Water, Nitrogen and Plant Density Affect the Response of Leaf Appearance of Direct Seeded Rice to Thermal Time

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Abstract: Field experiments were conducted in the Ebro Delta area (Spain), from 2007 to 2009 with two rice varieties: Gleva and Tebre. The experimental treatments included a series of seed rates, two different water management systems and two different nitrogen fertilization times. The number of leaves on the main stems and their emergence time were periodically tagged. The results indicated that the final leaf number on the main stems in the two rice varieties was quite stable over a three-year period despite of the differences in their respective growth cycles. Interaction between nitrogen fertilization and water management influenced the final leaf number on the main stems. Plant density also had a significant influence on the rate of leaf appearance by extending the phyllochron and postponing the onset of intraspecific competition after the emergence of the 7th leaf on the main stems. Final leaf number on the main stems was negatively related to plant density. A relationship between leaf appearance and thermal time was established with a strong nonlinear function. In direct-seeded rice, the length of the phyllochron increases exponentially in line with the advance of plant development. A general model, derived from 2-year experimental data, was developed and satisfactorily validated; it had a root mean square error of 0.3 leaf. An exponential model can be used to predict leaf emergence in direct-seeded rice.

Key words: rice; leaf appearance; nitrogen fertilizer; water management; plant density

Leaf emergence dynamics have been reported to offer a very useful tool for describing, modelling and understanding the growth and development of grasses and aspects such as leaf number and appearance rate, which are important aspects of their development. Here, the phyllochron, which is the time interval between the appearance of successive leaves on the main stem (Wilhelm and McMaster, 1995), is used to describe leaf emergence dynamics in rice.

Leaf appearance is closely linked with other aspects of plant development, such as internode elongation, booting and flowering (Counce et al, 2000), tillering (Kirby et al, 1985; Miyamoto et al, 2004), root growth and panicle development (Ellis et al, 1993; Nemoto et al, 1995; Lee et al, 2001; Tivet et al, 2001; Jaffuel and Dauzat, 2005). Knowledge of the phyllochron is therefore useful for formulating models and for characterising plant development and determining when to apply management practices that depend on the crop developmental stage (Petrócz and Matuz, 2002).

Experiments under controlled conditions show that the phyllochron is affected by genotype as well as by day length and temperature (Itoh et al, 2006). Day length usually affects the total leaf number in rice through its influence on growth duration and vegetative development (Lee et al, 2001). Temperature is the principal environmental determinant of rice leaf appearance (Yin and Kropff, 1996).

Modelling is useful for predicting leaf appearance in different crops. Most models are based on the response of the phyllochron to day length and temperature, whereas other environmental factors, such as water, salinity and light intensity, are considered as minor importance (Wilhelm and McMaster, 1995; McMaster, 2005; Jamieson et al, 2008). McMaster and Wilhelm (1995) evaluated the accuracy of nine different equations to predict phyllochron of wheat under field conditions.
conditions. The result of this comparative study was that the models with the best adjustments were considered to be those proposed by Baker (1980) and Kirby (1987), both cited in McMaster and Wilhelm (1995), which assumed a constant phyllochron throughout the growth cycle. McMaster et al (2003) observed that, under field conditions, phyllochron performance in plants of spring wheat could be described by both models. Linear relationships between leaf appearance in calendar or thermal time have been reported in various crops (Cao and Moss, 1989; Ellis et al, 1993; McMaster et al, 2003). Variations in the phyllochron over the rice cycles have also been described under both field and growth chamber conditions (Gao et al, 1992; Yin and Kropff, 1996; Sie et al, 1998; Streck et al, 2008). However, the combination of water, nitrogen and plant density affecting the response of leaf appearance to thermal time in direct-seeded rice under field conditions is lack of knowledge.

The objective of this research was to develop a methodology to predict the rate of leaf appearance in direct-seeded rice under field conditions in a Mediterranean climate and to analyze the factors that influence the phyllochron.

**MATERIALS AND METHODS**

**Experimental design**

Two different field experiments were carried out from 2007 to 2009 in experimental fields belonging to the IRTA (Agriculture and Food Research Institute) in the Ebro Delta area (Tarragona, Spain) (40.71° N; 0.63° E). The two experiments, although physically separated in independent units, were located next to each other and were conducted at the same time. The general crop management practices and measurements applied to the plants were therefore the same.

**Experiment 1**

Experiment 1 included three factors: water management, nitrogen fertilization and sowing rate. The rice variety used was Gleva, a japonica rice with medium grain size and a growth duration of 120 d, which is widely grown in the Ebro Delta area, Spain.

In 2007 and 2008, two seed application rates were used, whereas only one was applied in 2009. The fields were organized in split-plot (2007–2008) and randomized block (2009) designs with four replicates. The main plots included factorial combinations of water and nitrogen levels, and the subplots included sowing rate. The main plot and subplot areas were 100 m² and 45 m², respectively.

Two water management systems were compared: a standard water management (SWM) system, which is usually practiced in the area, and an alternate wetting and drying (AWD) system. Both treatments were applied during tillering (corresponding to the 3.5- to 10-leaf stages on the main stems). The SWM consisted of a 7-cm water layer and AWD was in a shallow intermittent layer of 3-cm deep water from the 4- to 7-leaf stages and of a 5-cm deep water layer from the 7- to 10-leaf stages.

The nitrogen treatments focused on the application time during the tillering stage: either early tillering fertilization at the 3.5-leaf stage (N4L) or late tillering fertilization at the 8.5-leaf stage (N8L).

Two sowing rates: 160 and 210 kg seeds per ha were studied. According to the 1000-grain weight (36.33 g), these corresponded to seed densities of 440.0 and 577.4 seeds/m², respectively.

**Experiment 2**

This experiment included two factors: variety and sowing rate.

Two rice varieties with different growth duration, Gleva (120 d) and Tebre (140 d), which are widely grown in the Ebro Delta area, Spain, were compared in 2007 and 2008. Experiments were designed in a split-plot with four replicates. The main plots included the variety, and the sowing rate was on the subplot. The main plot area was 100 m² and the subplot areas were 13.5 m² in 2007 and 22.0 m² in 2008.

In 2007, six sowing rates were used: 60, 110, 160, 210, 260 and 310 kg/hm². In 2008, the number of sowing rates was reduced to four, in term of 80, 160, 240 and 320 kg/hm² (Table 1). The seed density resulting from each sowing rate was estimated through the seed weight of each year and variety.

**Crop management**

Field preparation started in February using the common local practices. A total amount of 120 kg/hm² of nitrogen fertilizer was applied, split into three applications of 40 kg/hm². The first consisted of the application and the incorporation of urea into the soil before sowing. For the second and third splits, ammonium sulphate was applied as topdressing at the tillering and panicle initiation (PI) stages. A total of 45 kg/hm² of potassium (K₂O) and 45 kg/hm² of phosphorus (P₂O₅) were applied also following the common practices of the area.

The pre-germinated seeds were then sown by hand.
The seeds were carefully scattered by trained people in order to get an even distribution. The water level from sowing to the 4-leaf stage was maintained at approximately 1 cm in order to promote seedling establishment. From the 10-leaf stage onwards, the water level was increased and then maintained at approximately 8 cm. In the Experiment 2, an AWD irrigation system was applied.

Crop protection chemicals were used to minimize pests and diseases. Weeds were controlled either by herbicide or by hand-weeding. It is relevant to highlight the lower seedling establishment recorded in the Experiments 1 and 2 in 2007 (31%) than in 2008 (60%), which was due to high levels of the chironomid pest resulted in low plant densities. Rates of seedling mortality were high despite insecticide (Malathion, 50%) sprayings.

Data collection

Leaf emergence on the main stems was monitored for 10 plants per subplot, with three replicates per treatment. These plants were identified and tagged with plastic labels in the both experiments. Leaf number on the main stems was monitored and recorded at 4- to 5-day intervals, starting at the 3.5-leaf stage when the seedlings were established. Haun’s method (Haun, 1973) was used to record leaf development. The Haun stage describes the number of leaves that have been produced on a shoot. The leaf stage is calculated by taking the number of fully developed leaves plus the decimal fraction of the length of the latest leaf to have developed. The decimal fraction begins with the appearance of each leaf and ends with the appearance of the next one (Haun, 1973).

Climate data were obtained from the meteorological station of the Catalonian Meteorological Service located close to the field experiments. The soil and water temperatures under the different water management systems were also registered. In the Experiment 1, temperature sensors (model TMC6-HD) with data loggers (HOBO® U12) were installed to monitor the three replications on the water management treatment plots. On each plot, two sensors were installed: at a depth of 3 cm to register soil temperature and at the soil surface to record water temperature. Data were recorded every 2 h throughout rice crop growth.

Data analysis

The final leaf numbers of the tagged plants on each plot were averaged and analyzed. For analysis of this variable over the different years, the blocks and years were assumed to cause random effects. The factors were analyzed within each year because of the different patterns observed in the Experiment 1 and also because of the different sowing rate treatments in the Experiment 2 in 2007 and 2008.

Leaf appearance was described by regressing leaf number against thermal time; the last thermal time was obtained by converting dates to growing degree days (GDD) from the emergence of the seedlings. Air growing degree days (ºCd) were calculated according to the Method 1 of McMaster et al (2003).

\[ GDD = \frac{(T_{\text{max}} - T_{\text{min}})}{2} - T_{\text{base}} \]  

Where \( GDD \) is the growing degree days and \( T \) is the temperature. \( T_{\text{base}} \) is a base temperature of 8 ºC (Yin and Kropff, 1996). Exponential growth functions were transformed into linear functions, for a linear regression analysis, using the equation:

\[ y = ae^{bx} \rightarrow \ln y = \ln a + bx \]  

The SAS statistical package (SAS 9.1) was used for data analysis. Linear regression was analyzed using the REG procedure.

Analysis of variance (ANOVA) was made using the MIXED and ANOVA procedures and mean separation tests were performed using the adjusted Tukey’s least significant difference (LSD) test.

Given by ºCd/leaf, the phyllochron is defined as the interval between the emergence of successive leaves on a stem (Wilhelm and McMaster, 1995). It was estimated by calculating the difference in accumulated thermal time between subsequent leaves.

The model for predicting leaf appearance was based on an estimated equation derived from the experimental data in 2007 and 2008. The simulation was applied from the 4th leaf age of the plants. Predicted data were contrasted with observed data in 2009. The root mean square error (RMSE) was used to validate the model. In order to improve the accuracy of the validation
method, the mean square error (MSE) was calculated and divided into the systematic (MSEs) and unsystematic or random error (MSEu) terms. These calculations were made following Xue et al (2004). A necessary pre-condition of a ‘good’ model is that the MSEs is low and the MSEu is close to the MSE.

RESULTS

Climatic data

Water and soil temperatures during leaf ontogeny in 2007 and 2008 were averaged and the influence of water management was analyzed. The average water and soil temperatures were the same (25.6 °C). The soil temperature under SWM was repeatedly higher (not significant) than that under AWD, with mean values of 25.8 °C and 25.4 °C, respectively.

Final leaf number

In 2007 and 2008, the final number of leaves on the main stems of Gleva ranged from 13.0 to 13.4, with no significant differences between years (Table 2). The final leaf number in 2007 showed a wider range of values, which was probably a result of greater heterogeneity in plant status caused by the effects of the chironomid pest at the seedling stage. Chironomid pest damages to rice plants in the Ebro Delta consisted of fewer germinated seeds and weak seedling growth and development (Ferrer and Tomàs, 2001, unpublished annual technical report for the Rice Farmers Association in Ebro Delta rice growing area). No significant differences were observed between the two varieties studied, although Tebre repeatedly produced more leaves (13.8) than Gleva (13.0).

On averaging the data from the Experiment 1 over the two years (Table 3), the plants under SWM produced significantly more leaves (13.3) than those under AWD (12.8). Within each year, a significant response was only found in 2007 (13.1 and 12.3 leaves under SWM and AWD, respectively).

In the Experiment 1, sowing rates did not affect the final leaf number or any of the other variables considered. All the data presented here therefore corresponded to the averages for the two treatments.

The response of the final leaf number to the water × nitrogen interaction was significant (Table 3). The plants in the system which combines alternate wetting and drying irrigation and late-tillering nitrogen fertilization (AWD-N8L) produced fewer leaves (12.6) than those in deep standing water and late nitrogen fertilization (SWM-N8L) (13.6 leaves). This trend was found in both years.

The final leaf number on the main stems was linearly and negatively related to plant density (Fig. 1). In 2007, the values recorded ranged from 13.8 to 12.5 leaves, corresponding to the plant densities of 53 and 250 plants/m², respectively; and from 13.8 to 13.0 leaves corresponding to the plant densities of 157 and 480 plants/m², respectively, in 2008.

Leaf emergence dynamics

As shown in Fig. 2, Gleva leaf emergence dynamics followed an exponential function:

\[ GDD = a e^{bLN} \]  

(3)

Where, GDD is the sum of the growing degree days from the time of seedling emergence; LN is the leaf number (Haun stage); a is the intercept point; and b is the exponent.

The estimation of a single equation to describe leaf appearance dynamics showed a high level of adjustment (\( R^2 = 0.99 \)). The estimated values were 82.28 ± 1.02

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**Table 2. Final leaf number for Gleva variety in 2007 and 2008.**

<table>
<thead>
<tr>
<th>Year</th>
<th>Average ± a</th>
<th>Range</th>
<th>Standard deviation (2 df)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>13.0 ± 0.6</td>
<td>0.677</td>
<td>0.3722</td>
</tr>
<tr>
<td>2008</td>
<td>13.4 ± 0.16</td>
<td>0.163</td>
<td>0.0828</td>
</tr>
</tbody>
</table>

Two-year data from Experiment 1 was pooled and averaged in order to find the general trend for Gleva grown in rice fields in the Ebro Delta, Spain. The heterogeneity observed in 2007 was probably due to the heterogeneity of the plant status and was related to the problems of crop establishment caused by the chironomid pest.

* The same letter after the data means no significant difference (LSD, \( P < 0.05 \)); df, Degrees of freedom.

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**Table 3. Final leaf number in water and water × nitrogen treatments.**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Water × nitrogen</th>
<th>SED (6 df)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SWM-N4L</td>
<td>SWM-N8L</td>
</tr>
<tr>
<td>Leaf number</td>
<td>13.0 ± 0.6</td>
<td>13.6 ± 0.5</td>
</tr>
</tbody>
</table>

*a Each value represents the mean of the least square ± SE of the mean for two-year averaged values. Significant effects are indicated by * at \( P < 0.05 \).

The data correspond to the total number of leaves produced in Gleva, considering water × nitrogen effects. In the Experiment 1, data from 2007 and 2008 were pooled. SWM, Standing water management at a depth of 7 cm; AWD, Alternate wetting and drying at depths of 3 cm and 5 cm until mid-tillering and onwards, respectively; N4L, Nitrogen fertilization at the 3.5-leaf stage; N8L, Nitrogen fertilization at the 8.5-leaf stage; SED, Standard error of the least square difference (LSD, \( a = 0.05 \)); df, Degrees of freedom of the error.
and 0.19 ± 0.003 for the a and b coefficients, respectively (eq. 3), at the 0.05 significance level (Fig. 2). According to these results, from the 4th leaf stage to the flag leaf, phyllochron increased exponentially from 30.4 °Cd to 168 °Cd.

With the aim of finding the most useful results for technology transfer to farmers, we also evaluated the fit of the dynamics of leaf emergence to a linear function (eq. 4) to test whether the phyllochron could be considered constant during leaf ontogeny. The phyllochron would be given by the slope (b parameter) of the equation:

\[ GDD = a + b'LN \]  

(4)

The results showed a good fit for the observed data to a linear regression \( (R^2 = 0.91) \) and an estimated \( b' \) coefficient of \( 85.86 \pm 3.47 \) °Cd/leaf \( (P < 0.0001, \alpha = 0.05) \). It means that, for practical purposes, we could consider a linear response between leaf emergence and thermal time.

No genotypic response of leaf emergence dynamics was observed. However, flag leaf emergence in Tebre occurred 117.9 °Cd in 2007 and 99.2 °Cd in 2008 later than in Gleva, because of the longer growth duration of Tebre. Regression analysis provided the same exponential equation for both varieties, with a high level of adjustment \( (R^2 = 0.99) \) (Fig. 3).

In reference to water management, slight differences in leaf emergence dynamics were found between the two irrigation systems. SWM presented higher rates of development than AWD, which could be explained by slight differences in water temperature under the two different irrigation systems. Additionally, the plants fertilized at the late tillering stage showed slight differences in their leaf dynamics between the two irrigation regimes, with lower rates being associated with intermittent watering (Fig. 4).

Plant density also had a significant effect on the rate of leaf appearance, by lengthening the phyllochron (Fig. 5). In 2007, the estimated phyllochron values were within the range of 30.4 to 154 °Cd/leaf for the lowest plant density and from 33.5 to 221.9 °Cd/leaf for the highest plant density. In 2008, the phyllochron values ranged from 29.3 to 153.7 °Cd/leaf and from 32 to 193.3 °Cd/leaf for plant densities of 157 and 480 plants/m², respectively. The onset of plant competition was analyzed by defining the moment when plants under different plant densities showed differences in leaf numbers (Table 4). Plant competition was first detected after the emergence of the 8th leaf (589 °Cd after seedling emergence) and the 7th leaf (360 °Cd after
seedling emergence) in 2007 and 2008, respectively.

**Model validation**

Experimental data from 2009 was used to validate the model developed based on the 2007–2008 data for the leaf appearance dynamics. The model values for the \( a \) and \( b \) coefficients were 82.28 and 0.19, respectively (eq. 3). The predicted leaf number was plotted against the observed value in 2009 (Fig. 6); this resulted in a good performance by the model, as indicated by the RMSE (0.295 leaves). The estimated slope and the value of the determination coefficient (0.61 ± 0.01 and 1.00, respectively) also indicated high levels of accuracy in the predictions. In order to improve the precision of the method of validation, we calculated the percentage of the systematic and unsystematic errors. The results obtained showed that the MSE, whose value was 0.087, contained a 98.2% \((MSEs = 0.085)\) systematic error.
and a 2.8% unsystematic error (MSEu = 0.002). High levels of unsystematic error are desirable (Xue et al., 2004). Hence, the good levels of accuracy of the model indicated by the low RMSE and high determination coefficient were in part counteracted by the low unsystematic error.

**DISCUSSION**

The sowing dates and the average temperatures registered during leaf ontogeny were almost the same for both years, which indicates that the crops grew under almost the same environmental conditions in 2007 and 2008.

**Final leaf number and leaf emergence dynamics**

**General performance**

There were low variations in the final leaf number on the main stems of Gleva in both years. This agrees with the report by Yin and Kropff (1996), whose work showed that the variation in leaf number was small for constant temperature treatments and for normal diurnally fluctuating temperatures.

The relationship between leaf appearance and thermal time is described by an exponential equation of the form \( GDD = ae^{bLN} \) (where \( GDD \) is the growing degree days and \( LN \) is the leaf number) with high \( R^2 \) values for both years. The coefficient \( b \) measures the response of leaf appearance to the different levels of the factors studied: smaller \( b \) coefficient means higher rate of leaf emergence. The values of the \( b \) coefficient were very stable, ranging from 0.18 to 0.19, with only slight variations under the different growing conditions. Hence, the exponential function described how the phyllochron becomes progressively longer from the juvenile to the adult plant (Yin and Kropff, 1996).

Variations of the phyllochron over the rice leaf ontogeny have been described by other studies. Jaffuel and Dauzat (2005) also reported a wide range of phyllochron values. De Raissac et al (2004) described those variations through a bi-linear function whereas Yin and Kropff (1996) and Itoh et al (2006) reported a power law and quartic polynomial equations, respectively. In contrast, Ellis et al (1993) found that leaf appearance was linearly related to thermal time. Unlike the last, our results showed a loss of precision of the lineal model for leaf prediction (data not shown) that led us to reject it.

**Factors influencing final leaf number and leaf appearance dynamics**

**Variety**

The Tebre and Gleva varieties followed the same exponential pattern of leaf emergence and only slightly differed in the final leaf number, which was systematically higher in Tebre. The longer growth duration of Tebre (140 d as opposed to 120 d of Gleva) may have caused such variation (Slafer et al, 1994; Streck et al, 2006, 2009). Nevertheless, other studies have pointed out the influence of the genotype on leaf development (Streck et al, 2008). The low variability in the type of rice varieties grown in the Ebro Delta area would lead us to extend these results to other varieties grown in the same area. However, further studies on varietal performance should be carried out to confirm this.

**Water and nitrogen management**

Water management affected the phyllochron through its effect on the temperature, since leaf appearance is controlled by the temperature near the apical meristem (Ritchie and NeSmith, 1991). Consequently, the slightly higher leaf emergence rates recorded in SWM resulted in more leaves produced on the main stems. The influence of water management on final leaf number was probably due to its effect on water temperature, but not a result of the irrigation system *per se*. This finding was in agreement with Fukuda and Iwanami (2006) for rice and with Miglietta (1991) for wheat.

The slight lower rate of leaf appearance as well as the subsequent decline in the total number of leaves observed in the intermittent irrigation system and later fertilization (AWD-N8L) could be a response to a nitrogen deficiency caused by the added effects of 1) a loss of nitrogen through denitrification due to the watering system used and 2) the lack of nitrogen supply at the early plant developmental stage.

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[Fig. 6. Validation of the model for leaf emergence dynamics: observed vs. predicted leaf age.]

Observed leaf age corresponding to experimental data for 2009 and predicted leaf age given by the estimated model \( GDD = 82.28e^{0.19LN} \) (\( R^2 = 0.9888, P < 0.0001, a = 0.005 \)). The model was derived from the data relating to Experiment 1 in 2007 and 2008. The solid line is 1:1.
Nitrification takes place under aerated or drained conditions, producing nitrates that will be subsequently reduced to N₂ and N₂O through denitrification. In this sense, Sah and Mikkelsen (1983) found that intermittent flooding created conditions which promoted additional nitrogen losses due to nitrification and denitrification processes. Moreover, they observed that nitrogen uptake by rice plants and the nitrogen use efficiency (NUE) were slightly reduced in alternating flooded-saturated treatments. Therefore, the use of AWD requires more precision in the application of nitrogen fertilization. Our study highlights the fact that, in the study of water saving technologies such as AWD, special attention needs to be taken in reference to the timing of nitrogen fertilization and, thus, the interaction between both factors should be considered.

**Plant density**

The rate of appearance of the upper leaves decreased with an increase in plant density, reducing the total number of leaves on the main stems as a response to competition (De Raïssac et al, 2004) after the middle vegetative growth stage. The plant density could have reduced the irradiance due to shading effects resulting in a decline in photosynthetic synthesis (Birch et al, 1998), which reduced the rate of leaf emergence (Wilhelm and McMaster, 1995; Birch et al, 1998). Higher plant densities could have altered the light quality (by transmitting and reflecting more far-red radiation within the canopy) and thereby affected the phyllochron (Barnes and Bugbee, 1991). There were, however, only slight differences in the b coefficient of the treatments for each year, despite the wide range of plant densities studied. The low phyllochron response to plant density may have been related to the total leaf number on the main stems of the variety and also to the late onset of competition. Differences in leaf emergence dynamics between treatments occurred after the emergence of more than 50% of the total leaf number. The accumulated differences between the treatments were therefore probably limited by time to the emergence of the flag leaf.

**Model validation**

Model validation was high, with an RMSE value of 0.3 leaf, this indicated that the exponential model using the thermal time approach could satisfactorily predict leaf development. However, the percentage of the systematic error was high. This suggests that more data should be used to construct the leaf development model to reduce the systematic component of the total error.

**CONCLUSIONS**

The good validation of the model based on the thermal time approach developed in this study shows that it could be useful for predicting leaf emergence. Leaf emergence dynamics strongly fit with an exponential function and this means that the time required for the emergence of subsequent leaves increases over time. Furthermore, the same type of function can be used under different growing conditions.

Our results showed that the total leaf number on the main stems of the Gleva variety was stable over the years. A variety with longer growth duration and higher rate of leaf emergence were followed by a larger final leaf number on the main stems but not statistically significant. Plant density decreased the rate of leaf appearance for later leaves and subsequently reduced the final leaf number. However, these differences were small and only noticeable under a wide range of plant densities. We therefore conclude that the final leaf number in rice plants is a relatively stable trait, as the variation observed was less than one leaf per plant.

The management practices studied here, which could also be used to control other crop growth processes, such as tillering, did not affect leaf appearance dynamics. This means that the same phyllochron pattern can be used under a wide range of conditions, this makes it an easy tool to quantify and describe rice development during growth. Given the good results obtained for its validation, the model developed in this study could be used to predict leaf emergence. This model offers rice farmers and technicians an opportunity to improve the precision and timing of the application of agricultural practices through the capacity of predicting crop development. Moreover, this model could provide the basis for further studies into rice plant modelling in direct seeded rice exploitations in Mediterranean environments.

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