of this report), rice phenological phases in 2011 were not adequately reproduced by the three calibrated models, in particular the simulation of maturity date. Figure 15 (WARM), Figure 16 (WOFOST) and Figure 17 (CropSyst) show the results obtained with the improved formalization of the transplanting algorithm for AGB using the SD1 dataset, where rice was mechanically transplanted. No relevant differences of growth simulation arise in artificially and mechanically transplanted rice, both in calibration and in validation datasets.
Simulated trends of the three models were comparable to the ones obtained with direct sowing datasets: in 2011 simulated trends reached a plateau at maturity stage, while measured data followed a linear trend after flowering. In 2012 the three models correctly simulated all observations.

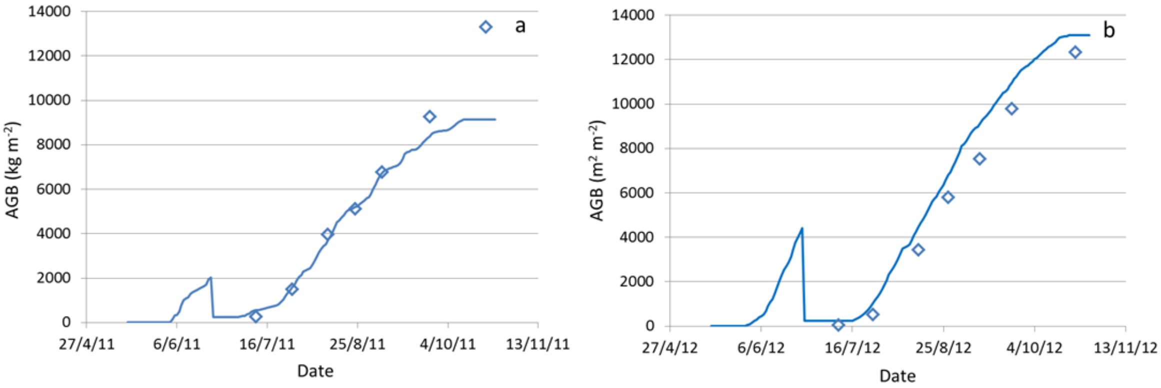


*Figure 15 Comparison between simulated (blue line) and measured (blue diamonds) aboveground biomass in 2011 (a) and 2012 (b). Site SD1, WARM model*

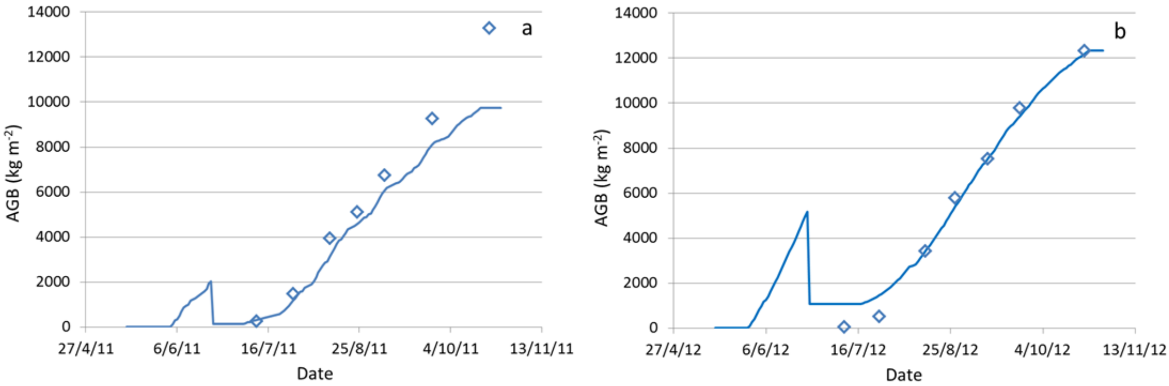


*Figure 16 Comparison between simulated (blue line) and measured (blue diamonds) aboveground biomass in 2011 (a) and 2012 (b). Site SD1, WOFOST model*

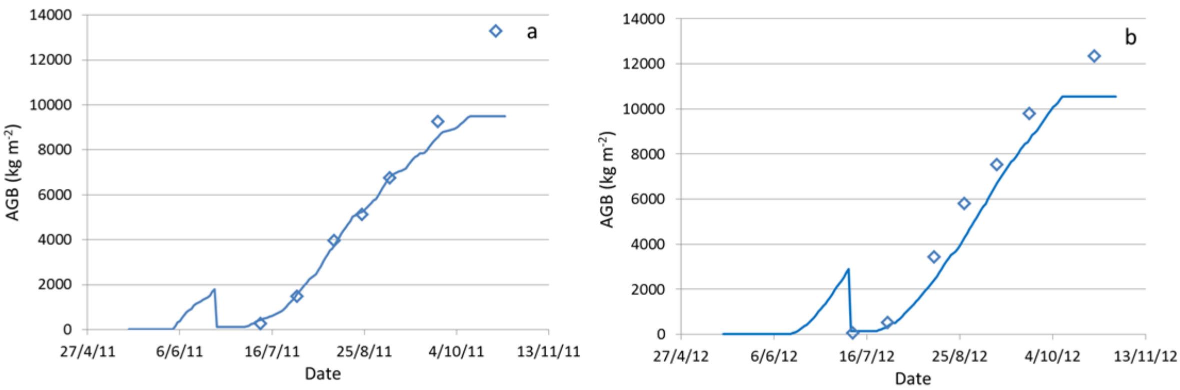


*Figure 17 Comparison between simulated (blue line) and measured (blue diamonds) aboveground biomass in 2011 (a) and 2012 (b). Site SD1, CropSyst model*

As explained in 2.1.1, GAI measurements in transplanted datasets were almost the same in 2011 and 2012, reaching a maximum value equal to 5 $m^2$ $m^{-2}$. Trends simulated by the three models reproduced in a good way the measured data both in 2011 and 2012 at SD1 site, as shown in Figure 18, Figure 19 and Figure 20. The good performance of models was confirmed by the simulation of GAI in the other sites, except at two sites chosen for validation: the three models underestimated GAI of SD9 dataset in 2011 and overestimated GAI of SD2 dataset in 2012.

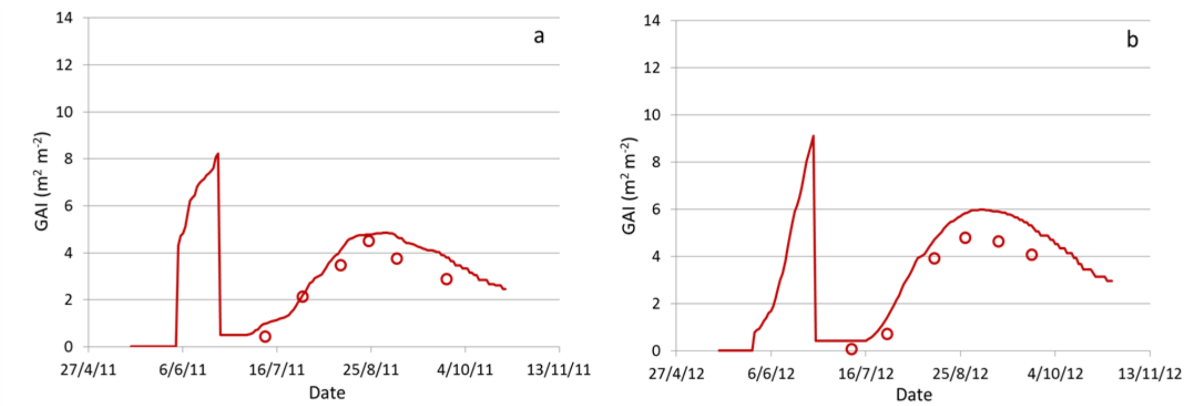


*Figure 18 Comparison between simulated (red line) and measured (red circles) green leaf area index in 2011 (a) and 2012 (b). Site SD1, WARM model*

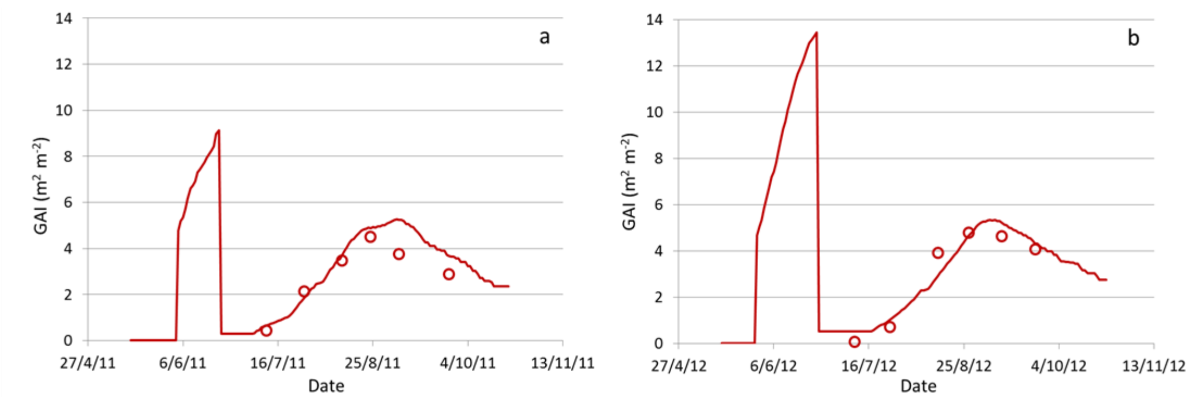


*Figure 19 Comparison between simulated (red line) and measured (red circles) green leaf area index in 2011 (a) and 2012 (b). Site SD1, WOFOST model*

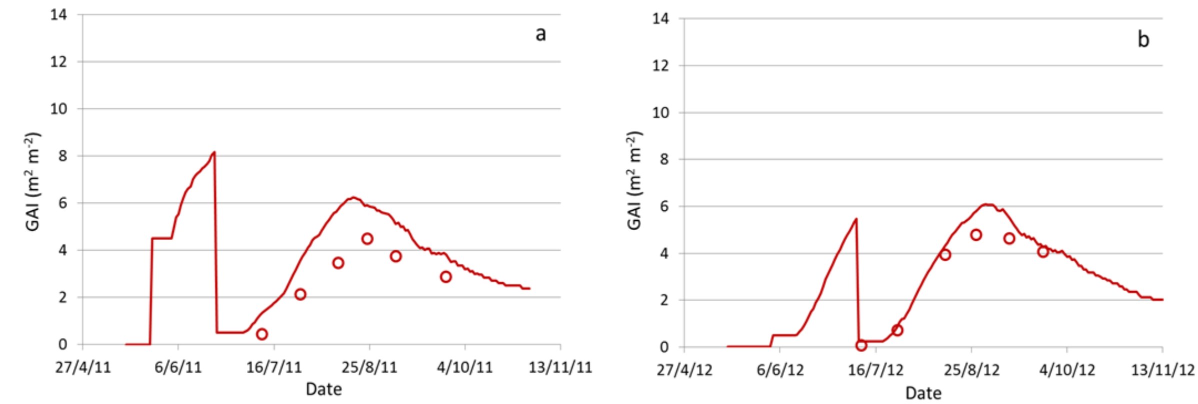


*Figure 20 Comparison between simulated (red line) and measured (red circles) green leaf area index in 2011 (a) and 2012 (b). Site SD1, CropSyst model*

Table 7, Table 8 and Table 9 show the values of the same fitting indices used for direct sowing datasets referred to transplanting datasets. WARM and WOFOST were the models which showed the best performances in simulating AGB trends, with an average value of RRMSE of 24% and EF of 0.85. The mean RRMSE of 18% referred only to 2012 datasets compared to 2011 RRMSE value of 30%, confirmed that models were not able to reproduce the anomalous final trend of measured data in 2011. The three models simulated GAI with similar performances, with RRMSE of 32%, 29% and 35% for WARM, WOFOST and CropSyst, respectively. The worse accuracy was observed in the simulation GAI measurements at SD2, with a value of RRMSE of about 80% and a negative value of modeling efficiency.

*Table 7 Regression indices and indices of agreement between measured and simulated AGB and GAI values referred to WARM model calibrated on transplanted datasets*

| Variable | Activity | Exp | RRMSE (%) | EF | CRM | Slope | Intercept | $R^2$ |
|---|---|---|---|---|---|---|---|---|
| | | | ***Year 2011*** | | | | | |
| **AGB** | Calibration | SD1 | 28.12 | 0.85 | 0.12 | 1.33 | -0.98 | 0.94 |
| | | SD8 | 25.54 | 0.86 | 0.19 | 1.30 | -0.38 | 0.99 |
| | Validation | SD7 | 26.71 | 0.85 | 0.17 | 1.36 | -0.91 | 0.98 |
| | | SD9 | 38.36 | 0.69 | 0.19 | 1.69 | -3.37 | 0.92 |
| | | ***Mean*** | 29.68 | 0.82 | 0.17 | 1.42 | -1.41 | 0.96 |
| **LAI** | Calibration | SD1 | 22.41 | 0.76 | -0.20 | 0.92 | -0.30 | 0.95 |
| | | SD8 | 22.22 | 0.77 | 0.17 | 1.13 | 0.27 | 0.93 |
| | Validation | SD7 | 23.52 | 0.83 | 0.00 | 1.18 | -0.60 | 0.85 |
| | | SD9 | 28.26 | 0.49 | 0.12 | 1.24 | -0.47 | 0.61 |
| | | ***Mean*** | 24.10 | 0.71 | 0.03 | 1.12 | -0.27 | 0.83 |
| | | | ***Year 2012*** | | | | | |
| **AGB** | Calibration | SD1 | 17.71 | 0.946 | -0.16 | 0.94 | -0.51 | 0.99 |
| | | SD8 | 9.75 | 0.97 | 0.09 | 1.05 | 0.39 | 1.00 |
| | Validation | SD2 | 28.71 | 0.88 | -0.24 | 0.88 | -0.42 | 0.98 |
| | | SD7 | 16.88 | 0.91 | 0.13 | 1.22 | -0.68 | 1.00 |
| | | ***Mean*** | 18.26 | 0.92 | -0.05 | 1.02 | -0.31 | 0.99 |
| **LAI** | Calibration | SD1 | 31.31 | 0.75 | -0.29 | 0.86 | -0.36 | 0.99 |
| | | SD8 | 33.22 | 0.06 | -0.15 | 0.56 | 1.51 | 0.67 |
| | Validation | SD2 | 83.70 | -0.84 | -0.69 | 0.57 | 0.10 | 0.97 |
| | | SD7 | 17.37 | 0.76 | -0.09 | 0.83 | 0.40 | 0.87 |
| | | ***Mean*** | 41.40 | 0.18 | -0.31 | 0.70 | 0.41 | 0.87 |
| | | **Mean (AGB, 2011-2012)** | **23.97** | **0.87** | **0.06** | **1.22** | **-0.86** | **0.97** |
| | | **Mean (GAI, 2011-2012)** | **32.75** | **0.45** | **-0.14** | **0.91** | **0.07** | **0.85** |

*Table 8 Regression indices and indices of agreement between measured and simulated AGB and GAI values referred to WOFOST model calibrated on transplanted datasets*

| Variable | Activity | Exp | RRMSE (%) | EF | CRM | Slope | Intercept | $R^2$ |
|---|---|---|---|---|---|---|---|---|
| | | | ***Year 2011*** | | | | | |
| **AGB** | Calibration | SD1 | 25.97 | 0.87 | 0.17 | 1.28 | -0.33 | 0.98 |
| | | SD8 | 22.90 | 0.89 | 0.09 | 1.40 | -2.05 | 0.99 |
| | Validation | SD7 | 35.31 | 0.74 | 0.28 | 1.42 | -0.18 | 0.99 |
| | | SD9 | 45.55 | 0.57 | 0.27 | 1.86 | -3.21 | 0.92 |
| | | ***Mean*** | 32.43 | 0.77 | 0.20 | 1.49 | -1.44 | 0.97 |
| **LAI** | Calibration | SD1 | 25.61 | 0.68 | -0.17 | 0.76 | 0.31 | 0.90 |
| | | SD8 | 21.35 | 0.79 | 0.09 | 0.99 | 0.40 | 0.83 |
| | Validation | SD7 | 29.75 | 0.73 | 0.05 | 0.96 | 0.30 | 0.74 |
| | | SD9 | 36.14 | 0.16 | 0.18 | 0.82 | 1.72 | 0.40 |
| | | ***Mean*** | 28.21 | 0.59 | 0.04 | 0.88 | 0.68 | 0.72 |
| | | | ***Year 2012*** | | | | | |
| **AGB** | Calibration | SD1 | 9.98 | 0.98 | -0.03 | 1.11 | -0.76 | 0.99 |
| | | SD8 | 17.32 | 0.90 | 0.13 | 1.24 | -0.75 | 0.99 |
| | Validation | SD2 | 16.37 | 0.96 | -0.14 | 0.93 | -0.26 | 0.99 |
| | | SD7 | 24.99 | 0.80 | 0.15 | 1.54 | -3.31 | 0.99 |
| | | ***Mean*** | 17.17 | 0.91 | 0.03 | 1.20 | -1.27 | 0.99 |
| **LAI** | Calibration | SD1 | 17.65 | 0.92 | -0.02 | 1.01 | -0.11 | 0.92 |
| | | SD8 | 19.22 | 0.69 | -0.01 | 0.72 | 1.15 | 0.81 |
| | Validation | SD2 | 83.17 | -0.82 | -0.66 | 0.55 | 0.21 | 0.95 |
| | | SD7 | 6.93 | 0.96 | 0.05 | 1.00 | 0.22 | 0.98 |
| | | ***Mean*** | 31.74 | 0.44 | -0.16 | 0.82 | 0.37 | 0.91 |
| | **Mean (AGB, 2011-2012)** | | **24.80** | **0.84** | **0.12** | **1.35** | **-1.36** | **0.98** |
| | **Mean (GAI, 2011-2012)** | | **29.98** | **0.51** | **-0.06** | **0.85** | **0.52** | **0.82** |

*Table 9 Regression indices and indices of agreement between measured and simulated AGB and GAI values referred to CropSyst model calibrated on transplanted datasets*

| Variable | Activity | Exp | RRMSE (%) | EF | CRM | Slope | Intercept | R2 |
|---|---|---|---|---|---|---|---|---|
| | | | ***Year 2011*** | | | | | |
| **AGB** | Calibration | SD1 | 25.40 | 0.88 | 0.10 | 1.28 | -0.85 | 0.94 |
| | | SD8 | 31.04 | 0.80 | 0.24 | 1.36 | -0.27 | 0.99 |
| | Validation | SD7 | 31.14 | 0.80 | 0.20 | 1.46 | -1.24 | 0.98 |
| | | SD9 | 47.16 | 0.54 | 0.29 | 1.93 | -3.43 | 0.93 |
| | | ***Mean*** | 33.68 | 0.75 | 0.21 | 1.51 | -1.45 | 0.96 |
| **LAI** | Calibration | SD1 | 51.21 | -0.27 | -0.49 | 0.80 | -0.52 | 0.93 |
| | | SD8 | 22.93 | 0.76 | 0.04 | 0.89 | 0.61 | 0.78 |
| | Validation | SD7 | 27.80 | 0.77 | -0.15 | 1.07 | -0.77 | 0.84 |
| | | SD9 | 43.49 | -0.21 | 0.13 | 0.35 | 3.62 | 0.04 |
| | | ***Mean*** | 36.36 | 0.26 | -0.12 | 0.78 | 0.73 | 0.65 |
| | | | ***Year 2012*** | | | | | |
| **AGB** | Calibration | SD1 | 19.22 | 0.94 | 0.16 | 1.13 | 0.26 | 0.99 |
| | | SD8 | 23.77 | 0.82 | 0.17 | 1.35 | -1.03 | 0.98 |
| | Validation | SD2 | 22.23 | 0.93 | -0.19 | 0.93 | -0.51 | 0.99 |
| | | SD7 | 36.13 | 0.58 | 0.29 | 1.60 | -1.41 | 0.99 |
| | | ***Mean*** | 25.34 | 0.82 | 0.11 | 1.25 | -0.67 | 0.99 |
| **LAI** | Calibration | SD1 | 18.90 | 0.91 | -0.15 | 0.87 | -0.01 | 0.99 |
| | | SD8 | 21.48 | 0.61 | 0.04 | 0.89 | 0.63 | 0.63 |
| | Validation | SD2 | 80.31 | -0.70 | -0.71 | 0.64 | -0.22 | 0.90 |
| | | SD7 | 20.24 | 0.68 | 0.07 | 1.01 | 0.26 | 0.72 |
| | | ***Mean*** | 35.23 | 0.37 | -0.19 | 0.85 | 0. 17 | 0.81 |
| | | **Mean (AGB, 2011-2012)** | **29.51** | **0.78** | **0.16** | **1.38** | **-1.06** | **0.97** |
| | | **Mean (GAI, 2011-2012)** | **35.80** | **0.32** | **-0.15** | **0.81** | **0.45** | **0.73** |

The values of the index of robustness calculated for the transplanted datasets is shown in Table 10. WARM maintained the same level of robustness than in direct sowing datasets, both for AGB and GAI. WOFOST and Cropsyst were less robust in simulating AGB, with an average $I_R$ value equal to 0.8, compared to 0.2 obtained with direct sowing datasets. The three models achieved a very similar value of $I_R$ value with respect to GAI simuilation (i.e., about 3.5).

*Table 10 Robustness index relative to the transplanted datasets (*σ: standard deviation)*

| Variable | Model | σEF* | σSAM | Robustness |
|---|---|---|---|---|
| **AGB** | WARM | 0.083 | 0.167 | 0.498 |
| | WOFOST | 0.134 | 0.167 | 0.803 |
| | CropSyst | 0.148 | 0.167 | 0.885 |
| **LAI** | WARM | 0.581 | 0.167 | 3.469 |
| | WOFOST | 0.592 | 0.167 | 3.536 |
| | CropSyst | 0.611 | 0.167 | 3.649 |

# 4. **Conclusions**

The evaluation of the WARM, WOFOST, and CropSyst models in simulating rice development and growth at the Jiangsu province was carried out in two separate steps, and the models performances in simulating AGB and GAI of directly-sown and transplanted rice were analyzed. The nine observations datasets available were split in two parts, the first used for calibration and the second for validation purposes.

All the three models demonstrated to be able to reproduce AGB trends of directly sown rice both in calibration and in validation datasets, whereas, especially WOFOST and CropSyst, showed difficulties in reproducing measured values of GAI, which were almost double in 2012 datasets compared to 2011 ones. Similar performances were obtained by the three models applied in the transplanted datasets to simulate both AGB and GAI, in the two experimental years.

Although WOFOST and Cropsyst were more robust in simulating rice biomass in the direct sowing datasets, the value of the index of robustness assumed worse values in the transplanted datasets. WARM maintained the same degree of robustness with both cultivation methods and it resulted also as the more robust in simulating GAI trends.

According to AIC index, WARM proved to be also the less complex model, able to maintain good performance using few parameters, whereas WOFOST obtained comparable results, but requiring a decidedly higher number of parameters.

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## Appendix A. Parameter values and determination (C: calibrated parameters; L: literature; D: default) relative to WARM model.

| Parameter | Unit | Value | D* |
|---|---|---|---|
| ***Development*** | | | |
| Base temperature for development (TbaseD) | °C | 12 | C |
| Maximum temperature for development (TmaxD) | °C | 42 | C |
| GDD emergence (GDDem) | °C-d | 90 | C |
| GDD flowering (GDDfl) | °C-d | 1185 | C |
| GDD maturity (GDDmat) | °C-d | 365 | C |
| ***Growth*** | | | |
| Maximum radiation use efficiency (RUE) | g $MJ^{-1}$ | 2.5 | C |
| Extinction coefficient for solar radiation (k) | - | 0.45 | C |
| Base temperature for growth (Tbase) | °C | 13 | C |
| Optimum temperature for growth (Topt) | °C | 29 | C |
| Maximum temperature for growth (Tmax) | °C | 42 | C |
| Initial specific leaf area (SLAini) | $m^2$ $kg^{-1}$ | 32 | C |
| Specific leaf area at tillering (SLAtill) | $m^2$ $kg^{-1}$ | 21 | C |
| Partition coefficient to leaf at early stages (RipL0) | kg $kg^{-1}$ | 0.67 | C |
| Leaf duration (LeafDur) | °C-d | 920 | C |

* Determination method of parameters

## Appendix B. Parameter values and determination (C: calibrated parameters; L: literature; D: default) relative to WOFOST model.

| Parameter | Unit | Value | D* |
|---|---|---|---|
| ***Development*** | | | |
| Base temperature for emergence (TBASEM) | °C | 12 | C |
| Maximum temperature for emergence (TEFFMX) | °C | 30 | C |
| Temperature sum emergence (TSUMEM) | °C-d | 90 | C |
| Temperature sum from emergence to anthesis (TSUM1) | °C-d | 1225 | C |
| Temperature sum from anthesis to maturity (TSUM2) | °C-d | 380 | C |
| Daily increase in temperature sum at Tavg[b] = 12 (DTSMTB12) | °C; °C-d | 0 | C |
| Daily increase in temperature sum at Tavg = 30 (DTSMTB30) | °C; °C-d | 19 | C |
| Daily increase in temperature sum at Tavg = 42 (DTSMTB42) | °C; °C-d | 0 | C |
| ***Growth*** | | | |
| Leaf area index at emergence (LAIEM) | $m^2$ $m^{-2}$ | 0.3 | C |
| Relative leaf area growth rate (RGRLAI) | °C $d^{-1}$ | 0.009 | C |
| Specific leaf area at DVS[a] = 0 (SLATB00) | ha $kg^{-1}$ | 0.0032 | C |
| Specific leaf area at DVS[a] = 20 (SLATB20) | ha $kg^{-1}$ | 0.0030 | C |
| Specific leaf area at DVS[a] = 30 (SLATB30) | ha $kg^{-1}$ | 0.0027 | C |
| Specific leaf area at DVS[a] = 40 (SLATB40) | ha $kg^{-1}$ | 0.0024 | C |
| Specific leaf area at DVS[a] = 50 (SLATB50) | ha $kg^{-1}$ | 0.0022 | C |
| Specific leaf area at DVS[a] = 100 (SLATB100) | ha $kg^{-1}$ | 0.0022 | C |
| Specific leaf area at DVS[a] = 200 (SLATB200) | ha $kg^{-1}$ | 0.0022 | C |
| Life span of leaves growing at 35°C (SPAN) | d | 34 | C |
| Base temperature for leaves aging (TBASE) | °C | 10 | C |
| Extinction coefficient for diffuse visible light at DVS = 0 (KDIF000) | - | 0.4 | D |
| Extinction coefficient for diffuse visible light at DVS = 65 (KDIF65) | - | 0.4 | D |
| Extinction coefficient for diffuse visible light at DVS = 100 (KDIF100) | - | 0.6 | D |
| Extinction coefficient for diffuse visible light at DVS = 200 (KDIF200) | - | 0.6 | D |
| Light use efficiency at Tavg = 10°C (EFFTB10) | kg $ha^{-1}$ $h^{-1}$ $J^{-1}$ | 0.54 | D |
| Light use efficiency at Tavg = 40°C (EFFTB40) | kg $ha^{-1}$ $h^{-1}$ $J^{-1}$ | 0.35 | D |
| Maximum $CO_2$ assimilation rate at DVS = 000 (AMAXTB000) | kg $ha^{-1}$ $h^{-1}$ | 24 | C |
| Maximum $CO_2$ assimilation rate at DVS = 100 (AMAX100) | kg $ha^{-1}$ $h^{-2}$ | 24 | C |
| Maximum $CO_2$ assimilation rate at DVS = 200 (AMAX200) | kg $ha^{-1}$ $h^{-1}$ | 24 | C |
| AMAX reduction factor at Tavg = 0°C (TMPFTB0) | °C | 0 | C |
| AMAX reduction factor at Tavg = 12°C (TMPFTB12) | °C | 0.69 | C |
| AMAX reduction factor at Tavg = 18°C (TMPFTB18) | °C | 0.85 | C |
| AMAX reduction factor at Tavg = 24°C (TMPFTB24) | °C | 1 | C |
| AMAX reduction factor at Tavg = 30°C (TMPFTB30) | °C | 1 | C |
| AMAX reduction factor at Tavg = 36°C (TMPFTB36) | °C | 0.87 | C |

| | | | |
|---|---|---|---|
| AMAX reduction factor at Tavg = 42°C (TMPFTB42) | °C | 0.27 | C |
| Efficiency of conversion into leaves (CVL) | kg kg$^{-1}$ | 0.6 | C |
| Efficiency of conversion into storage organs (CVO) | kg kg$^{-1}$ | 0.684 | D |
| Efficiency of conversion into roots (CVR) | kg kg$^{-1}$ | 0.754 | D |
| Efficiency of conversion into stems (CVS) | kg kg$^{-1}$ | 0.685 | C |
| Relative increase in respiration rate for 10°C of temp increase (Q10) | - | 1.8 | C |
| Relative maintenance respiration rate for leaves (RML) | kg $CH_2O$ kg$^{-1}$ d$^{-1}$ | 0.02 | C |
| Relative maintenance respiration rate for storage organs (RMO) | kg $CH_2O$ kg$^{-1}$ d$^{-1}$ | 0.01 | C |
| Relative maintenance respiration rate for roots (RMR) | kg $CH_2O$ kg$^{-1}$ d$^{-1}$ | 0.01 | D |
| Relative maintenance respiration rate for stems (RMS) | kg $CH_2O$ kg$^{-1}$ d$^{-1}$ | 0.015 | D |
| Fraction of total biomass to roots at DVS = 0 (FRTB000) | kg kg$^{-1}$ | 0.5 | D |
| Fraction of total biomass to roots at DVS = 43 (FRTB43) | kg kg$^{-1}$ | 0.25 | D |
| Fraction of total biomass to roots at DVS = 100 (FRTB100) | kg kg$^{-1}$ | 0 | D |
| Fraction of total biomass to roots at DVS = 200 (FRTB200) | kg kg$^{-1}$ | 0 | D |
| Fraction of aboveground dry matter to leaves at DVS = 0 (FLTB000) | kg kg$^{-1}$ | 0.76 | C |
| Fraction of aboveground dry matter to leaves at DVS = 9 (FLTB009) | kg kg$^{-1}$ | 0.76 | C |
| Fraction of aboveground dry matter to leaves at DVS = 29 (FLTB029) | kg kg$^{-1}$ | 0.66 | C |
| Fraction of aboveground dry matter to leaves at DVS = 52.5 (FLTB052) | kg kg$^{-1}$ | 0.5 | C |
| Fraction of aboveground dry matter to leaves at DVS = 72 (FLTB072) | kg kg$^{-1}$ | 0.4 | C |
| Fraction of aboveground dry matter to leaves at DVS = 89.5 (FLTB089) | kg kg$^{-1}$ | 0.35 | C |
| Fraction of aboveground dry matter to leaves at DVS = 100 (FLTB100) | kg kg$^{-1}$ | 0 | C |
| Fraction of aboveground dry matter to leaves at DVS = 127.5 (FLTB127) | kg kg$^{-1}$ | 0 | C |
| Fraction of aboveground dry matter to leaves at DVS = 200 (FLTB200) | kg kg$^{-1}$ | 0 | C |
| Fraction of aboveground dry matter to storage organs at DVS = 0 (FOTB000) | kg kg$^{-1}$ | 0 | C |
| Fraction of aboveground dry matter to storage organs at DVS = 29 (FOTB029) | kg kg$^{-1}$ | 0 | C |
| Fraction of aboveground dry matter to storage organs at DVS = 52.5 (FOTB052) | kg kg$^{-1}$ | 0 | C |
| Fraction of aboveground dry matter to storage organs at DVS = 72 (FOTB072) | kg kg$^{-1}$ | 0 | C |
| Fraction of aboveground dry matter to storage organs at DVS = 89.5 (FOTB089) | kg kg$^{-1}$ | 0.2 | C |
| Fraction of aboveground dry matter to storage organs at DVS = 100 (FOTB100) | kg kg$^{-1}$ | 0.6 | C |
| Fraction of aboveground dry matter to storage organs at DVS = 127.5 (FOTB127) | kg kg$^{-1}$ | 1 | C |
| Fraction of aboveground dry matter to storage organs at DVS = 200 (FOTB200) | kg kg$^{-1}$ | 1 | C |
| Fraction of aboveground dry matter to stems at DVS = 0 (FSTB000) | kg kg$^{-1}$ | 0.24 | C |
| Fraction of aboveground dry matter to stems at DVS = 9 (FSTB009) | kg kg$^{-1}$ | 0.24 | C |
| Fraction of aboveground dry matter to stems at DVS = 29 (FSTB029) | kg kg$^{-1}$ | 0.34 | C |
| Fraction of aboveground dry matter to stems at DVS = 52.5 (FSTB525) | kg kg$^{-1}$ | 0.5 | C |

| | | | |
|---|---|---|---|
| Fraction of aboveground dry matter to stems at DVS = 72 (FSTB072) | kg $kg^{-1}$ | 0.6 | C |
| Fraction of aboveground dry matter to stems at DVS = 89.5 (FSTB089) | kg $kg^{-1}$ | 0.45 | C |
| Fraction of aboveground dry matter to stems at DVS = 100 (FSTB100) | kg $kg^{-1}$ | 0.4 | C |
| Fraction of aboveground dry matter to stems at DVS = 127.5 (FSTB127) | kg $kg^{-1}$ | 0 | C |
| Fraction of aboveground dry matter to stems at DVS = 200 (FSTB200) | kg $kg^{-1}$ | 0 | C |
| Relative death rate of roots at DVS = 0 (RDRRTB0) | kg $kg^{-1}$ $day^{-1}$ | 0 | D |
| Relative death rate of roots at DVS = 151 (RDRRTB150) | kg $kg^{-1}$ $day^{-1}$ | 0.02 | D |
| Relative death rate of roots at DVS = 200 (RDRRTB200) | kg $kg^{-1}$ $day^{-1}$ | 0.02 | D |
| Relative death rate of stems at DVS = 0 (RDRSTB0) | kg $kg^{-1}$ $day^{-1}$ | 0 | D |
| Relative death rate of stems at DVS = 151 (RDSRTB150) | kg $kg^{-1}$ $day^{-1}$ | 0.02 | D |
| Relative death rate of stems at DVS = 200 (RDSRTB200) | kg $kg^{-1}$ $day^{-1}$ | 0.02 | D |
| Specific stem area at DVS = 0 (SSA000) | ha $kg^{-1}$ | 0.0003 | D |
| Specific stem area at DVS = 90 (SSA090) | ha $kg^{-1}$ | 0.0003 | D |
| Specific stem area at DVS = 200 (SSA200) | ha $kg^{-1}$ | 0 | D |
| Initial total crop dry weight (TDWI) | kg $ha^{-1}$ | 110 | C |

[a] Development stage code (unitless; 0: emergence, 100: flowering, 200: physiological maturity)
[b] Average air daily temperature (°C)

## Appendix C. Parameter values and determination (C: calibrated parameters; L: literature; D: default) relative to CropSyst model.

| Parameter | Unit | Value | Det. |
|---|---|---|---|
| ***Development*** | | | |
| Base temperature (Tbase) | °C | 12 | C |
| Cutoff temperature (Tcutoff) | °C | 42 | C |
| GDD emergence (GDDem) | °C-d | 90 | C |
| GDD flowering (GDDfl) | °C-d | 1270 | C |
| GDD from flowering to maturity (GDDm) | °C-d | 1620 | C |
| ***Growth*** | | | |
| Biomass-transpiration coefficient (BTR) | kPa kg $m^{-3}$ | 6.8 | C |
| Radiation use efficiency (RUE) | g $MJ^{-1}$ | 2.95 | C |
| Specific leaf area (SLA) | $m^2$ $kg^{-1}$ | 29 | C |
| Stem/leaf partition coefficient (SLP) | - | 2.5 | C |
| Leaf duration (LeafDur) | °C-d | 1000 | C |
| Extinction coefficient for solar radiation (k) | - | 0.53 | C |
| Base temperature for growth (Tbase) | °C | 12 | C |
| Optimum temperature for growth (Topt) | °C | 28 | C |
| Initial leaf area index (LAIini) | $m^2$ $m^{-2}$ | 0.015 | C |
| Full canopy coefficient (Kc) | - | 1.2 | C |