

Impact of Agromanagement Practices on Rice Elongation: Analysis and Modelling

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Abbreviations: ABG, aboveground biomass; AIC, Akaike Information Criterion; CRM, coefficient of residual mass; EF, modeling efficiency; L0, nonsubmerged (the soil was kept saturated but no floodwater was present); L1, submerged (8 cm below the third leaf stage, 15 cm later); LAI, leaf area index; N0, 70 kg N ha⁻¹; N1, 150 kg N ha⁻¹; PH, plant height (distance from the soil surface to the upper leaf auricles); PNC, plant nitrogen concentration; PNC_c, critical value of plant nitrogen concentration; RRMSE, relative root mean square error; S0, sowing density of 200 seeds m⁻² in 2010 and 100 seeds m⁻² in 2011; S1, sowing density of 400 seeds m⁻² in 2010 and 500 seeds m⁻² in 2011; SBh, average value for rice pseudoculms biomass at heading under unlimiting conditions for water and nutrients; SSA, specific stem area; WARM, Water Accounting Rice Model.

THE HEIGHT OF RICE PLANTS has a great influence in determining their behavior and yield potential. Among the main aspects concerning plant height (PH), the positive relationship between this variable and susceptibility to lodging, crop–weed competition (Kropff and Van Laar, 1993), and the relationship

with harvest index play a major role. Street et al. (1986) demonstrated how lodging can negatively affect speed and efficiency of harvesting procedures, whereas Shimono et al. (2007) underlined the negative effect of lodging on quality and quantity of yields, mainly because of lower carbon fixation rates caused by self-shading (Setter et al., 1997) and of problems during translocation to kernels (Hitaka and Kobayashi, 1961). Setter et al. (1997) demonstrated that moderate degrees of lodging (height of lodged plants reduced by 35% compared with controls) can lead to yield losses of about 20%, whereas losses up to 50% were observed for more severe degrees of lodging.

As for many agronomic issues, the need to contain PH can be faced with genetics (e.g., Ishimaru et al., 2004) and with proper modulation of management practices. For the former, the attempt to reduce susceptibility to lodging, by reducing the height of the plant center of mass, has led to the introduction of dwarf and semi-dwarf rice varieties since the early 1960s. Instead, the analysis of the biophysical processes involved with the effect of management practices on plant elongation is—to a certain extent—an open issue, especially for quantitative studies aimed at formalizing knowledge in tools for comparing management scenarios and for management support at field level.

In paddy rice, the rate of PH increase is strongly influenced by the floodwater level (Vergara et al., 1976). The reduced oxygen concentration in water (O_2 is much less soluble in water than in air) induces the plant tissues below the air–water interface to increase the synthesis of C_2H_4 , which in turn increases the tissue elongation rate (Raskin and Kende, 1984) with an effect mediated by Gibberellins. This mechanism is crucial, since it allows the plant to regulate its height coherently with the level of floodwater (Raskin and Kende, 1984). Another factor that can influence PH is related to light interception. Photosynthetic structures absorb preferentially in the red region of the spectrum. While light penetrates into the canopy, the red to far red ratio decreases, as red photons are absorbed by the upper canopy layers. Changes in this ratio are detected by plants through the photoreceptor phytochrome, which triggers processes aimed at increasing PH (Ballaré et al., 1991). This mechanism has important agroecological and production implications, as experimental evidence has proved that the phytochrome-mediated reactions responsible for the increased PH are able to increase canopy productivity (Ballaré et al., 1991). This could be explained by changes in canopy architecture, which lead to a better penetration of diffused light (Warrington et al., 1989). Another explanation relates to a feedback mechanism induced by the higher carbon demand in the elongating tissues, which stimulates photosynthesis in leaves (Humphries, 1963). This process is important for both inter- (i.e., weeds) and intraspecific competition and is strongly dependent on plant density. Shimono et al. (2007) demonstrated the

effect of the plant N nutritional status on PH: especially in certain phenological phases, N luxury consumption can lead to an increase in the elongation rate of tissues.

Cropping system simulation models have been developed and revised in recent decades with the aim of formalizing knowledge on underlying biophysical systems through sets of mathematical equations. Starting from the early 1980s, they have been increasingly used to support crop management at field level and to evaluate and compare alternative management scenarios. Despite the effect of management practices on rice PH (e.g., floodwater and N management, sowing density) and of their implications on yield potential, no simulation models are available to reproduce the biophysical processes involved. Indeed, even without considering the management effect on PH, few approaches are available for the simulation of this variable, and in most cases they are markedly empirical, providing S-shaped curves driven by air temperature (Kotera and Nawata, 2007), phenology (Lizaso et al., 2005), or leaf area index (e.g., Bechini and Stöckle, 2007; Confalonieri et al., 2005).

This study, performed with students of the Cropping Systems MS course of the University of Milan, had scientific and educational objectives. The former was analyzing and modeling the effect of floodwater level, N fertilization, and sowing density on the rate of rice plant elongation. The latter, following previous experiences (e.g., Confalonieri et al., 2011a), was the use of models as tools for supporting education. In this study, students were divided in five work packages: project coordination, greenhouse experiments, analysis and modeling of processes, statistical analyses (for both experimental results and model performances), and dissemination. The aims were assuring a proper project development and assigning tasks to students according to their personal aptitudes (students mostly selected their work package autonomously). Periodic bilateral meetings between work packages and plenary discussions on processes, methods, and results were also organized to promote a participatory way of learning about the specific issues and about how new knowledge on cropping systems can be formalized.

MATERIALS AND METHODS

Experimental Data

Data were collected in 2010 and 2011 during two greenhouse experiments with rice (Indica type, 'Gladio', short cycle, semi-dwarf) grown in 70 by 45 cm plastic pots. The soil (silt loam, USDA classification; www.nrcs.usda.gov/wps/portal/nrcs/site/soils/home/) was taken from a rice paddy. Basal fertilization with 130 kg K_2O ha^{-1} and 50 kg P_2O_5 ha^{-1} was performed in both years on the basis of soil nutrient content and average values of crop nutrient uptake.

Experimental factors (floodwater level, N fertilization, sowing density) were arranged in a split-plot design with three replicates, with floodwater level and N fertilization in factorial

combination in the main plot and sowing density in the subplot. Two levels for each factor were applied. For floodwater level, the treatments were: submerged (L1; 8 cm before the third leaf stage, 15 cm later) and nonsubmerged (L0; the soil was kept saturated but no floodwater was present). For N fertilization, plants received 70 kg N ha⁻¹ (N0) and 150 kg N ha⁻¹ (N1) as urea, half at sowing and half at the panicle initiation. On the basis of the periodic monitoring of the plant N status, N0 was determined as that which was able to maintain plant N concentration (PNC) around its critical value (PNC_c). The concept of critical N concentration is that proposed by Salette and Lemaire (1981), with PNC_c identifying the threshold below which the crop is growing with limited N availability. Fertilizing at the N1 level was thus able to guarantee luxury consumption. For sowing density, the treatments corresponded to 200 (S0) and 400 (S1) seeds m⁻² in 2010 and 100 (S0) and 500 (S1) seeds m⁻² in 2011. Rice was sown on 9 April in 2010 and on 17 May in 2011.

Plant height and chlorophyll meter (SPAD-502, Konica Minolta Inc., Tokyo, Japan) measurements were taken twice a week, starting from 26 April in 2010 and 31 May in 2011, on five plants randomly selected for each elementary plot. For PH, the distance from the soil surface to the upper leaf auricles was determined. The PNC, leaf area index (LAI), aboveground biomass (AGB), and the biomass of the different plant organs were determined every 15 d; PNC was measured using an Elementary Analyzer (NA 1500, series 2, Carlo Erba, Italy), whereas LAI was measured with the planimetric (destructive) method. Yield was measured at physiological maturity.

Plant height data for each measuring event were analyzed by means of a standard ANOVA for a split-plot experiment, with N and floodwater level arranged according to a complete factorial design in the main plot and sowing density in the subplot, with two levels for each factor and three blocks.

Modelling Plant Height in Response to Weather and Management Practices

A two-step strategy was used to develop a process-based model able to reproduce the effect of floodwater level, N fertilization, and sowing density on rice PH. The first step was the development of a model (base model hereafter) able to simulate PH under “standard” growing conditions, defined by sowing density avoiding competition, N availability avoiding luxury consumption, and absence of floodwater. The second step dealt with (i) the development of three impact models, one for each of the management practices considered and (ii) the integration of the three impact models on the basis of the analysis of the interaction of their effects.

Base Models for Plant Height

The base model is an evolution of that proposed by Confalonieri et al. (2011b). The rationale behind this approach is that increases in PH are mainly driven by the allocation of photosynthates to the pseudoculms:

$$PH_i = \frac{PH_{max} \times \sum_{i=Eday}^{today} Pstems_i}{SSA \times SBh \times 100} \quad [1]$$

where PH_{*i*} is the PH on the *i*th day; PH_{max} is the maximum PH (i.e., a variety-specific parameter representing PH at heading); Eday is the emergence day; SSA (range: 1.7–4.0 m² kg⁻¹; Van Diepen et al., 1988) is the specific stem area; SBh (range: 0.15–0.25 kg m⁻²; e.g., Amiri, 2008; Bouman and van Laar, 2006) is an average value for rice pseudoculms biomass at heading under unlimiting conditions for water and nutrients; Pstems_{*i*} (range: 0–1) is the fraction of photosynthates partitioned to pseudoculms on the *i*th day in case mean daily air temperature is higher than base temperature. Pstems_{*i*} is calculated by whatever crop model that implements a dynamic partitioning to plant organs (e.g., Water Accounting Rice Model [WARM], Confalonieri et al., 2009; models belonging to the SUCROS family, Van Ittersum et al., 2003).

The model presented in Eq. [1] was altered to improve the reproduction of the dynamics determining plant elongation in the different phenological phases. In particular, the decrease in the allocation of resources to the main stem during the first part of the tillering phase—when the new pseudoculms are not self sufficient and the plants maximize investment in root apparatus—is reproduced by multiplying each day Pstems_{*i*} by tillering factor (Tf_{*i*}):

$$Tf_i = \begin{cases} 1 & DVS_i \leq DVS_1 \\ \tau + \frac{(0.5 - \tau)(DVS_i - DVS_1)}{DVS_2 - DVS_1} & DVS_1 < DVS_i \leq DVS_2 \\ 1 & \text{otherwise} \end{cases} \quad [2]$$

where DVS_{*i*}, DVS₁, and DVS₂ are, respectively, the SUCROS-type development stage codes (e.g., Van Ittersum et al., 2003; with 0.0: emergence; 1.0: flowering; 2.0: physiological maturity) for day *i* and for the stages of beginning of tillering (code 22 of the Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie [BBCH] scale for rice; Lancashire et al., 1991) and panicle initiation (BBCH code = 30); τ is the reciprocal of the variety tiller number per plant under standard growing conditions.

During the stem elongation phase, the internode elongation contributes to increasing PH by spacing out the insertion points of leaf sheaths. Cell wall extension, caused by the uptake of water by the internode cells, plays a key role in this process and explains the high rates of plant elongation observed in this phase. In practice, during stem elongation, PH increase is driven not only by the relative partition of dry matter to the different organs but also by an important increase in cell volume, that can be effectively represented using the general equation of mechanohydraulic cell growth, also known as the Lockhart equation (Lockhart, 1965; Schopfer, 2006)):

$$\frac{dV}{dtV} = \frac{\varphi L}{\varphi + L} (\Delta\Psi + P - Y) \quad [3]$$

where φ (range: 0.08–0.24 MPa⁻¹ h⁻¹; Cosgrove, 1985) represents the irreversible time-dependent cell wall extensibility; L (up to 2.09 MPa⁻¹ h⁻¹; Cosgrove, 1985) is the cell wall water

conductance; $\Delta\Psi$ (range: 0.0002–0.3734 MPa; Cosgrove, 1985) is the difference in water potential between protoplast and apoplast; $P - Y$ (with $P \geq Y$; range: 0–0.31 MPa; Cosgrove, 1985) is the turgor above the threshold Y , which must be exceeded to get a plastic wall extension. Under the conceptual representation of internode cells as cylinders with the bases orthogonal to the internode axis, we assumed that (i) the increase in the diameter of the internode cells is negligible compared with the increase in the height of the same cells, (ii) the behavior of the internode tissue is equal to that of the sum of a vertical column of cells, (iii) the state of the system is stationary (i.e., φ , $\Delta\Psi$, L , P , and Y are constant during the stem elongation phase (about 22 d for rice according to Nishiyama (1995))). These assumptions (Schopfer, 2006) and Eq. [3] led to estimation of the internodes length at time t using:

$$Ih_t = Ih_0 \times \exp\left[\frac{\varphi L}{\varphi + L}(\Delta\Psi + P - Y)t\right] \quad [4]$$

where Ih_t (cm) and Ih_0 (default 1 cm) are the cumulated internode lengths at the beginning of the stem elongation phase (BBCH code = 34) and at time t (hours after BBCH code 34), respectively.

The assumption of a stationary state also allowed the expression of all the terms of Eq. [4] as a function of days instead of hours, thus obtaining a situation that is coherent with the daily time step used by the majority of crop models. To avoid Ih_t assuming unreasonable values, the stem elongation effect on PH (Eq. [4]) is limited to the 22 d after panicle initiation (Nishiyama, 1995).

Therefore, the base model used in this study is:

$$PH_i = \begin{cases} \frac{PH_{\max} \times \sum_{i=Eday}^{today} (Pstems_i \times Tf_i)}{SSA \times SBh \times 100} + Ih_t & DVS_2 < DVS_i \leq DVS_3 \\ \frac{PH_{\max} \times \sum_{i=Eday}^{today} (Pstems_i \cdot Tf_i)}{SSA \times SBh \times 100} & \text{otherwise} \end{cases} \quad [5]$$

with DVS_3 being the development stage code of the 22nd day after DVS_2 is reached.

Models for the Effect of Agronomic Practices on Plant Height

The model for the simulation of the effect of floodwater level on PH is:

$$PH(WL)_i = PH_i + \beta \times \sum_{i=Eday}^{today} DFR_i \quad [6]$$

$PH(WL)_i$ is the plant height as influenced by floodwater; β (range: 0.1–0.3) is a variety-specific parameter indicating the aptitude of the variety to increasing its elongation rate in response to submergence; DFR_i is the relative increase in PH due to floodwater in the i th day and it is calculated according to:

$$DFR_i = \begin{cases} 1 & \frac{WL_i}{PH_i} \geq 1 \\ \frac{WL_i}{PH_i} & \frac{WL_i}{PH_i} < 1 \end{cases} \quad [7]$$

where WL_i is the floodwater level in the i th day.

The direct representation of changes in the red/far red ratio, caused by the differential light absorption through the canopy layers, was considered incoherent with the level of detail used by available crop models. Therefore, light penetration through the canopy and its effect in modulating the elongation rate were represented by modifying the Lambert–Beer law and calculating each day the shading effect according to:

$$PH(SH)_i = \begin{cases} PH_i & LAI \leq 3 \\ PH_i [1.2 - \exp(-k \times LAI_i)] & LAI > 3 \end{cases} \quad [8]$$

where $PH(SH)_i$ is the plant height as influenced by shading and k is the canopy extinction coefficient for global solar radiation.

The influence of N fertilization on PH is calculated as a function of PNC:

$$PH(N)_i = PH_i \frac{PNCa_i}{PNCc_i} \quad [9]$$

where $PH(N)_i$ is the plant height as influenced by nutritional (N) status; $PNCa_i$ and $PNCc_i$ are, respectively, the actual and critical PNC on day i .

Model Evaluation

A calibration line was derived using the eight pairs PNC–SPAD available from the two greenhouse experiments and used to estimate values of PNCa from the other SPAD measurements that were taken twice a week. These estimates were then interpolated to obtain daily values of PNCa (needed in Eq. [9]). Daily LAI values—needed in Eq. [8] and in Eq. [9] to obtain PNCc using the approach proposed by Confalonieri et al. (2011a)—were instead simulated using WARM (Confalonieri et al., 2009) after forcing the model to fit observations for all the available variables (LAI, AGB, and biomass of the different plant organs). The daily values for PNCa and LAI were derived using these procedures because the collection of daily measures using destructive methods would have led to the need for a total number of plants per plot which would have been incoherent with a greenhouse experiment.

Calibration of the parameters of the base model (Eq. [5]) was performed using the data collected in 2010 from the treatment L0–N0–S0 (no floodwater, no N luxury consumption, low plant density); data collected in 2011 from the same treatment were used for validation. Parameters of the models for the effect of agronomic practices were calibrated using the 2010 data from the respective “pure” treatments (e.g., parameters of the model for the effect of floodwater were calibrated using

data from treatment L1-N0-S0 [flooded conditions]) to prevent interferences from other experimental factors. This enabled isolation of the treatments effect and coherent calibration of the parameters involved in the simulated processes. The remaining data were used for validation.

The agreement between measured and simulated data was evaluated using RRMSE (0 to $+\infty$, best model performance when 0%), Nash and Sutcliffe modeling efficiency (EF; from $-\infty$ to 1, the closer to 1, the better the model; if negative, the average of measured values is a better predictor than the model), coefficient of residual mass (CRM; Loague and Green, 1991; $-\infty$ to $+\infty$, best at CRM = 0; if positive, indicates model underestimation, conversely for a negative value). Parameters of the linear regression equation between measured and simulated values were also calculated. To evaluate whether the increase in complexity of the base model proposed in this study (Eq. [5]) compared with that proposed by Confalonieri et al. (2011b) (Eq. [1]) was reasonably counterbalanced by a significant increase in accuracy, we used the Akaike Information Criterion (AIC; Akaike, 1974; $-\infty$ to $+\infty$, optimum = $-\infty$; Eq. [10]), based on the concept of information entropy:

$$AIC = n \times \log(\text{MSE}) + 2T \quad [10]$$

where n is the number of observed–simulated pairs, MSE is the mean square error, and T is the number of inputs in the model.

RESULTS

Experimental Results

The experimental factor with the largest effect on the plant elongation rate was the floodwater level (Fig. 1c and d): the related differences in PH were always significant ($p < 0.05$) in 2010 and after 6 June in 2011. Nitrogen fertilization led to similar results, although the differences between treatments were, in this case, less important (Fig. 1e and f), with significant differences observed after 3 May in 2010 and in four measurement events in 2011 (7, 25, and 28 July). Indeed, for N fertilization in 2011, differences were significant mainly because of the limited variability among replicates (error bars in Fig. 1 represent one standard deviation) since the treatment had little impact on the considered variable in the second year. The third factor (i.e., sowing density) led to significant differences only in one measurement event in 2010 (14 June) and 2011 (7 July). Interactions among factors were never significant, with the only exceptions represented by sowing density \times floodwater level on 16 June 2011, and by sowing density \times N fertilization on 21 June 2010.

Integration of Base and Impact Models, Parameterization, and Evaluation

Since ANOVA revealed that the effect of plant density was not significant, we avoided introducing the submodel presented in Eq. [8] in the whole model for management effect on PH. According to ANOVA, the effects of the

interaction among factors also were not significant. This made it possible to consider the factors as additive. These two considerations led to the model structure presented in Eq. [11]:

$$\text{PH}(\text{WL}, N)_i = \text{PH}_i + [\text{PH}(\text{WL})_i - \text{PH}_i] + [\text{PH}(N)_i - \text{PH}_i] \quad [11]$$

Combining Eq. [11] with Eq. [5, 6, 7, and 9], it is possible to obtain the whole model for the simulation of the management effect on PH:

$$\text{PH}_i = \begin{cases} \frac{\text{PNCa}_i}{\text{PNCc}_i} \left[\frac{\text{PH}_{\max} \times \sum_{i=\text{Eday}}^{\text{today}} (\text{Pstems}_i \times \text{Tf}_i)}{\text{SSA} \times \text{SBh} \times 100} + \text{lh}_i \right] \\ + \beta \left[\frac{\text{WL}_i}{\frac{\text{PH}_{\max} \times \sum_{i=\text{Eday}}^{\text{today}} (\text{Pstems}_i \times \text{Tf}_i)}{\text{SSA} \times \text{SBh} \times 100} + \text{lh}_i} \right] & \text{DVS}_2 < \text{DVS}_i \leq \text{DVS}_3 \\ \frac{\text{PNCa}_i}{\text{PNCc}_i} \left[\frac{\text{PH}_{\max} \times \sum_{i=\text{Eday}}^{\text{today}} (\text{Pstems}_i \times \text{Tf}_i)}{\text{SSA} \times \text{SBh} \times 100} \right] \\ + \beta \left[\frac{\text{WL}_i}{\frac{\text{PH}_{\max} \times \sum_{i=\text{Eday}}^{\text{today}} (\text{Pstems}_i \times \text{Tf}_i)}{\text{SSA} \times \text{SBh} \times 100}} \right] & \text{otherwise} \end{cases} \quad [12]$$

The parameter PH_{\max} was set to 40 cm, coherently with the cultivar features and with the cultivation of rice under growth chambers and greenhouse conditions (Ohnishi et al., 2011) that led to a reduction of the maximum PH values observed for the treatment L0-N0-S0 in both years (Fig. 1a and 1b). The values used for SSA ($2 \text{ m}^2 \text{ kg}^{-1}$) and SBh (0.2 kg m^{-2}) are coherent, respectively, with what was proposed by Van Diepen et al. (1988) and measured by, for example, Bouman and van Laar (2006); whereas the final value of τ and β were set to 0.33 (average tiller number in 2010 experiment was three) and to 0.17 (calibrated), respectively.

The values assigned to the parameters of the Lockhart equation for mechanohydraulic cell growth are consistent with values normally found in literature: the value of $\Delta\Psi$ (0.02 MPa), φ ($2.85 \text{ MPa}^{-1} \text{ d}^{-1}$) and L ($25 \text{ MPa}^{-1} \text{ d}^{-1}$) are within the range of those measured by Cosgrove (1985), whereas the value used for $P - Y$ (0.025 MPa) is coherent with what was reported by Cosgrove (1987). Given the sensitivity of Eq. [4] to φ , $\Delta\Psi$, and $P - Y$, it is suggested to avoid changing the values proposed without strong evidence.

Table 1 and Fig. 1a and b show the agreement between observations for treatment L0-N0-D0 and data simulated using the base models proposed by Confalonieri et al. (2011b) (dotted line) and developed during this study (Eq. [5]) (continuous line) (2010 and 2011 datasets, respectively, referring to calibration and validation).

Table 1. Indices of agreement between measured plant height and simulation results. EF: modeling efficiency; CRM: coefficient of residual mass. Datasets used for calibration are in italics.

Treatment [†]	Year	Model [‡]	RRMSE [§]	EF [¶]	CRM [#]	Slope	Intercept	R ²
L0-N0	<i>2010</i>	<i>C</i>	16.03	0.72	-0.10	0.74	3.86	0.94
	2011	C	31.10	-1.02	-0.20	0.47	8.08	0.86
	<i>2010</i>	<i>T</i>	4.23	0.98	-0.01	0.99	-0.15	0.98
	2011	T	9.06	0.83	-0.04	0.82	2.77	0.91
L1-N0	<i>2010</i>	<i>WL</i>	7.42	0.95	-0.02	1.02	-0.94	0.95
	2011	WL	11.52	0.81	-0.06	0.87	1.90	0.88
L0-N1	<i>2010</i>	<i>N</i>	7.12	0.94	0.01	0.92	1.89	0.94
	2011	N	12.41	0.73	-0.10	0.85	1.19	0.93
L1-N1	2010	WLN	7.44	0.95	0.04	1.08	-1.01	0.97
	2011	WLN	11.07	0.87	0.01	1.08	-1.70	0.87

[†] L0, saturated soil with floodwater level = 0 cm; L1, floodwater level = 8 cm before the third leaf stage, 15 cm later; N0, 70 kg N ha⁻¹; N1, 150 kg N ha⁻¹.

[‡] C, plant height model proposed by Confalonieri et al. (2011b); T, plant height model developed in this study; WL, T + model for the effect of floodwater level; N, T + model for the effect of N luxury consumption; WLN, T + models for the effect of floodwater level and N luxury consumption.

[§] RRMSE, relative root mean square error.

[¶] EF, modeling efficiency.

[#] CRM, coefficient of residual mass.

As expected, the two models presented the same behavior until the beginning of tillering. During the following period, only the model proposed in this study was able to correctly reproduce the decrease in PH due to the allocation of resources to the new pseudoculms and to relative root apparatus. Even the high increase in PH during the stem elongation phase is correctly reproduced by the new approach, though this effect is not evident in 2011, since problems with the thermal regulation system in the greenhouse after mid-July partly affected the dynamics of crop growth. The indices of agreement confirmed positive performance of the approach proposed in this study (Table 1), with near optimum values for all metrics.

The models for the effect of submergence (Fig. 1c and d) and for N luxury consumption (Fig. 1e and f) made it possible to reproduce the impact of both factors on the investigated variable for both the calibration (2010) and validation datasets (2011), though, for the former, the values of the performance metrics were always slightly better. In any case, RRMSE values ranged between 7.42% (calibration) and 11.52% (validation) for the effect of submergence and between 7.12% (calibration) and 12.41% (validation) for the effect of N luxury consumption; EF was always higher than 0.73 (0.95 and 0.94 for the calibration datasets; 0.81 and 0.73 for validation). These results allowed the models for the effects of the two agronomic practices to be considered satisfactory when isolated.

When the complete model (Eq. [12]) was tested using the data from the treatment resulting from the combination of submergence and N luxury consumption, results (Fig. 1g and h) highlighted good capability of the model to reproduce all the processes involved, including the additive effect of the two experimental factors. Although the lower quality of the 2011 datasets led to achieving better results for 2010, the comparison of measured and

simulated PH values always led to satisfactory values for the agreement metrics (Table 1).

Contrary to what was observed for the Confalonieri et al. (2011b) model, the approaches proposed in this study did not present any relevant under- or overestimation, with CRM values always very close to zero (Table 1).

DISCUSSION

As expected, rice was affected by the greenhouse conditions, with root apparatus limited by the volume of the plastic pots that led to a reduction in plant size compared with what is normally observed under field conditions (Ohnishi et al., 2011). This led to observed maximum PH values (measured at the upper leaf auricles) ranging from 24 cm (Fig. 1b) to 50 cm (Fig. 1g) according to the years and treatments, whereas the cultivar used normally exceeds 60 cm under field conditions.

Although the new base model for plant elongation presents a higher degree of complexity compared with the more simplified approach proposed by Confalonieri et al. (2011b), the better performances achieved fully justify its adoption. The values of AIC (Akaike, 1974) calculated for the model proposed in this study (32 and 24 respectively considering the total number of input needed by the model and just the number of editable parameters) are indeed decidedly lower than the corresponding ones achieved by the Confalonieri et al. (2011b) approach (107 and 103). The new approach was coupled with specific models for the impact of floodwater level and N luxury consumption, and results demonstrated the suitability of the complete model in reproducing the main processes involved with rice plant elongation. However, the complete model (i.e., including the effects of water management and N fertilization) should be considered as valid within the range of conditions explored during the experiments used to derive and test it. Indeed, although

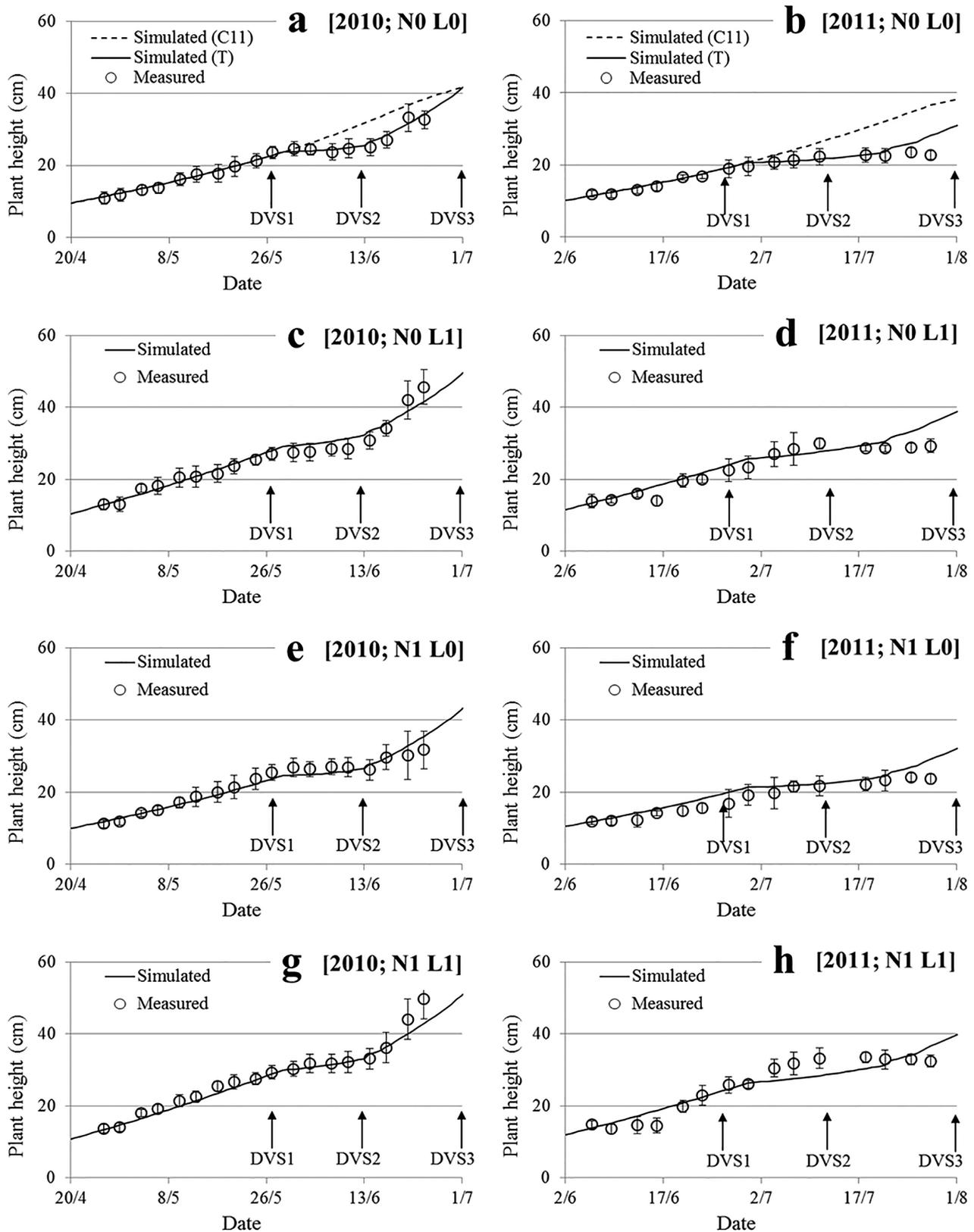


Figure 1. Comparison between measured and simulated plant height values; (a) and (b): saturated soil without submergence (L0), no N luxury consumption (NO) and low plant density; continuous and dotted lines refers, respectively, to the model developed in this study and to the one proposed by Confalonieri et al. (2011b); (c) and (d): flooding conditions (L1), NO, low plant density; (e) and (f): N luxury consumption (N1), L0, low plant density; (g) and (h): L1, N1, averaged for low and high plant densities; (a), (c), and (e) were used for calibration, the others for validation. Error bars correspond to the standard deviations calculated on the three replicates for each treatment and measuring date.

the amount of N provided to the plants that received the largest dose (150 kg N ha⁻¹) was high for nondrained pots, it may not have been enough to maximize the effect of N luxury consumption on elongation rate. Moreover, the sowing density used to generate intraspecific competition for light (500 seeds m⁻²) was probably insufficient—under greenhouse-pot conditions—to lead the phytochrome to perceive self-shading. This last consideration is supported, again, by the effect of pot volume on root apparatus, which in turn prevented the full expansion of the canopy (Ohnishi et al., 2011) and was likely to have limited intraspecific competition for light interception.

Although further research is needed to evaluate the approaches proposed in this study under field conditions, the inclusion of plant height models in cropping system simulators—other than representing a step forward in the formalization of knowledge compared with simplistic approaches (e.g., Kotera and Nawata, 2007)—should be considered crucial for many reasons. The simulation of the impact of agronomic practices on the plant elongation rate would indeed allow the comparison of management scenarios dealing, in the case of rice, with a variety of important processes. An example is provided by scenario analyses aimed at optimizing water management while accounting for its effect on temperature, leaf wetness (Luo and Goudriaan, 1999), greenhouse gas emissions (Ku wagata et al., 2008), crop-weed competition (Kropff and Van Laar, 1993), and susceptibility to lodging (Street et al., 1986). Moreover, in light of the interest of geneticists in aspects involved with plant height (e.g., Ishimaru et al., 2004), the availability of detailed models for plant elongation would decidedly increase the suitability of crop simulators for *in silico* ideotyping studies.

Besides the scientific results, this study—performed with students of a cropping systems MS course and following previous experiences (e.g., Confalonieri et al., 2011a; Graves et al., 2002)—further demonstrated the key role of models in education (Van Dam et al., 1997).

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