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Phenology, mass accumulation patterns and growing degree days in common bean

Fenología, patrones de acumulación de masa y grados día de crecimiento en frijol común

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ABSTRACT

The common bean represents approximately half of the global production of leguminous grains. Brazil is the world's largest producer, as it is a primary source of protein in the population's diet. This research aimed to relate the phenological stages of the common bean under greenhouse conditions and establish a connection between mass accumulation patterns and the environment, specifically temperature, by estimating Growing Degree Days (GDD) during two periods with different temperatures throughout the year. Once a week, after seed germination, plants were collected and weighed to quantify fresh and dry mass to determine biomass allocation within the plant. This procedure was carried out until the plant's growth cycle was completed. The environment was systematically monitored using a thermo-hygrometer. GDD accumulation was estimated for the phenological stages from V0 to R8 during two evaluation periods. Fresh and dry mass accumulation was fitted to logistic models that generated sigmoidal-type curves. It was observed that the bean plants accumulated 803.5 GDD in the first period and 808.6 GDD in the second period, from V0 to R8, with different fresh and dry mass accumulation patterns in various plant organs. This demonstrates the relationship between temperature and the growth and development of the bean plant and can provide important information for selecting the optimal planting time for this significant crop.

Keywords: growth, legume; logistic model; *Phaseolus vulgaris L.*; temperature; thermal requirement.

RESUMEN

El frijol común representa aproximadamente la mitad de la producción mundial de granos de leguminosas. Brasil es el mayor productor mundial, ya que es una fuente básica de proteínas en la dieta de la población. El propósito de esta investigación fue relacionar las etapas fenológicas de frijol común bajo condiciones de invernadero y establecer una conexión entre los patrones de acumulación de masa y el ambiente, específicamente con la temperatura, mediante la estimación de los Grados Día de Crecimiento (GDC) durante dos periodos con diferentes temperaturas en el año. Una vez a la semana, después de la germinación de las semillas, se recolectaron y pesaron plantas para cuantificar la masa fresca y seca, con el fin de determinar la asignación de biomasa de la planta. Este procedimiento se realizó hasta que se completó el ciclo de crecimiento de la planta. El ambiente fue monitoreado sistemáticamente utilizando un termohigrómetro. Se estimó la acumulación de GDC para las etapas fenológicas de V0 a R8 durante dos periodos de evaluación. La acumulación de masa fresca y seca se ajustó a modelos logísticos que generaron curvas de tipo sigmoidal. Se observó que las plantas de frijol acumularon 803.5 GDC en el primer período y 808.6 GDC en el segundo período, desde V0 hasta R8, con diferentes patrones de acumulación de masa fresca y seca en los distintos órganos de la planta. Esto demuestra la relación entre la temperatura y el crecimiento y desarrollo de la planta de frijol, y puede proporcionar información importante para seleccionar el momento óptimo de siembra para este importante cultivo.

Palabras clave: crecimiento; leguminosa; modelo logístico; *Phaseolus vulgaris* L.; temperatura, requerimientos térmicos.

INTRODUCTION

The common bean (*Phaseolus vulgaris* L.) is the most important representative of the Fabaceae family among vegetable crops (Lucio *et al*., 2016) and plays a crucial role in food security, for being an important source of nutrients in the human diet (Câmara *et al*., 2013). Brazil is the world's largest producer of beans, as this legume is a fundamental source of dietary protein for the Brazilian population (Ferreira & Freitas, 2021). Bean production in Brazil spans from the south to the north and is distributed across three seasons. The wet and dry growing seasons account for the largest area of common bean production under a rainfed system. At the same time, winter planting occurs in limited areas and is carried out under a full irrigation system (Heinemann *et al*., 2016). Thus, better environmental characterization provides information that maximizes the productive potential of genotypes in regions of importance for production (Heinemann *et al*., 2022).

Phenology is the study of the changes occurring in plants from emergence to harvest maturity and how these changes are affected or influenced by the environmental conditions of the region, with temperature being one of the most important driving forces for the development and growth of crops at all phenological stages (Salazar-Gutierrez *et al*., 2013; Cavalcante *et al*., 2020). Thus, to reach each of the phenological stages, depending on the type of plant, there is a specific temperature requirement that must be met beforehand (Sikder, 2009). Nowadays, it is recognized that accumulated temperature is the main factor influencing phenological changes, as an increase or decrease in temperatures generally accelerates or delays phenological development (Asseng *et al*., 2011).

In agricultural systems, there is a combination of time and temperature known as thermal time, heat degree days, growth degree days, or physiological time (Yang *et al*., 1995; López et al., 2010; Romero-Cuervo *et al*., 2022). The growing degree days theory (GDD) represents the amount of accumulated heat to which the plant is exposed throughout the day, or the daily accumulation of energy within the temperature ranges tolerated by the plants, expressed in terms of their cardinal temperatures (Souza *et al*., 2013), the minimum-base and maximum-base temperatures.

Growing degree days (GDD) is a temperature-based approach frequently used as a meteorological indicator to assess crop development and is a reliable predictor of the development of many crops throughout the growing season (Ishaq *et al*., 2017). One of the most commonly used indices is the GDD, where accumulating these for each phenological stage is relatively constant and independent of the planting date to estimate plant growth and development. However, there are differences between hybrids, varieties, or cultivars of the same species (Hoyos *et al*., 2012; Leguízamo-Medina *et al*., 2022; Romero-Cuervo *et al*., 2022). Generally, the GDD are used to account for the effects of temperature on development and to analyze the timing of biological processes in plants, such as mass gain or organ emergence (Colauto *et al*., 2006). They can also be used to determine an appropriate planting date, the growing period, and the corresponding physiological characteristics of crops under specific climatic conditions (Anandhi, 2016).

To describe and analyze the growth and development of cultivated plants, a series of methodologies are used to understand their response pattern under natural, semi-natural, or controlled conditions (Hunt, 2017). Functional analysis growth is performed based on simple primary data, such as weights, areas, and volumes, which reflect changes in the plant system (Leguízamo-Medina *et al*., 2022; Romero-Cuervo *et al*., 2022). These are evaluated at frequent time intervals using a small number of plants (Hunt, 2017) and modeled through growth curves that describe natural events involving response changes over time (Szabelska *et al*., 2010). These curves are generated using nonlinear regression models, an important alternative for analyzing data from agricultural processes (Archontoulis & Miguez, 2015). Nonlinear models offer significant advantages over linear regression models, such as parsimony in the case of simple nonlinear models and the biological interpretability of the estimated parameters (Fernandes *et al*., 2014).

Thus, crop growth and development models based on processes can aid in understanding the mechanisms involved in the plant's responses to the environment (Lima Filho *et al*., 2013). Therefore, the research aimed to determine the growth and development of the common bean associated with its phenology and its relationship with temperature, using growing degree days as the estimator. This information can become an essential tool for improving planting date planning by producers of this important crop.

MATERIAL AND METHODS

Location. The research was conducted under greenhouse conditions during two periods of the year: the first from April to June, corresponding to the autumn season, and the second from July to September, corresponding to the winter season (Ávila *et al*., 2014), located at the Federal University of Lavras-MG campus (21°14′43″S, 44°59′59″E; 919 m). Temperature and relative humidity conditions (Figure 1) were monitored using a Minikin QTHi model thermo-hygrometer, and small dataloggers with PAR sensors.

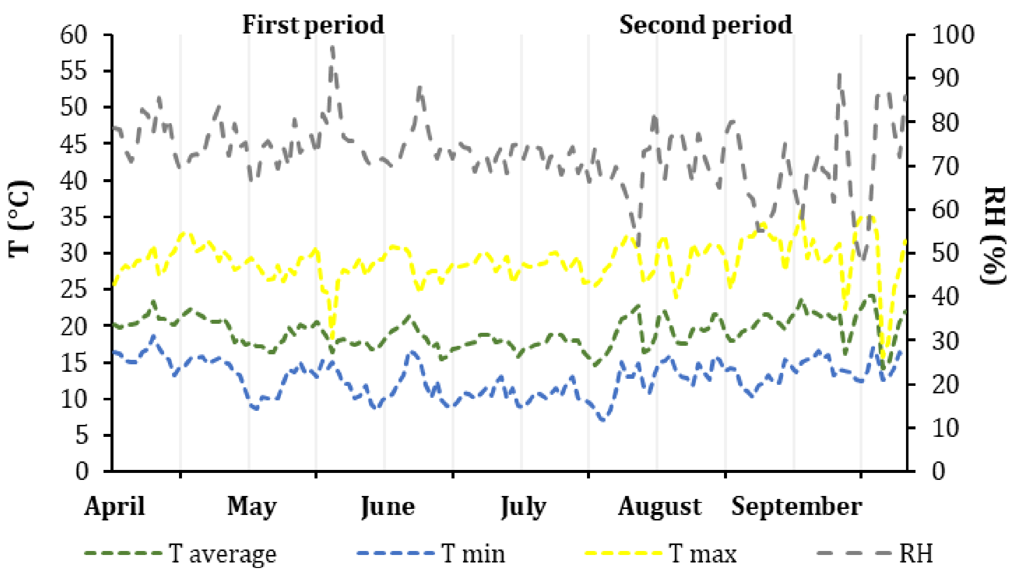


Figure 1. Temperature (T) and relative humidity (RH) in the greenhouse during the research development.

Plant material. Common bean (*Phaseolus vulgaris* L.) plants of the 'BRSMG Marte' variety were used as plant material. This variety is one of the new red bean cultivars recommended by the Agricultural Research Corporation of Minas Gerais (EPAMIG), the Federal University of Viçosa (UFV), the Federal University of Lavras (UFLA), and the Brazilian Agricultural Research Corporation (Embrapa). This variety aims to meet the regional preferences of the Zona da Mata region in Minas Gerais, given its bright red beans, resistance to angular leaf spots, upright plant architecture, and erect growth habit, an important trait for mechanical harvesting (Guimarães, 2021).

Methodology. In each evaluation period, the research began with the planting of 45 pots filled with a mixture of clayey soil and sand (2:1 ratio). Four seeds were sown in each pot to prevent losses due to handling or phytosanitary issues, but only one plant per pot was retained. The nutritional plan was adjusted according to the crop requirements described by de Oliveira *et al*. (2018), with adjustments for nitrogen (N), phosphorus (P), and potassium (K) using simple fertilizer sources such as urea, MAP, and KCl, along with micronutrients applied through YaraMila® COMPLEX fertilizer. The plants were irrigated to maintain the substrate at approximately 80% of the available water, monitored using a capacitive sensor (model ML2x Theta Probe, Delta-T Devices© Ltd., Cambridge, UK), connected to a computer running DeltaLINK© software, version 3.8.2. Weekly, five plants were collected until reaching the R8 phenological stage. Fresh and dry mass variables were measured for each organ (root, stem, leaves, and bean pods) and the entire plant. Five bean pods per plant were analyzed to determine their total fresh and dry mass. This procedure was carried out identically during both evaluation periods.

The accumulation of growing degree days (GDD) was determined using the following equation (Yang *et al*., 1995):

$$GDD = Tm\text{-}Tbase \quad \text{(Equation 1)}$$

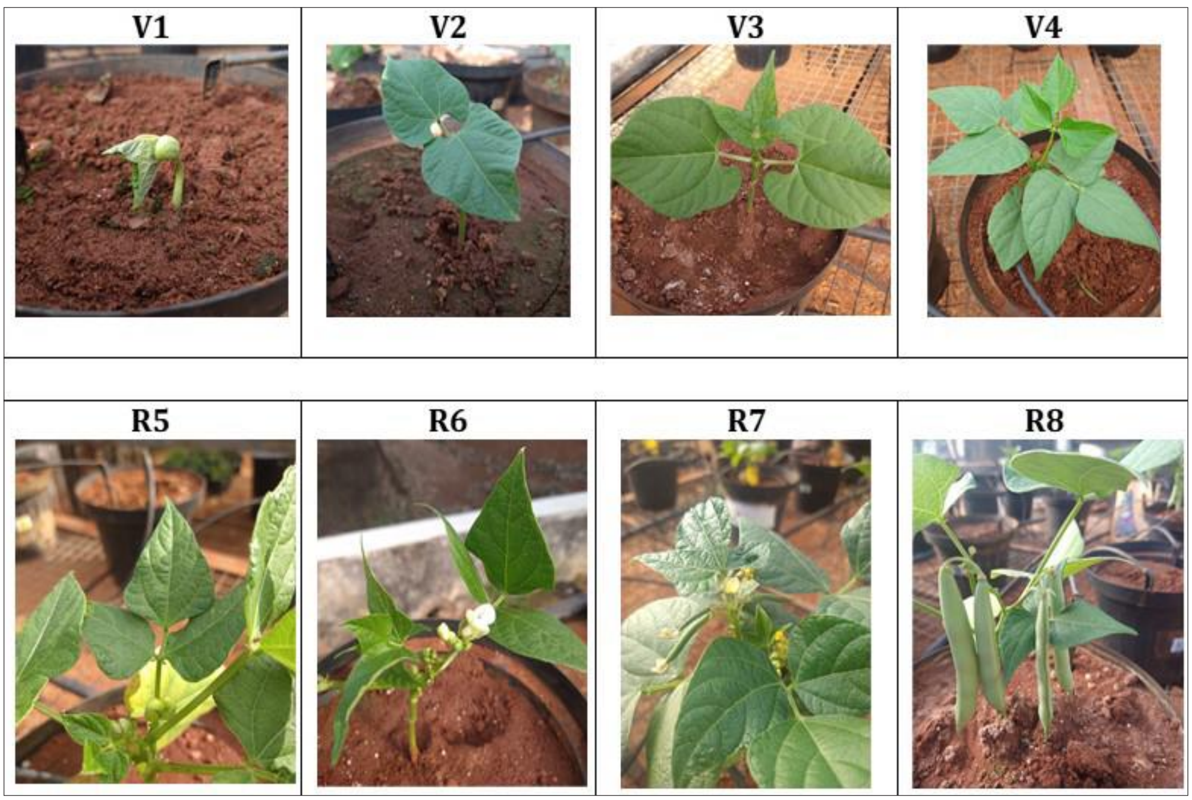
Where Tm is the daily average air temperature, calculated based on the temperature recorded every 30 minutes using the Minikin datalogger; Tbase, or the crop's critical temperature, is the lower temperature at which metabolic processes begin to be affected. The base temperature used was 8.3 °C, as reported for beans by Barrios-Gómez & López-Castañeda (2009).

The dependent variables quantified were total fresh mass and fresh mass per organ (root, stem, leaves, and bean pods). Five plants at each sampling point were divided by organs and weighed using a precision scale. Dry mass was measured in the plants for which fresh mass was quantified at each sampling point after undergoing a drying process at 65 °C in a forced-air circulation oven until a constant weight was reached (approximately 72 hours).

Statistical analysis. A descriptive analysis was conducted to determine the mean and standard error at each sampling point. Based on the obtained data, the response pattern of each variable concerning growing degree days was plotted. The most suitable regression model for each dependent variable was then determined. Descriptive statistics and figures were created using Excel, and the functional growth analysis was performed using the 'sicegar' package in the R statistical software (R Core Team, 2022).

RESULTS AND DISCUSSION

Phenology description. Based on the phenological scale proposed by de Oliveira *et al*. (2018), 4 stages were identified in the vegetative phase (V1 to V4) and 4 stages in the reproductive phase (R5 to R8) for the 'BRSMG Marte' common bean plant (Figure 2). When analyzing the response pattern in the accumulation of chronological time and thermal time, it was observed that during the first evaluation period from April to June (autumn season), the plants required 40 days with an accumulation of 467.6 GDD to progress from stage V1 to V4, and during the reproductive phase, 35 days were required, with an accumulation of 335.9 GDD to progress from stage R5 to R8 (Figure 2). In the second evaluation period from July to September (winter season), 46 days were required with an accumulation of 473.5 GDD to progress from stage V1 to stage V4. During the reproductive phase, 27 days were required with an accumulation of 335.1 GDD to progress from stage R5 to R8 (Figure 2).



*Accumulated data phenological stages first period (days, GDD). **V1**: 11, 145.8; **V2**: 6, 78.9; **V3**: 18, 186.6; **V4**: 5, 56.3; **R5**: 6, 55.9; **R6**: 8, 80.9; **R7**: 7; 70.7; **R8**: 14, 128.4. **Total**: 75, 803.5. Accumulated data phenological stages second period (days, GDD). **V1**: 17, 150.7; **V2**: 7, 80.8; **V3**: 17, 186.2; **V4**: 5, 55.8; **R5**: 4, 51.2; **R6**: 7, 93.5; **R7**: 6, 70.4; **R8**: 10, 120.0. **Total**: 73, 808.6.

Figure 2. Description of the phenological stages and the relationship between phenology, chronological time (days), and growing degree days (GDD) in common bean cv. 'BRSMG Marte' over two evaluation periods.

The variation observed in chronological time between the first and second evaluation periods can be associated with increased or decreased average temperatures. For the first evaluation period (autumn season), the vegetative phase began with an average temperature of 20.8°C and ended with 19.3°C, and the reproductive phase began with an average temperature of 19.3°C and ended with 18.1°C. In contrast, during the second period (winter season), the vegetative phase began with an average temperature of 18.8°C and ended with 20.6°C, while the reproductive phase began with an average temperature of 20.6°C and ended with 23.3°C (Table 1).

Table 1. Environmental data recorded during the research development.

	Environmental variables						
	T (°C)			RH (%)			PAR (μmol photons m^{-2} s^{-1})
Month	**Min**	**Max**	**Avg**	**Min**	**Max**	**Avg**	**Avg**
April	14,9	31,1	20,8	71,1	85,5	78,1	398,1
May	8,7	32,8	19,3	65,7	97,2	75,2	417,4
June	8,4	30,8	18,1	68,1	88,7	74,3	436,9
July	7,1	32,4	18,8	68,1	75,6	72,6	456,9
August	10,3	35,9	20,6	51,9	83,0	70,6	428,5
September	13,3	35,8	23,3	47,2	91,0	68,2	395,9

According to Dhillon *et al*. (2020), a lack of understanding of morphological scales creates significant complications in decision-making, such as inappropriate timing for planting or harvesting crops. Conversely, determining phenology associated with adjusted estimators like GDD allows for the development of growth models based on real environments and represents the exact conditions under which the crop developed. This approach provides a specific and refined method and a methodology that reduces the uncertainty and complexity generated by subjective morphological scales, which vary from place to place.

Growth in plants or their organs is defined as increased dry mass, volume, length, or area resulting from cell division, expansion, and differentiation (Lambers & Oliveira, 2019). During both evaluation periods, bean plants of the BRSMG Marte variety exhibited all phenological stages described by de Oliveira *et al*. (2018) (Figure 2). However, variations in biomass accumulation and growth patterns were observed, caused by the temperature differences between the two periods. Plants exposed to a greater number of days with low temperatures during the vegetative phase (winter season) showed a 60.7% reduction in total dry mass by the end of the vegetative phase, which resulted in a 64.6% loss in dry mass during the reproductive phase. Based on these findings, temperature is identified as a determining factor in growth and development processes, influencing the dynamics of plant biomass accumulation (Figures 3, 4, and 5).

Defining phenological phases and accumulating Growing Degree Days (GDD) is a key tool for designing a practical and reliable crop management plan by observing the plant's phenological stages. According to Cavalcante *et al*. (2020), priority should be given to water supply and fertilization during the vegetative phase. This phase is characterized by the maximum growth of foliar structures, and nutritional deficiencies or water deficits can reduce leaf size and number. Leaves are responsible for the production of photoassimilates, which directly influence the growth of the shoot and root systems, ultimately affecting grain yield.

Nonlinear models and functional growth analysis. The statistical analysis performed on the growth and development of the common bean presented means adjusted based on standard error, allowing for growth analyses using a nonlinear logistic model for the variables of fresh root mass, upper part mass (leaves and stem), and total mass, as well as dry root mass, upper part mass, and total mass, in both evaluated periods. The models showed coefficients of determination (R^2) above 0.9, indicating they are well-suited to explain each of the biological phenomena studied, using growing degree days (GDD) as the dependent variable (Tables 2 and 3).

Table 2. Equations of the parameters evaluated in the determination of growth of the common bean cv. BRSMG Marte from April to June 2023. *Shoots: stem + leaves; GDD: Growing Degree Days.

Variable	Equation	R^2
Fresh mass root	Y=21.2483/(1+EXP(-0.03156*(GDD-280.51)))	0.9
Fresh mass shoots*	Y=13.108/(1+EXP(-0.012*(GDD-263.17)))	0.9
Fresh mass total	Y=34.2026/(1+EXP(-0.01953*(GDD-272.38)))	0.9
Dry mass root	Y=2.4150/(1+EXP(-0.03874*(GDD-272.38)))	0.9
Dry mass shoots*	Y=3.1459/(1+EXP(-0.0099*(GDD-347.64)))	0.9
Dry mass total	Y=5.2226/(1+EXP(-0.01615*(GDD-300.82)))	0.9
Fresh mass bean pods	Y=27.6291/(1+EXP(-0.02861*(GDD-690.16)))	0.9
Dry mass bean pods	Y=8.8839/(1+EXP(-0.03952*(GDD-734.42)))	0.9

Table 3. Equations of the parameters evaluated in the determination of growth of the common bean cv. BRSMG Marte from July to September 2023. *Shoots: stem + leaves. GDD: Growing Degree Days.

Variable	Equation	R^2
Fresh mass root	Y=12.059/(1+EXP(-0.0330*(GDD-295.73)))	0.9
Fresh mass shoots*	Y=8.7482/(1+EXP(-0.01441*(GDD-250.32)))	0.9
Fresh mass total	Y=21.5399/(1+EXP(-0.02150*(GDD-286.66)))	0.9
Dry mass root	Y=1.2501/(1+EXP(-0.0302*(GDD-301.65)))	0.9
Dry mass shoots*	Y=1.6972/(1+EXP(-0.01373*(GDD-285.80)))	0.9
Dry mass total	Y=3.0293/(1+EXP(-0.01795*(GDD-298.88)))	0.9
Fresh mass bean pods	Y=18.5806/(1+EXP(-0.0538*(GDD-711.01)))	0.9
Dry mass bean pods	Y=5.7600/(1+EXP(-0.1117*(GDD-786.50)))	0.9

Mass dynamic accumulation. A difference was observed in the accumulation of fresh mass at the organ level and total. During the growth period from April to June, the plants reached a maximum fresh mass accumulation of 21.8 g in the root and 12.71 g in the aerial part (leaves + stem). In contrast, from July to September, the plants achieved a fresh mass accumulation of 11.4 g in the root and 8.9 g in the aerial part. In both periods, the root had a greater mass due to higher water accumulation, indicating an adequate moisture level in the soil and, consequently, in the plant (Figure 3).

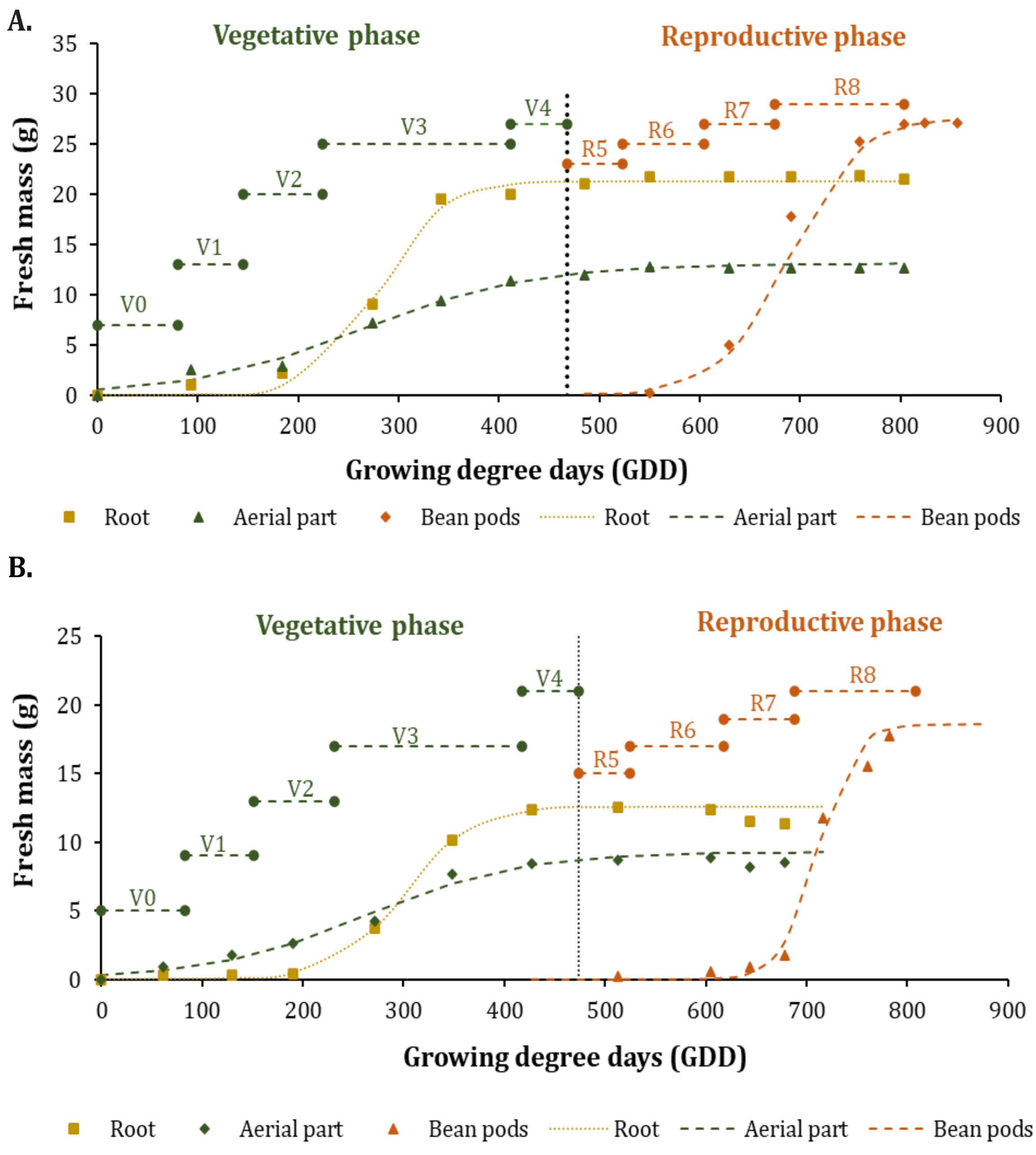
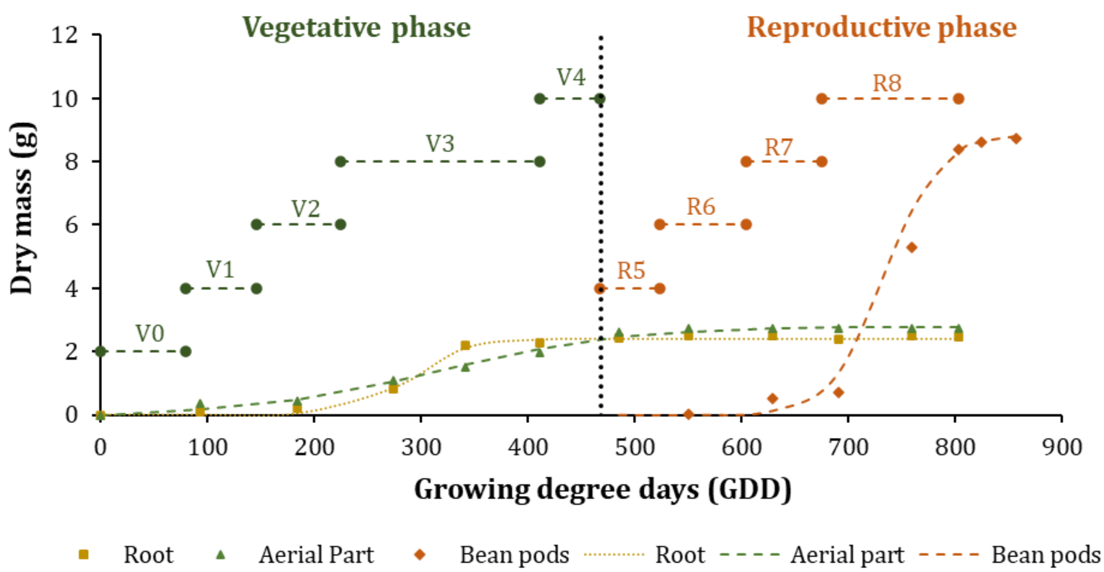


Figure 3. Growth curves based on fresh mass by organ and accumulation of GDD for common bean. A. First period: April-June; B. Second period: July-September.

The accumulation of dry mass also differed between the two evaluated periods. During the growth period from April to June, the bean plant reached a maximum dry mass accumulation of 2.5 g in the root and 2.7 g in the aerial part (leaves + stem). In contrast, from July to September, the plant achieved a dry mass accumulation of 1.2 g in the root and 1.7 g in the aerial part. It was observed that, unlike fresh mass, dry mass is symmetrically allocated between the root and the aerial part during both evaluated periods (Figure 4).

When analyzing total dry mass, it was noted that in the first evaluation period, there was a greater accumulation both in the vegetative phase, with a total dry mass of 5.1 g and an accumulation of 467.6 GDD, and in the reproductive phase (bean pods), with 8.37 g and an accumulation of 329.9 GDD. In comparison, in the second evaluation period, the vegetative phase reached a total dry mass of 3.1 g and an accumulation of 473.5 GDD, and the reproductive phase (bean pods) had 5.54 g and an accumulation of 330.0 GDD, showing a reduction of 40% in the vegetative phase and 33.8% in the reproductive phase (Figure 5).

A.



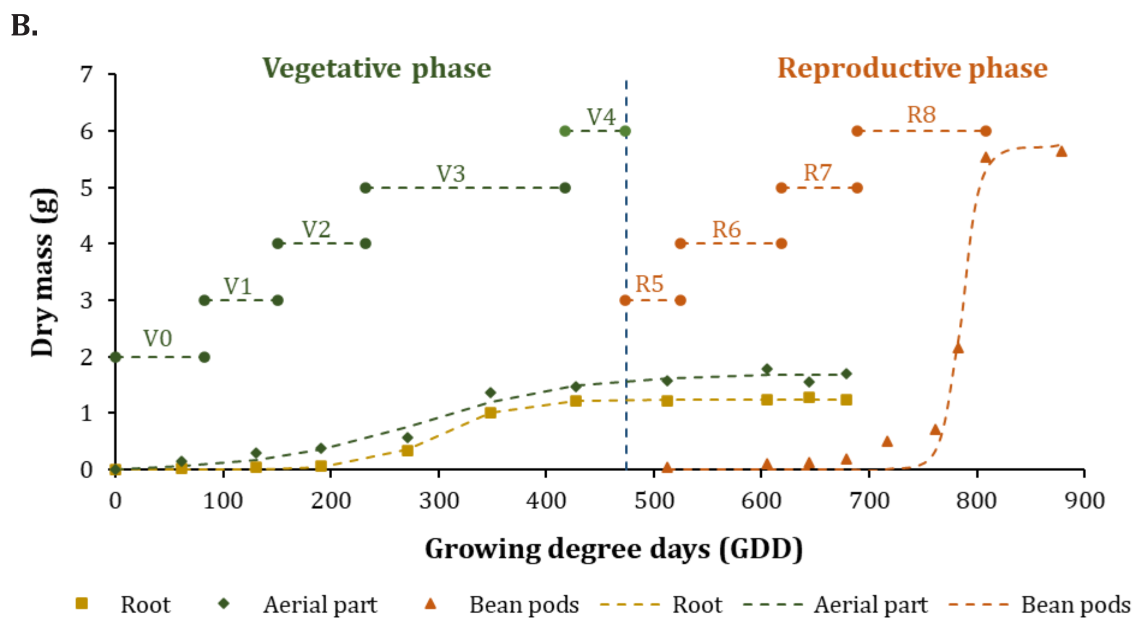


Figure 4. Growth curves based on dry mass by organ and accumulation of GDD for common bean. A. First period: April-June; B. Second period: July-September.

Upon analyzing the average temperature, it was observed that during the first evaluation period, higher average temperatures occurred during the vegetative phase and the beginning of the reproductive phase. In contrast, the second evaluation period recorded lower average temperatures during the vegetative phase and the beginning of the reproductive phase (Figure 1). Plants exposed to a higher number of days at low temperatures during the vegetative phase (second period) showed a 60.7% decrease in total dry mass by the end of the vegetative phase, resulting in a 64.6% loss in dry mass during the reproductive phase. This indicates that temperature is a determining factor in growth and development processes, influencing the dynamics of plant mass accumulation.

It was observed that plants in the first evaluation period exhibited better growth, with higher fresh and dry mass accumulation. This facilitated better preparation for the reproductive phase, where photoassimilates are primarily transported from the leaves to the pods, as pods serve as a major reservoir (Taiz *et al*., 2017). The time required for this process is crucial for the success of each variety, as it determines the final yield.

Temperature changes can lead to a reduction of up to 10% in the yields of various agronomic species, with minimum air temperature significantly affecting growth and phenology (Hatfield *et al*., 2011). In the case of the analyzed variety, a decrease of approximately 0.3°C in the average temperature during the vegetative phase (Table 1) was observed between the first and second periods, which resulted in a 33.3% reduction in bean pods dry mass (Figure 5). According to Knowles *et al*. (2006), there is a high probability that minimum air temperatures will change due to climate change, as maximum temperatures are influenced by local conditions, particularly soil water content and evaporative heat loss (Alfaro *et al*., 2006).

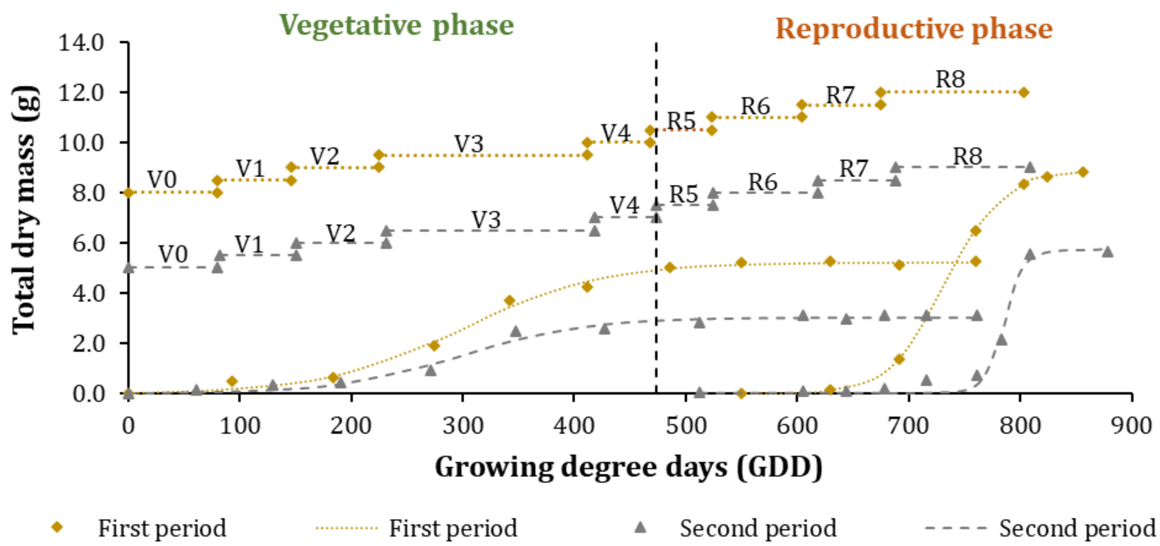


Figure 5. Growth curves based on Total dry mass (g) and accumulation of Growing degree days (GDD) for common bean, cv. BRSMG Marte. A. First period: April-June; B. Second period: July-September.

Therefore, in areas where climate change is expected to increase precipitation or where irrigation is prevalent, significant increases in maximum temperatures are less likely compared to regions prone to drought (Hatfield & Dold, 2019). Minimum air temperatures affect the nighttime respiration rates of plants and can reduce biomass accumulation and crop yields (Hatfield & Prueger, 2015). While increased minimum temperatures reduced rice yield, increased maximum temperatures had the opposite effect (Welch *et al*., 2010). However, under future warming scenarios, it was found that maximum temperatures could reduce yields if they approached the maximum tolerance limit (Hatfield & Prueger, 2015).

Hatfield & Prueger (2015) indicate that vegetative development (rate of node and leaf appearance) declines as temperatures fall below the species' optimal level because, for most plant species, vegetative development generally has a higher optimal temperature than reproductive development. Additionally, it is suggested that the interaction between temperature and other factors, such as photoperiod, can strongly affect plant phenology and directly impact agricultural productivity (Liu *et al*., 2020). Lack of heat during the growing period or inadequate temperatures during a particular growth stage will reflect in reduced quality and/or yield (Liu *et al*., 2020).

CONCLUSIONS

This research demonstrates the relationship between temperature and the patterns of total and organ-specific mass accumulation in the bean plant. It provides insights into aspects of phenology, growth, and the dynamics of growing degree days accumulation during both the vegetative and reproductive phases. This information becomes a crucial tool for selecting the optimal planting time for this important crop, meeting the needs of both producers and markets.

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Conflict of interest: The authors declare that there is no conflict of interest.

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