Testing the performance of ORYZA1, an explanatory model for rice growth simulation, for Mediterranean conditions

D. Casanova a,*, J. Goudriaan b, A.D. Bosch c

a Food and Agriculture Organization of the UN, Apartado Postal 1524, Managua, Nicaragua
b TPE Department, Wageningen Agricultural University, PO Box 430, 6700 AK Wageningen, The Netherlands
c MACS Department, University of Lleida, c/ Alcalde Rovira Rout 177, 25198 Lleida, Spain

Received 4 November 1997; received in revised form 21 July 1998; accepted 18 January 2000

Abstract

ORYZA1 is an explanatory model to simulate rice growth, development and leaf area index (LAI) under potential production. The present study aims at testing the performance of ORYZA1 for Mediterranean conditions (farming practices, cultivars, weather) for fully irrigated direct-seeded rice. ORYZA1 was calibrated and validated with field data of two cultivars, a short-grain (Tebre) and a long-grain cultivar (L-202), grown in various years in the Ebro Delta of Spain. Phenological development of the rice crop, daily dry matter production and leaf area development were calibrated. Tebre and L-202 had no significant differences in the total length of the development period. The pre-heading period, however, was longer and the post-heading period shorter in L-202 than in Tebre. This induced differences in translocation characteristics, spikelet number per unit area, weight of the grains and harvest index. The following crop characteristics were similar between cultivars: extinction coefficient (increased with development stage), dynamics of nitrogen distribution, partitioning of assimilates, relative death rate of leaves, relative growth rate of leaf area during exponential growth, specific leaf area and a strongly decreasing specific stem green area. The simulated curve fitted much better the observations, which was clear from a strongly reduced value of RMSE, when considering that LAI comprises the leaf blade area only, without a photosynthetic contribution by stem green area. The model simulated rice growth very accurately until flowering. After flowering, however, divergences appeared and increased especially at the yellow ripe stage. From then on the crop did not grow much more, whereas it continued in the simulation. This reduction of growth rate was usually accompanied by an increase in the relative death rate of leaves and the drying of the grains. The main source of error may be a limited understanding of the ripening and sink limitation processes. A considerable yield gap between potential and observed yield remained. A climatic variability assessment over 10 years, from 1987 to 1996, showed a small but correlated variation ($r = 0.7$) in both simulated and measured rice yields. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Crop parameters; Development; LAI; Crop model

* Corresponding author. Tel.: + 505-277-2185; fax: + 505-278-0804.
E-mail address: david.casanova@pobox.com (D. Casanova)
1. Introduction

Crop simulation models are increasingly being used in agricultural research and development (Wisiol, 1987). Testing over a range of environmental conditions is required to establish confidence in applying models (Goudriaan and Van Laar, 1994). A large number of models have been developed in the past but most have not been evaluated adequately (Silva, 1985). Models for simulating rice growth have been developed; ORYZA1 (Kropff et al., 1994), CERES-Rice (Singh et al., 1993), TRYM (Williams et al., 1994), VSM (Kobayashi, 1994), SIMRIW (Horie et al., 1992), RICAM (Yin and Qi, 1994) and a rice-weed competition model (Graf et al., 1990). Each model has its specific objective(s) and, hence, its own set of underlying assumptions and complexity.

ORYZA1 was chosen because it was a readily available and widely-used process model which suited our purposes by emphasizing rice physiology and nitrogen dynamics at the field level. ORYZA1 was developed based on data from the Philippines where conditions differ widely from those prevailing in European rice areas.

Rice in Europe is commonly grown as a lowland direct-seeded crop under fully irrigated conditions and the growing cycle is determined by temperature constraints and cultivars characteristics (Casanova, 1998). The climate is characterised by long days, high solar radiation and relatively large diurnal temperature fluctuations (Hill et al., 1991). When direct-seeded, the same rice cultivars have lower tillering and require greater N inputs to produce the same yield (Dingkuhn et al., 1991). It is, therefore, important for models to be parameterised and validated in different agro-environments (START, 1997).

The objective of this study was to calibrate and test the performance of the ORYZA1 model for direct-seeded fully irrigated rice with a commonly grown short-grain cultivar, Tebre, and a long-grain cultivar, L-202, in a Mediterranean climate. ORYZA1 is an explanatory dynamic mathematical model to simulate rice growth and development under potential production conditions. Potential crop production is attained when the crop is optimally supplied with water and all essential nutrients, and grows without interference from weeds, pests and diseases. Crop growth is then a function of weather (radiation and temperature) and the physiological characteristics of the cultivar (Rabbinge 1993).

In order to get as close as possible to the potential yield, the most productive farms (with higher production than in the rice experimental station) in the Ebro Delta were chosen. In these farms, the best plots were selected for monitoring crop growth in 1994, 1995 and 1996. Calibration of phenological development, daily dry matter production and leaf area development was done mainly with data from 1995, and the calibrated model was validated with data from 1994 to 1996. Validation of crop models is an important consideration in their use for predicting outcomes (Hammer and Muchow, 1994). Rice yield variability due to climate variability can be assessed by using the calibrated and validated model. As an additional test, the model was used to predict the relative effect of climatic interannual variations in the Ebro Delta over 10 years, from 1987 to 1996. An important result of this entire process is that such a model could be used as a powerful tool for European rice research in order to improve rice management and economic viability.

2. Materials and methods

2.1. Description of field and laboratory measurements

Experiments were performed on farms in the Ebro Delta (latitude 40°45’N, longitude 0°43’E and sea level), in north-eastern Spain, in the growing seasons of 1994, 1995 and 1996. Four farms were selected in 1995 and two farms in 1994 and 1996. The selected farms had minimal limitations by water, nutrient, weeds, diseases or pests, so that production was considered to be limited only by temperature and radiation. Rice production on these farms were the highest in the area and consistently higher than in the Ebro Delta agricultural research station (Institut de Recerca i Tecnologia Agraria, IRTA) of the Autonomous Government.
The rice cultivars used in 1995 were both Japonica-type, typical for a temperate climate but with differences in grain size; Tebre is a short-grain and L-202 or Thaibonnet is a long-grain cultivar. Agronomic management was done in order to be as close as possible to maximum crop production levels. Sowing and maturity dates were ca. the 15th April and 20th September. N–P–K applications were on average 180, 50 and 100 kg \( \text{ha}^{-1} \), respectively. N application was done as a 40% basal dressing and the rest in two split applications. Weed control was done with molinate and bentazone, and funga control was by two preventive applications of a mixture of carbendazime and mancozeb.

Crop samples were taken at three sites within the plots approximately twice monthly during the rice growing seasons. A round frame of 0.5 m\(^2\) was used for crop sampling. The rice samples were cleaned and kept cold in a portable refrigerator. A sub-sample was chosen and separated into different components: stems, green leaves, dead leaves and grains. By rice grain is meant the true fruit or brown rice (caryopsis) and the hull, which encloses the brown rice (Yoshida, 1981). Fresh weight of leaves, stems and grains were measured. Leaf blade area and stem area were determined with a LI-300 area meter. Oven dry weight measurements (65–70°C during 24 h) were made independently for every component of the plant sample. Finally, the dry matter of leaf blade samples were analyzed at the laboratory for organic nitrogen (Kjeldahl). A final harvest of 5 m\(^2\) of crop with three replicates per plot was collected.

A Decagon Sunfleck Ceptometer (Model SF-80, Decagon Devices Inc. 1989) was used to measure the photosynthetically active radiation (400–700 nm) above and below the canopy at each sampling. Daily maximum and minimum temperature and global short-wave radiation were recorded at the agricultural station of Amposta, within a radius of 10 km from the experimental farms.

Data were split by year; data of 1995 were used to calibrate crop parameters, while data of 1994 and 1996 were used to validate the calibrated model. In order to evaluate the model for a wide range of environmental conditions, data on phenological development and final yield were also obtained from two other sources in the Ebro Delta: the agricultural research station of IRTA and the trials done by Migjorn S.A. (Caballero i Lluch, 1992). These additional data were used for visualizing the year-to-year variation between simulated potential yield and observed actual values and their correspondence.

2.2. Model description

The general structure of the model ORYZA1 is presented in Kropff et al. (1994). Under optimum growth conditions, light, temperature and differences in varietal characteristics for phenological, morphological and physiological processes are the main factors determining the growth rate of the crop on a specific day. The model simulates daily dry matter production of the plant organs and the rate of phenological development. By integrating these rates over time, dry matter production is simulated throughout the growing season. Input requirements of the model are: latitude, daily weather data (global radiation, maximum and minimum temperature) and seeding date (no transplanting effects were considered). The model description is split into phenological development (Section 2.2.1), growth (Section 2.2.2) and leaf area growth (Section 2.2.3).

2.2.1. Crop development calibration

The development stage (DVS) of a plant defines its physiological age. It determines the formation of the various organs and their appearance. As many physiological and morphological processes change with the phenological stage of the plant, accurate quantification of phenological development is essential in any simulation model for plant growth (Yin, 1996). Four stages are defined (Keulen and Seligman, 1987); seeding date (DVS = 0), panicle initiation (DVS = 0.65), flowering (DVS = 1) and maturity (DVS = 2). No photosensitivity was considered for these cultivars (Tseng et al., 1984). Maturity stage was defined as the time when maximum grain weight is attained. This is not the same as the time of harvest, which is usually determined by farmers’ experience, and based on grain colour and leaf senescence. The development stage of rice at every sampling time
was defined according to a linear temperature sum model (Kropff et al., 1994). According to Gao et al. (1992), for Japonica-type cultivars the base temperature is 10°C, the optimum temperature 28°C, and the maximum 40°C. Data on sowing, flowering and maturity dates from IRTA and Caballero i Lluch (1992) were also used for calculating the required temperature sum (TS) to reach the defined phenological stages.

2.2.2. Crop growth calibration

Canopy photosynthesis is the leaf photosynthesis accumulated over the canopy. The maintenance respiration and growth respiration modules (Penning de Vries and Van Laar, 1982), and the spikelet fertility module (Horie et al., 1992) of the ORYZA1 model were not modified. The calibrated crop parameters were:

- Extinction coefficient ($K$) because of its influence on canopy CO$_2$ assimilation. It was derived from the relation between the fraction of PAR transmitted and the leaf area index (LAI).
- Surface leaf nitrogen weight (SLNW) because it has a relation with the maximum leaf photosynthesis (Cook and Evans, 1983; Peng et al., 1995).
- Partitioning of assimilates (FSO, FST, FLV). Experimentally these fractions were derived by analyzing the fractions of new dry matter production distributed to the plant organs between two subsequent harvests. For dead leaves the increase in dry weight is difficult to measure. It was assumed that new leaf growth ceased when the maximum weight of leaves was reached, and the decline of green leaves was due to death of leaves (RDR).
- The fraction of reserves translocated (FSTR) from the stems to the grains and the moment of translocation (MTR). FSTR is calculated as the difference between maximum and minimum stem weight (from flowering onwards) divided by maximum stem weight.
- Sink-size related parameters. The spikelet growth factor (SPGF) which is equal to the ratio of number of spikelets to growth of above-ground biomass between panicle initiation and flowering. The weight of mature grains (WGRMX) for each cultivar needs to be introduced also because it is used for estimating the maximum growth rate of individual grains.

2.2.3. Leaf area development calibration

The green leaf area of plants determines the amount of absorbed light and thereby CO$_2$ assimilation. The LAI of a crop is the total surface of one side of green leaves per unit of soil surface. The calibrated crop parameters were:

- The relative growth rate of leaf area during exponential growth (RGRL). RGRL is the change of the natural logarithm of LAI with respect to temperature sum (calculated as in the crop development module).
- The specific leaf area (SLA) which is the inverse of the specific leaf weight. SLA is an indirect measure of leaf thickness, which changes with development stage, and is used to convert from leaf weight to leaf area when the canopy closes. The surface area of stems may be also determined by multiplying their weight by their specific stem green area (SSGA).

3. Results

3.1. Calibration

The model documentation (Kropff et al., 1994) aids in the estimation of the input parameters. Calibrated parameters may be inserted in the model as a constant or as a function of development stage. The results of the calibration process can be summarized as follows.

3.1.1. Crop development

Development rate in the pre-heading and post-heading periods. The crop development rates were calibrated using the simple approach proposed in ORYZA1 where sowing, flowering and maturity dates together with temperature were used as input. The predictions and standard errors have been standardized (using regression techniques) by averaging over two factors; year and source of data (e.g. Caballero i Lluch, IRTA and our experimental farms in 1995). A special emphasis was
made on defining the proper maturity stage moment when the maximum weight of the grains was reached. This moment, based on our own observations, usually coincided with 26–25% moisture content of the grain. The temperature sum from seeding to maturity, with a temperature base of 10°C, is on average 1650 degree-days for both cultivars. The pre-heading and post-heading periods, however, differ among cultivars. The average value and standard deviation for the development rates per degree-day in the pre-heading and post-heading period are 1.033 ± 0.014 \( \left(10^{-3} \text{C}^{-1} \text{day}^{-1}\right) \) and 1.500 ± 0.036 \( \left(10^{-3} \text{C}^{-1} \text{day}^{-1}\right) \) for Tebre and 0.875 ± 0.009 \( \left(10^{-3} \text{C}^{-1} \text{day}^{-1}\right) \) and 1.933 ± 0.048 \( \left(10^{-3} \text{C}^{-1} \text{day}^{-1}\right) \) for L-202, respectively.

3.1.2. Dry matter production

Extinction coefficient \((K)\). The fraction of light transmitted was plotted against LAI using the experimental data from 1995 (Fig. 1). The slope of Fig. 1 corresponds to the \(K\) value (Monsi and Saeki, 1953). A linear model on a log-scale, assuming a constant \(K\), would give an overall extinction coefficient of 0.54. Fig. 1, however, shows that the extinction coefficient is not constant and increases with development stage. The result of the calibration of the extinction coefficient, differentiating the three clearly defined development phases, is illustrated in Fig. 1. The scatter in the data is highest at the last development phase, probably because yellow (senesced) plant material was present in most experiments and the canopies were lodged to some degree.

Decline of nitrogen over time. The N content of green leaves during the rice growing seasons declined from \(\sim 5.5\%\) at early tillering, to 2.5% at flowering and 1.3% at maturity. The input parameter, SLNW, was derived at each stage by dividing the N content in the leaves by the specific leaf area. SLNW dynamic behavior with development stage is shown in Fig. 2.

Partitioning of assimilates. The relationships used in the model are given in Fig. 3. The dry matter distribution patterns in the various experiments agreed well with each other, indicating small management and varietal effects. The grains attract most of the assimilates after flowering, though small fractions may still go to leaves or stems.

RDR of the leaves. The dynamics of green and dead leaves is illustrated in Fig. 4. Values of RDR were derived as indicated in Kropff et al. (1994).
Mobilization of reserves. The magnitude of the loss of stem weight is presented in Fig. 5. The calculated average FSTR for those cultivars is 0.25. Our data shows that mobilization starts at different development stages for Tebre and L-202. A new variable, MTR expressed in development stage, is introduced in the model. This MTR is defined within the model in the section of parameters and is called directly when calculating the loss rate of stem reserves. It does not affect the simulation of total crop growth because it merely affects the partitioning between stems and grains, which both are considered to have no assimilatory activity at all. Based on Fig. 5, an average MTR at development stage of 1.3 for Tebre and 1.0 for L-202 is chosen.

Sink-size related parameters. SPGF (spikelets g\(^{-1}\)) and WGRMX (mg grain\(^{-1}\)) have significant differences among cultivars. The average value and standard deviation (n = 36) for SPGF and WGRMX are 42.5 ± 7.1 and 31.1 ± 1.6 for Tebre and 55.5 ± 9.0 and 23.1 ± 0.3 for L-202, respectively. Note, however, that SPGF x WGRMX is similar for both cultivars and equal to 1.3 g of grains dry weight g\(^{-1}\) of above-ground biomass.
3.1.3. Leaf area development

LAI increases as growth advances and reaches a maximum at around heading. Average maximum LAI (measuring leaf blades only) of 6.5 for L-202 and 5.5 for Tebre were found.

- RGRL: when the canopy is not closed, plants grow exponentially as a function of temperature sum (Fig. 6). The exponential phase ends when mutual shading becomes substantial (we used a TS of 500 degree-days which corresponds to a LAI of \( \approx 2.5 \)). In fact, RGRL is the slope of Fig. 6. Fitting a linear equation to Fig. 6 as proposed in ORYZA1 v1.3 gives a constant value of 0.009 per degree-day for RGRL. The measured data shows, however, that RGRL is not constant and declines as temperature sum increases. This variation of RGRL was better expressed in a polynomial equation of second order. The equation shown in Fig. 6, which gives a slope of 0.028 – 0.00005 x TS, implies that RGRL diminishes from 0.028 at sowing to 0.003 at a TS of 500 degree-days.

- SLA: Fig. 7 shows the SLW, inverse of SLA, dynamics at various development stages in 1995. SLW is plotted instead of SLA because linear equations can be fitted. The scattering of the data is quite large. An average SLA value of 20 m² leaf kg⁻¹ DM (500 kg dry matter per hectare of leaf) was obtained, slightly lower at flowering and slightly higher at early development stages.

- SSGA: Fig. 8 shows the experimental data and calibrated values of SSGW, inverse of SSGA, with development stage in 1995. Note, especially, the small scattering in the data and the enormous difference with the values originally used in ORYZA1 v1.3. Based on our measured data, SSGW increases until development stage...
Fig. 8. Experimental data and calibrated relation (lines) between specific stem green weight (SSGW) and development stage (DVS) for cultivars Tebre in 1994 and 1995, and L-202 in 1995. Vertical solid lines are standard deviation. The solid line represents the calibration as it was used in the model: [DVS, SSGW] = [0.0, 200 0.2, 400 1.2, 5000 1.5, 3300 2.0, 3800]. The dashed line corresponds to SSGW values as they were used in ORYZA1 v1.3.

3.2.2. Crop growth validation

Our calibrated SSGA shown in Fig. 8 (as its inverse SSGW) was much higher than the values that were used earlier in ORYZA1 v1.3 (Kropff et al., 1994), where it was constantly low from sowing to heading. Although our value of SSGA resulted in a higher and presumably more realistic stem area index than the one in Kropff et al. (1994), the rate of crop growth was overestimated. When adding stem green area, growth rates (i) increased too early at the first (canopy cover limiting) phase and (ii) were too high during the generative (radiation limiting) period. In all subsequent simulations, LAI was therefore taken as leaf blade area without any contribution of leaf sheath or stem area. In the ORYZA1 model it is possible to use either simulated or measured values of LAI for simulating crop growth. Both options are presented in Fig. 9, with the comparisons between simulated and observed dry matter values during the growing season in 1995: WTDM (above-ground, not including dead leaves), WSO (grains). The results for the runs with LAI simulated were very close to the ones with LAI measured (showing that the simulation of LAI was sufficiently similar to the observations of LAI). Table 1 shows that the root mean square error of the prediction was in the order of 5% of final biomass. Regression between the difference of predicted and observed values versus observed values for above-ground (WTDM) and grains (WSO) biomass showed that the intercept was not significantly different from 0 ($P > 0.05$) in any case (Table 1). The slope was in all cases significantly different from 0 and had positive values between 0.05 and 0.08 indicating the overestimation of the predictions. This shows that the prediction error increased as the crop grew. Fig. 10 shows measured and simulated values of WTDM and WSO for the validation runs using the data of 1994 and 1996. The root mean square error of above-ground and grains biomass was 2275 and 1304 kg ha$^{-1}$, respectively ( ~ 10% of final biomass). Incomplete recovery of dead tissues can contribute to discrepancy between simulated and observed above-ground biomass after flowering. The regression between the difference of predicted and observed versus observed values for WTDM
and WSO, respectively, showed that the intercepts were \(-77.8 \pm 496.1\) \((P = 0.87)\) and \(167 \pm 254\) kg ha\(^{-1}\) \((P = 0.51)\), and the slopes were \(-0.204 \pm 0.047\) \((P = 0.0001)\) and \(-0.107 \pm 0.051\) \((P = 0.04)\). As in the 1995 data, the intercepts were not significantly different from 0 \((p > 0.05)\), but the slopes differed in both cases. These results show that the prediction was accurate until flowering (Figs. 9 and 10; DAS \(\sim 100\)). From flowering onwards the prediction error increased (Fig. 10). Cultivar L-202 in 1996, in particular, had a significant sink limitation due to an insufficient number of spikelets. The spikelet number of L-202 was usually \(45\,000–49\,000\), but in 1996 it was only \(37\,000\), due to a poor plant establishment.

3.2.3. Leaf area development validation

Leaf area dynamics are very important for crop growth, especially at the early stages before the canopy closes. The longevity of the green tissue should be considered when assessing the photosynthetic contribution of different plant parts during ripening. The panicle turns yellow relatively early, but the leaves remain green much longer. Fig. 11 presents the observed and simulated leaf area during the growing cycle in 1994 and 1995. Differences between measured and simulated LAI time course in 1994 are small. The standard errors of measurement of LAI are particularly large during the ripening phase, due to the difficulty in differentiating green healthy from yellow senesced leaves, which also contributes to the high prediction error at late stages.

4. Discussion

4.1. Crop development

To define accurately the main physiological stages is of major importance. Maturity stage, especially, is not the same as harvesting stage. Harvesting date depends on cultural and farm management. Many data are available on harvesting date, but not on maturity. Maturity stage was defined from the growth curves and it usually coincided with a 26–25% moisture content of the grain. Results obtained in development rates showed a strong interannual consistency with less than three percent variability. L-202 and Tebre have a similar total growth duration from sowing to maturity. L-202 had, however, a lower pre-heading and a higher post-heading development rate than Tebre. This means that L-202 takes more days to flower and, thus, has a higher biomass at flowering, but a shorter post-heading period. This development rate difference has effects; higher maximum LAI, later moment of translocation and higher grain number but smaller individual grain weight (Table 2) for L-202 in comparison with Tebre.
Table 1
Regression analysis between the difference of predicted and observed values versus observed values for above-ground (WTDM) and grains (WSO) biomass with the 1995 data by using the measured and the simulated LAI time course

<table>
<thead>
<tr>
<th>N = 39</th>
<th>LAI measured</th>
<th>LAI simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WTDM</td>
<td>WSO</td>
</tr>
<tr>
<td>Intercept (kg ha(^{-1}))</td>
<td>–103.5 ± 238.1</td>
<td>–83.6 ± 82.7</td>
</tr>
<tr>
<td></td>
<td>((P = 0.66))</td>
<td>((P = 0.32))</td>
</tr>
<tr>
<td>Slope</td>
<td>0.083 ± .020</td>
<td>0.046 ± .017</td>
</tr>
<tr>
<td></td>
<td>((P = 0.001*))</td>
<td>((P = 0.012*))</td>
</tr>
<tr>
<td>RMSE (kg ha(^{-1}))</td>
<td>1242</td>
<td>442</td>
</tr>
</tbody>
</table>

* In addition, the root mean square error (RMSE in kg ha\(^{-1}\)) of the predictions is given.
* The value is significantly different from 0 at the \(\alpha = 0.05\) probability level.

4.2. Crop growth

The growth rate of the rice crop can be determined from the slope of the curve between total above-ground dry matter and days after seeding. According to our results, three clear stages are distinguishable, and this agrees with Hsiao (1993); a first phase (canopy cover limiting), a vegetative and generative period with the highest growth rate (radiation limiting) and a senescence phase where the slope tends to diminish again. At our experimental sites, a standard growth rate during the intermediate phase of \(\sim 250\) kg dry matter ha\(^{-1}\) day\(^{-1}\) was achieved. During the grain filling period, grain growth was in the order of 170 kg dry matter ha\(^{-1}\) day\(^{-1}\). It seems that from DVS 1.6 to 1.7 onwards (after the so-called ‘rapid grain growth’), the crop growth slowed down, and especially the grains dried until they reached maturity. ORYZA1 seems to overestimate growth rate and therefore grain production at those late stages. This error at those late stages may be due to an overestimation of leaf photosynthesis and also to an underestimation of maintenance processes.

ORYZA1 v1.3 simulates the development of number of spikelets, as well as grain filling in dependence of temperature and radiation. However, relevant rice literature (Matsuo et al., 1995; Shin et al., 1994) mentions also a strong relation between the spikelet number and management. A correct simulation of the sink size was found vital for understanding the source–sink interrelationships. Sink limitation could reduce photosynthesis or lead to storage in the stem as shown in Fig. 3. This effect was clearly visible for cultivar L-202 in 1996 (see Fig. 10). It is not a matter only of the grain number but also of the weight/size of the grains. The product of SPGF \(\times\) WGRMX (number of spikelets per growth between PI and flowering, times the weight of the grains) was similar for both cultivars. This implies a compensatory relationship between the spikelet number and the

![Fig. 10. Measured (*) and simulated (*-S) weights of above-ground green biomass (WTDM) and grain (WSO) using simulated LAI against days after sowing (DAS) for cultivars Tebre and L-202 (number in brackets is year and farm identification) in 1994 and 1996. Vertical solid lines are standard sampling error. *Sink limitation was observed for L-202 in 1996.](image-url)
4.3. Leaf area development

In the actual version of ORYZA1 v1.3, the effect of temperature on relative growth during the exponential phase (RGRL) was considered to remain the same. Yet, Fig. 6 shows how RGRL (the slope of the curve) diminished with temperature sum. Because of its strong sensitivity when simulating leaf area (and therefore crop growth), it is still needed to better quantify these early processes of leaf area growth. This paper proposes as a simple alternative a linear drop of RGRL with TS, as is also done in other crop models such as SIMRIW (Horie et al., 1992) during this early stage.

After the exponential phase the simulation of LAI is merely carbohydrate-dependent, which means that LAI is derived directly from the weight of the green leaves by multiplying with the SLA. Other models simulate LAI from nitrogen content (TRYM; Williams et al., 1994), from temperature sum (SIMRIW; Horie et al., 1992), or from a combination of carbohydrate dependence and nitrogen (APSIM; McCown et al., 1996). Values of SLA measured in other years for similar cultivars have shown a large variability (Casanova, 1998). This result, together with evidence that LAI is also a function of nitrogen, leads into question the stability of SLA as a crop characteristic.

Fig. 11. Measured (*–X) and simulated (*–S) LAI (leaf blade area) against development stage (DVS) for cultivars Tebre and L-202 (number in brackets is year and farm identification) in 1994 and 1995. Vertical solid lines are standard sampling error.

A cold-induced sterility was not recorded, either because of cultivar adaptation or because of proximity to the sea of the Ebro Delta. This phenomenon would require, though, further attention in other rice belts of Europe such as the Camargue or the Po valley with a tighter temperature constraint. Minimum recorded night temperatures in the Ebro Delta at flowering stage were 20°C in 1995 and 1996, and 19°C in 1994. Temperature as a major difference between tropical and temperate conditions, however, is still implied through its effects on development rate, photosynthesis and leaf area extension growth.
4.4. Growth and development extrapolation over 10 years

Rice yield variability due to climate variability was assessed by using the model. Data on rice yields over 10 years, from 1987 to 1996, in the Ebro Delta was obtained from Caballero i Lluch (1992) and the local experimental agricultural station (IRTA). They are average observed yields at field level, far below potential yield. They do give, however, a trend on the interannual yield variability. The simulated potential yields during the 10 years were calculated for a standard sowing date such as the 20th April (Fig. 12). Interannual rice variability was small (coefficient of variance of 10%). The trend in simulated potential yields and measured observed yields was correlated, $r = 0.7$. As in the validation section, the simulated values

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Summary of the calibration for the main rice characteristics in the Ebro Delta (Spain)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Tebre</td>
</tr>
<tr>
<td>Origin</td>
<td>Spain</td>
</tr>
<tr>
<td>Grain type</td>
<td>Short ($&lt;5.2$ mm)</td>
</tr>
<tr>
<td><strong>Cultivar</strong></td>
<td></td>
</tr>
<tr>
<td>Total crop duration, (°C day)$^a$</td>
<td>1650</td>
</tr>
<tr>
<td>Develop. rate pre-flowering (°C day)$^{-1}$</td>
<td>$1.033 \times 10^{-3}$</td>
</tr>
<tr>
<td>Develop. rate post-flowering (°C day)$^{-1}$</td>
<td>$1.500 \times 10^{-3}$</td>
</tr>
<tr>
<td>Fraction of stems translocated$^a$</td>
<td>25% (shown in Fig. 5)</td>
</tr>
<tr>
<td>Moment of translocation (DVS)</td>
<td>1.3 (shown in Fig. 5)</td>
</tr>
<tr>
<td>Spikelet growth factor (spikelets g$^{-1}$)</td>
<td>42.5</td>
</tr>
<tr>
<td>Panicles per square meter$^b$</td>
<td>400–450</td>
</tr>
<tr>
<td>Grains per square meter$^b$</td>
<td>32 000–36 000</td>
</tr>
<tr>
<td>Weight of 1000 grains (g)</td>
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</tr>
<tr>
<td>LAI$_{max}$$^b$</td>
<td>5.5</td>
</tr>
<tr>
<td>Harvest index$^b$</td>
<td>0.54</td>
</tr>
<tr>
<td>Extinction coefficient$^a$</td>
<td>Shown in Fig. 1; 0.35 during the vegetative stage, 0.49 during the internode elongation stage and 0.61 during the ripening period.</td>
</tr>
<tr>
<td>Nitrogen dynamic distribution$^a$</td>
<td>Key values were 3.5% N at PI, 2.5% N at flowering and 1.3% N at maturity. The leaf N concentration on a per area basis is shown in Fig. 2.</td>
</tr>
<tr>
<td>Partitioning of assimilates$^a$</td>
<td>Shown in Fig. 3. Note, though, the observation of a decline in the partitioning to the grains accompanied by an increase in partitioning to the stems at the end of the ripening phase. This feature could have been induced by sink limitation or lodging.</td>
</tr>
<tr>
<td>Death rate of leaves$^a$</td>
<td>It starts at panicle initiation and continues until harvesting. The AFGEN function used, based on Fig. 4, was [DVS,RDR]: 0.0,0.0,0 0.5,0.0 0.65,0.0,05 0.9,0.0,09 1.3,0.01 1.6,0.03 2.0,0.06.</td>
</tr>
<tr>
<td>Growth rate of leaves$^a$</td>
<td>RGRL had a value of 0.026–0.00005 × TS, with a base temperature of 10°C (shown in Fig. 6).</td>
</tr>
<tr>
<td>Specific leaf area$^a$ (m$^2$ leaf kg$^{-1}$ DM)</td>
<td>Shown in Fig. 7. From 25 (DVS ≈ 0.2) to 15 (DVS ≈ 1).</td>
</tr>
<tr>
<td>Specific stem green area$^a$ (m$^2$ stem kg$^{-1}$ DM)</td>
<td>Shown in Fig. 8. From 20 (DVS ≈ 0.2) to 2 (DVS ≈ 1.2).</td>
</tr>
</tbody>
</table>

$^a$ No significant differences between cultivars was found.

$^b$ Not input in the model.
were always higher than the measured ones, highlighting the existence of a yield gap between potential and observed yields.

Additionally, simulation results for different sowing dates within 1 year, showed that early seeding in general should be positive for final yield. This result is in accordance with normal practice. Farmers in the study area like to sow early if possible, when not hampered by winter rains that prevent early ploughing or by the control measures for wild rice.

5. Conclusions

For direct-seeded rice grown in a temperate climate (Ebro Delta, Spain) under optimal conditions (potential yield, limited by varietal characteristics and the seasonal pattern of environmental variables such as temperature and radiation), the following conclusions can be drawn.

(1) Tebre and L-202 have a similar overall growth duration, but have different development rates in the pre-heading and post-heading period which induce differences in plant properties between cultivars (Table 2).

(2) The simulated curve fitted much better the observations, which was clear both from visual inspection and from a strongly reduced value of RMSE, when considering that LAI comprises the leaf blade area only, without photosynthetic contribution by stem green area.

(3) A good simulation of (i) development and (ii) LAI is essential. At present time, LAI simulation in ORYZA1 v1.3 is very sensitive to the RGRL value. RGRL was found to diminish with temperature sum and equal to 0.028– 0.00005 \times \text{TS} (with a T_{\text{base}} of 10°C).

(4) Simulation results show that ORYZA1 can simulate rice growth accurately until flowering. After flowering, however, divergences appear and increase specially after DVS \approx 1.6–1.7. The main sources of error may be caused by a limited comprehension of the ripening, maintenance and sink limitation processes.

(5) Experimental data of several years show that during the last stages (DVS \leq 1.6–1.7) there is little growth. Drying of grains seems the most important continuing process.

(6) A compensatory relationship appears between the spikelet number and the grain size, canceling each other’s variation. This implies that two cultivar-specific characteristics could be joined to form a rather stable variable, namely sink size, independent of cultivar type.

(7) The climatic variability assessment over 10 years showed a small variation (CV = 10%) in the potential rice yield. Simulated and measured rice yields showed a correlated trend, in spite of a considerable yield gap between observed and potential yield in all years.

Acknowledgements

This work was carried out as part of the project of the Commission of the European Communities number: ERB-4001-GT931494. It is part of the core research programme of the ‘Rice Network’ within the ‘Global Change and Terrestrial Ecosystem’ of the IGBP.

References


