DSSAT-ORYZA linkage project

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Cheryl Porter (UF) and Tao Li (IRRI)

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Background

The Global Futures project at the International Food Policy Research Institute (IFPRI, http://www.ifpri.org/pressrelease/global-futures) uses the DSSAT Cropping Systems Model (CSM, Hoogenboom, et al., 2011 and Jones, et al., 2003) to generate predictions of crop yields and other outputs based on present and future climate and management scenarios on a global scale. The ORYZA2000 rice model (Bouman et al., 2001), developed at the International Rice Research Institute (IRRI), is widely used to predict yields and to optimize management options for rice cropping systems. It would be advantageous for IFPRI scientists to be able to use their existing DSSAT simulation environment for generating large-scale simulations of rice yield predictions using the ORYZA2000 model. The goal of this project was to couple the ORYZA2000 model with DSSAT-CSM to enable this capability.

A similar model linkage was previously done with APSIM (www.apsim.info) and ORYZA2000 in 2005 (Zhang et al., 2006), but that linkage required significant modifications to the ORYZA2000 code and resulted in a version of ORYZA which was not easily maintained and did not benefit from subsequent improvements to the stand-alone ORYZA2000 model. For this reason, it was decided that a DSSAT-CSM linkage with ORYZA2000 would be done such that the ORYZA plant growth subroutines were not significantly modified, so that model maintenance could continue to be performed by IRRI scientists, with any updates simply replacing older code with no additional modifications required for the DSSAT linkage.

This DSSAT-ORYZA linkage was accomplished by Tao Li of IRRI and Cheryl Porter of the University of Florida (UF). The strategy consists of calling the ORYZA2000 plant growth routines from the CSM Plant module. Thus all of the CSM soil processes, energy balance routines, weather data and management functions are used to provide inputs necessary for the ORYZA plant growth routine.

Procedure

Both DSSAT-CSM and ORYZA2000 models are structured using the van Kraalingen modular structure (Kraalingen, 1995) in which each module reads data from files, initializes variables, performs rate calculations, integrates state variables and produces output in separate functional sections of each module. Because the structures of the models are so similar, the direct coupling could be accomplished with a minimum of coding changes in both models. More importantly, the ORYZA2000 plant growth model can now be maintained outside of the DSSAT system with upgrades “plugged in” periodically as they become available. This has distinct advantages for both models in that the IRRI model development team does not have to maintain separate versions of their model and the DSSAT development team does not have to expend resources converting new features from future releases of the ORYZA2000 model.

The project was accomplished in phases, with each phase being compiled, debugged and evaluated separately. These model development phases are: 1) potential production, i.e., the growth and development that would be expected with no stresses due to water or nutrient deficiencies or other limiting factors; 2) water limited production and 3) nitrogen limited production.

Figure 1 shows the configuration of the ORYZA2000 stand-alone model. The green highlighted boxes show plant growth routines which were imported from ORYZA2000 to the DSSAT system for modeling of potential production (phase 1). The blue highlighted box shows the routine which was imported to enable water limited production (phase 2). With nitrogen limited production (phase 3), an additional routine was introduced which is highlighted in yellow in Figure 1.

Figure 2 shows the components of the DSSAT-CSM with linkage of ORYZA2000 plant routines. The ORYZA2000 crop growth module was linked as another crop in the DSSAT-CSM suite of crop growth modules, called by the PLANT primary module. Phase 2, water limited production, required the introduction of modifications to existing CSM routines:

1. The ORYZA2000 water stress variables are based on a water characteristic curve. Routines were added to DSSAT-CSM to define the water characteristic curve based on user input values of lower limit, drained upper limit, and saturation water content for each soil layer in the profile. This code is based on the RETC software, developed by van Genuchten (1991). Direct input of the van Genuchten parameters from the soil file was also added as an alternative.
2. Water uptake within DSSAT-CSM is based on root length density, whereas in ORYZA2000 it is based on root mass density. These routines were permanently restructured within the ORYZA2000 system to separate water stress calculations from water uptake calculations, as these functions are performed in different modules within DSSAT-CSM.
3. The transpiration calculations for ORYZA2000 differ significantly from those in the DSSAT-CSM model. A separate crop-specific computation was added to the CSM Soil-Plant-Atmosphere Module (SPAM) to allow the ORYZA2000 transpiration functions to be used. Prior to making this adjustment, the water uptake and therefore nitrogen uptake for the linked DSSAT-ORYZA model were significantly below those in the stand-alone ORYZA2000 model and therefore simulated yields differed widely between the two models.

Interface routines were written which minimized the re-coding of existing model subroutines. This allowed the ORYZA2000 plant growth routines to maintain independence from the DSSAT system. Thus, when new versions of ORYZA2000 are released, the appropriate routines can be plugged directly into the DSSAT-CSM structure with a minimum of additional coding. Figure 3 shows the new interface routines in green highlighting. The PLANT module of DSSAT-CSM calls an interface routine (ORYZA Interface), which in turn calls the ORYZA2000 plant growth routines (ORYZA1), the water and nitrogen stress or non-stress calculation routines, an Input Generator and an Output Converter. The main interface routine translates DSSAT variable names to ORYZA variable names and ensures that units are consistent. Default values are provided for variables which are required by DSSAT, but not supplied by ORYZA2000. The routine also re-creates the necessary composite pointer variables used by ORYZA2000 for passing global variables.

The ORYZA2000 plant growth routines read some parameter values from files, including several which will be supplied from DSSAT-CSM. In order to minimize re-coding current routines as well as updates of ORYZA2000, the Input Generator will write these variables to a temporary file for initialization only, which can then be read to parameterize ORYZA2000 subroutines in their initialization section.

DSSAT-CSM requires some standardized output formats for consistency with post-processors and graphing utilities. The Output Converter will take ORYZA2000 output variables and write DSSAT-compliant format. Conversion of units and some manipulation of data were also undertaken by the Output Converter. In addition, seasonal summary variables were compiled by this routine for output by the DSSAT-CSM summary utility routines. These variables include harvest residues which can be used in crop rotation simulations and long-term soil carbon studies.

Testing and Evaluation

Three datasets were used for testing and evaluation of the linked models. These are:

- IRRI 1992 dry season. IR72 cultivar. 3 nitrogen fertilizer treatments.
- IRRI 1992 wet season. IR72 cultivar. 8 nitrogen fertilizer treatments.
- China 2003 water and nitrogen limited. HD297 cultivar. 3 irrigation and N fertilizer treatments.

No calibration was done for the DSSAT-ORYZA model. The model cultivar coefficients as calibrated for the stand-alone ORYZA2000 model were used for each experiment. For all experiments, the potential production was simulated as well as all treatments using both the stand-alone ORYZA2000 model and the linked DSSAT-ORYZA model.

Statistical analyses on the prediction ability of both models were performed by computing Bias, model efficiency (M_eff), and normalized RMSE (RMSEn). Methods described in Wallach et al. (2006) and Nash and Sutcliffe (1970) were used for these calculations.

The bias value gives an indication of whether each model tends to over-predict (positive bias) or under-predict (negative bias). The normalized root mean squared error (RMSEn) gives an indication or the error of prediction, relative to the average of the observations.

Modeling efficiency (Nash and Sutcliffe, 1970) ranges from minus infinity (poor model) to 1.0 (perfect model) and is computed as:

$$M\_eff = 1 - \frac{\sum_{i=1}^{N} (Y_i - X_i)^2}{\sum_{i=1}^{N} (X_i - \overline{X})^2}$$

where X_i and Y_i are the observed and simulated values, N is the number of observations and $\overline{X}$ is the mean of the measured values.

Each of these measures are used in this paper to quantify and compare errors between simulated and observed plant growth quantities including leaf area index (LAI), total above-ground biomass, panicle biomass, stem biomass, green leaf biomass, dead leaf biomass, and leaf N concentration.

Results

Figures 4-6 show graphically the simulated LAI, aboveground biomass and panicle mass of the stand-alone ORYZA2000 model and the DSSAT-ORYZA linked model. In each case, the results for potential production are identical. This outcome was necessary for a successful implementation of the linked models, since there are no interactions between the plant growth and soil processes for potential production. Introduction of water and nitrogen limitations resulted in some differences between the models. This outcome was also expected because the soil water and soil nitrogen computation algorithms differ significantly between the two models.

Figure 4 presents simulated and measured variables related to the IRRI dry season experiment with three N fertilizer application rates (0, 180 and 225 kg[N]/ha). Both models reflect the response of the N applications and capture the relative effects of N fertilization rates. For this experiment, the two higher N application rates resulted in near-potential production. Both models reflected this response, although they both slightly under-predicted LAI for these two treatments. The linked DSSAT-ORYZA model captured the response of LAI to low N conditions better than the stand-alone model. Total biomass and panicle mass were well-predicted by both models, although both models tended to under-predict these variables for the high N treatments.

Figure 5 presents output for the IRRI wet season nitrogen experiment for three of the 8 treatments, representing fertilizer application rates of 0 kg[N]/ha, 80 kg[N]/ha and 110 kg[N]/ha. Measured data for this experiment showed a larger N response than the dry season experiment. Both models performed acceptably well, with DSSAT-ORYZA performing slightly better for the low N treatment. Biomass and panicle mass simulated by DSSAT-ORYZA were generally lower than the predicted stand-alone ORYZA2000 variables, but compared to observed data, both models performed equally well based on graphical inspection.

Figure 6 presents output for the China water and N limited experiment for three N and irrigation interaction treatments. The three treatments were observed to have very similar patterns of growth. Biomass production for all three treatments was affected by water or nitrogen deficiencies, as seen in the LAI and aboveground biomass observations, which are significantly below the simulated potential. Panicle mass, however, is not reduced due to water or nutrient stresses, as shown by both measured and observed values. The simulated responses are very similar for both models for all three variables.

Table 1 presents a summary of the results of the statistical analyses, performed to assess goodness-of-fit for both the stand-alone ORYZA2000 model and the DSSAT-ORYZA model.

In general, both models performed well for most variables. The model efficiencies are above 0.9 in most cases, indicating a good model fit for both models. The exceptions are for LAI, which gives an overall model efficiency of 0.76 for ORYZA2000 and 0.85 for DSSAT-ORYZA. The stand-alone ORYZA2000 tends to over-predict LAI, and DSSAT-ORYZA tends to under-predict as indicated by the bias. In general, the DSSAT-ORYZA does a better job of predicting LAI, particularly for the low N treatments (based on statistical and graphical analyses).

For total above-ground biomass, in general, ORYZA2000 does a better job of predicting, but all model efficiencies for both models are greater than 0.9, indicating very good model fit. In general both models tended to under-predict total biomass, but ORYZA2000 gave better simulated results. Panicle biomass is also very well predicted by both models, with DSSAT-ORYZA having a slight edge over the results from the stand-alone model. Model efficiencies for all biomass variables and for leaf N are very good.

Figure 7 shows comparisons of water and nitrogen-related variables for the stand-alone ORYZA2000 and the DSSAT-ORYZA models. No observations were made for these variables, so model evaluations cannot be performed. Graphs (a), (c) and (e) on the left side, each show soil evaporation and plant transpiration for both models, for (a) the dry season IRRI experiment, high N treatment, (c), the wet season IRRI experiment, high N treatment and (e) the China water and N limited experiment, water control treatment. Graphs (a) and (c) represent near-potential production under flooded paddy management. For these conditions, the DSSAT-CSM model simulated slightly lower soil evaporation than the stand-alone ORYZA2000 model. Plant transpiration rates are very similar for the two models. For the water limited experiment, graph (e), DSSAT-CSM simulated much higher soil evaporation rates than the stand-alone ORYZA2000 model (150 mm vs. 50 mm). The ORYZA2000 plant transpiration rates were slightly higher than those calculated by the DSSAT-CSM model.

On the right side of Figure 7, graphs (b), (d) and (f) present two nitrogen time series, plant N uptake and soil mineral N, which were simulated by the two models for the same 3 experiments and treatments as presented in the left side graphs. In all three cases, the total N uptake is much lower for the linked DSSAT-ORYZA model than for the stand-alone ORYZA2000 model, although the simulated leaf N concentrations are nearly identical (not shown). In each case, the simulated soil mineral N is lower at the end of season for the DSSAT-ORYZA model than for the stand-alone ORYZA2000 model, reflecting the differences in N uptake and mineralization rates (not shown).

Future work

Although the linkage is complete and we have high confidence in the model, additional testing should be performed to assess model robustness. This work should include the following:

1. DSSAT rice experiments for cultivars which have already been calibrated for ORYZA2000, such as IR72.
2. Extreme environmental conditions, including drought, flood, low N, high temperatures, low temperatures, CO_2 enhancement.

We discussed several methods to enhance the operation of the linked DSSAT-ORYZA model. These include the following options.

1. Modify the CSM irrigation management routines to allow stage-dependent irrigation scheduling, consistent with the ORYZA2000 model. The DSSAT input files were originally set up to allow input of stage-dependent irrigation records, but for the current model, these are just placeholders. The stage-dependent irrigation routine needs to be developed in a very generic way so that it can be used for all DSSAT crops, including ORYZA-rice.
2. Link the ORYZA clay soil shrink-swell prediction algorithms into the DSSAT soil dynamics module. This may require addition of some of the ORYZA soil water balance routines for correct implementation.
3. Currently, the ORYZA_Interface routine takes data from CSM and generates ORYZA2000 input files. The linked ORYZA routine, then reads these input files, just as the stand-alone ORYZA2000 model does. This exchange of information through written text files is inefficient, but was expedient from a development point of view. It would be useful to transfer information from memory rather than through files and this can be accomplished by replacing the ORYZA2000 read functions with identically-named routines that do not rely on the ORYZA external files.
4. We discussed simulation and reporting of greenhouse gas (GHG) emissions in DSSAT and ORYZA. Tao Li has been investigating linking DNDC model (DeNitrification-DeComposition, Giltrap et al., 2010) with ORYZA to allow better modeling of organic matter and prediction of GHG emissions. Within DSSAT, it may be useful to modify the existing CENTURY soil organic matter module to include some GHG modeling routines that have been developed for DayCent (Del Grosso et al., 2001). We have had discussions with Peter Grace at Queensland University who has been collecting data for model validation and is interested in collaborating on a DSSAT-DayCent linkage.
5. Future development for the ORYZA2000 model will include a genetic plasticity component, which will benefit the trait assessment of a rice 'virtual crop' for future agriculture production under changing climate conditions.

Conclusions

Both models performed very well compared to the measured data. ORYZA2000 stand-alone tends to over-predict plant growth variables, particularly for low N treatments. DSSAT-ORYZA tends to improve on the prediction of low N dynamics, but in general slightly under-predicts response to higher N levels. Based on the validations implemented for three datasets, the integration between DSSAT and ORYZA2000 is substantially complete. The conceptualized approach for model integration using 'model wrapping' is demonstrated to be efficient although the further improvements are need to simplify the wrapping interface and to improve communication of data between models.

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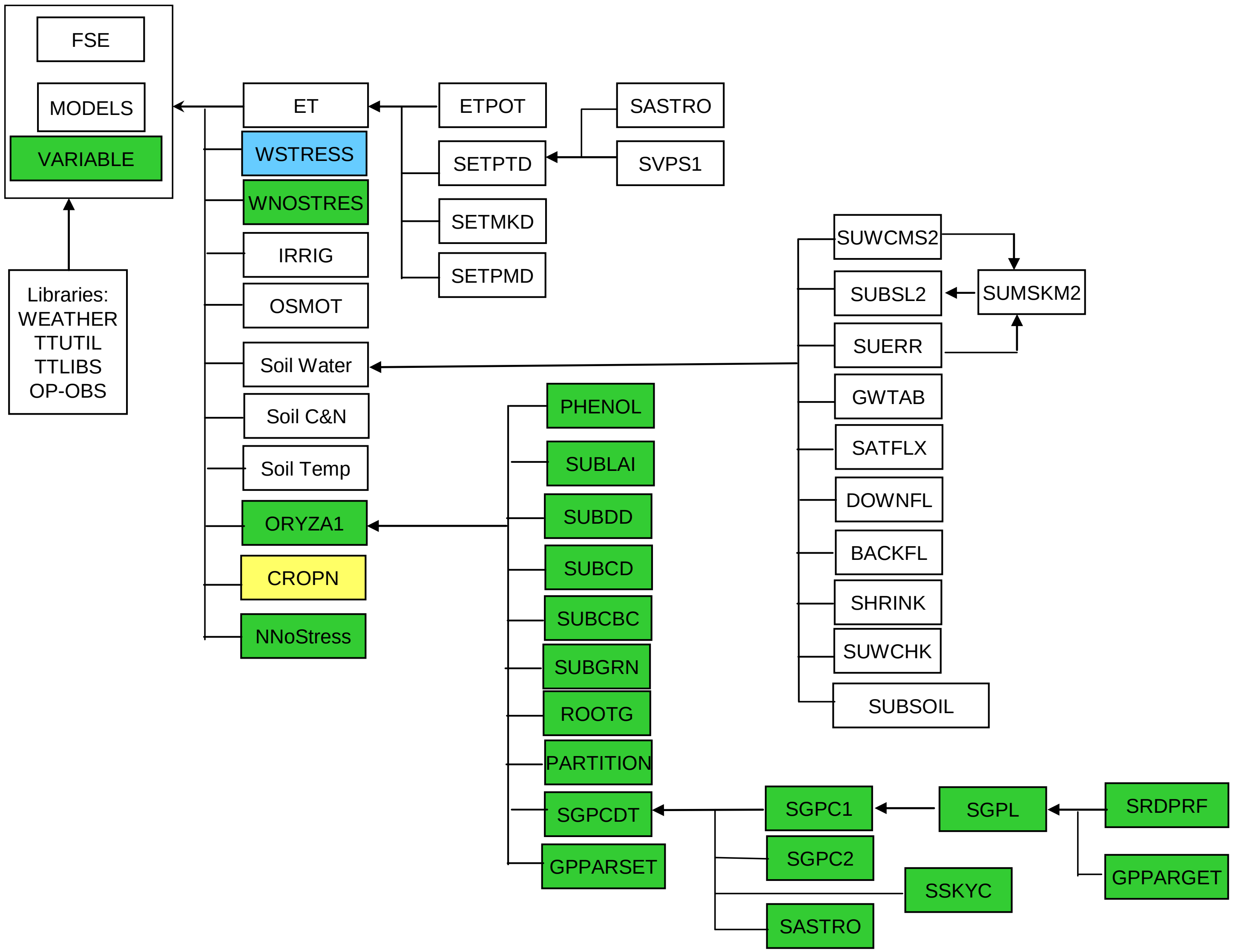

Figure 1. Structure of ORYZA2000 model. Green highlights indicate routines that are added for prediction of crop growth and development. Water limited analysis required the blue-highlighted routine. Nitrogen-limited analysis required the yellow-highlighted box.

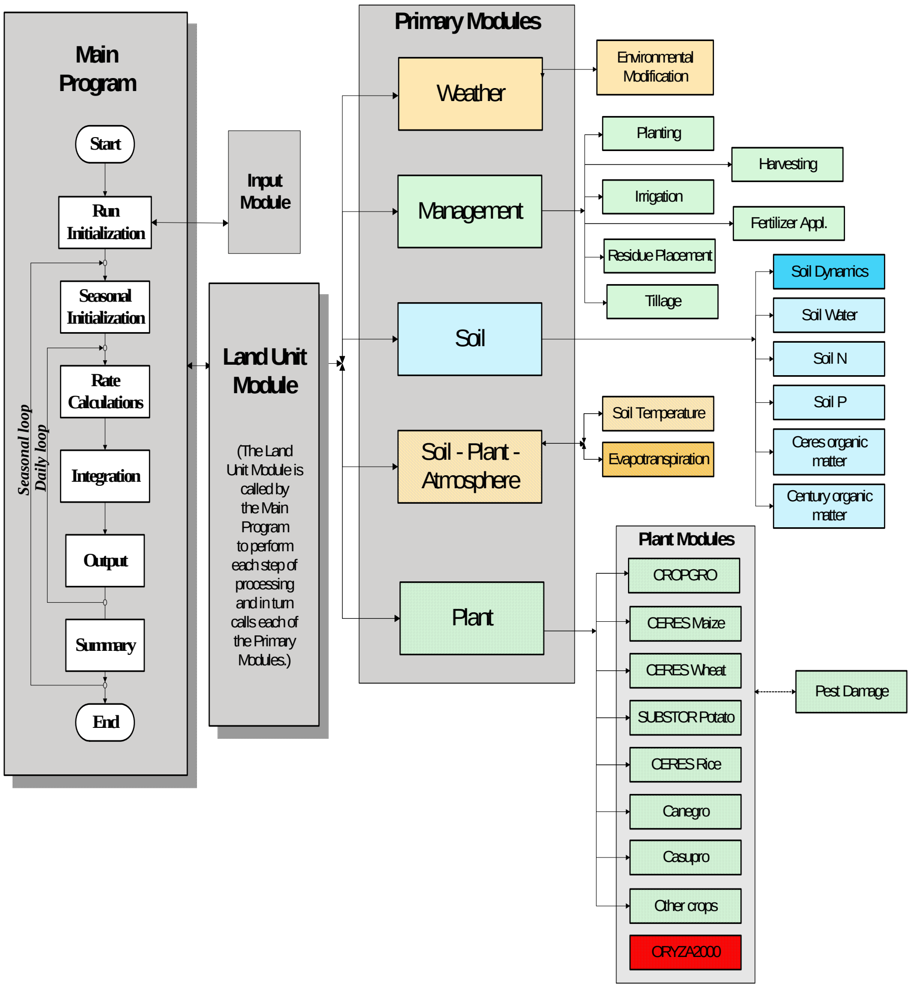

Figure 2. DSSAT-CSM model structure. The ORYZA2000 plant growth routines will be added as another crop option in the PLANT module.

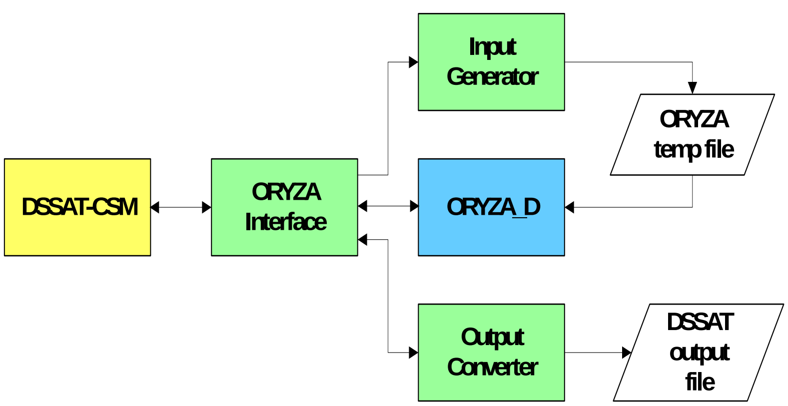

Figure 3. DSSAT-ORYZA2000 interface routines (green color) written to call the ORYZA2000 plant growth module, convert units; prepare required inputs from DSSAT to ORYZA2000; and to prepare the required outputs from ORYZA2000 to DSSAT.

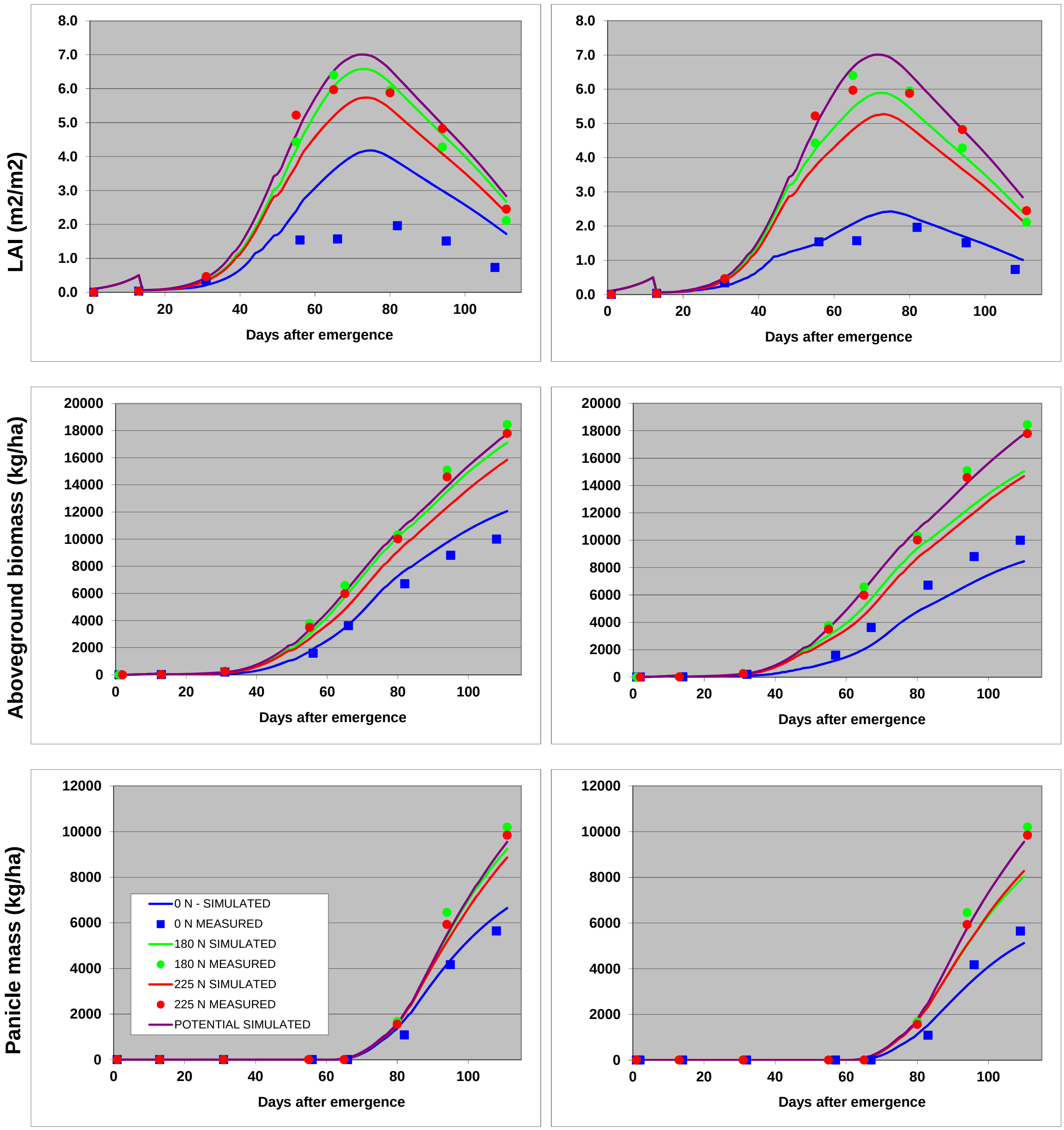

Figure 4. IRRI dry season nitrogen experiment showing simulated and measured LAI, aboveground biomass and panicle mass for ORYZA2000 stand-alone model (left) and for the linked DSSAT-ORYZA model (right).

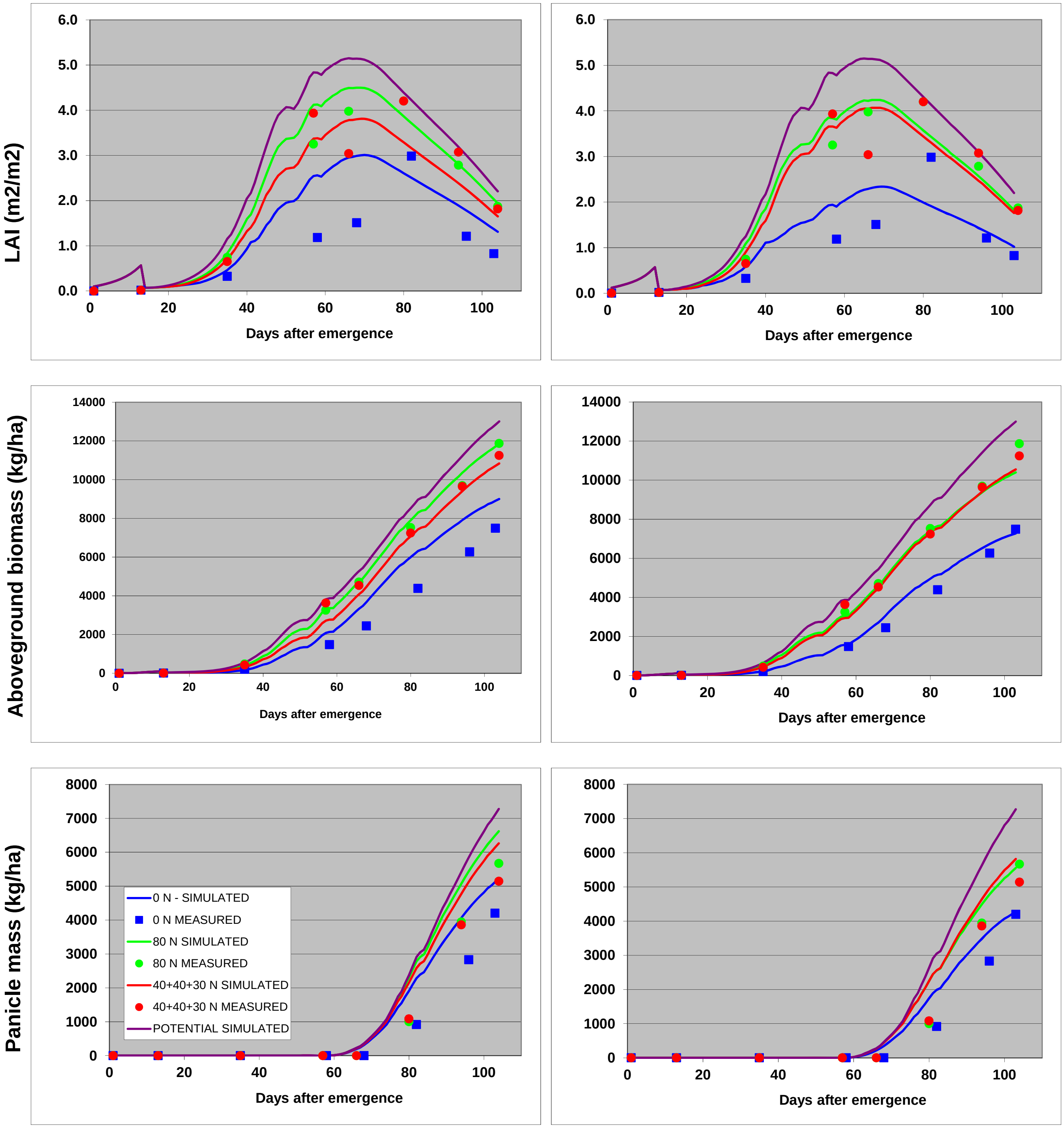

Figure 5. IRRI wet season nitrogen experiment showing simulated and measured LAI, aboveground biomass and panicle mass for ORYZA2000 stand-alone model (left) and for the linked DSSAT-ORYZA model (right).

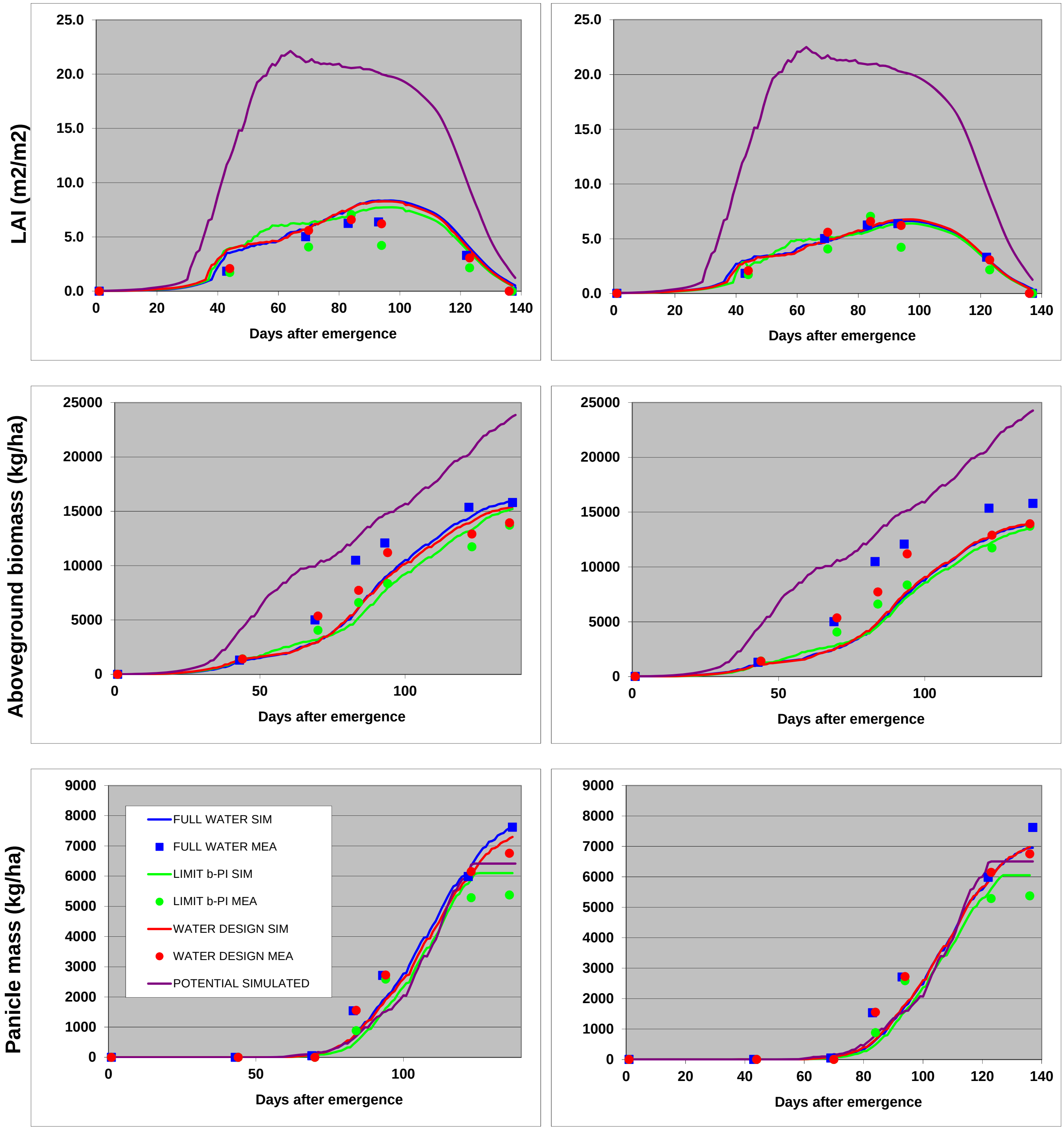

Figure 6. China water and nitrogen interaction experiment showing simulated (SIM) and measured (MEA) LAI, aboveground biomass and panicle mass for ORYZA2000 stand-alone model (left) and for the linked DSSAT-ORYZA model (right).

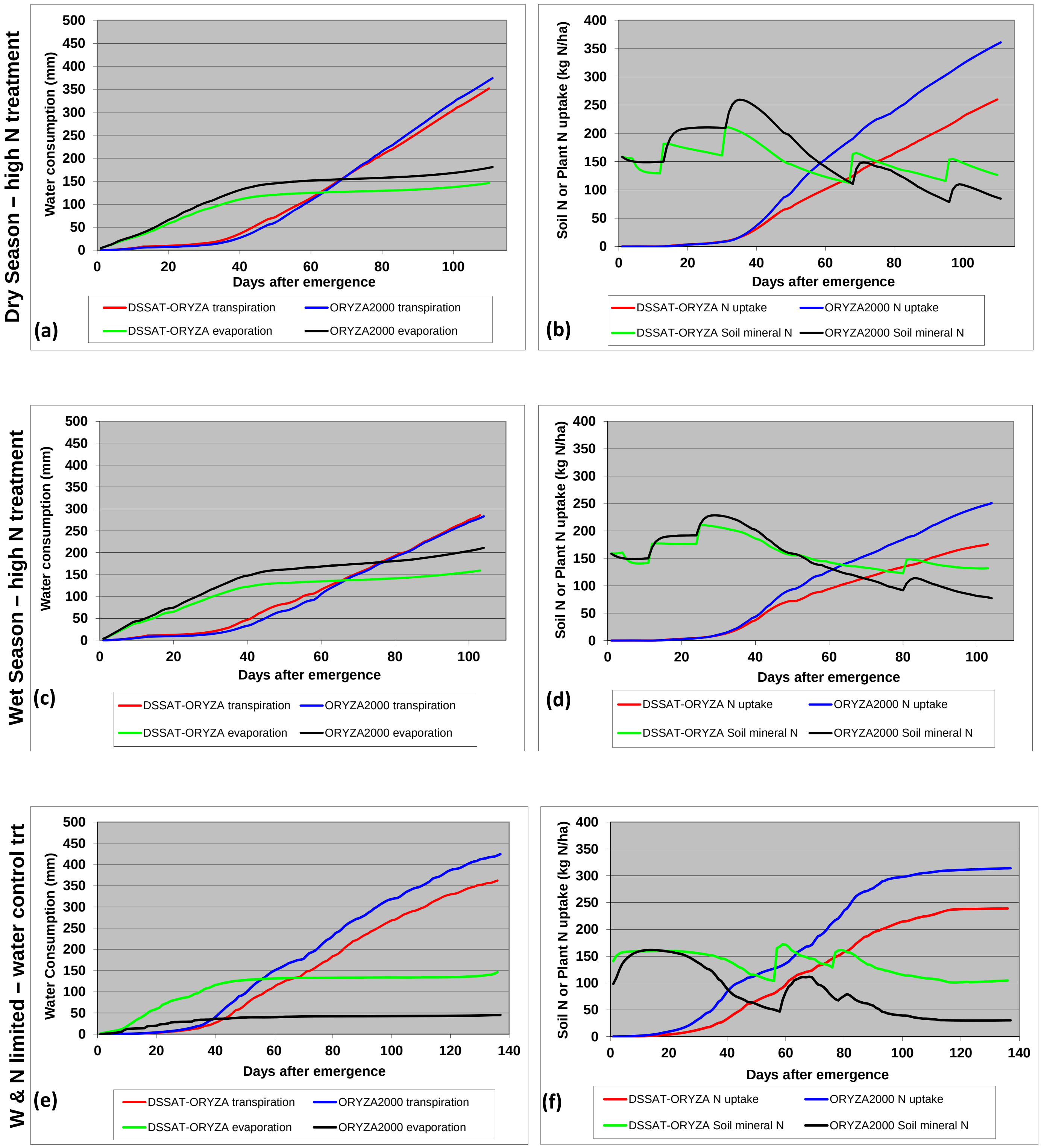

Figure 7.Comparison of simulated outputs for DSSAT-ORYZA and ORYZA2000 stand-alone model showing plant transpiration and soil evaporation in graphs (a), (c) and (e); and plant N uptake and soil mineral N in graphs (b), (d) and (f).

Table 1. Statistical analyses for ORYZA2000 (ORYZA) and DSSAT-ORYZA (DSSAT) models outputs with observed values. Blue highlighting shows statistical values for which ORYZA2000 performed better, orange highlighting shows values for which DSSAT-ORYZA performed better.

	LAI (m2/m2)		Total above-ground biomass (kg/ha)		Panicle Biomass (kg/ha)		Stem biomass (kg/ha)		Green leaf biomass (kg/ha)		Dead leaf biomass (kg/ha)		Leaf nitrogen (g N/m2 leaf)	
	ORYZA	DSSAT	ORYZA	DSSAT	ORYZA	DSSAT	ORYZA	DSSAT	ORYZA	DSSAT	ORYZA	DSSAT	ORYZA	DSSAT
Dry season nitrogen application experiment in 1992														
N	21	21	21	21	9	9	21	21	21	21	15	15	24	24
Bias	0.273	-0.225	-365	-1008	-264	-491	204	-139	-224	-405	-333	-388	0.012	0.012
RMSEn	0.342	0.234	0.159	0.224	0.136	0.204	0.213	0.154	0.340	0.422	0.460	0.567	0.177	0.180
M_eff	0.836	0.927	0.986	0.972	0.987	0.970	0.971	0.985	0.930	0.892	0.886	0.827	0.986	0.986
Wet season nitrogen application experiment in 1992														
N	56	56	56	56	24	24	56	56	56	56	40	40	56	56
Bias	0.188	-0.123	200	-396	1033	462	120	-101	-189	-295	-292	-334	-0.029	-0.046
RMSEn	0.303	0.314	0.150	0.197	0.318	0.234	0.243	0.226	0.338	0.418	0.478	0.533	0.236	0.231
M_eff	0.815	0.803	0.987	0.977	0.922	0.958	0.961	0.967	0.924	0.884	0.852	0.816	0.911	0.914
Water and nitrogen management experiment for aerobic rice in 2003														
N	15	15	18	18	13	13	18	18	15	15	15	15	no observed data	
Bias	1.449	-0.053	-782	-1842	-206	-294	-974	-1387	-59	-540	272	72		
RMSEn	0.388	0.252	0.210	0.305	0.163	0.209	0.347	0.456	0.210	0.354	0.529	0.455		
M_eff	0.163	0.647	0.966	0.928	0.981	0.969	0.904	0.835	0.962	0.893	0.881	0.912		
Combined experiments														
N	92	92	95	95	46	46	95	46	92	95	73	92	77	92
Bias	0.413	-0.135	-111	-805	429	62	-69	-353	-176	-360	-180	-259	-0.012	-0.024
RMSEn	0.367	0.286	0.184	0.259	0.233	0.221	0.307	0.363	0.306	0.412	0.488	0.525	0.224	0.220
M_eff	0.757	0.854	0.980	0.960	0.961	0.965	0.940	0.916	0.939	0.889	0.870	0.850	0.969	0.970

Definitions

N	Number of observations
Bias	Mean absolute difference between observed and simulated data
RMSEn	Normalized root mean square error
M_eff	Model efficiency