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Plastochron, phenology, and production of green pea in different growing seasons

Plastocrono, fenologia e produção de ervilha verde em diferentes épocas de cultivo

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ABSTRACT

Pisum sativum L. is a multi-purpose crop. The duration of its vegetative and reproductive periods is determined by a combination of temperature and humidity and genotype response to these conditions. To minimize the loss of productivity due to adverse conditions in sensitive periods of the crop, we evaluated the phenological development and production of *Pisum sativum* L. in different growing seasons. We used a randomized block design, and the experiments were conducted across five growing seasons, with four replications and eight plants per experimental unit. The variables analyzed were as follows: plastochron, number of days to start flowering, full flowering, and beginning of harvest, the accumulated thermal sum to start flowering, full flowering, and beginning of harvest, and the number of pods, pod mass, and total productivity per unit area. The analysis of variance was performed, and the mean values of the data were compared using the Scott-Knott test. Principal component analysis was also performed from Pearson's correlation matrix of phenological and production variables. In seasons 1, 4, and 5, the plants reached full flowering earlier, and the pod mass was considerably lower, resulting in lower yields. Seasons 2 and 3 were the most productive and showed lower results for plastochron, less thermal sum until full flowering, and a shorter photoperiod, which, combined with low temperatures during the growing season, resulted in a longer cultivation cycle.

Index terms: *Pisum sativum* L.; number of nodes; temperature; thermal sum; development.

RESUMO

Pisum sativum L. é uma cultura multiuso, cuja duração de seu período vegetativo e reprodutivo é determinada pela combinação de temperatura, umidade e resposta do genótipo a essas condições. Diante do exposto, visando minimizar as perdas de produtividade por condições adversas em períodos sensíveis da cultura, o objetivo foi avaliar o desenvolvimento fenológico e a produção de *Pisum sativum* L. em diferentes épocas de cultivo. Utilizou-se o delineamento em blocos casualizados, com cinco estações de cultivo, quatro repetições e oito plantas por unidade experimental. As variáveis analisadas foram: plastocrono, número de dias para início da floração, plena floração e início da colheita, soma térmica acumulada para início da floração, plena floração e início da colheita, número de vagens, massa de vagens e produtividade total por unidade de área. A análise de variância foi realizada e as médias comparadas pelo teste de Scott Knott. Também foi realizada a análise de componentes principais da matriz de correlação de Pearson's das variáveis fenológicas e de produção. Nas estações 1, 4 e 5, as plantas atingiram a plena floração mais cedo e a massa de vagens foi consideravelmente menor, resultando em menores rendimentos. As estações 2 e 3 foram as mais produtivas e apresentaram menores resultados para o plastocrono, menor soma térmica até a plena floração e fotoperíodo mais curto, o que aliado às baixas temperaturas durante o ciclo vegetativo, resultou em um ciclo de cultivo mais longo.

Termos para indexação: *Pisum sativum* L.; número de nós; temperatura; soma térmica; desenvolvimento.

INTRODUCTION

The green pea (*Pisum sativum* L.) is a multi-purpose crop used for human consumption and as animal feed. The plant also helps in recovering soil fertility and green manure by incorporating nitrogen (Schiavon et al., 2018). Its grains have a high nutritional value, high digestibility, and high-quality proteins (Nosworthy et al., 2017). It also contains phenolic acids, which decrease the effects of free radicals, thus helping in improving human health (Udahogora, 2012). According to the data from (Food and Agriculture Organization of the United Nations FAOSTAT, 2021), in 2019, the countries that produced the most quantity of peas in the world were China, India, and

France, producing 13,399,958, 5,562,000, and 282,190 tons, respectively.

Pea productivity is high under favorable climatic conditions; low water availability decreases vegetative development, and consequently, crop productivity decreases since water restriction reduces nutrient absorption and induces stomatal closure, thus reducing sweating (Carvalho et al., 2012). The duration of the vegetative and reproductive periods in peas is determined by the combination of temperature and humidity and the genotype response to these conditions. Plants are taller in many rainy years than in those times when they are influenced by drought and high temperatures (Kuznetsov et al., 2020).

Low water availability and high temperatures affect the photosynthetic behavior of plants, causing stomatal closure to retain water in the cells. These changes, in turn, affect plant productivity and physiology (Moisa et al., 2019). These conditions also directly influence the phenology of pea plants, affecting their growth and development and, when not ideal, shortening the time required for a new leaf to emerge and its cultivation cycle, ensuring the perpetuation of the species (Sadras et al., 2019).

A good understanding of agroclimatic needs is necessary for successful agricultural planning. The accumulated thermal sum (STa) can be used to decrease the climatic risks during the crop cycle, as knowing the thermal needs of the crop can help predict the duration of the plant cycle, estimate the date of harvest, and later, commercialize the products rationally, without having any conflicts with the interest of the farmers (Cavalcante et al., 2020). The STa is a more accurate measure of time than calendar days (Gilmore; Rogers, 1958).

Among plant development processes, plastochron can help in quantifying the stages of plant development, as it informs about the time required in °C day^{-1} for the appearance of two new nodes in dicotyledonous plants. The emergence speed and the final number of plant nodes are directly affected by the air temperature (Streck, N. A. et al., 2008; Martins et al., 2011). Thus, based on the knowledge of the phenological development and the agroclimatic needs of the crop, combined with the weather forecasts for the agricultural year, sowing can be performed at ideal times so that the critical periods of the crop do not overlap with the period of the worst weather conditions predicted for the agricultural year. Such careful planning can minimize the loss of productivity due to adverse conditions during sensitive periods of the crop.

Pea is becoming an important off-season large crop in Brazil. Thus, several studies have investigated *Pisum sativum* L. to explain its physiological responses and behaviors in different environments (Carvalho et al., 2012; Kuznetsov et al., 2020). However, further studies must be conducted to understand the development of pea culture at different times and places of cultivation. Therefore, in this study, we evaluated the phenological development and production of *Pisum sativum* L. at different times of cultivation.

MATERIAL AND METHODS

Description of the place of cultivation, preparation of the area, and experimental design

A field experiment was conducted in 2020 in Santa Maria, Southern Brazil (29° 42' 23''S, 53° 43' 15'' W, and 95 m above sea level). According to the Köppen climate classification, the region has a Cfa type of climate, an average air temperature of 19.1 °C (0 to 38 °C), and an average accumulated annual rainfall of 2,040 mm (Alvares et al., 2013)with well recognized simple rules and climate symbol letters. In Brazil, climatology has been studied for more than 140 years, and among the many proposed methods Ko ̈ppen0s system remains as the most utilized. Considering Ko ̈ppen's climate classification importance for Brazil (geography, biology, ecology, meteorology, hydrology, agronomy, forestry and environmental sciences. The soil in the study area was classified as arsenic dystrophic red argisol (Streck, E. V. et al., 2008).

The soil at the site of the experiment was prepared using the rotary hoe, and basic fertilization was performed according to the analysis of the soil and recommendations for the crop (Comissão de Química e Fertilidade do Solo - CQFS, 2016). Drip irrigation was performed when required. The other cultural management was performed following technical recommendations and the guidelines of good agricultural practices. A randomized block experimental design was used; the pea cultivar Itapuã 600 Isla® was sown in five growing seasons (S1: 09/04/2020; S2: 02/05/2020; S3: 25/05/2020; S4: 15/06/2020 e; S5: 02/07/2020), totaling five treatments in four replications, with eight plants per experimental unit.

Evaluations Performed

The variables analyzed included plastochron, the number of days to start flowering (DBF) (considering when the first flower of the block was open), full flowering (DFF) (when 100% of the plants that made up the block were in anthesis stage) and beginning of harvest (DFH), and the accumulated thermal sum for the beginning of flowering (ATSBF), full flowering (ATSFF), and beginning of harvest (ATSFH). The production variables were also evaluated as follows: the number of pods (NP), the mass of pods (MP, g plant^{-1}), and total productivity per unit area (Prod, kg ha^{-1}).

For determining the plastochron, the number of nodes (NN) was counted every three days, from the beginning of the emergence of nodes until the parcel reached full flowering. The NN was recorded in four plants per plot, with 16 plants per sowing time. The node was considered to be visible when the leaf attached to it presented unrolled leaf blade.

The data on ambient temperature were collected from the automatic meteorological station of the National Institute of Meteorology (INMET), located approximately 50 m away from the site of the experiment; the average air temperature was calculated from the data. The daily thermal sum (STd) was calculated using the following Equation 1 (Arnold, 1960):

$$STd = \left(Tmed - Tb\right).1dia \qquad \left\{^{o}Cdia\right\} \tag{1}$$

Here, STd indicates the daily thermal sum (°C day), Tmed indicates the average temperature, and Tb indicates the base temperature.

The base temperature (Tb) is the daily sum of thermal units above a lower base temperature, below which the development of the plant is negligible or absent (Rosa et al., 2013). For peas, the base temperature of 3 °C was used (Olivier; Annandale, 1998).

The thermal sum was calculated from the day of sowing in each growing season, and the accumulated thermal sum (STa), which is the sum of the daily thermal sum, was evaluated as follows by Equation 2.

$$STa = \sum Std \qquad \left\{^{o}Cdia\right\} \tag{2}$$

For determining the plastochron, a linear regression was performed between the number of nodes and the accumulated thermal sum. The plastochron (°C day node^{-1}) was defined as the inverse of the slope of the linear regression (Streck et al., 2005).

The number of pods and pod mass were determined after counting and weighing the pods collected in the laboratory. The data were evaluated via analysis of variance (ANOVA) to determine the effect of different pea-growing seasons. When significant, the mean values of all variables were grouped using the Scott-Knott test. We also performed principal component analysis (PCA) based on Pearson's correlation matrix of the phenological and production variables, and the results were interpreted based on the linear relationships between the variables and the responses of the growing seasons. All statistical analyses were performed using the R software (R Core Team, 2021) and the packages FactoMineR (Le; Josse; Husson, 2008), ExpDes.pt (Ferreira; Cavalcanti; Nogueira, 2021), ggplot2 (Wickham, 2016), and metan (Olivoto; Lúcio, 2020). The results were considered to be significant at $p < 0.05$.

RESULTS AND DISCUSSION

The result of ANOVA (Table 1) showed a significant difference for all response variables across seasons ($p \leq 0.05$), indicating that the sowing time influenced the variables analyzed. The coefficient of variation was low for DBF and DFH and medium for DFF, PLAS, NP, MP, and Prod; according to the rating proposed by Pimentel Gomes (2000), CVs are low when they are less than 10%, medium when they are between 10% and 20%, high when they are between 20% and 30%, and very high when they are greater than 30%.

During the pea crop cycle in each growing season, the maximum and minimum temperatures showed a great variation, ranging from –1.8 °C to 33.9 °C. In S1, at the beginning of the cycle, the temperatures were higher, and throughout the cycle, the average temperatures ranged between 10 °C and 20 °C. In S2, S3, S4, and S5, sowing was performed at milder temperatures. Frost occurred after the plants were established in the field, and it did not affect the crop severely. Heavier rains occurred in May and June, and more regular and milder rainfall was distributed over the rest of the evaluation period (Figure 1).

Pisum sativum L. grows best between 13 °C and 18 °C. The species can tolerate low temperatures and can grow between 4 °C and 24 °C. The reproductive phase is the most sensitive to temperatures below 0 °C and above 30 °C, which can cause the abortion of flowers and pods (Barbano et al., 2002). Thus, negative temperatures with periods of frost during the flowering stage in the S1 growing season might have caused flowers to abort, resulting in low productivity in this season.

From the results of ANOVA, we found significant differences for the following variables: the beginning of flowering (DBF), full flowering (DFF), the beginning of harvest (DFH), plastochron (PLAS), the number of pods (NP), pod mass (MP), and productivity (Prod), as determined by the F test at 5% probability (Figure 2).

Table 1: Summary of the ANOVA for phenological and productive variables as a function of the growing season. The phenological variables included the days required for the beginning of flowering (DBF), days required for full flowering (DFF), days required for the beginning of harvest (DFH), and plastochron (PLAS). The productivity variables included the number of pods (NP), pod mass (MP), and productivity (Prod).

Source of variation	Degrees of freedom	Mean square						
		DBF	DFF	DFH	PLAS	NP	MP	Prod
Block	3	0.98^{ns}	52.98^{ns}	0.87^{ns}	52.75^{ns}	1.15^{ns}	21.07^{ns}	210655.00^{ns}
Season	4	60.93*	145.50*	167.95*	222.26*	35.35*	1656.90*	16568994.00*
Residue	12	3.53	40.90	3.28	30.78	3.73	58.77	587691.00
CV (%)	-	4.27	14.29	2.35	10.12	19.74	16.77	17.77

*, ^{ns} – Significant and not significant at $p \leq 0.05$ by the F test, respectively.

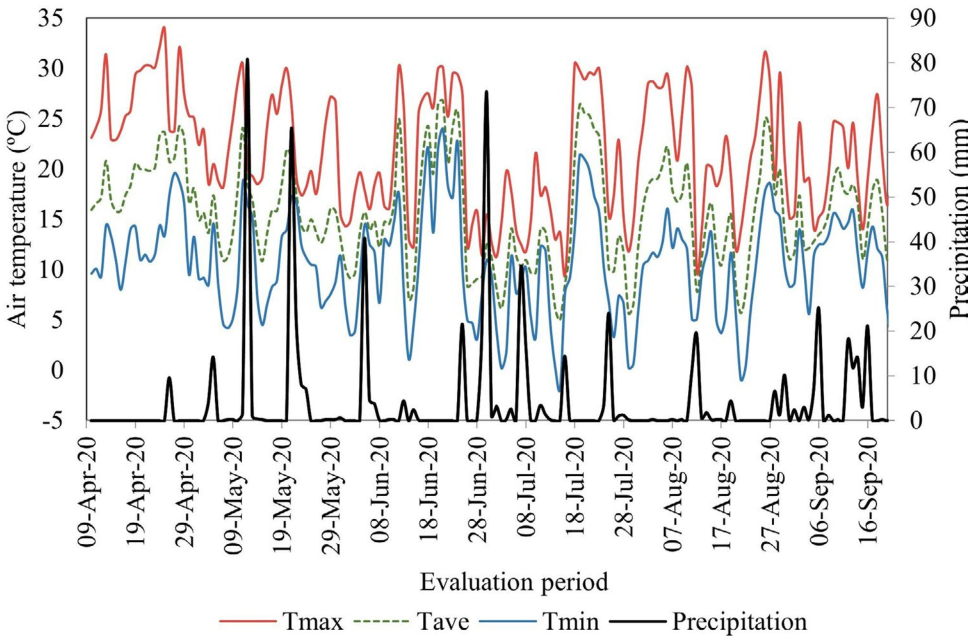

Figure 1: The precipitation (mm) and the maximum, average, and minimum air temperatures (°C) were recorded at the weather station in the Crop Science Department, Federal University of Santa Maria, RS, Brazil, during the evaluation period between May and September 2020.

Regarding DBF, the S1 season had the lowest number of days from sowing to the beginning of flowering (38.75 days), followed by the S4 and S5 seasons. The initiation of flowering took longer in the S2 and S3 seasons. Full flowering (DFF) occurred sooner in the growing seasons S1, S4, and S5 (45, 47, and 47 days, respectively) than in the S2 and S3 seasons. DFH was the earliest in S5, followed by S1, i.e., the harvest in S5 started earlier than it started in the other seasons. The growing season that started the harvest in the longest period was S3 (85.25 days after sowing) (Figure 2).

Regarding the relationship between the emission of nodes and the STa, in season S1, a longer thermal time was necessary for the emergence of a node in the pea plant (67.36 °C day^{-1} node^{-1}). The responses were similar among the other growing seasons, requiring 54.90, 52.15, 51.76, and 47.86 °C day^{-1} for the successful emergence of the node in seasons S2, S3, S4, and S5, respectively (Figure 2).

Carvalho et al. (2012) studied *Pisum sativum* L. in a protected environment and maintained the temperature of the study area close to its ideal range. The average temperature inside the greenhouse was 20 °C (9 °C – 32

°C). Their results were very similar to those recorded for the S3 cultivation time in this study regarding the duration of the phenological phases (47 days until the beginning of flowering and 87 days until the beginning of harvest). In S3, the average air temperature during the crop cycle was around 15 °C, and negative temperatures (-1.8 °C)

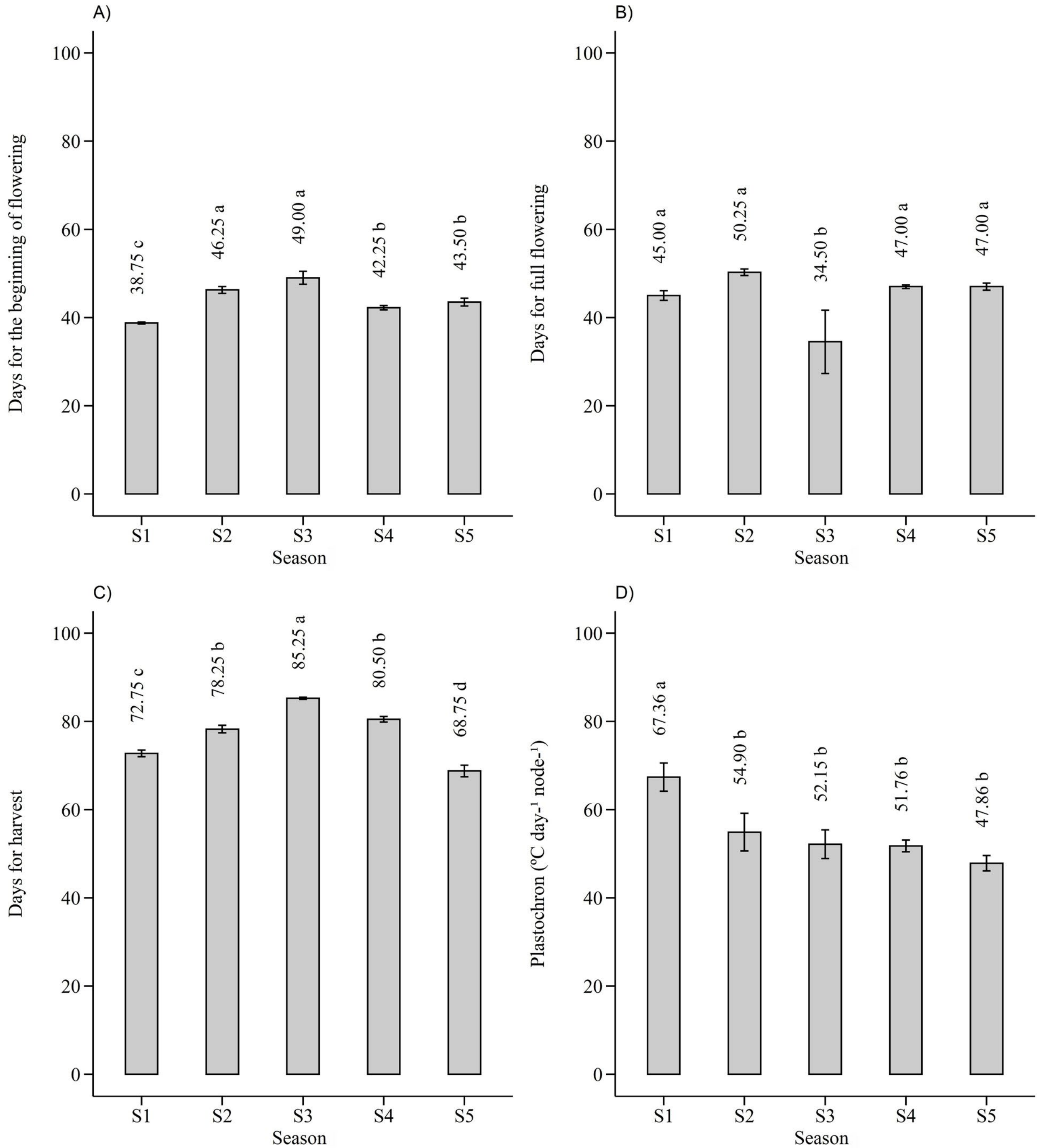

Figure 2: Phenology of the pea plants grown in different growing seasons. The mean values followed by the same letter are not different, as determined by the Scott-Knott test at 5% probability.

occurred 55 days after sowing, during which the plants were in the flowering and critical development phases. Although very low temperatures during these phases can damage crops, this season was still the most productive. Similar results of higher productivity in areas with an average temperature close to that found in S3 were reported by Roro et al., (2016the impact of solar UV on growth and production potential of commercial pea (Pisum sativum), who studied the behavior of *Pisum sativum* L. and found that cultivation at higher altitudes increased the number of fruits per plant (by 2–4 times) compared to cultivation at a lower altitude (by 1–2 times). The average air temperature during the crop cycle was 13 °C at the highest altitude and 20 °C at the lowest altitude.

Our findings showed that the greatest thermal requirement of this pea cultivar in the S1 growing season was around 800 °C day^{-1}, which led to the emergence of 12 nodes per plant. In the S4 growing season, it required less accumulated thermal sum (about 700 °C day^{-1}) for the emergence of the same number of nodes. In the S2, S3, and S5 seasons, 10, 11, and 11 nodes emerged, respectively, until the full flowering of the crop (Figure 3). Although the emergence of the first flowers and the start of flowering were sooner in S1, it did not have the same characteristics for the emergence of leaves.

Until full flowering, in the S2 and S3 seasons, in which a lower thermal sum was required, the number of total nodes was lower due to the shorter photoperiod and low temperatures during the growing season at that time of year, which resulted in the longest crop cycle. These conditions were favorable for the cultivation of *Pisum sativum* L., as they showed higher productivity in these two growing seasons.

The thermal sum accumulated in each stage of development of *Pisum sativum* L. was different across the growing seasons. As Sta is a more accurate parameter than the days of the civil calendar for plant evaluation, Sta should be used to define the size of the cycle. The cycle was longer in S3 and S1 than in S2, S4, and S5. In all growing seasons, a higher Sta was observed in the ATSFH phase, since in this phase, the formation and filling of the grains occurred until the time of harvest (Figure 4).

The average air temperature plays an important role in quantifying the thermal sum, which can be used to predict and reduce climatic risks during the crop cycle. The information on thermal needs can be used to predict the duration of the plant cycle. The knowledge of agroclimatic needs contributes to agricultural planning, helping in estimating the harvest date and also the rational commercialization of the grains without any conflict with the interest of farmers (Cavalcante et al., 2020). It also helps in understanding and making decisions to choose the best sowing times based on climatic estimates for the crop cycle, allowing farmers to avoid overlapping critical periods with climatic stresses that might compromise production. In this study, the total culture cycle was around 2,000 °C day^{-1}. Barbano et al. (2002) studied pea culture and found that in their experiments, 713.7 °C day^{-1} was necessary for the plants to start flowering and accumulated a total STa of 1,359 °C day^{-1} from emergence to harvest.

The accumulated thermal sum is widely used to understand the time required for the appearance of two new nodes in dicotyledonous plants; this measure is known as plastochron, and it is used to quantify the stages of plant development (Streck, N. A. et al., 2008; Martins et al., 2011). In this study, S2 and S3 showed lower results for plastochron, i.e., the nodes emerged faster in these growing seasons than in the other growing seasons, and thus, the photosynthetic efficiency was greater in these two seasons. Higher photosynthetic efficiency was related to the faster emergence of the nodes, which resulted in the development of more leaves and a greater leaf area. Due to this reason, the leaves of the plants in S2 and S3 intercepted more photosynthetically active radiation and converted the raw materials into photoassimilates, which increased their productivity.

By evaluating the differences in the number of pods, we found that S2 (13.95 pods per plant) showed the highest number of pods, while S1 and S4 showed the lowest numbers (Figure 5A). Because of this reason, the pod mass variable followed the same trend, i.e., heavier pods occurred at S2 and S3 (67 g per plant ±in each), while lighter pods occurred at S1, S4, and S5 (Figure 5B). By quantifying the productivity of the pea crop per unit area, we found that the highest yields occurred in S2 and S3 (6,700.00 and 6,795.10 kg ha^{-1}, respectively), and pod mass and the number of pods contributed to the greatest productivity. Lower yields were recorded in S1, S4, and S5 (2,430.55, 3,644.44, and 3,286.62 kg ha^{-1}, respectively) (Figure 5C).

In southern Brazil, *Pisum sativum* L. is usually sown in July and harvested in October, coinciding with milder temperatures but also overlapping with the rainy season, which lowers seed production and quality, besides greatly increasing the incidence of fungal infection (Giordano et al., 1997). The high oscillation of the air temperature observed during the cultivation cycle in this study might have limited plant productivity in the S1, S4, and S5 seasons. For S4 and S5, temperatures above the optimum probably caused the loss of productivity.

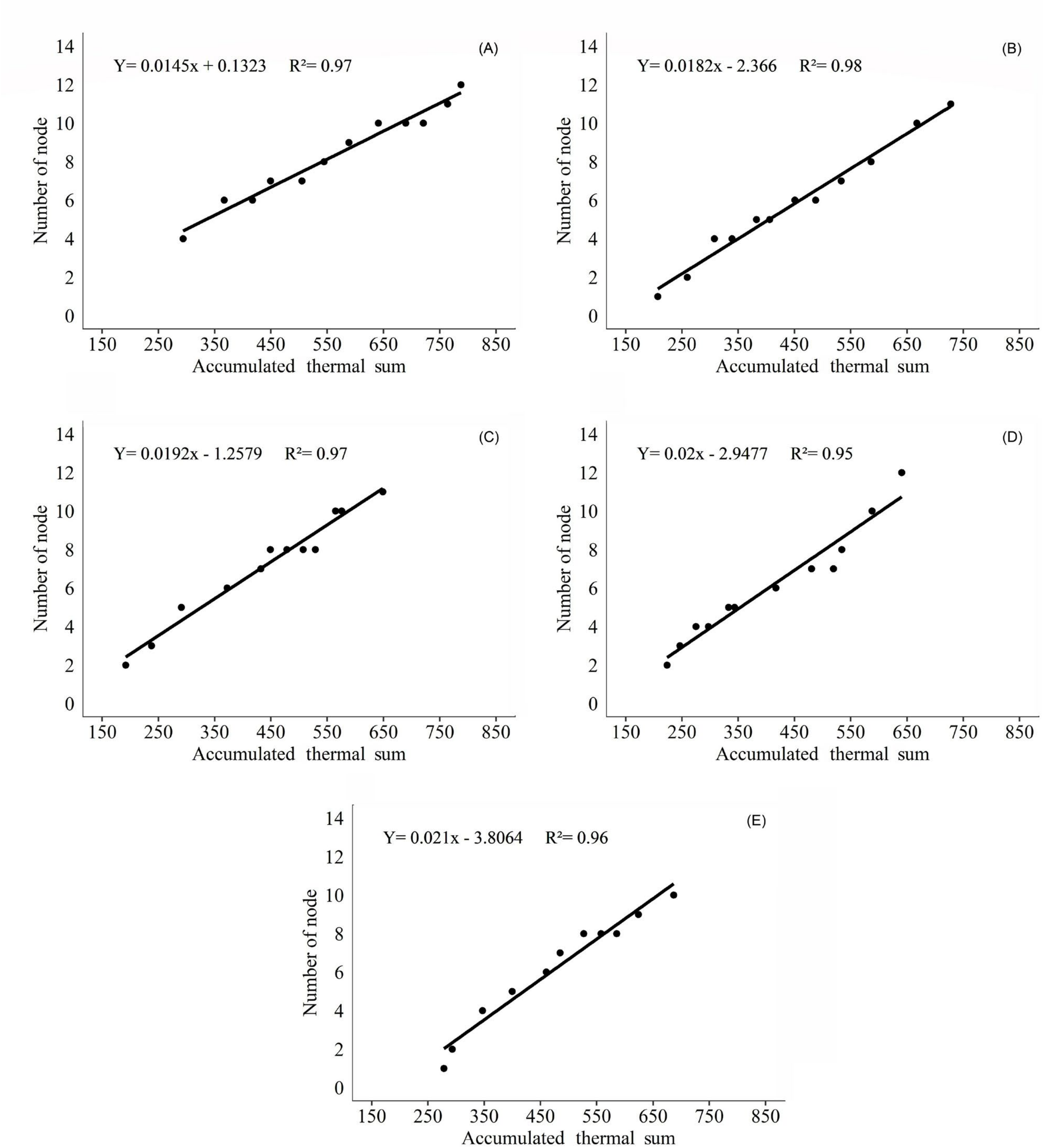

Figure 3: Linear regression was performed to estimate the plastochron of pea plants grown in different growing seasons. A) Season 1, B) Season 2, C) Season 3, D) Season 4, and E) Season 5.

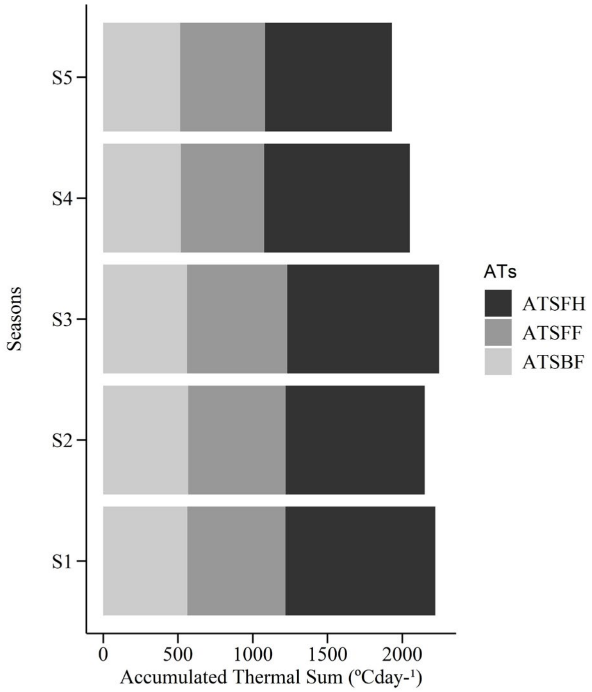

Figure 4: The cumulative thermal sum for the beginning of flowering (ATSBF, °C day^{-1}), the accumulated thermal sum for full flowering (ATSFF, °C day^{-1}), and the accumulated thermal sum for the beginning of the harvest (ATSFH, °C day^{-1}) for peas grown in different growing seasons.

The contribution of the first two main components (PC1 and PC2) was 64.15% and 15.14%, respectively; thus, the accumulated contribution rate was above 79%, which indicated that a significant percentage of the variability was extracted using the first two axes (Figure 6). The relationship between the variables DFH and DFF, determined via ANOVA, was also found in the results of the PCA. As the number of days to the start of flowering increased, the number of days to full flowering also increased, which in turn increased the number of days to the beginning of the harvest and extended the crop cycle.

The vectors of the variables MP and Prod in the same direction and on the path to the biplot showed a direct relationship between the mass of the pods and production. This relationship was expected because productivity increases with an increase in the mass of pods. We found a negative relationship between PLAS and NP, which indicated that as the plastochron increased, the number of pods decreased, i.e., when the emergence of the nodes took longer, the production of pods was lower, and consequently, productivity was also low. This pattern occurred in S1, where the plastochron was higher, and production was lower.

The responses differed across the growing seasons. For example, S2 and S3 were more productive, as they are shown on the right of the center of the graph (Figure 6), on the same side as the variables in the first and fourth quadrants, and at a positive position. However, periods S1, S4, and S5 were not very productive since they are shown on the opposite side of the productive variables in the second and third quadrants (Figure 6).

The negative relationship between PLAS and NP indicated that when it took longer for the nodes to emerge, pod production was lower, which in turn caused lower productivity. Lower NN indicates fewer leaves, lesser leaf area, lesser sunlight interception, and hence, lower production. This occurs because photosynthesis depends directly on the interception of light and its conversion into chemical energy (Favarin et al., 2002). Several studies investigated different plant cultures and reported that low leaf area results in lower productivity. Netto et al. (1995) studied the behavior of *Pisum sativum* L. and found that the reduction of water potential in the soil was associated with lesser leaf area and lower productivity. Durli et al. (2020) evaluated the performance of different cultivars of *Glycine max* L. The plants underwent artificial defoliation in the vegetative (V6) and reproductive (R3) periods; the researchers found that the cultivars showed a decrease in productivity. Silva et al. (2020) evaluated the effects of the reduction of leaf area in *Zea mays* L., due to artificial defoliation and diseases. They found that productivity decreased regardless of the type of defoliation. These findings indicated that the photosynthetically active leaf area is important for achieving high productivity.

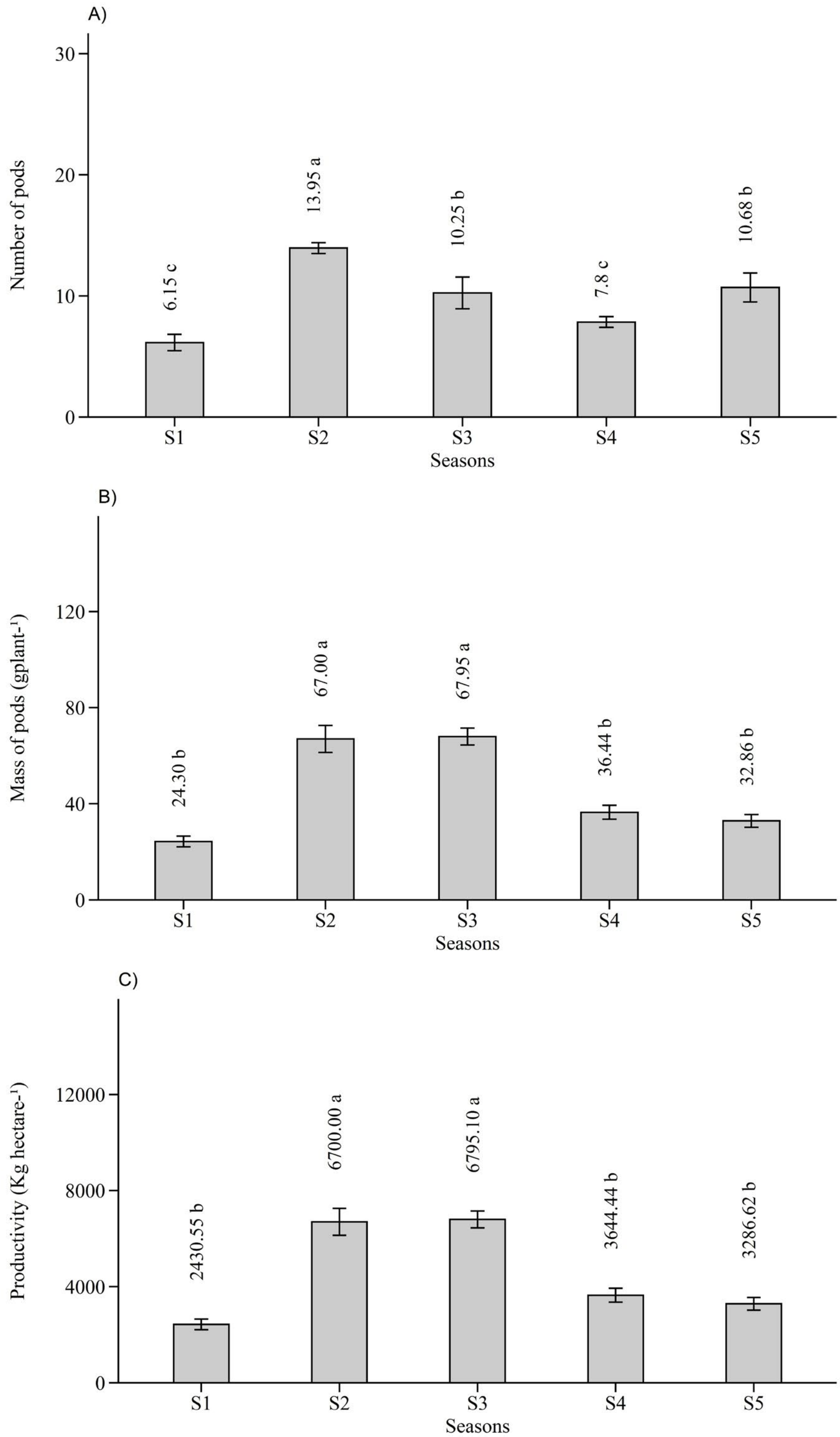

Figure 5: The number (un.) and mass of pods (g plant^{-1}) and productivity (kg ha^{-1}) of peas grown in different growing seasons. The mean values followed by the same letter indicate that the values are not significantly different, determined by the Scott-Knott test at 5% probability.

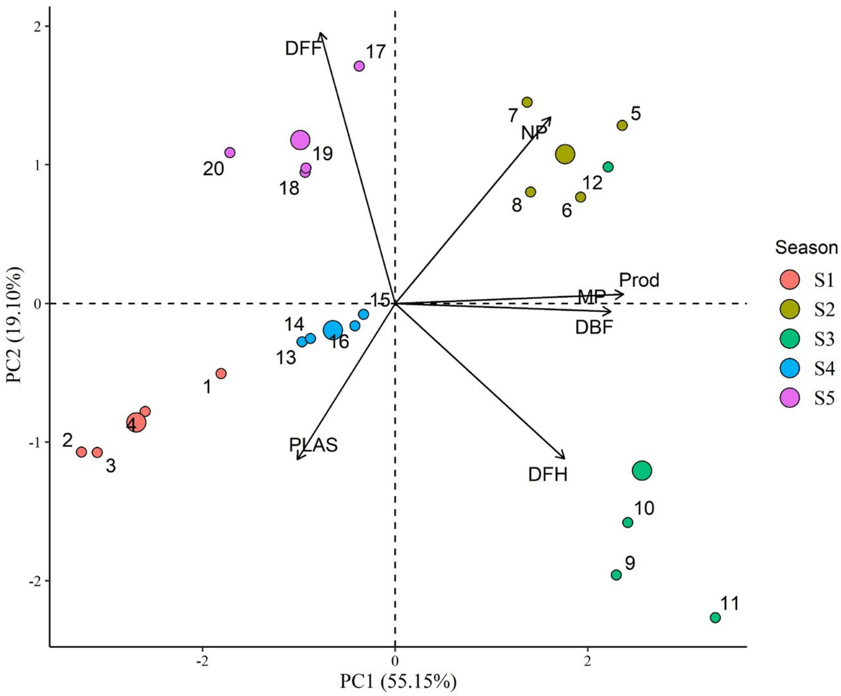

Figure 6: Biplot of different pea growing seasons (IPCA1 x IPCA2). DBF: the number of days to start flowering, DFF: the number of days to full flowering, DFH: the number of days to start harvesting, PLAS: plastochron, NP: number of pods, MP: pod mass, and Prod: productivity. Colored dots on the biplot represent individuals corresponding to different seasons.

CONCLUSIONS

We found that seasons 2 and 3 were the most productive and showed lower results for plastochron, i.e., shorter thermal time for the emergence of nodes. The thermal sum until full flowering was lower, and the photoperiod was shorter. These factors, along with low temperatures during the growing season, resulted in a longer crop cycle, which led to higher photosynthetic efficiency. In seasons 1, 4, and 5, the plants reached the flowering stage earlier, and the pod mass was lower, which resulted in lower productivity.

AUTHOR CONTRIBUTION

Conceptual Idea: Lambrecht, D.M.; Diel, M.I.; Methodology design: Lambrecht, D.M.; Diel, M.I.; Lúcio, A.D.; Data collection: Lambrecht, D.M.; Diel, M.I.; Tischler, A.L.; Data analysis and interpretation: Lambrecht, D.M.; Diel, M.I.; Lúcio, A.D.; Sgarbossa, J.; Peripolli, M.; and Writing and editing: Lambrecht, D.M.; Diel, M.I.; Lúcio, A.D.; Sgarbossa, J.

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