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Article

Phenological Restriction of the Oryza (v3) Model

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Abstract

Photoperiod sensitivity affects the rice development cycle and its flowering. Crop simulation models, such as ORYZA (v3), use equations that depend on two main parameters calibrated by the user: sensitivity to photoperiod and minimum optimal photoperiod. Day length, determined by latitude and day of the year, also affects crop development. This study explores the interaction of these parameters in the ORYZA (v3) phenological model. When the optimum minimum photoperiod is shorter than the day length, photoperiod sensitivity delay or inhibit flowering. To ensure a proper simulation, these parameters need to be adjusted to avoid excessive prolongation of the vegetative phase. If calibrated incorrectly, or if let in constant low photoperiod conditions, the plant may remain in the vegetative state. The model presents challenges with cultivars that are highly sensitive to photoperiod in conditions where day length is constantly longer than the ideal minimum photoperiod. This situation may generate uninterpretable results and complicate the calibration of parameters via optimization algorithms. Therefore, it is crucial to properly adjust the optimal minimum photoperiod based on latitude and limit photoperiod sensitivity to ensure accurate and precise simulations of flowering.

Keywords: flowering, day length, photoperiod, parameter estimation, calibration.

Restrição Fenológica do Modelo Oryza (v3)

Resumo

A sensibilidade ao fotoperíodo influencia o ciclo de desenvolvimento do arroz, afetando o florescimento. Modelos de simulação de culturas, como o ORYZA (v3), utilizam equações que dependem de dois parâmetros principais, calibrados pelo usuário: sensibilidade ao fotoperíodo e fotoperíodo mínimo ideal. O comprimento do dia, determinado pela latitude e dia do ano, também influencia o desenvolvimento da cultura. Este estudo explora a interação desses parâmetros no modelo fenológico do ORYZA (v3). Quando o fotoperíodo mínimo ideal é menor que o comprimento do dia, a sensibilidade ao fotoperíodo pode atrasar ou inibir o florescimento. Para garantir a simulação correta, esses parâmetros precisam ser ajustados para evitar um prolongamento excessivo da fase vegetativa. Se calibrados incorretamente, ou em condições constantes de baixo fotoperíodo, a planta pode permanecer em estado vegetativo. O modelo apresenta dificuldades com cultivares altamente sensíveis ao fotoperíodo em condições onde o comprimento do dia é constantemente superior ao fotoperíodo mínimo ideal, o que pode gerar resultados não interpretáveis e complicar a calibração dos parâmetros via algoritmos de otimização. Portanto, é crucial ajustar adequadamente o fotoperíodo mínimo ideal com base na latitude e limitar a sensibilidade ao fotoperíodo para garantir simulações precisas e acuradas do florescimento.

Palavras-chave: florescimento, comprimento do dia, fotoperíodo, estimativa de parâmetros, calibração.

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1. Introduction

The network of genetic and biochemical processes that regulate flowering is complex. It depends on interactions between endogenous and environmental factors (Blümel *et al.*, 2015), mainly air temperature and day length (Song *et al.*, 2012), known as photoperiod (Runkle, 2002). Rice (*Oryza sativa* L.) mainly promotes its flowering through photoperiod (Lee and An, 2015; Song *et al.*, 2012). Rice is a quantitative short-day plant, but sensitivity to photoperiod depends on the cultivar. However, when the plant is exposed to a photoperiod shorter the ideal minimum and is at the appropriate age, flowering accelerates (Shim and Jang, 2020; Lee and An, 2015; Tsuji *et al.*, 2011).

Equations that calculate photoperiod for rice genotypes are widely used by process-based crop simulation models (CSM), such as CERES-Rice (Hoogenboom *et al.*, 2019) and ORYZA (v3) (Li *et al.*, 2017). Sensitivity to photoperiod affects the crop cycle, the end of the juvenile phase, and the continuity of its development stages, such as panicle formation, flowering and physiological maturity. These changes in crop cycle have significant effects on the physiological and morphological processes of the plant, including its structural growth and the allocation of resources to different plant parts. In the CSM ORYZA (v3), the equation that calculates the sensitivity of genotype to photoperiod has three parameters: photoperiod sensitivity (*PPSE*), minimum optimal photoperiod (*MOPP*), and day length (*DL*).

For cultivars less sensitive to photoperiod, air temperature determines phenological development in the ORYZA (v3) model. However, for more sensitive cultivars, the crop development rate (*DVS*) between the end of the basic vegetative development stage ($DVS = 0.40$) and the beginning of panicle formation ($DVS = 0.65$) is calculated by the accumulation of heat units over time (*TT*), *PPSE*, *MOPP* (Bouman *et al.*, 2001).

The *PPSE* ranges from 0 to 1, reflecting sensitivity to photoperiod. A value equal to 0 indicates that the plant is insensitive to photoperiod, while a value equal to 1 indicates that the *MOPP* must be shorter than or very close to *DL* for flowering to occur. Therefore, when applying the CSM ORYZA (v3), it is necessary to adjust the *PPSE* and *MOPP* (Bouman *et al.*, 2001). In most cases, *PPSE* is assigned values very close to 0, regardless of the genotype, environmental conditions, or management. This is partially justified in subtropical rice production regions in Latin America, where it is assumed that genotypes are insensitive or only slightly sensitive to photoperiod (Lorençoni *et al.*, 2010; Santos *et al.*, 2017; Duarte *et al.*, 2021). In some tropical regions, such as Southwest Asia, the use of photoperiod-sensitive genotypes as a management strategy is common. In this case, the *PPSE* is adjusted to values very close to 1 (Boling *et al.*, 2011; Sujariya *et al.*, 2023). Many studies omit information about the values and calibration methods of these parameters, or fix default values (Li *et al.*, 2020; Tan *et al.*, 2022, Yu *et al.*, 2023). Despite being a strategy to simplify parameterization in CSM depending on the purpose of its use, it is important to optimize the parameters that guide the calculation of photoperiod (van Oort *et al.*, 2011). *PPSE* adjustment is usually empirical and performed through trial and error so that simulated panicle beginning dates correspond as closely as possible to observed dates (Boling *et al.*, 2011). Empirical methods are useful, but they are hardly effective in optimizing hyperparameters of an equation in which there is a combinatorial analysis, for example. Due to advances in computational capacity, advanced techniques that use modern and efficient optimization algorithms for model parameterization can be applied easily (Tan *et al.*, 2022). However, it is necessary that the combinations of parameter values are appropriate to the model's assumptions and that their interactions allow the crop cycle to be completed.

This study aims to understand how *PPSE*, *MOPP*, and *DL* interact and affect the functioning of the ORYZA (v3) phenological model, especially under unfavorable photoperiodic conditions. We seek to describe the limitations of CSM photoperiod calculation equations and propose an efficient method to establish a range of values for these parameters, ensuring the simulation of flowering for Brazilian conditions.

2. Methodology

2.1. Model

In the CSM ORYZA (v3), potential *DVS* is calculated as a function of air temperature and photoperiod. However, in this CSM, water deficit is a limiting factor that affects *DVS* (Bouman *et al.*, 2001). In this study, which focuses on irrigated rice, we assume that there are no biotic and abiotic limitations to crop development. Thus, only air temperature and photoperiod affect *DVS*.

Thermal time (*TT*) is calculated based on daily temperatures considering that development linearly increases above a minimum basal temperature (*TBD*) up to an optimum temperature (*TOD*) and decreases up to reaching the maximum development temperature (*TMD*), beyond which development ceases.

Eq. (1) through Eq. (5) describe how *TT* is calculated:

$$T_d = \frac{T_{\min} + T_{\max}}{2} + \frac{T_{\max} - T_{\min}}{2}\cos(0.2618(h - 14)), \tag{1}$$

$$\text{Se } T_d \le TBD \text{ e } T_d \ge TMD : HUH = 0 \tag{2}$$

$$\text{Se } TBD < T_d \le TOD : \mathrm{HUH} = \frac{T_d - TBD}{24} \tag{3}$$

$$\text{Se } TOD < T_d < TMD: \text{HUH} = \frac{TOD - (T_d - TOD) \times \dfrac{TOD - TBD}{TMD - TOD}}{24} \quad (4)$$

$$TT = \sum_{h=1}^{24} HUH_h \quad (5)$$

where T_d is the daily temperature, $T_{\min}$ and $T_{\max}$ are the minimum and maximum temperature, respectively, h is the time of day and HUH is the hourly increase of air temperature.

According to daily weather conditions and rice variety characteristics, the CSM ORYZA (v3) assigns specific values of TT required to complete each phenological phase. This is done through a specific correction factor for each phenological phase and genotype over the TT accumulated on a given day. Thus, the vegetative phase requires a certain amount of TT to be completed. At this phase, the TT is corrected by the specific factor, called $DVRJ$ (development rate during the juvenile phase), as follows:

$$DVR_{DAYJ} = TT_{DAYJ} \times DVRJ \quad (6)$$

where $DAYJ$ is the Julian day and DVR is the crop development rate, which is added to the DVS on each simulation day. Thus, the phase change occurs when DVS reaches the specific value for the given phase. For the juvenile vegetative phase, the established DVS value is 0.4. From this value, the vegetative phase begins, which is sensitive to the photoperiod.

The most important phenological change is the transition from the vegetative to the reproductive phase. Between these two phases is the photoperiod-sensitive phase (DVS from 0.40 to 0.65). This phase determines the moment when the plant is sufficiently mature and prone to stimulation by photoperiod. At this point, the model simulates the DL from the astronomical day length ($DAYL$) plus 0.90 to consider the effect of low levels of solar radiation after sunset and before sunrise.

The DL is calculated as follows:

$$DEC = -\sin^{-1}\left(\sin(23.45 \times 0.017453292) \times \cos\left(\frac{2\pi \times (DAYJ + 10)}{365}\right)\right), \quad (7)$$

$$AOB = \tan(0.017453292 \times LAT) \times \tan(DEC), \quad (8)$$

$$DAYL = 12 \times \left(1 + \frac{2 \times \sin^{-1}(AOB)}{\pi}\right), \quad (9)$$

$$DL = DAYL + 0.9 \quad (10)$$

where DEC is the sun's declination angle, AOB is an auxiliary variable, and LAT is the latitude of the location.

The CSM compares the $MOPP$ to the DL under analysis. If it is short, a factor called $PPFAC$ assumes the value 1. If the DL is longer than the $MOPP$, the model applies the $PPSE$ parameter on the difference of $MOPP$ and DL to calculate the $PPFAC$:

$$PPFAC_{DAYJ} = 1 - (DL_{DAYJ} - MOPP) \times PPSE \quad (11)$$

$$PPFAC_{DAYJ} = min(1, max(0, PPFAC_{DAYJ})) \quad (12)$$

$PPFAC$, now modulated between 0 and 1, is used as a correction to calculate the DVR. A specific development rate for panicle initiation ($DVRI$) is also applied to it. Therefore, at this stage, the DVR is calculated as follows:

$$DVR_{DAYJ} = DVRI \times TT_{DAYJ} \times PPFAC_{DAYJ} \quad (13)$$

Finally, for flowering to occur, the DVR is added to the DVS, adjusting the calculations for each day until the DVS is greater than 0.65.

$$DVS = DVS + DVR_{DAYJ} \quad (14)$$

2.2. Implementation

The phenology calculation equations from the CSM ORYZA (v3) PHENOL subroutine were implemented in R to simulate only phenology and simplify analyses, focusing on functions related to photoperiod. Henceforth, these equations are called the photoperiod model. The photoperiod model in the R language was assessed for several parameters compared with its original versions in Fortran with the aim of verifying whether there is any inconsistency in the script in the R language.

2.3. Model calibration

The cardinal temperatures for the BRS 7 Taim cultivar were previously calibrated (da Conceição *et al.*, 2018). The $DVRI$ was self-calibrated according to the observed data, described in sub-item 2.4, based on the genetic parameters. To this end, the accumulated TT was calculated in the interval of days between the vegetative phase V6 and the observed panicle initiation (R0). The daily TT value was corrected by $PPFAC$, normalized, and adjusted to the range between 0.40 and 0.65. This range refers to the DVS of the photosensitive phase and represents the relative variation range for the *DVRI*. In short:

$$DVRI = (0.65 - 0.40) \times \left(\frac{1}{\sum_{i=V6}^{R0} (TT_{DAY} \times PPFAC_{DAY})} \right) \quad (15)$$

2.4. Experimental data

A phenological database of the cultivar BRS 7 Taim was used. It was created for the 2005/06 agricultural season in Capão do Leão, RS, Brazil (latitude -31.79, longitude -52.51), as described by Steinmetz *et al.* (2009). The field trial had a spacing of 17.5 cm between rows and a sowing density of 80 suitable seeds per meter. The development of ten plants (main stem) was monitored by sampling throughout the cycle, characterizing each stage according to the scale proposed by Counce *et al.* (2000).

2.5. Site

In this study, there were two extreme locations in relation to photoperiod: the municipalities of Pelotas (latitude -31.61, longitude -52.33) in Rio Grande do Sul and Cantá (latitude 2.41, longitude -60.67) in Roraima. To calculate the day length (DL), Eq. (1) to Eq. (5) were used, applied to the respective latitudes of Pelotas and Cantá. Figure 1 shows the variation in day length (*DL*) for both locations.

2.6. Climate data

Climate data were obtained from the Infoclima system database (Embrapa, 2024), covering the period from 1991 to 2009. The dataset includes the maximum and minimum air temperatures for Pelotas and were used to calculate the *TT*.

3. Results and Discussion

For *PPSE* equal to 0, the value of *MOPP* is irrelevant. This denotes insensitivity to the photoperiod. Some studies have ignored this, assigning *MOPP* values to insensitive genotypes (Poulton *et al.*, 2015; Biswas *et al.*, 2021). This calculation process is shared by several CSM (Bai *et al.*, 2019).

For a *MOPP* greater than DL, 1 is assigned to *PPFAC* since the plant's photoperiodic needs were met. In this case, the *PPSE* value becomes irrelevant because Eq. (10) and Eq. (11) are not executed (Bouman *et al.*, 2001). Although the plant is sensitive to photoperiod, the location and growing season of the simulation may not allow the expression of this characteristic. On the other hand, if the *MOPP* is lower than the DL, the *PPSE* value becomes decisive, and the *PPFAC* value is calculated daily since *DL* varies between days (Fig. 1) but not between years. Thus, if the relationship between *PPSE*, *MOPP* and *DL*, in Eq. (11), returns consecutive values close to 0, the plant extends its cycle. If *PPFAC* is greater than 0, flowering occurs as long as the thermal gain corrected by *PPFAC* and *DVRI* (Eq. (13)) is sufficient for this, respecting the amount of temperature data available.

As the *DL* varies throughout the year (minimum in July for Pelotas and in December for Cantá; Fig. 1), the sowing date should consider, in terms of photoperiod, whether the *PPSE* and *MOPP* sets are suitable for the *DL* of the estimated flowering period. If the *MOPP* is lower than the minimum *DL* of the region, flowering is still viable. For this to occur, *PPSE* needs to be close to 0 or *MOPP* should be close to *DL* values. As the *MOPP* approaches the DL, the *PPSE* may be slightly larger, as Fig. 2 shows.

In the case of the municipality of Pelotas, whose minimum *DL* is 10.84 h, highly sensitive cultivars (*PPSE* = 1) can flower in July when the *MOPP* is longer than 9.85 h, resulting in a *PPFAC* of 0.01 (Fig. 2A). However, *PPFAC* increases to values to close to 1 as *MOPP* approaches *DL* (Fig. 2). This is in line with the fact that most rice genotypes are quantitative short-day plants (Shim and Jang, 2020; Lee and An, 2015; Tsuji *et al.*, 2011).

The decrease in *PPSE* may also compensate for the mismatch between *MOPP* and the minimum DL. A *PPSE* below 0.101 still allows flowering, even when *MOPP* tends to 0. However, very low values for *MOPP* do not reflect reality. Restricting the *MOPP* range to values close to reality is interesting, as it increases the amplitude of the *PPSE*. Nevertheless, most combinations between *PPSE* and *MOPP* lower than *DL* resulted in *PPFAC* equal to 0 (Fig. 2).

When *PPFAC* is equal to 0, the product of Eq. (13) is 0. The CSM ORYZA (v3) simulates plant growth day by day. When the combination of parameter values results in constant zeros at *PPFAC*, growth stagnates. The *DVR* generated daily under this condition, when added to the *DVS* (Eq. (14)), does not result in any change. Therefore, there is no change in phenological phase, and the calculation remains in this cycle until there is no more daily climate

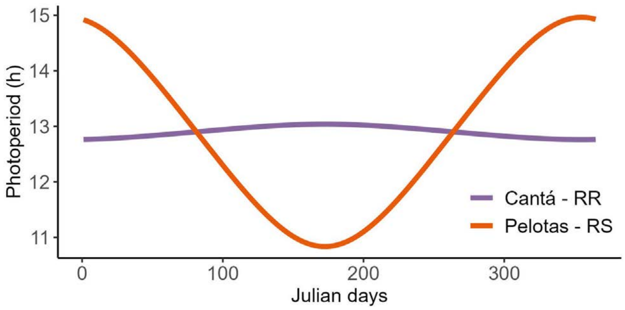

Figure 1. - Variation in day length (*DL*) throughout the year calculated using Eq. (1) to Eq. (5) for the latitudes -31.61 (Pelotas-RS) and 2.41 (Cantá-RR).

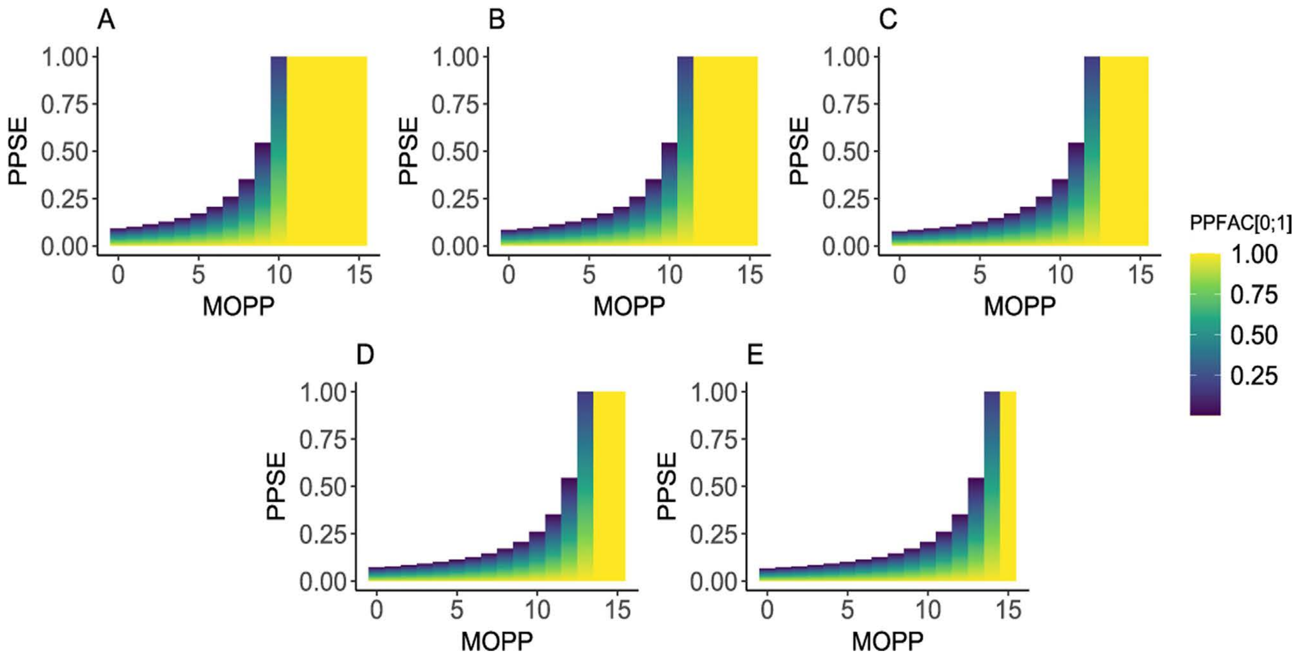

Figure 2. - Photoperiod sensitivity (*PPSE*) values as a function of the minimum optimal photoperiod (*MOPP*) for the factor *PPFAC* to be greater than 0, given a day length (*DL*) in Pelotas of (A) 10.84 h, (B) 11.84 h, (C) 12.84 h, (D) 13.84 h, and (E) 14.84 h.

data available for calculation. This reveals a limitation of the model to adequately deal with cultivars highly sensitive to photoperiod under unfavorable conditions, when *DL* is constantly higher than *MOPP*, resulting in outputs without a logical interpretation ("-10000").

To elucidate the functioning of the CSM, Fig. 3 illustrates a hypothetical highly sensitive genotype grown in unfavorable environments. Considering that genotypes sensitive to photoperiod generally have a *PPSE* close to 0.7 (Boling *et al.*, 2011), a *PPSE* of 0.8 was adopted to represent high sensitivity. The *MOPP* value was set at 11.5, as it is commonly used (Tan *et al.*, 2022; Yu *et al.*, 2023). If this hypothetical genotype were cultivated in Pelotas-RS, it would only flower during the period when the *MOPP* approaches the *DL* (Fig. 3A). In contrast, this same cultivar does not flower in Cantá-RR, as the *PPFAC* remains constantly at 0 (Fig. 3B).

The permanence in the vegetative phase observed for this genotype in Cantá (Fig. 3B) does not suggest an inconsistency in the ORYZA (v3) model, but rather a limitation of it. There are records of highly sensitive genotypes cultivated in continuously long photoperiods that remained in the vegetative phase for more than ten years (Yoshida, 1981). For Pelotas-RS, the sowing date for this supposed genotype must consider the coincidence of the photosensitive phase with the reduction in day length. If the photosensitive phase occurs after this period of shorter DL, the vegetative phase may be longer, flowering only in the following year, which is also predicted in the literature. Dore (1959), in studies conducted in Malaysia, where the *DL* is very close to that of Cantá (RR), recorded the response of a genotype with high sensitivity to the photoperiod in January (increasing *DL*), in which situation it flowered at 329 days due to a small difference in the annual amplitude of *DL* (only 14 minutes). When grown in September (decreasing *DL*), it flowered at 161 days. However, a positive *PPFAC* does not necessarily lead to flourishing either. Thus, the speed of flowering onset depends on its relationship with *TT* and *DVRI* (Eq. (13)). Regarding *PPFAC*, for the *DVS* to reach the value necessary to change the phenological phase from V6 to R0 (0.65), it needs to be close to 1 so that the *DVR* generated on each day of simulation, when added to the *DVS* (Eq. (14)), increases its value at a speed that allows flowering before the simulation period ends.

When calculating the *DVR*, the factor related to the climate condition may increase the degree of complexity in the relationship between parameters. Figure 4A2 and B2 show this scenario. It is similar to that Fig. 3A shows for Pelotas. The *PPFAC* value does not change between years, but the *DVR* value does. For the *DVR* calculation, the *DVRI* is relative to the genotype (fixed). The *TT*, on the other hand, varies according to the climatic conditions of the year (Figs. 4A1 and B1) and is calculated considering cardinal temperatures (Eq. (1) to Eq. (5)), which also do not change during the simulation. *DVRI*, *TOD*, *TBD*, and *TMD* are reported by users and considered fixed by the ORYZA (v3) model. These factors affect the *DVR* value, which varies daily (Figs. 4A2 and B2).

Figure 4 shows the period before day 100, and the *DVR* is 0, reflecting a null *PPFAC*. This repeats after day

250, where the *DL* is increasing and longer than *MOPP* again. Figure 3 shows that as *PPFAC* approaches 1, the *DVR* increases. The magnitude of the increase depends on the *TT* accumulated on the day and the *DVRI*. This was not

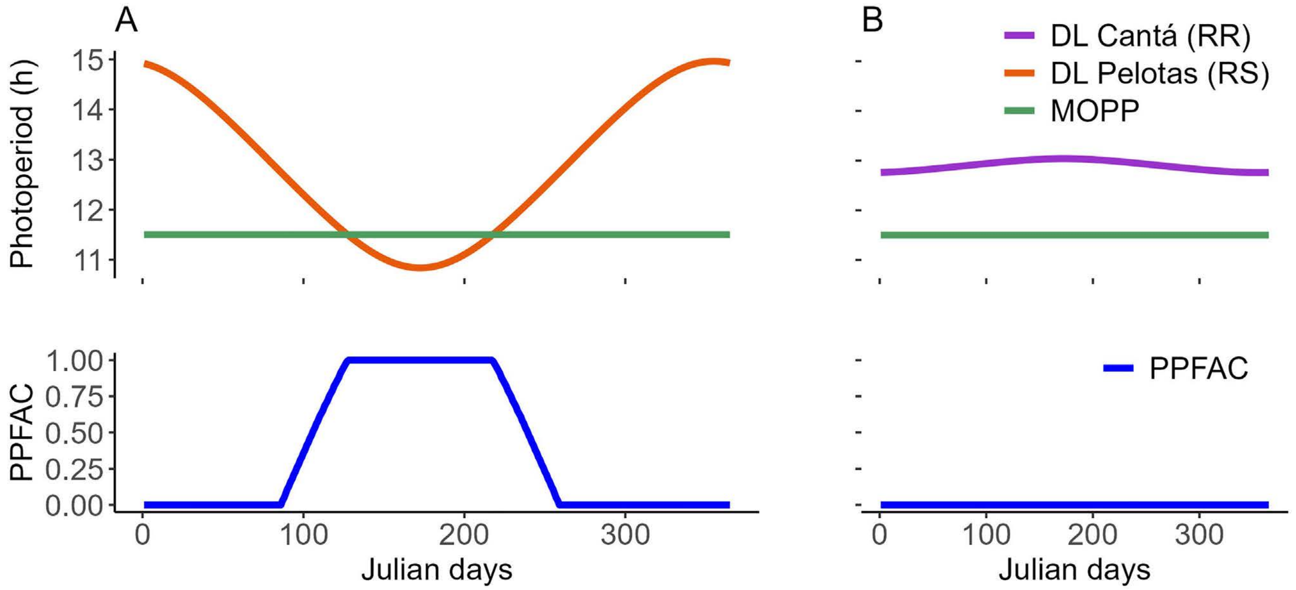

Figure 3. - Response to photoperiod (*DL*) according to the ORYZA model (v3) for a fictitious genotype with photoperiod sensitivity (*PPSE*) of 0.8 and minimum optimal photoperiod (*MOPP*) of 11.5 h, grown in (A) Pelotas-RS and in (B) Cantá-RR.

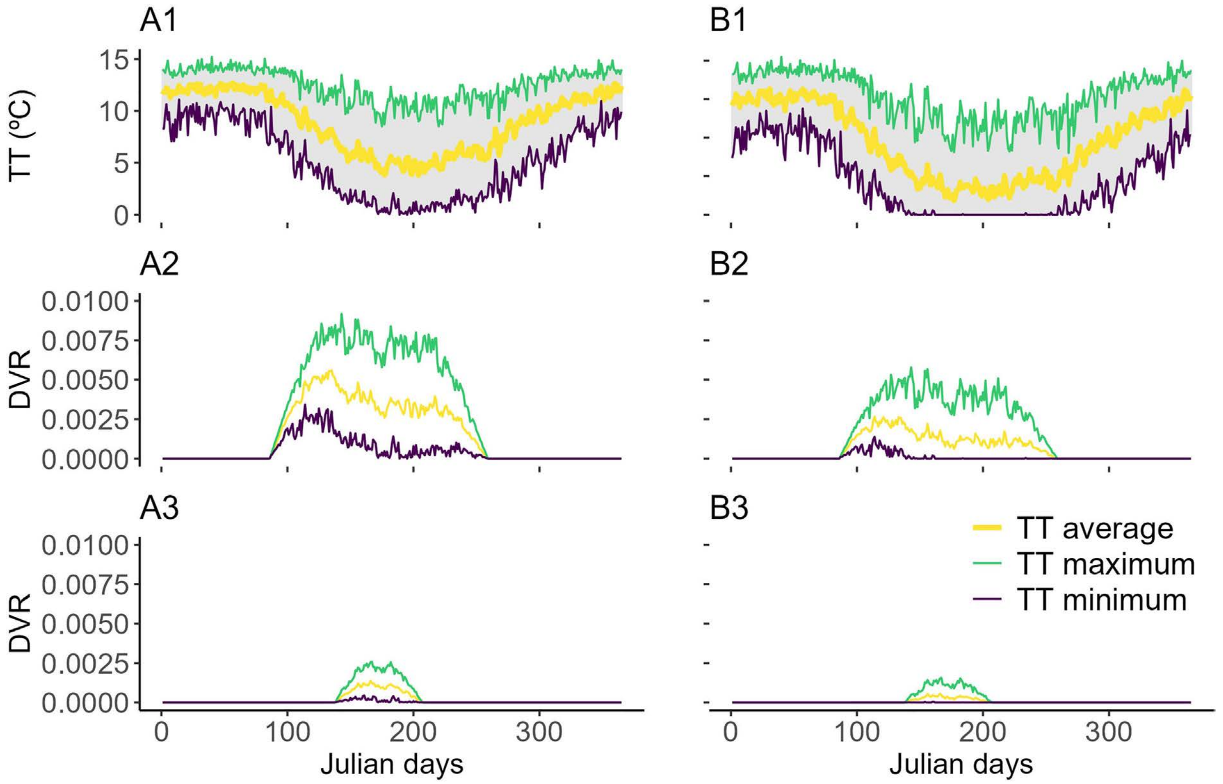

Figure 4. - (A1) Thermal time (*TT*) calculated using a minimum basal temperature of 9 °C, an optimum temperature of 25 °C, and a maximum development temperature of 36 °C, calibrated for the BRS 7 Taim cultivar, and (B1) considering an increase in minimum basal temperature to 14 °C from 1991 to 2009 for Pelotas-RS. Crop development rate (*DVR*) was calculated for minimum, average, and maximum temperatures, considering (A2 and B2) a minimum optimal photoperiod (*MOPP*) of 11.5 h and (A3 and B3) a *MOPP* of 10.0 h, both with photoperiod sensitivity (*PPSE*) of 0.8 and a development rate at panicle initiation (*DVRI*) of 0.0008709396.

demonstrated for Cantá, as the constantly null *PPFAC* does not allow flowering (Fig. 3B).

The increase in *TBD* causes a reduction and even nullification of *TT* in low temperature scenarios (Fig. 4B1). Coincidentally, the minimum temperatures occur in the same shortest photoperiods in Pelotas. This means that, even under good photoperiods, there is no *TT* in extremely cold conditions. This reflects on the *DVR*, assigning 0 to it. However, with too many consecutive days below *TBD*, the CSM kills the plant and ends the simulation. The slightest reduction in the *MOPP* value may also lead to large reductions in the *DVR* value (Figs. 4A3 and B3), especially when associated with low *TT* values.

Table 1 shows the sum of annual *DVR* and the number of years required for flowering to occur based on the parameters shown in Fig. 4, whose *DVRI* is not self-calibrated. The 1.5-h reduction in *MOPP*, combined with the increase in *TBD* from 9 °C to 14 °C, increases the need from 8.6 simulated years to 1,276.8 years for flowering to occur, which is undesirable. This shows that the *DVR* is very sensitive to any of its direct or indirect parameters.

Table 1 - Sum of the annual crop development rate (*DVR*) and number of years simulated for flowering to occur under the conditions shown in Fig. 4.

*MOPP** (hours)	*TBD** (°C)	*TT** (Degree-days)	*DVR* Annual Sum	Time to flowering (years)
10.0	9	minimum	0.009813662	25.5
10.0	14	minimum	0.0001958052	1276.8
10.0	9	average	0.05355447	4.7
10.0	14	average	0.01881494	13.3
10.0	9	maximum	0.1100469	2.3
10.0	14	maximum	0.06096323	4.1
11.5	9	minimum	0.1701145	1.5
11.5	14	minimum	0.0290618	8.6
11.5	9	average	0.5540252	0.5
11.5	14	average	0.2231328	1.1
11.5	9	maximum	1.006132	0.2
11.5	14	maximum	0.5750299	0.4

**MOPP* is the minimum optimal photoperiod; *TBD* is the minimum basal temperature; *TT* is the thermal time.

The reducing effect on *TT* is not exclusive to *TBD*. All three cardinal temperatures can reduce *TT* and affect flowering ability. With *TOD* ranging from 15 to 32 °C, *TBD* and *TMD* fixed at 14 and 33 °C, respectively, Fig. 5A shows the effect of *TOD* on *TT* under average temperature conditions. As after *TOD* the thermal gain starts to decrease as it approaches *TMD*, and with a high *TBD*, low *TOD* values suppress the *TT*, which drastically affects the *DVR*. Similarly, high *TOD* allows for higher *TT*.

In summary, *MOPP*, *PPSE*, *TBD*, *TOD*, and *TMD* directly affect the *DVR*. Indirectly, it is influenced by the day and latitude, which make up the *DL*, and by the climatic characteristics of the region. The combination of these parameters must ensure that:

$$\sum_{i=1}^{DAYJ} \left(DVRI \times TT_{DAYJ} \times PPFAC_{DAYJ}\right) = 0.25 \tag{16}$$

where the number of Julian days simulated between V6 and R0 (*DAYJ*) should be close to the number of observed days.

A way to get around the difficulty posed by the complexity of this relationship is the self-calibration of the *DVRI*. *DVRI* is fixed during simulation and compensates for low *PPFAC* and *TT* values. Auto-adjustment forces its value to increase so that flowering occurs within the observed period. Figure 5B shows its adjustment as a function of *TOD*. Very restrictive cardinal temperatures require a higher *DVRI* to flourish (Fig. 6); this also occurs for the other parameters. This is a point of attention, as very high development rates and very restrictive parameters may not reflect reality. If the *DVRI* is not self-adjusted, restrictive combinations in cardinal temperature parameters can also prevent flowering.

However, this approach is error-prone. *DVRI* can override an error in the values of the *TBD*, *TOD*, *TMD*, *MOPP*, and/or *PPSE*. Similarly, cardinal temperatures can

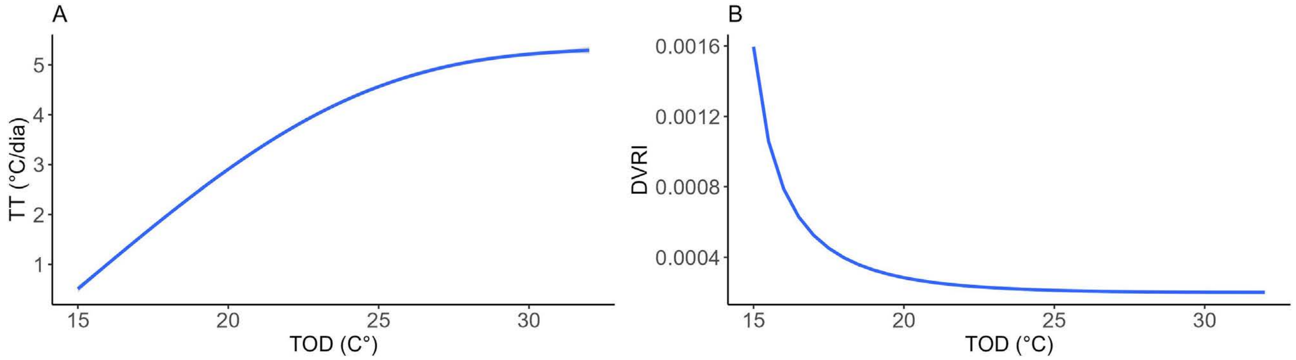

Figure 5. - (A) Thermal time (*TT*) and (B) self-adjustment of the development rate at panicle initiation (*DVRI*) as a function of the optimum development temperature (*TOD*).

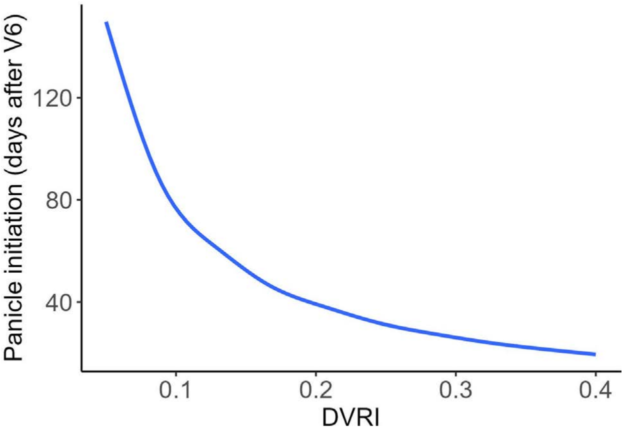

Figure 6. - Relationship between development rate at panicle initiation (*DVRI*) and days after the start of the photosensitive phase (V6) for panicle initiation, setting *PPFAC* at 0.032 and thermal time at 1 °C day^{-1}.

compensate an error in photoperiod response variables. Thus, there are several sets of parameters that provide identical simulations of phenology, making it impossible to determine which parameters reflect the true values of a cultivar (van Oort *et al.*, 2011). Based on the sensitivity of the ORYZA (v3) model to *DVRI*, many studies have disregarded the other phenological parameters, setting them at the default values for the IR72 genotype and calibrating only the development rates (Tan *et al.*, 2022; Yu *et al.*, 2023). This creates a gap in accuracy of the phenological model when applied to other locations, as it depends on specific characteristics of the experiment location (van Oort *et al.*, 2011).

When using inferential statistical techniques for parameter optimization, it is necessary to make assumptions about the range of parameter values. *DVRI*'s self-adjustment reduces the need to worry about the parameter space of cardinal temperatures to nothing more than biological coherence. This simplifies the choice of parameter values by allowing the necessary constraints to be applied only to the *MOPP* and *PPSE* parameters. Therefore, it is essential to ensure that at some point in the simulation, and for a sufficient time, the following condition is met:

$$(DL - MOPP) \times PPSE < 1 \qquad (17)$$

Similarly:

$$DL - MOPP < PPSE^{-1} \qquad (18)$$

$$DL - PPSE^{-1} < MOPP \qquad (19)$$

The determination of *MOPP* and *PPSE* can be conducted experimentally, involving different sowing times throughout the year (Sujariya *et al.*, 2023) or in controlled environments with regulated photoperiod (Pennisi *et al.*, 2020). Some authors choose to calibrate this parameter empirically after adjusting the other parameters (Boling *et al.*, 2011), giving it less importance. Although experimental determination is ideal, it is not always feasible due to the high cost and time required.

Assuming that the *MOPP* is unknown but higher than 8, to flower at any time of the year in Pelotas the *PPSE* parameter needs to be lower than 0.146 (Fig. 2E) or, at most, 0.352 when photosensitivity occurs in July (Fig. 2A). The closer to the equator, the shorter the *DL* amplitude (Fig. 1). This reduces the influence of sowing date on *DL* and on the choice of the *MOPP* and *PPSE* parameters (Fig. 7). However, for genotypes with high sensitivity, even a small variation in *DL* may drastically change flowering dates (Dore, 1959).

As mentioned above, as the *MOPP* value increases or *DL* decreases, the maximum *PPSE* limit can expand (Fig. 4). Since in a calibration process the sowing date is fixed, the *DL* is known and must be considered when choosing the maximum *PPSE* limit. Forsythe *et al.* (1995) discuss differences in approaches to calculating DL. In the phenological calibration process, the angle of the sun at which twilight still affects day length must also be estimated. This angle can reach up to -6°, resulting in up to

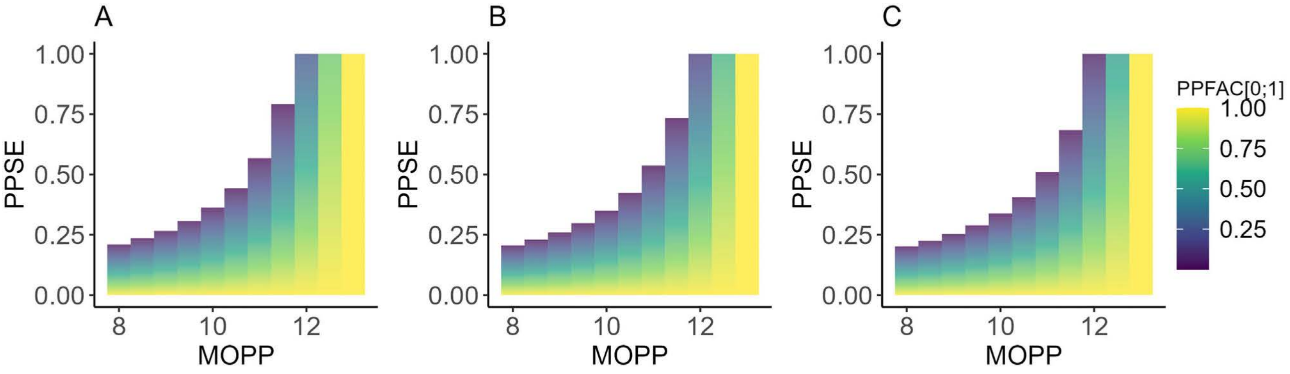

Figure 7. - Photoperiod sensitivity (*PPSE*) values as a function of the minimum optimal photoperiod (*MOPP*) for *PPFAC* to be greater than 0, given day lengths (*DL*) in Cantá-RR of (A) 12.76 h, (B) 12.86 h, and (C) 12.96 h.

1.5 h more light than when the sun was below the horizon (0°). The CSM ORYZA (v3) considers 0.90 h of light beyond the 0° angle. The inconsistency between the methods used to estimate the observed *DL* and the approach adopted by the ORYZA (v3) model may systematically under- or overestimate the effects of photoperiod, requiring transparency and methodological consistency (van Oort *et al.*, 2011).

Once the *DL* is defined according to the observed flowering date and the assumed or already known minimum value of *MOPP*, the highest value of *PPSE* can be defined as:

$$PPSE < \frac{1}{DL - MOPP} \tag{20}$$

Bai *et al.* (2019) described a similar approach for the CSM APSIM. This model, derived from ORYZA (v3), has a similar phenological subroutine. Different from that proposed in Eq. (20), Bai *et al.* (2019) incorporated the average effect of the photoperiod into the denominator to determine a specific value for the *PPSE*. This effect is estimated as a function of the *TT* accumulated until panicle initiation over the difference between stage V6 and flowering. Thus, errors in estimating the effects of photoperiod are related to errors in estimating cardinal temperatures.

In southern Brazil, rice can be cultivated between September and December, depending on the cultivar cycle (Steinmetz *et al.*, 2019; Duarte *et al.*, 2021). Especially when grown in September, the sensitivity range coincides with the period of maximum *DL* in Rio Grande do Sul, which occurs around December (14.84 h) (Steinmetz *et al.*, 2022). Considering a minimum *MOPP* value of 10, for *PPFAC* to be greater than 0 in this period:

$$PPSE < (14.84 - 10)^{-1} \tag{21}$$

$$PPSE < 0.20 \tag{22}$$

$$PPFAC \approx 0.032 \tag{23}$$

A low *PPFAC* value can impede the simulation if the *TT* and *DVRI* are not high enough to provide flowering. However, considering the measures proposed in this study, a *PPFAC* close to 0 is not an obstacle.

Boling *et al.* (2011) estimated photoperiod sensitivity parameters for a highly photoperiod-sensitive rice genotype (KDML105) grown in northeastern Thailand (latitude 18.73, longitude 98.94). The authors determined the *MOPP* value at 12.50 h, which was the maximum duration of the day when the panicle initiation stage occurred. *PPSE* was empirically estimated at 0.70 by pairing simulated panicle initiation dates with observed dates. However, this parameter estimation method dissociates *MOPP* from *PPSE*. Maintaining these values, flowering could occur up to a *DL* of 13.91 h. However, the maximum *DL* at which flowering occurred was 12.50 h. If the authors chose to simultaneously calibrate both parameters using automatic estimation techniques, the basic assumption about the value of *MOPP* should be at least 11.08 h for *PPSE* up to 0.70, or 11.60 h if they considered *PPSE* up to 1.00. The *DVRI* was adjusted similarly to Eq. (15).

4. Conclusion

There is a significant limitation of the ORYZA (v3) phenological model when photoperiod sensitivity is insufficient for flowering combined with finite meteorological data. This reflects a limitation in the model's ability to analyze highly photoperiod-sensitive cultivars under consistently unfavorable conditions.

We highlight the importance of carefully constraining genetic parameters, considering the specific conditions of the growing environment, to avoid uninterpretable responses. *DVRI* auto-adjustment simplifies this process by allowing necessary constraints to be applied to the *MOPP* and *PPSE* parameters to ensure flourishing.

By establishing minimum values for *MOPP* based on the observed *DL* for the flowering date, the maximum value of *PPSE* can be mathematically determined, thus facilitating the model calibration process. Eq. (20) offers a practical and accurate approach that simplifies this process and can be adopted for any latitude.

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