ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.28, n.10, e278299, 2024
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v28n10e278299

Original Article

Improving understanding of the plastochron of determinate and indeterminate soybean cultivars[1]

Melhorando o entendimento do plastocrono de cultivares de soja de hábito de crescimento determinado e indeterminado

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HIGHLIGHTS:

This study identifies plastochron phases in soybean cultivars based on growth habit and water regime.
The plastochron varies according to the growth habit rather than the maturity group of soybean cultivars.
Determinate and indeterminate soybean cultivars have different plastochrons under different water regimes.

ABSTRACT: The aim of this study was to identify plastochron phases in soybean cultivars with determinate and indeterminate growth habits. Experiments were conducted from 2010/2011 to 2022/2023 at four locations in Rio Grande do Sul state (RS), Brazil, using 25 soybean cultivars with determinate (6) and indeterminate (19) growth habits. This study divided the plastochron into phases during the soybean node emission stage. In irrigated cultivars with a determinate growth habit, the plastochron has an early and late phase of 59.7 and 65.7 °C day node^{-1}, respectively. In rainfed (non-irrigated) environments, there is no difference between the early and late plastochron phases. The early and late plastochrons of irrigated cultivars with an indeterminate growth habit are 64.1 °C day node^{-1}, while the intermediate phase is 58.5 °C day node^{-1}. In rainfed environments, the average value of the early and intermediate phases is 60.6 °C day node^{-1}, with a late plastochron of 79.4 °C day node^{-1}. Dividing the plastochron into phases during node emission, as proposed in this study, improves understanding of vegetative development in soybean cultivars with determinate and indeterminate growth habits and establishes ecophysiological foundations for chronological function construction.

Key words: agricultural modeling, node emission, plant development

RESUMO: O objetivo deste estudo foi identificar as fases de plastocrono em cultivares de soja com hábito de crescimento determinado e indeterminado. Os experimentos foram conduzidos no período de 2010/2011 a 2022/2023 em quatro locais do estado do Rio Grande do Sul, Brasil, com 25 cultivares de soja com hábito de crescimento determinado (6) e indeterminado (19). Este estudo buscou dividir o plastocrono em fases durante o período de emissão de nós da soja. Em cultivares irrigadas de hábito de crescimento determinado, o plastocrono apresenta duas fases, a fase inicial de 59,7 °C dia nó$^{-1}$ e a fase final de 65,7 °C dia nó$^{-1}$. Em ambientes não irrigados, não há diferença entre as fases inicial e final do plastocrono. As cultivares de hábito de crescimento indeterminado com irrigação apresentam um plastocrono médio inicial e final de 64,1 °C dia nó$^{-1}$, ao contrário da fase intermediária onde o plastocrono é de 58,5 °C dia nó$^{-1}$. Em ambientes de sequeiro, as fases inicial e intermédia têm um valor médio de 60,6 °C dia nó$^{-1}$, ao contrário da fase final com um plastocrono de 79,4 °C dia nó$^{-1}$. A divisão do plastocrono em fases durante o período de emissão de nós na cultura da soja, proposta neste estudo, permite-nos melhorar o entendimento do desenvolvimento vegetativo de cultivares de soja de hábito de crescimento determinado e indeterminado e estabelecer bases ecofisiológicas para a construção de uma função cronológica.

Palavras-chave: modelagem agrícola, emissão de nós, desenvolvimento vegetal

• Ref. 278299 – Received 07 Sept, 2023
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• Accepted 21 Apr, 2024 • Published 19 Jun, 2024
Editors: Ítalo Herbet Lucena Cavalcante & Hans Raj Gheyi

Introduction

In Brazil, the soybean (*Glycine max* (L.) Merrill) is grown in subtropical and tropical environments, where regional characteristics affect growth and development processes. Temperature is one of the environmental factors that most affects plant development, such as the leaf emergence rate of annual plant species (Tenorio et al., 2017).

Several mathematical models simulate soybean development based on meteorological data, soil type, and crop management practices. Currently, the most widely used models are CROPGRO-SOYBEAN (Sun et al., 2022) SOYDEV and SOYSIM (Setyono et al., 2007; 2010). These models use a chronological function to represent the rate at which soybean plants emit nodes. However, they only partially consider the impact of the overlap between vegetative (from emergence to last node emission) and reproductive phases (from the start of flowering to physiological maturity) on the node emission rate after the onset of the reproductive stage (Setyono et al., 2007).

In soybean vegetative development, the plastochron is defined as the interval, in thermal time (°C day), between the emergence of successive nodes on the main stem (Martins et al., 2011; Bexaira et al., 2021). However, soybean plastochrons are calculated from the date of seedling emergence (VE) to the number of final node (Streck et al., 2008; Martins et al., 2011; Rockenbach et al., 2016; Bossolani et al., 2022), without considering the reduction in the node emission rate at the onset of the reproductive stage (Setyono et al., 2007). As such, it is important to conduct an in-depth analysis of the plastochron in soybean during the vegetative stage to better understand the node emission process during the overlap between the vegetative and reproductive stages and develop a biologically meaningful chronology function in process-based mathematical models. The aim of this study was to identify plastochron phases in soybean cultivars with determinate and indeterminate growth habits.

Material and Methods

The study consisted of 17 experiments carried out in seven growing seasons (2010/2011, 2011/2012, 2012/2013, 2013/2014, 2016/2017, 2017/2018, and 2022/2023), with all the experimental plots located in Rio Grande do Sul state (RS) in southern Brazil. The experiments were conducted at universities and commercial fields in the municipalities of Santa Maria (SM, 29° 41' S 53° 48' W; 139 m above sea level), Frederico Westphalen (FW, 27° 21' S 53° 23' W; 535 m above sea level), Restinga Seca (RS, 29° 48' S 53° 22' W; 49 m above sea level), and Itaqui (ITA, 29° 9' S 56° 33' W; 64 m above sea level), areas representative of the soybean-growing regions in the state. The climate in the study locations is classified as humid subtropical (Cfa) according to Köppen's classification, with hot summers and no defined dry season (Wrege et al., 2011).

The locations vary considerably in terms of photoperiod, (11 to 14 hours), soil characteristics, and temperature, from -0.6 °C to maximum values near the upper base temperature for soybean node emission. Irrigated and non-irrigated (rainfed) experiments were carried out, with sowing dates from August to March, for different locations and seasons (Tables 1 and 2). A total of 25 soybean cultivars were used, 6 of which had a determinate and 19 an indeterminate growth habit, with the relative maturity group (RMG) ranging from 4.8 to 8.2 (Table 1).

The experiments were conducted under different water regimes, with no water deficit in those involving additional irrigation, and different water levels in experiments in rainfed environments. Accumulated rainfall and reference evapotranspiration (AET) at the Restinga Seca (RS) location were 344.2 and 416.6 mm, respectively, resulting in a water deficit of 72.4 mm during the study period. Rainfall in Frederico Westphalen (FW) was 496.2 mm and AET 282.6 mm, indicating no water deficit in the 2013/2014 growing season. In Itaqui (ITA), rainfall of 529 and 472 mm and AET of 413.2 and 310.4 mm were recorded for experiments E13 and E14, respectively, in the 2016/2017 season, demonstrating no water deficit during the these experiments. The Santa Maria (SM) experiment in the 2022/2023 growing season showed a water deficit of 287.3 mm, with rainfall of 119.8 mm and AET of 407.1 mm.

The experiments in SM (2010/2011 to 2017/2018) and FW (2013/2014) used a randomized block design with four replicates, those in ITA (2016/2017) randomized blocks with three repetitions, and in RS (2013/2014) and SM (2022/2023) demonstration plots with five 5 meter-long rows for each treatment. Spacing between rows in all the experiments was 0.45 m, with sowing density of 30 plants m^{-2}. Crop management practices were in accordance with the recommendations for soybean cultivation in southern Brazil, controlling diseases,

Table 1. Soybean cultivars used to determine the plastochron in 17 soybean experiments in four locations in Rio Grande do Sul, Brazil, in seven growing seasons

Cultivar	RMG*	Growth Habit	Location
NS 4823 RR	4.8	Indeterminate	Santa Maria, Itaqui
TMG 7161 RR INOX	5.4	Indeterminate	Santa Maria
BMX Zeus IPRO	5.5	Indeterminate	Santa Maria
BMX Elite IPRO	5.5	Indeterminate	Santa Maria
BMX Energia RR	5.5	Indeterminate	Santa Maria
TMG 2757 IPRO	5.7	Indeterminate	Santa Maria
BMX Lança RR	5.8	Indeterminate	Itaqui
M 5947 IPRO	5.9	Indeterminate	Santa Maria
P 96Y90	6.0	Indeterminate	Santa Maria
BMX Turbo RR	6.0	Indeterminate	Santa Maria
TMG 7362 IPRO	6.2	Indeterminate	Santa Maria
TEC IRGA 6070 RR	6.3	Indeterminate	Itaqui
NA 5909 RG	6.3	Indeterminate	Santa Maria
BMX Fibra IPRO	6.4	Indeterminate	Santa Maria
CZ 26B47	6.4	Indeterminate	Santa Maria
IAS 5	6.4	Determinate	Santa Maria
BS IRGA 1642 IPRO	6.4	Indeterminate	Itaqui
Igra RA 518 RR	6.6	Indeterminate	Santa Maria
BMX Potência RR	6.7	Indeterminate	Santa Maria, Restinga Seca
BMX Ícone IPRO	6.8	Indeterminate	Santa Maria
FEPAGRO 36 RR	7.2	Determinate	Santa Maria
BRS 246 RR	7.2	Determinate	Santa Maria
BRAAG	7.3	Determinate	Frederico Westphalen, Santa Maria
SYN 1378	8.0	Determinate	Itaqui
CD 219 RR	8.2	Determinate	Santa Maria, Restinga Seca

*RMG - Relative maturity group

Table 2. Maximum (Tmax), minimum (Tmin), and average (Tave) temperatures for the different locations, experiments, and sowing dates during the soybean crop cycle in seven growing seasons at four locations

Location	Experiment	Sowing date	Tmax* (°C)	Tmin* (°C)	Tave (°C)	Water regime
Santa Maria (SM)	E1	10/12/2010	36.20	7.00	23.53	Irrigated
	E2	08/01/2011	36.20	6.70	22.27	
Santa Maria	E3	19/11/2011	38.70	6.40	24.75	Irrigated
	E4	28/01/2012	38.30	4.40	22.21	
Santa Maria	E5	22/09/2012	38.60	3.70	22.89	Irrigated
	E6	03/11/2012	38.60	6.80	23.43	
	E7	01/12/2012	38.60	6.80	23.17	
	E8	06/02/2013	33.30	1.50	20.12	
Santa Maria	E9	27/09/2013	40.00	7.40	23.70	Irrigated
	E10	19/02/2014	34.70	-0.60	18.51	
Restinga Seca (RS)	E11	14/11/2013	40.00	7.40	24.93	Non-irrigated
Frederico Westphalen (FW)	E12	23/11/2013	36.70	8.00	24.00	Non-irrigated
Itaqui (ITA)	E13	22/11/2016	36.90	9.20	24.80	Non-irrigated
	E14	14/12/2016	36.90	12.80	25.12	
Santa Maria	E15	02/09/2017	38.30	7.10	22.11	Irrigated
	E16	17/10/2017	38.30	7.10	23.05	
Santa Maria	E17	24/08/2022	36.70	2.50	20.09	Non-irrigated

*Tmax and Tmin - Daily maximum and minimum temperatures during the soybean crop cycle

insects, and weeds to prevent abiotic stress (Tagliapietra et al., 2022). Fertilization was performed in accordance with the fertilization and liming manual for the states of Rio Grande do Sul and Santa Catarina (SBCS, 2004).

The seedling emergence (VE stage) date in the experiments was when the cotyledons of 50% of the plants were above ground level at an angle of 45° (Tagliapietra et al., 2022). In experiments with a randomized block design, 5 to 8 plants were randomly marked in each plot (each repetition being the average of these plants) and 10 plants in the demonstration plots (each plant was considered a repetition). The plants were marked as soon as the unifoliolate leaves emerged, the number of nodes (NN) on the main stem was counted two or three times a week, and the date of the reproductive stage (R1 to R8) was established (Fehr & Caviness, 1977) when 50% of the marked plants reached the relevant development stage.

The criterion for identifying NN is when the leaf at the node above it has expanded enough that the edges of the leaflets are not touching (Fehr & Caviness, 1977). NN was counted weekly up to stage R3 in determinate cultivars and R5 in their indeterminate counterparts.

From seedling emergence to R5 (Fehr & Caviness, 1977), the daily thermal time (TTd, °C day) was calculated according to Arnold (1960):

$$\mathrm{TTd} = (\mathrm{Topt} - \mathrm{Tb}) \cdot \left(\frac{(\mathrm{Tave} - \mathrm{Tb})}{\mathrm{Topt} - \mathrm{Tb}} \right) \cdot 1 \text{ day when } \mathrm{Tb} < \mathrm{Tave} \leq \mathrm{Topt} \quad (1)$$

$$\mathrm{TTd} = (\mathrm{Topt} - \mathrm{Tb}) \cdot \left(\frac{(\mathrm{Tave} - \mathrm{TB})}{\mathrm{Topt} - \mathrm{TB}} \right) \cdot 1 \text{ day when } \mathrm{Topt} < \mathrm{Tave} \leq \mathrm{TB} \quad (2)$$

$$\mathrm{TTd} = 0 \text{ when } \mathrm{Tave} < \mathrm{Tb} \text{ or } \mathrm{Tave} > \mathrm{TB} \quad (3)$$

where:

Tave - average temperature calculated based on the daily minimum and maximum temperatures;

Tb - lower base temperature (7.6 °C);

Topt - optimum temperature (31 °C); and

TB - upper base (40 °C) temperature for soybean node emission (Tagliapietra et al., 2022).

The accumulated thermal time (ATT, °C day) was calculated as follows:

$$\mathrm{ATT} = \sum \mathrm{TTd} \quad (4)$$

Daily minimum (Tmin) and maximum (Tmax) temperature data during the experiments were obtained from automatic weather stations belonging to the National Institute of Meteorology (INMET) (SM, FW, and RS) and an automatic weather station at the Itaqui Campus (ITA) of the Universidade Federal do Pampa.

Unlike other investigations that only determine one plastochron from the cotyledon stage (VC) to the final number of leaves, the present study aimed to divide the plastochron into phases during the soybean node emission stage. In determinate cultivars, where there is a small overlap between the vegetative and reproductive stages, the plastochron was divided into two phases: early (from the first visible node, one pair of unifoliate leaves, to R1) and late plastochron (R1 to R3). In indeterminate cultivars, the plastochron was divided into three phases: early (from the first visible node, one pair of unifoliolate leaves, to R1), intermediate (R1 to R3) and late plastochron (R3 to R5).

The plastochron was estimated for each plant in each growing season, location, water regime, and experiment via the inverse of the angular coefficient of the linear regression between the NN on the main stem and ATT (Sinclair et al., 2005; Streck et al., 2008; Martins et al., 2011). The plastochron data were tested for homogeneity and normality using Levene's and the Shapiro-Wilk tests, with results indicating non-homogeneous and non-normal data. Thus, descriptive and inferential statistics were applied, with results expressed as measures of central tendency and variation. To that end, measures of position (arithmetic mean and median) and dispersion (coefficient of variation) were calculated.

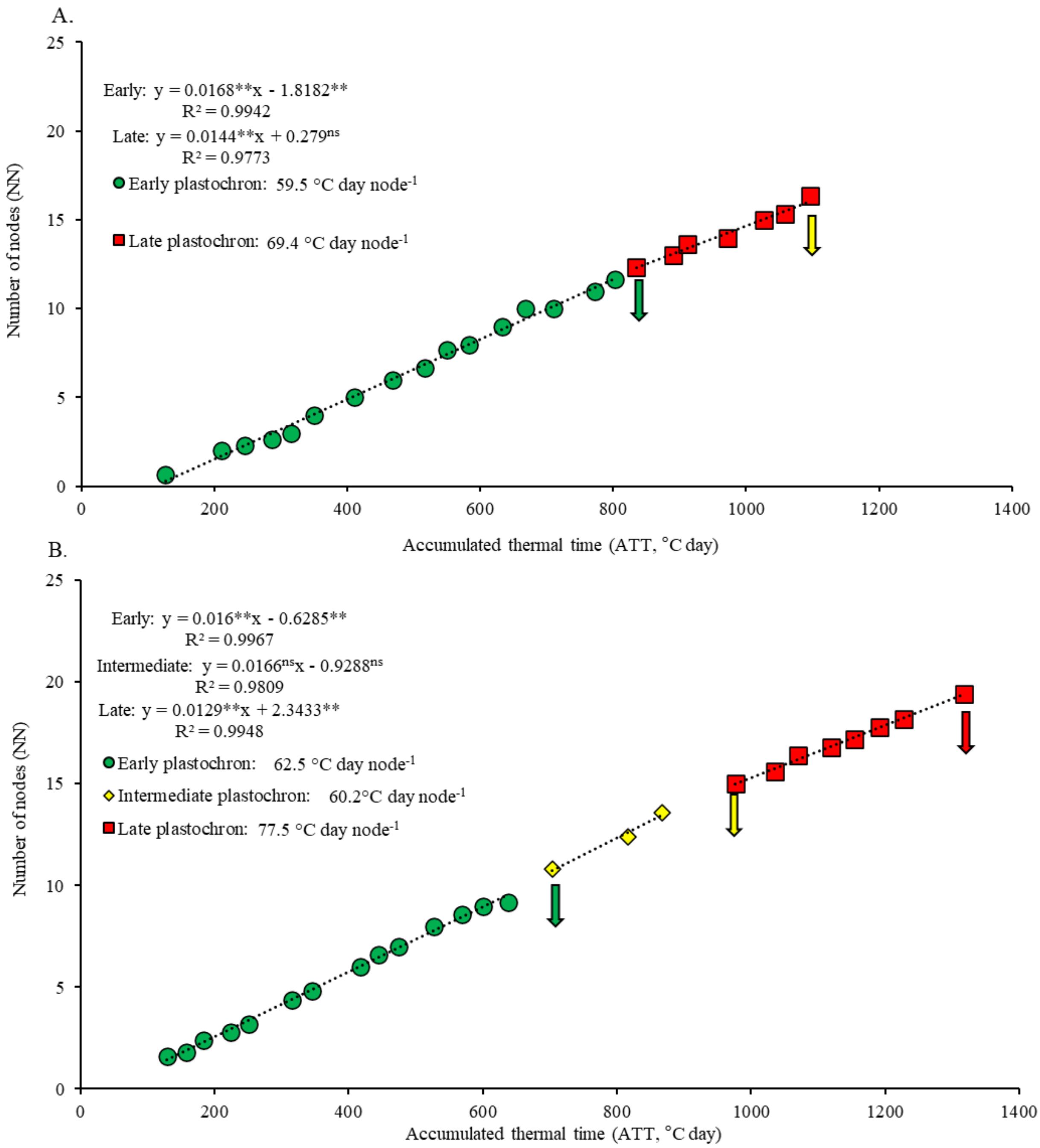
Plastochron data according to water regime, phase, location, experiments, and cultivars were compared via the

Kruskal-Wallis test with Dunn's post hoc, using a p-value adjusted according to Bonferroni's methodology. The analyses were performed using R software version 4.3.0 (R Development Core Team, 2019).

Results and Discussion

The range of temperatures observed in this study (Table 2) are similar to those reported in other studies that determined plastochron values for soybean crops (Martins et al., 2011; Tenorio et al., 2017). Exposing plants to different weather conditions is important in plant development studies and for using thermal time as a measure of plant biological time, as well as in simulation models for agricultural crops (Zeist et al., 2020).

The linear regression model between NN on the main stem and ATT showed a high coefficient of determination ($R^2 > 0.9$) between these two variables. This indicates that thermal time is the main factor that determines the evolution of NN in soybean and as such, estimating the plastochron by inverting the angular coefficient of linear regression is appropriate. Examples of the NN x ATT relationship for determinate (FEPAGRO 36 RR) (Figure 1A) and indeterminate soybean cultivars (Igra RA 518 RR) (Figure 1B) in the 2011/2012 (03/19/2011) and 2012/2013 (09/22/2012) growing seasons, respectively, and how the plastochron phases were divided, are shown in Figure 1.



Symbols and colors indicate the different stages of plastochron calculation. Arrows represent the reproductive stages R1 (green), R3 (Yellow) and R5 (Red) (Fehr & Caviness, 1977). Not significant (^{ns}), significant at $p < 0.05$ (*) and significant at $p < 0.01$ (**)

Figure 1. Relationship between the number of nodes on the main stem (NN, nodes plant^{-1}) and the accumulated thermal time (ATT, °C day), used to estimate the plastochron of the determinate FEPAGRO 36 (A) and indeterminate Igra RA 518 RR cultivars (B)

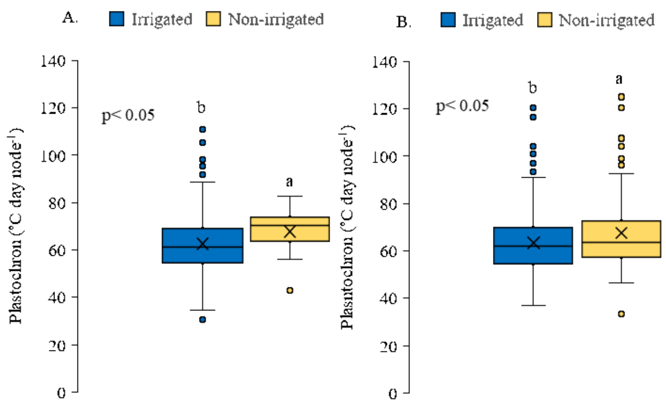
According to the Kruskal-Wallis test, plastochron data for the water regimes showed a difference between irrigated and rainfed cultivars with determinate and indeterminate growth habit (Figure 2). The median plastochron value for determinate irrigated cultivars was 61.4 °C day node^{-1} and 70.2 °C day node^{-1} under rainfed conditions (Figure 2A). For indeterminate cultivars, median plastochron values were 62.1 and 63.7 °C day node^{-1} for irrigated and rainfed environments, respectively (Figure 2B).

Plastochron values increased from the irrigated to the rainfed experiments (Figure 2), possibly due to the influence of water deficit on soybean development in rainfed crops, thereby delaying the development cycle and increasing the plastochron (Bossolani et al., 2022).

Since differences were observed between the water regimes, the irrigated and rainfed environments were evaluated separately. Assessment of the different plastochron phases for determinate cultivars showed that the early phase (59.7 °C day node^{-1}) is lower than late phase (65.7 °C day node^{-1}) under irrigation (Figure 3A), whereas there were no significant differences between phases in rainfed conditions, with a mean plastochron of 70.1 °C day node^{-1} (Figure 3B).

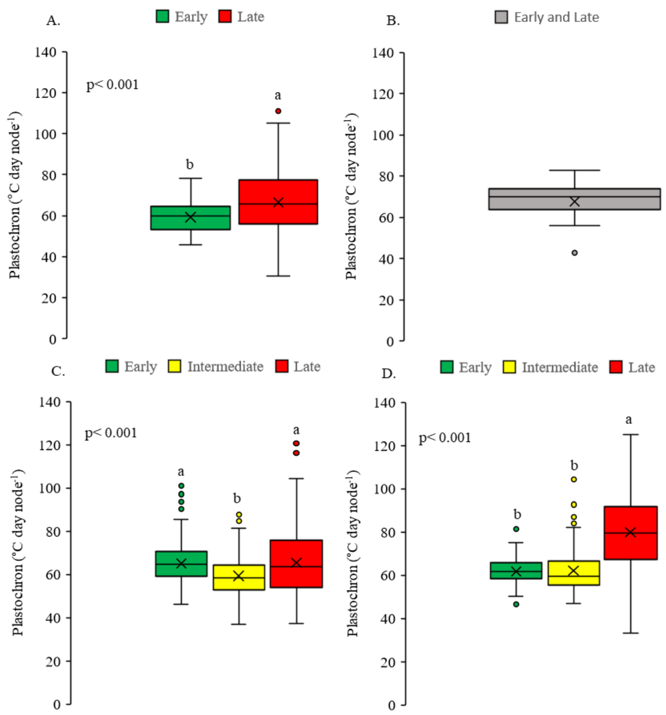
On the other hand, indeterminate cultivars showed no differences between the phases for irrigated and rainfed environments (Figure 3C and D). There was no difference between the early and late phases in irrigated environments, with a mean plastochron of 64.1 °C day node^{-1}, differing statistically from the intermediate phase, with a plastochron of 58.4 °C day node^{-1} (Figure 3C). Under rainfed conditions, the early and intermediate phases did not differ, with the mean plastochron of 60.6 °C day node^{-1}, while the late phase exhibited a plastochron of at 79.3 °C day node^{-1} (Figure 3D).

Previous studies report plastochron values of 48.1 to 60.3 °C day node^{-1} (Streck et al., 2008), similar to those obtained here. However, no studies were found in literature that divide the plastochron into phases, with only a single plastochron calculated for the entire node emission period in soybean (Streck et al., 2008; Martins et al., 2011; Rockenbach et al., 2016; Bossolani et al., 2022). Dividing the plastochron



The solid line indicates the median and X the mean. Different colors and letters are significant according to Dunn's Post Hoc test at 0.05 probability, by phase, with the p-value shown in the figure

Figure 2. Boxplots for the plastochron in each water regime (blue: irrigated; yellow: rainfed) (°C day node^{-1}) for determinate (A) (CV= 20%) and indeterminate cultivars (B) (CV= 20.9%) in seven growing seasons and 17 experiments



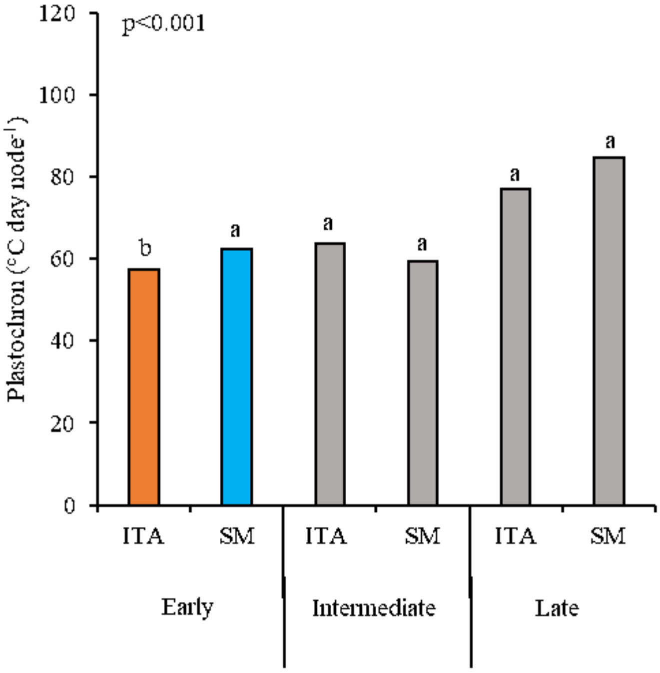
The solid line indicates the median and X the mean. The p-values for Dunn's Post Hoc test at 0.05 probability are shown the figure. Different letters indicate differences between plastochron phases

Figure 3. Box plots of plastochron phases (°C day node^{-1}) for irrigated (A) (CV= 20.5%) and non-irrigated (B) (CV= 13.1%) determinate and irrigated (C) (CV= 19.6%) and rainfed (D) (CV= 22.3%) indeterminate soybean cultivars in seven growing seasons and 17 experiments

according to the different phenological phases of soybean and, in particular, considering the overlap between the vegetative and reproductive stages at node emission, represents a major advance in understanding soybean growth during the cycle. The plastochrons of 77.5 to 148.5 °C day node^{-1} obtained in a study with soybean cultivars in the Brazilian Cerrado (Bossolani et al., 2022) differ from the average values obtained in our study found for the different plastochron phases in determinate and indeterminate cultivars in irrigated and rainfed environments.

Differences between plastochron values can be attributed to the different cardinal temperatures, whereby the lower base temperature in the present study was 7.6 °C, and 10 °C in research by Bossolani et al. (2022). The method used to calculate TTd also influences plastochron values, with previous studies using a methodology that considers only one cardinal temperature (Streck et al., 2008; Bossolani et al., 2022).

Assessment of the plastochron at the different locations showed statistical differences for determinate and indeterminate cultivars only under rainfed conditions, according to the Kruskal-Wallis and Dunn's Post Hoc tests. Irrigated experiments were only conducted in SM. For determinate cultivars, there was no significant difference between locations, with a mean plastochron of 66.4 °C day node^{-1} (CV= 13.1%). Indeterminate cultivars in rainfed conditions were evaluated based on the plastochron phases, with a difference between the municipalities of SM (62.5 °C day node^{-1}) and ITA (57.4 °C day node^{-1}) (Figure 4) in the early phase.



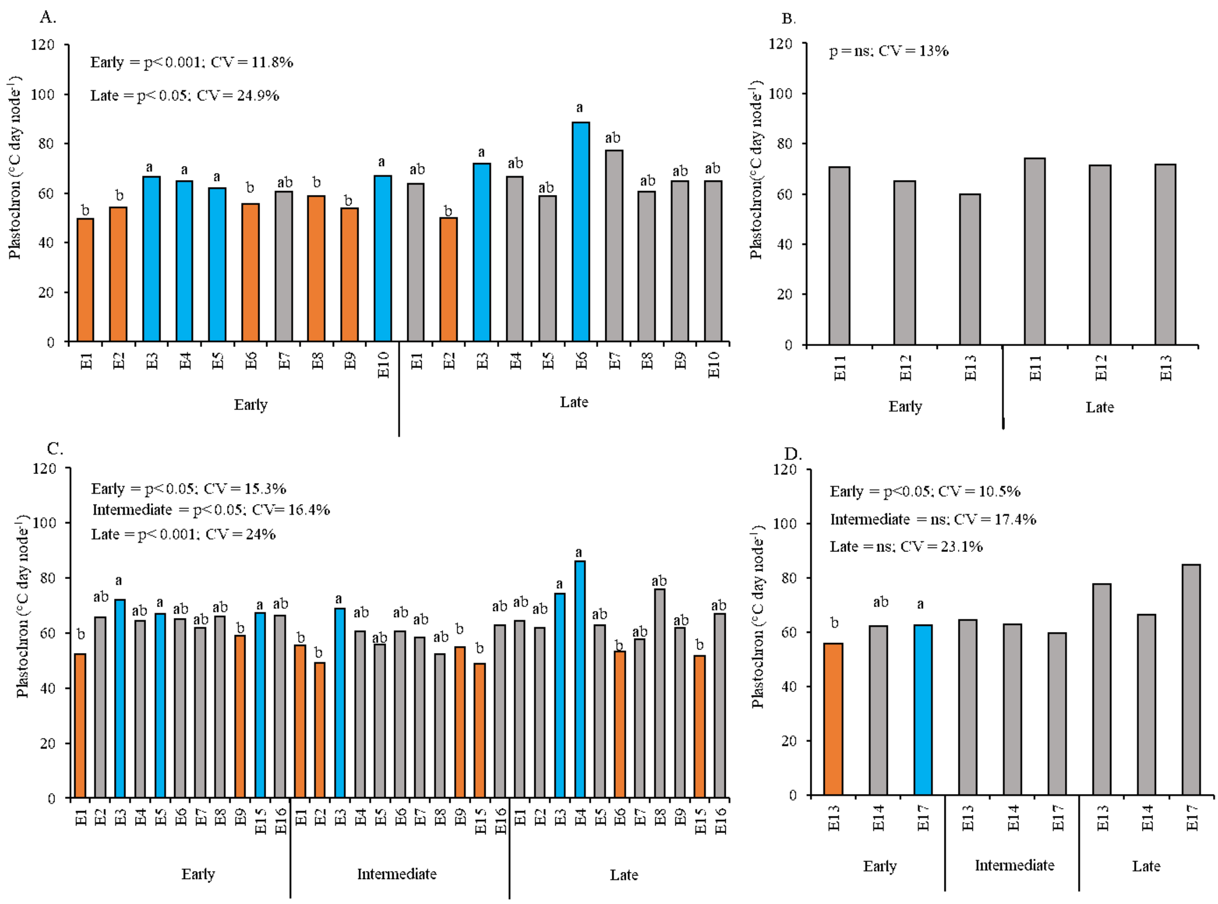
Locations: SM - Santa Maria and ITA - Itaqui. The blue and orange bars and different letters differ significantly according to Dunn's Post Hoc test at 0.05 probability, by phase, with the p-value shown in the figure. The gray bars indicate no significant difference between the blue and orange bars within each plastochron phase

Figure 4. Median plastochron and its phases in indeterminate soybean cultivars (CV= 22.3%) for comparison between locations in seven growing seasons and 17 experiments

The differences between the locations can be attributed to soil and climate variables. The experiments were conducted at different locations, which, according to Streck et al. (2018), have different soil types with different water-related characteristics, such as soil water retention capacity (SWRC) (Reichert et al., 2009). The municipality of SM has an SWRC of 0.128 m^3 m^{-3}, while values for FW, ITA, and RS are 0.134, 0.124, and 0.116 m^3 m^{-3}, respectively (Reichert et al., 2009).

Based on these SWRC values and the varying environmental conditions of the experiments, growing soybean in locations with different soil properties and at different sowing times may expose the plants to variations in temperature, water demand and availability. This is evident in the water requirement of 407.1, 361.8 (average for E13 and E14), 282.6, and 416.6 mm SM, ITA, FW, and RS, respectively. For indeterminate cultivars in dryland areas, there was a significant difference between SM and ITA in the early phase, possibly due to periods of water deficit during this plastochron phase (VE to R1).

The different sowing dates, which ranged from August to March, were considered distinct experiments (Table 2). For irrigated determinate cultivars in the early phase, there was a significant difference among experiments E3, E4, E5, and E10, and among E1, E2, E6, E8, and E9, with a median plastochron of 67.1 °C day node^{-1} (E10) to 49.5 °C day node^{-1} (E1) (Figure 5A). Thus, for the late phase, E3 (71.9 °C day node^{-1}) and E6 (88.6 °C day node^{-1}) differed statistically from E2 (50 °C day node^{-1}) (Figure



The blue and orange bars and different letters differ according to Dunn's Post Hoc test at 0.05 probability, by phase, with the p-value and coefficient of variation (CV) shown in the figure. ns: not significant according to Dunn's Post Hoc test at 0.05 probability. The gray bars (ab) indicate no difference between the blue and orange bars within each plastochron phase

Figure 5. Median plastochron and its phases in irrigated (A) and rainfed determinate cultivars (B) and irrigated (C) and rainfed indeterminate cultivars (D) at different development stages, for comparison between experiments in seven growing seasons and four locations

5A). Cultivars grown under rainfed conditions exhibited no significant difference, with a mean plastochron of 68.7 °C day node^{-1} (Figure 5B).

For irrigated indeterminate cultivars, in the early phase experiments E3, E4, and E15 differed significantly from E1 and E9, with a plastochron variation of 19 °C day node^{-1} between E3 and E1 (Figure 5C). In the intermediate phase, E3 (68.9 °C day node^{-1}) differed significantly from E1, E2, E9, and E15, whose median plastochrons were 55.6, 49.2, 54.9, and 48.78 °C day node^{-1}, respectively. The late plastochron of indeterminate irrigated cultivars differed from E3 and E4 to E6 and E15.

In the rainfed experiments with indeterminate cultivars, differences were only observed in the early phase, with the highest plastochron recorded for E17 (62.5 °C day node^{-1}) and the lowest for E13 (55.7 °C day node^{-1}). Although these two experiments differed, they did not vary from E14 (Figure 5D). In the intermediate and late phases, no differences were observed between experiments, with mean plastochrons of 62.3 and 76.2 °C day node^{-1}, respectively (Figure 5D).

Plastochron values fluctuated between different experiments and sowing dates. Martins et al. (2011) found that the plastochron of different cultivars decreased at later sowing times, unlike what was observed in the present study. This decline in the plastochron may be linked to the number of daylight hours (photoperiod), which can increase the rate of soybean vegetative development (Tagliapietra et al., 2022). However, joint analysis of the data from the 17 experiments over the 7 growing seasons indicated no effect of the photoperiod on soybean node emission.

The photoperiod is a key factor that influences soybean development, particularly the flowering stage (Tagliapietra et al., 2022). Rocha et al. (2018) found significant differences in the plastochron values of different soybean varieties, even within the same photoperiod range. This result is consistent with our findings, whereby there is no direct relationship between the photoperiod and node emission rate in soybean cultivars with different growth habits sown on different dates. Rocha et al. (2018) also investigated the final number of nodes (FNN) as a function of photoperiod and found that photoperiod influenced FNN. A lower FNN was recorded for plants sown in September (when the photoperiod is longer in southern Brazil), January and February (shorter photoperiod in southern Brazil). This pattern is attributed to the fact that the photoperiod triggers flowering in soybean plants, which shortens the development cycle and results in fewer nodes being formed.

Assessment of the determinate soybean cultivars indicated no significant difference in the early ($p > 0.05$ and CV = 11.8%) and late plastochrons ($p > 0.05$ and CV = 24.9%) under irrigated conditions, with mean values of 59.7 and 65.8 °C day node^{-1}, respectively. Additionally, the determinate cultivars in rainfed environment did not differ statistically ($p > 0.05$ and CV = 13.1%), with an average plastochron of 70.1 °C day node^{-1}.

The indeterminate cultivars differed significantly according to the water regimes and plastochron phases. Under irrigated conditions, differences were observed for cultivars only in the early phase, with the highest median plastochrons obtained for cultivars NS 4823 RR (66.7 °C day node^{-1}) and BMX Energia RR (67.5 °C day node^{-1}), which differed from Igra RA 518 RR (60.4 °C day node^{-1}). However, these three cultivars did not differ statistically from the others within the early phase (Figure 6A). Mean plastochron values in the intermediate and late phases were 56.8 and 61.6 °C day node^{-1}, respectively.

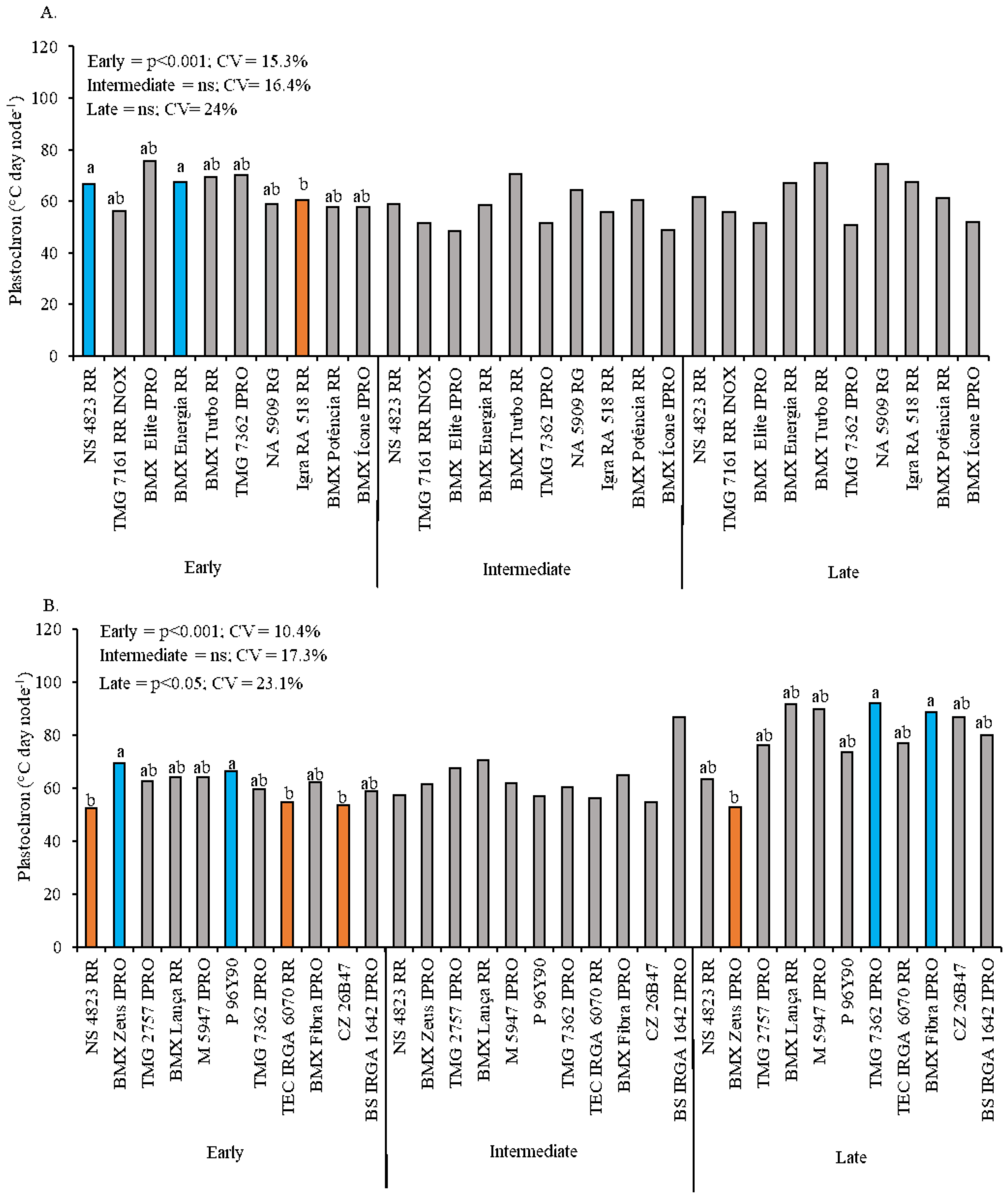
In the early phase under rainfed conditions, cultivars BMX Zeus IPRO (69.4 °C day node^{-1}) and P 96Y90 (66.2 °C day node^{-1}) obtained the highest median plastochron values, differing statistically from NS 4823 RR (52.2 °C day node^{-1}), TEC IRGA 6070 RR (54.6 °C day node^{-1}), and CZ 26B47 (53.4 °C day node^{-1}) (Figure 6B). As such, there was no significant difference between determinate cultivars in the intermediate phase in rainfed environments. In the late phase, the median plastochrons of TMG 7362 IPRO and BMX Fibra IPRO were 92.2 and 88.5 °C day node^{-1}, differing from BMX Zeus IPRO (52.9 °C day node^{-1}), which obtained the lowest median value in this phase (Figure 6B).

Martins et al. (2011) studied determinate soybean cultivars and observed a difference between their plastochron values, unlike the present study, which found no significant difference between determinate cultivars. However, the early and late plastochron values of the cultivars studied here are similar to those reported by Martins et al. (2011). Plastochron values of 57.3 to 75.8 °C day node^{-1} were reported for the BMX Ativa RR cultivar for different row spacing at sowing (Rockenbach et al., 2016), similar to the values obtained here for determinate cultivars.

The plastochron results for the different indeterminate growth habit cultivars were not related to the cultivars' development cycle (different relative maturity group), as observed in older soybean cultivars by Sinclair et al. (2005) and Streck et al. (2008). Early plastochron values for indeterminate cultivars in the present study are similar to those reported in previous research (Streck et al., 2008; Martins et al., 2011; Rockenbach et al., 2016). However, values in the late phase for some cultivars are close to those obtained by Bossolani et al. (2022), who only considered a single plastochron.

The higher plastochron values in this study when compared to previous research may be related to breeding programs and the release of new soybean cultivars every year. According to Winck et al. (2023), soybean yield has increased by 41 kg ha^{-1} year^{-1} due to genetic improvement.

Dividing the plastochron into phases during the soybean node emission period, as proposed in this study, improves understanding of the vegetative development of determinate and indeterminate cultivars. As a follow-up to the study carried out by Bexaira et al. (2021), who built a model to estimate the rate of node emission in soybean with practical applications, this division provides an ecophysiological foundation for the construction of a biologically significant chronological function, improving knowledge about the vegetative development of soybean crops and enabling the creation of a reliable process-based mathematical model.



The blue and orange bars and different letters differ according to Dunn's Post Hoc test at 0.05 probability, by phase, with the p-value and coefficient of variation (CV) shown in the figure. ns: not significant according to Dunn's Post Hoc test at 0.05 probability. The gray bars (ab) indicate no difference between the blue and orange bars within each plastochron phase

Figure 6. Median plastochron of indeterminate soybean cultivars in irrigated (A) and rainfed (B) environments in the early, intermediate, and late phases in seven growing seasons, four locations and 17 experiments

Conclusions

1. In irrigated cultivars of determinate growth habit, the plastochron has two phases, an early phase of 59.7 °C day node^{-1} and late phase of 65.7 °C day node^{-1}. There is no difference between the early and final plastochron phases in rainfed environments.

2. In irrigated indeterminate cultivars, the mean value of the early and late plastochron is 64.1 °C day node^{-1}, in contrast to the intermediate phase with 58.5 °C day node^{-1}. Under rainfed conditions, the mean value in the early and intermediate phases is 60.6 °C day node^{-1}, with 79.4 °C day node^{-1} in the late phase.

Contribution of authors: Felipe S. D. Porta: Research design, Data collection, analysis and interpretation, manuscript preparation, and literature review. Nereu A. Streck: Research design, manuscript preparation, and work supervision. Cleber M. Alberto: Research design, analysis and interpretation, and manuscript preparation. Michel R. da Silva: Research design, analysis and interpretation, and manuscript preparation. Enrico F. Tura: Data collection, analysis and interpretation, literature review, and manuscript preparation. Gilnei F. Uliana: Data collection, analysis and interpretation, and literature review. Eduardo L. Tagliapietra: Data collection, analysis and interpretation, and literature review. Alexandre F. Alves: Data collection, analysis and interpretation, and literature review. José E. M. Winck: Data collection, analysis and interpretation, and literature review. Maurício F. Soares: Research design, analysis and interpretation, literature review, and manuscript preparation. Alencar J. Zanon: Research design, manuscript preparation, and work supervision.

Supplementary documents: There are no supplementary sources.

Conflict of interest: The authors declare no conflict of interest.

Financing statement: This study was partially funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES).

Acknowledgement: The authors would like to thank the FieldCrops Team, Federal University of Santa Maria and Federal University of Pampa.

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