# Understanding the Temperature Range for Foliar Development of Neotropical Forest Species during the Seedling Stage: Implications for Biology and Ecology

**Lais Mello Araújo**
Federal Rural University of Rio de Janeiro: Universidade Federal Rural do Rio de Janeiro
**Fabrina Bolzan Martins**
Federal University of Itajubá: Universidade Federal de Itajuba
**Gustavo Bastos Lyra**
Federal Rural University of Rio de Janeiro: Universidade Federal Rural do Rio de Janeiro
**José Carlos Arthur Junior**
Federal Rural University of Rio de Janeiro: Universidade Federal Rural do Rio de Janeiro
**Emanuel José Gomes Araújo**
Federal Rural University of Rio de Janeiro: Universidade Federal Rural do Rio de Janeiro
**Rodolfo Cesar Real de Abreu**
Federal Rural University of Rio de Janeiro: Universidade Federal Rural do Rio de Janeiro
**Marcel Carvalho Abreu**
marcelc.abreu@gmail.com

Universidade Federal Rural do Rio de Janeiro https://orcid.org/0000-0002-6457-421X

**Research Article**

**Keywords:** plant development, temperature range, Growing Degree-Days, Heat accumulation, air temperature, experimental approach

**Posted Date:** August 24th, 2023

**DOI:** https://doi.org/10.21203/rs.3.rs-3267137/v1



**Version of Record:** A version of this preprint was published at International Journal of Biometeorology on January 3rd, 2026. See the published version at https://doi.org/10.1007/s00484-025-03088-y.

## Abstract

This study aimed to estimate the cardinal temperatures for the foliar development of seedlings from four forest species native to Brazilian biomes: *Handroanthus heptaphyllus*, *Tabebuia roseoalba*, *Ceiba speciosa*, and *Schinus terebinthifolia*. An experiment was conducted with ten sowing times between December 2019 and April 2021. Seven methods were employed to estimate the inferior cardinal temperature, the phyllochron concept for the optimal temperature, and mathematical models for the superior temperature. The results indicated significant variations in the inferior cardinal temperatures among the four species, ranging from 9.8°C to 11.5°C, as well as distinct optimal temperatures ranging from 22.7°C to 25.7°C. Furthermore, disparities were observed between species and sowing times concerning the determination of the phyllochron, with *Ceiba speciosa* exhibiting an average phyllochron ranging from 75.6 to 246.2 ºday$^{-1}$. These findings offer valuable insights into the biological and ecological aspects of native forest species and enhance our understanding of key parameters for modeling vegetal growth. However, the limited availability of species-specific information in the Brazilian biome raises concerns regarding the applicability of these models. In conclusion, this study successfully estimates the cardinal temperatures (inferior, optimal, and superior) for foliar development of four important forest species native to Brazilian biomes, thereby contributing to the knowledge base of forestry research.

## INTRODUCTION

The rise in temperature affects all life forms, particularly plants, which are sessile organisms with physiological activities directly influenced by temperature (Fagundes et al. 2021). Therefore, there is a growing concern about the potential impacts of temperature increases on plant development, specifically in Brazil, where projections indicate temperature increases ranging from 1.5°C to 5°C (IPCC 2013; Reis et al. 2021; Torres et al. 2021). Recent studies have demonstrated that these temperature increases are sufficient to alter the initial development rate of forest species, specifically during the seedling and sapling phases. As a result, the length of time that seedlings spend in nurseries and the management practices involved, such as increased irrigation frequency and the utilization of shading, may be affected (Lin et al. 2019; Fagundes et al. 2021; Reis et al. 2021). These changes have the potential to increase the operational costs of nurseries and compromise the quality of seedlings, thereby posing challenges for forest restoration and recovery programs (Costa and Streck 2018; Grossnickle and MacDonald 2018; Ferreira et al. 2019b; Florêncio et al. 2019; Martins et al. 2007; Martins and Streck 2007; Reis et al. 2021).

To project species behavior under different temperature scenarios, development models have been utilized (Fagundes et al. 2021; Reis et al. 2021; Martins et al. 2022). However, the accurate estimation of cardinal temperatures, which are species-specific thermal limits for plant development, is crucial as input data for these models (Ferreira et al. 2019a; Florêncio et al. 2019; Reis et al. 2021; Martins et al. 2022). Cardinal temperatures include the minimum (Tb) and maximum (TB) temperatures at which plant development ceases or becomes negligible respectively, while the optimal temperature (Tot) represents the maximum temperature for development (Martins et al. 2014; Freitas et al. 2017). Despite their importance, limited studies have determined the cardinal temperatures for forest species, particularly those native to Brazil. For instance, Fagundes et al. (2021), Ferreira et al. (2019a), and Martins et al. (2022) noted that the primary challenge in using development models for native species lies in the lack of input data, such as Tb, Tot, and TB.

To estimate Tb, various methods have been employed, including the minimum standard deviation method, the minimum coefficient of variation method (in days or degree days), regression coefficient, relative development (RD), and the least mean square error (MSE) method (Ferreira et al. 2019a, b; Freitas et al. 2017; Souza and Martins 2014; Yang et al. 1995). The phyllochron concept, which represents the thermal accumulation for leaf emergence, can be utilized to estimate Tot (Fagundes et al. 2021; Martins et al. 2007 and 2022). TB can be estimated using multiple functions based on plant development data under high-temperature conditions (Ferreira et al. 2019b; Silva et al. 2020). Typically, these methods require exposing plants to a wide range of temperatures, especially for Tb and TB, through multiple sowing dates (Freitas et al. 2017; Martins et al. 2014; Silva et al. 2020). Despite the widespread application of these methods (Bartz et al. 2017; Ferreira et al. 2019a, b; Freitas et al. 2017; Martins et al. 2007; Souza and Martins 2014), the specificities of each method under different climatic conditions and their suitability for native forest species in Brazilian biomes remain scarce.

Knowledge of cardinal temperatures for forest species of significant importance in the Brazilian forestry context, such as *Handroanthus heptaphyllus* (Vell.) Mattos, *Tabebuia roseoalba* (Ridl.) Sandwith, *Ceiba speciosa* (A. St. Hil.) Ravenna, and *Schinus terebinthifolia* Raddi, is essential for understanding the biological responses of these species to temperature, determining developmental thresholds, and facilitating the use of development models under current and future climatic conditions (Fagundes et al. 2021; Reis et al. 2021; Martins et al. 2022; Silva et al. 2020).

Given the significance of the aforementioned forest species combined with the limited information available regarding their cardinal temperature values (Tb, Tot, and TB) for development, the present study aims to estimate the minimum, optimal, and maximum cardinal temperatures for foliar development in seedlings of *H. heptaphyllus, T. roseoalba, C. speciosa*, and *S. terebinthifolia* using widely employed methods described in the existing literature.

## METHODS

The experimental procedure was performed in the forest nursery (22°46'27" " S, 43°41'10"" W, 26 m a. s. l.) of the Forest Institute of the Federal Rural University of Rio de Janeiro (UFRRJ), located in the municipality of Seropédica, southeastern Brazil (Fig. 1). The region is characterized by a tropical

climate with a dry season in winter and autumn (classified as Aw by the Köppen-Geiger climatic classification system (Alvares et al. 2013). The weather data employed in the study originated from an automatic weather station (ID A601) at the National Institute of Meteorology (INMET), which is situated approximately 1 km away from the experimental area. The data consisted of hourly maximum air temperature (Tx – °C), instantaneous temperature (Tm – °C), minimum air temperature (Tn – °C), relative air humidity (RU – %), and precipitation (prec – mm)."

## Study species

*H. heptaphyllus*, a native species of Brazil, is distributed across the Amazônia, Caatinga, Cerrado, Mata Atlântica, Pampa, and Pantanal biomes (Lohmann 2020a). It has diverse applications, including as a source of timber, for forest restoration, and in traditional healing practices (Lima et al. 2014). Due to its remarkable flowering, it is frequently utilized as an ornamental plant in urban afforestation projects (Lima et al. 2014).

*T. roseoalba* is found in the Caatinga, Cerrado, and Mata Atlântica, with a slightly more limited distribution compared to *H. heptaphyllus* (Lohmann 2020b). The wood of *T. roseoalba* is highly regarded in the construction industry and widely employed in reforestation, landscaping, and urban afforestation projects (Santos et al. 2005).

*C. speciosa* is present in all Brazilian biomes, including the Amazon, Caatinga, Cerrado, Mata Atlântica, Pampa, and Pantanal (Carvalho-Sobrinho 2020). Its fruit, known as "paina," is utilized in the textile industry due to its similarity to cotton. Despite having thorns, the wood of *C. speciosa* holds significant value in various industries and is frequently used as an ornamental species in urban areas. It is also extensively employed in reforestation projects.

*S. terebinthifolia* is a species found in the Caatinga, Cerrado, Mata Atlântica, and Pampa biomes (Silva-Luz et al. 2020), with remarkable potential for timber production, ornamental use, degraded area rehabilitation, and reforestation purposes. It is particularly recognized for its fruit, Brazilian pepper, which is used in culinary endeavors (Marangoni et al. 2023).

## Experimental design

The experiment was conducted following a completely randomized design, with four forest species (*Handroanthus heptaphyllus*, *Tabebuia roseoalba*, *Ceiba speciosa*, and *Schinus terebinthifolia*) cultivated in 280 $cm^3$ tubes, across ten sowing periods (Table 1), with 15 replications for each period, totalling 600 repetitions (4 species × 10 sowing dates × 15 replications). The sowing periods were set at intervals of approximately 45 d to allow the seedlings to develop under a wide range of temperatures (Freitas et al. 2017; Ferreira et al. 2019a,b; Martins et al. 2022).

Table 1
Sowing, emergence, and end of the seedling phase dates (Day/Month/Year) of the experiment were carried out at the forestry nursery, Seropédica, Rio de Janeiro.

| Species | Sowing date | Sowing | Emergence | End | Species | Sowing date | Sowing | Emergence | End |
|---|---|---|---|---|---|---|---|---|---|
| *H. heptaphyllus* | SD1 | 16/12/2019 | 23/12/2019 | 07/04/2020 | *C. speciosa* | SD1 | 16/12/2019 | 30/12/2019 | 06/05/2020 |
| | SD2 | 15/01/2020 | 22/01/2020 | 22/07/2020 | | SD2 | 15/01/2020 | 29/01/2020 | 12/08/2020 |
| | SD3 | 17/02/2020 | 28/02/2020 | 12/08/2020 | | SD3 | 17/02/2020 | 04/03/2020 | 09/09/2020 |
| | SD4 | 07/04/2020 | 20/04/2020 | 29/09/2020 | | SD4 | 07/04/2020 | 20/04/2020 | 09/09/2020 |
| | SD5 | 06/05/2020 | 19/05/2020 | 29/09/2020 | | SD5 | 06/05/2020 | 10/06/2020 | 29/09/2020 |
| | SD6 | 10/06/2020 | 24/06/2020 | 29/10/2020 | | SD6 | 10/06/2020 | 24/06/2020 | 29/10/2020 |
| | SD7 | 21/07/2020 | 12/08/2020 | 17/12/2020 | | SD7 | 21/07/2020 | 12/08/2020 | 03/12/2020 |
| | SD8 | 09/09/2020 | 15/09/2020 | 01/03/2021 | | SD8 | 09/09/2020 | 29/09/2020 | 08/01/2021 |
| | SD9 | 29/10/2020 | 03/12/2020 | 11/02/2021 | | SD9 | 29/10/2020 | 15/11/2020 | 20/02/2021 |
| | SD10 | 03/12/2020 | 17/12/2020 | 01/03/2021 | | SD10 | 03/12/2020 | 17/12/2020 | 26/03/2021 |
| *T. roseoalba* | SD1 | 16/12/2019 | 23/12/2019 | 19/05/2020 | *S. terebinthifolia* | SD1 | 16/12/2019 | 30/12/2019 | 06/05/2020 |
| | SD2 | 15/01/2020 | 22/01/2020 | 24/06/2020 | | SD2 | 15/01/2020 | 29/01/2020 | 22/07/2020 |
| | SD3 | 17/02/2020 | 28/02/2020 | 20/09/2020 | | SD3 | 17/02/2020 | 04/03/2020 | 09/09/2020 |
| | SD4 | 07/04/2020 | 20/04/2020 | 29/09/2020 | | SD4 | 07/04/2020 | 20/04/2020 | 15/11/2020 |
| | SD5 | 06/05/2020 | 19/05/2020 | 21/10/2020 | | SD5 | 06/05/2020 | 29/05/2020 | 17/12/2020 |
| | SD6 | 10/06/2020 | 24/06/2020 | 17/12/2020 | | SD6 | 10/06/2020 | 24/06/2020 | 20/02/2021 |
| | SD7 | 21/07/2020 | 04/08/2020 | 08/01/2021 | | SD7 | 21/07/2020 | 12/08/2020 | 21/01/2021 |
| | SD8 | 09/09/2020 | 15/09/2020 | 21/01/2021 | | SD8 | 09/09/2020 | 29/09/2020 | 11/02/2021 |
| | SD9 | 29/10/2020 | 15/11/2020 | 26/03/2021 | | SD9 | 29/10/2020 | 22/11/2020 | 26/03/2021 |
| | SD10 | 03/12/2020 | 17/12/2020 | 06/04/2021 | | SD10 | 03/12/2020 | 17/12/2020 | 14/04/2021 |

Seeds were manually sown on a substrate composed of composted pine bark and vermiculite. Basal fertilization was performed following the procedure proposed by Gonçalves et al. (2000). For every 1m³ of substrate, 150 g of ammonium sulfate (N), 300 g of P2O5 (superphosphate), and 100 g of $K_2O$ (potassium chloride) were homogenized. Additionally, for micronutrient supply, 150 g of FTE Br12 (1.8% B, 0.8% Cu, 3.0% Fe, 2.0% Mn, and 0.1% Mo) was added per 1m³. The substrate-fertilizer mixture was homogenized before filling the tubes. After 30 days of sowing, topdressing fertilization was carried out by applying approximately 10 ml of a nutrient solution composed of 200 g of N and 180 g of $K_2O$ in 100 L of water monthly to each replicate. This nutrient solution was also supplemented with ammonium sulfate and potassium chloride (Gonçalves et al. 2000). This procedure is commonly used in nurseries to produce native Brazilian forest species (Calzavara et al. 2015). Daily irrigation was carried out using a sprinkler system to ensure that the plants developed without experiencing any water deficiency.

# Cardinal Temperature Estimation

The cardinal temperatures (Tb, Tot, and TB) were estimated based on the data of number of leaves (NL) measured for each species, sowing period, and replication, as well as temperature data. Tb, Tot, and TB were estimated using widely used methodologies in the literature (Bartz et al. 2017; Souza and Martins 2014; Monteiro et al. 2014; Silva et al. 2020). To estimate Tb, data from the four sowing periods were considered, as they presented lower values of Tmin and Tmed, according to the recommendations of Souza and Martins (2014), Ferreira et al. (2019a), and Silva et al. (2020). For Tot, NF data from all sowing periods were used, and for TB, data from two sowing dates with the highest Tm values were used (Martins et al. 2014; Ferreira et al. 2019).

# Base temperature (Tb)

The methods used to estimate Tb were the least standard deviation in degree days (SDdd), least standard deviation in days (SDd), coefficient of variation in days (CVd), coefficient of variation in degree days (CVdd), regression coefficient (RC), relative development (RD) (Arnold, 1959; Yang, Logan, Coffey, 1995), and lowest mean square error (MSE) (Sinclair et al. 2004). Tb values ranging from 0°C to 20°C at ± 0.5°C) were chosen to calculate the SDdd, SDd, CVdd, CVd, RC, and MSE methods. The Tb methods are described in Table 2 and require daily degree days (DDd = Tm - Tb × 1 d) and cumulative degree days (Tm - Tb × 1 d) values (DD = ∑(i = 1)^n DDd), obtained according to Sharratt et al. (1989) and Farias et al. (2015), in

which DDd = degree days (°C day), Tm = mean air temperature (°C), obtained by the arithmetic mean of hourly temperature from automatic weather station (A601 – Seropédica-Ecologia Agrícola), Tb = series of base temperature (°C) values ranging from 0°C to 20 (+ 0.5°C).

Table 2 presents an overview of the methods employed to estimate the base temperature for leaf development. These methods include several calculation approaches. The SDdd, SDd, CVdd and CVd are used as a measure of variability of GDD (SDdd and CVdd) or in days (SDd and CVd) for development stage. Using a range of Tb values from 0°C to 20°C, the correct Tb is the one resulting in the lowest standard deviation or coefficient of variation in GDD or in days required for the seedlings development. Additionally, the regression coefficient method (RC) consist of calculating the linear regression using the GDD as function of mean air temperature in the SD. Using a range of Tb values from 0°C to 20°C, the correct Tb is where the slope of regression equals zero. The linear regression analysis of the rate of seedlings development, defined as the ratio between 100 and number of days taken to reach the end of the seedling phase for each sowing date (n), as function of mean air temperature in the SD is the relative development method. Lastly, the lowest value of the mean square error (MSE) method use the linear regressions between the mean NL and the accumulated degree days (DD) during the SD and the Tb value for each SD was the one that showed the lowest MSE value of the linear regressions (Martins et al., 2012). The correct Tb is considered the arithmetic mean of the Tb values observed at different sowing dates.

Table 2
Traditional methodologies were used for the Tb estimation: standard deviation in degree days (SDdd), standard deviation in days (SDd), coefficient of variation in days (CVd), coefficient of variation in degree days (CVdd), regression coefficient (RC), relative development (RD) and lowest mean square error (MSE).

| Method | Equation | Description |
|---|---|---|
| Least standard deviation, in degree days ($SD_{dd}$) | $SD_{dd} = \left[\frac{1}{n}\sum_{i=1}^{n}(DD_i - GDD)^2\right]^{\frac{1}{2}}$ (1) | Tb is the one that results in the lowest standard deviation in degree days from the set of assumed Tb values (Arnold, 1959; Sharratt et al. 1989; Souza; Martins, 2014). |
| Least standard deviation, in days ($SD_d$) | $SD_d = \frac{\sum_{i=1}^{n}(d_i - \bar{d})^2}{n-1}$ (2) | Tb is the one that results in the lowest standard deviation in days from the set of assumed Tb values (Sharratt et al. 1989; Souza; Martins, 2014). |
| Coefficient of variation in degree days ($CV_d$) | $CV_d = \frac{DP}{GDD} \cdot 100$ (3) | Tb is the one that results in the lowest coefficient of variation in degree days from the set of assumed Tb values (Sharratt et al. 1989; Yang et al. 1995). |
| Coefficient of variation in days ($CV_{dd}$) | $CV_{dd} = \frac{DP}{\bar{X}_d} \cdot 100$ (4) | Tb is the one that results in the lowest standard deviation in days from the set of assumed Tb values (Sharratt et al. 1989; Yang et al. 1995). |
| Regression coefficient (RC) | $GDDi = a + b \cdot Tm$ (5) | Tb is the one that results in an angular coefficient closer to zero from the set of assumed Tb values. (Sharratt et al. 1989; Yang et al. 1995). |
| Relative Development (RD) | $DR = a + b \cdot T_m$ (6) | Tb is found by prolonging the equation to the X-axis, where the relative development is null. (Ferreira et al. 2019b) |
| Lowest mean square error (MSE) | $LN = a + b \cdot DD$ (7) | The Tb value is the one that presented the lowest MSE value obtained from a series of linear regressions between LN and DD calculated using the set of tb values (Freitas et al. 2017) |

# Optimum Temperature (Topt) Estimation

Topt was estimated based on the average Tm values obtained from sowing dates that presented the highest leaf development, that is, the lowest phyllochron (°C day leaf$^{-1}$) values (Freitas et al. 2017a; Ferreira et al. 2019a; Silva et al. 2020). To determine the optimal temperature for each forest species, phyllochron values were calculated using Eq. 8, which involved inverting the slope of the linear regression between the number of accumulated leaves on the main stem and the accumulated degree days. This calculation was performed for each forest species, sowing date, and replication. (Sharratt, Sheaffer and Baker, 1989).

NL = a. DD + b (8)

where NL represents the number of accumulated leaves on the main stem, and DD represents the accumulated degree of days (°C days).

# Maximum Temperature (TB) Estimation

The TB of each forest species was estimated by considering the condition TB > Tm > Tb (Ferreira et al. 2019b), using 10 equations (Lima and Silva 2008):

$$A = N_2 \bullet Tx_1 \bullet Tx_2 - N_2 \bullet Tx_2 \bullet Tn_1 \quad (9)$$

$$B = -N_1 \bullet Tx_1 \bullet Tx_2 + N_1 \bullet Tx_1 \bullet Tn_2 \quad (10)$$

$$C = (-Tx_1 + Tn_1) \bullet (-Tx_2 + Tn_2) \quad (11)$$

$$D = N_1 \bullet {Tn_2}^2 \bullet N_2 - 2 \bullet Tn_2 \bullet N_1 \bullet N_2 \bullet Tb - Tn_2 \bullet Tn_1 \bullet {N_1}^2 \quad (12)$$

$$E = -Tn_2 \bullet Tx_1 \bullet {N_1}^2 + {N_2}^2 \bullet Tx_1 \bullet Tn_2 - Tn_1 \bullet {N_2}^2 \bullet Tn_2 + 2 \bullet Tn_2 \bullet {N_2}^2 \bullet Tb)$$

$$F = Tn_1 \bullet {N_1}^2 \bullet Tx_2 - 2 \bullet {N_2}^2 \bullet Tx_1 \bullet Tb - 2 \bullet {N_1}^2 \bullet Tx_2 \bullet Tb \quad (14)$$

$$G = Tx_1 \bullet {N_1}^2 \bullet Tx_2 + {Tx_1}^2 \bullet N_2 \bullet N_1 - 2 \bullet Tn_1 \bullet N_2 \bullet N_1 \bullet Tb \quad (15)$$

$$H = 2 \bullet Tn_1 \bullet {N_2}^2 \bullet Tb + 2 \bullet N_1 \bullet Tx_2 \bullet N_2 \bullet Tb + 2 \bullet N_2 \bullet Tx_1 \bullet N_1 \bullet Tb \quad (16)$$

$$I = -2 \bullet N_2 \bullet Tx_1 \bullet N_1 \bullet Tx_2 + {N_2}^2 \bullet Tx_1 \bullet Tx_2 - Tn_1 \bullet {N_2}^2 \bullet Tx_2 \quad (17)$$

$$J = -N_1 \bullet Tx_2 + N_1 \bullet Tn_2 + N_2 \bullet Tx_1 - N_2 \bullet Tn_1 \quad (18)$$

$$TB = \frac{A + B \pm \sqrt{C.(D + E + F + G + H + I)}}{J} \quad (19)$$

Here, $N_1$ and $N_2$ are the duration (in days) of the seedling phase considering the two dates (1 and 2, respectively) with the highest temperature, $Tx_1$ and $Tx_2$ average of maximum air temperature (°C), and $Tn_1$ and $Tn_2$ average of minimum air temperatures (°C) during one and two sowing dates, respectively.

## Statistical analysis

Spearman's correlation coefficient (rs) was used to verify the relationship between the duration of each sowing date and Tx, Tm, and Tn values. A hypothesis test was conducted to determine whether the sample correlation coefficient was significantly different from zero or close to zero using a 5% probability (α = 5%). The effects of forest species and sowing date (as sources of variation) were verified using analysis of variance. The mean values of the phyllochrons were compared using the Scott-Knott test at 5% probability. Before conducting the statistical analysis, the normality assumption for the phyllochron values was verified using the Shapiro-Wilk test at 5% probability. If the data did not follow a normal distribution, they were transformed using Ln(phyllochron).

## RESULTS

The experiment exhibited variations in average meteorological conditions across different sowing seasons (Fig. 2), which is beneficial for accurate estimation of cardinal temperatures and reducing uncertainty in estimates. Uniform air temperatures and stable environmental conditions during certain periods can hinder the analysis, comparison of scenarios, and estimation of cardinal temperatures in plant development research (Ferreira et al. 2019b; Silva et al. 2020).

The lowest daily average temperature recorded during the experiment was 16.1°C in August (winter), while the highest daily average temperature was 32.2°C in October (spring). The absolute maximum air temperature reached 40.3°C (summer), and the minimum absolute temperature was 11.3°C (winter). December 2019 and 2020, as well as January and February 2020, had the highest accumulated precipitation, exceeding 150 mm in each of these months. Conversely, June and July 2020 experienced the lowest accumulated precipitation, with a total below 46 mm. The monthly average relative humidity (RH) ranged from 65.6–77.4%, with higher values observed in February and March 2020, exceeding an average RH of 76.0%. July 2020 and January 2021 had the lowest average RH, falling below 66.5%.

The sowing dates of SD3, SD4, SD5, and SD6 were used to estimate Tb values, as they had the lowest air temperatures, with the exception of *S. terebinthifolia*, which used SD2, SD3, SD4, and SD5 (Table 1). Generally, the coldest sowing dates result in longer seedling phases and less foliage development, making them ideal for estimating cardinal temperatures. Conversely, the two sowing dates with the highest temperature values, SD9 and SD10, resulted in the shortest seedling phase duration or the most rapid development for all four forest species.

Table 3
Variations in maximum (Tx), mean (Tm) and minimum air temperature (Tn) and seedling phase duration for each sowing date for four forest species in a forestry nursery experiment at Seropédica, Rio de Janeiro, Brazil.

| Species | Sowing date | N (days) | Tx (°C) | Tm (°C) | Tn (°C) |
|---|---|---|---|---|---|
| *H. heptaphyllus* | E1 | 106 | 30.75 | 25.48 | 21.22 |
| | E2 | 182 | 30.75 | 23.46 | 18.08 |
| | E3 | 166 | 28.22 | 22.70 | 18.08 |
| | E4 | 162 | 28.62 | 22.49 | 16.14 |
| | E5 | 133 | 28.62 | 22.45 | 16.14 |
| | E6 | 127 | 32.23 | 23.14 | 16.14 |
| | E7 | 149 | 32.23 | 24.05 | 16.14 |
| | E8 | 167 | 32.23 | 25.44 | 19.06 |
| | E9 | 70 | 31.21 | 25.70 | 19.61 |
| | E10 | 74 | 31.21 | 26.56 | 21.24 |
| *T. roseoalba* | E1 | 148 | 30.75 | 24.56 | 19.15 |
| | E2 | 154 | 30.75 | 24.11 | 19.15 |
| | E3 | 205 | 28.62 | 22.83 | 16.14 |
| | E4 | 162 | 28.62 | 22.49 | 16.14 |
| | E5 | 155 | 32.23 | 22.87 | 16.14 |
| | E6 | 176 | 32.23 | 23.45 | 16.14 |
| | E7 | 157 | 32.23 | 24.16 | 16.14 |
| | E8 | 128 | 32.23 | 25.00 | 19.06 |
| | E9 | 131 | 31.21 | 26.34 | 20.75 |
| | E10 | 110 | 31.21 | 26.48 | 21.24 |
| *C. speciosa* | E1 | 128 | 30.75 | 24.84 | 20.73 |
| | E2 | 196 | 30.75 | 23.23 | 18.08 |
| | E3 | 189 | 28.22 | 22.68 | 16.14 |
| | E4 | 142 | 27.52 | 22.18 | 16.14 |
| | E5 | 111 | 28.62 | 22.72 | 16.14 |
| | E6 | 127 | 32.23 | 23.11 | 16.14 |
| | E7 | 113 | 32.23 | 23.84 | 16.14 |
| | E8 | 101 | 32.23 | 25.14 | 19.61 |
| | E9 | 97 | 31.21 | 26.35 | 20.75 |
| | E10 | 113 | 31.21 | 26.65 | 21.24 |
| *S. terebinthifolia* | E1 | 128 | 30.75 | 24.83 | 20.73 |
| | E2 | 175 | 30.75 | 23.41 | 18.08 |
| | E3 | 189 | 28.22 | 22.68 | 16.14 |
| | E4 | 209 | 32.23 | 22.79 | 16.14 |
| | E5 | 202 | 32.23 | 23.34 | 16.14 |
| | E6 | 241 | 32.23 | 24.36 | 16.14 |
| | E7 | 162 | 32.23 | 24.61 | 16.14 |
| | E8 | 135 | 32.23 | 25.14 | 19.61 |

| Species | Sowing date | N (days) | Tx (°C) | Tm (°C) | Tn (°C) |
|---|---|---|---|---|---|
| | E9 | 124 | 31.21 | 26.50 | 21.24 |
| | E10 | 118 | 31.21 | 26.31 | 21.24 |

The mean air temperature and duration of the seedling phase showed an inverse relationship, as indicated by the Spearman's correlation coefficient for the four forest species (Table 3). *T. roseoalba* and *S. terebinthifolia* showed a particularly strong negative correlation (rs = -0.88 and − 0.81, respectively), with moderate negative correlation values noted in *H. heptaphyllus* and *Ceiba speciosa* (rs = -0.50 and − 0.52, respectively). These negative correlations suggest that as the mean air temperature increases, the duration of the seedling phase in the nursery decreases, accelerating plant development. Conversely, at cooler temperatures, seedling development was delayed, resulting in longer seedling phases. The maximum air temperature did not correlate significantly with DFM, whereas the minimum air temperature showed a negative correlation with seedling phase duration, except for *H. heptaphyllus* and *C. speciosa*.

Table 4
Spearman's correlation values between air temperature and the seedling phase duration for four forest species, where significance codes were attributed as follows: 0.01 '***'; 0.05 '**'; 0.1 '*'; ns indicating 'non-significant'. SPD stands for the seedling phase duration.

| Correlation between temperature and SPD | Tx (°C) | Tm (°C) | Tn (°C) |
|---|---|---|---|
| *Handroanthus heptaphyllus* | $-0.27^{ns}$ | $-0.50^{*}$ | $-0.38^{ns}$ |
| *Tabebuia roseoalba* | $-0.23^{ns}$ | $-0.88^{***}$ | $-0.86^{***}$ |
| *Ceiba speciosa* | $-0.53^{ns}$ | $-0.52^{*}$ | $-0.35^{ns}$ |
| *Schinus terebinthifolia* | $-0.35^{ns}$ | $-0.81^{**}$ | $-0.89^{***}$ |

The different methods applied for estimating Tb yielded similar results in terms of the value range, with the exception of the CR and RD methods, which displayed values outside the expected range for *H. heptaphyllus* and *T. roseoalba* (between ≥ 6.5 ºC and ≤ 20.0 ºC, as indicated by Ferreira et al. 2019b). These anomalous values were excluded from the arithmetic mean calculation to obtain Tb values for each forest species. The estimation methods exhibited mean Tb values ranging from 9.8 ºC to 11.3 ºC, with corresponding standard deviations ranging from 0.5 ºC to 3.3 ºC. For *H. heptaphyllus*, the estimated Tb was 11.3 ºC ± 3.3; for *T. roseoalba*, it was 10.0 ºC ± 0.5; for *C. speciosa*, it was 11.5 ºC ± 2.6; and for *S. terebinthifolia*, it was 9.8 ºC ± 1.8 (Table 2). Overall, the Tb estimation methods proved effective, with a graphical representation presented in Fig. 3.

Table 5
The estimated base temperature values were obtained using different methods, and the average and standard deviation between these methods were calculated.

| Species | $SD_{gd}$ | $SD_{d}$ | $CV_{gd}$ | $CV_{d}$ | RC | RD | MSE | Mean ± SD |
|---|---|---|---|---|---|---|---|---|
| *H. heptaphyllus* | 9.5 | 9.0 | 9.5 | 9.0 | 14.5 | 17.9 | 9.5 | 11.3 ± 3.3 |
| *T. roseoalba* | 10.5 | 9.5 | 10.5 | 9.5 | 20.0* | 39.3* | 9.8 | 10.0 ± 0.5 |
| *C. speciosa* | 10.0 | 9.5 | 10.0 | 9.5 | 15.5 | 15.7 | 10.0 | 11.5 ± 2.6 |
| *S. terebinthifolia* | 10.5 | 9.5 | 10.5 | 9.5 | 9.0 | 13.3 | 7.0 | 9.8 ± 1.8 |

*Values outside the appropriate temperature range for the base temperature according to Ferreira et al. (2019). SD is the standard deviation.

The CR and DR methods were unsuitable for estimating Tb *for H. heptaphyllus* and *T. roseoalba*, as they generated higher Tb values than the other methods. Additionally, the slope of the linear regression between the accumulated degree days and DR as a function of mean air temperature was not significant (p ≥ 0.05; Table 3), indicating that there was no significant increase in DR with increasing mean air temperature (Fig. 3 and Table 5).

Table 6
Regression coefficients and p-values for the relative development and mean air temperature, as well as the degree-days and mean temperature. RD = relative development; DD = degree days accumulated; b = linear and slope coefficients, respectively; $H_0$ = null hypothesis for the t-test, in which the regression coefficient is equal to zero; $r^2$ = coefficient of determination; $^{ns}$ = non-significant.

| Species | RD = a + bTm | | | | |
|---|---|---|---|---|---|
| | a | p-value ($H_0$: a = 0) | b | p-value ($H_0$: b = 0) | $r^2$ |
| *H. heptaphyllus* | -2.55$^{ns}$ | 0.60 | 0.14$^{ns}$ | 0.52 | 0.23 |
| *T. roseoalba* | 1.39$^{ns}$ | 0.66 | 0.04$^{ns}$ | 0.80 | 0.04 |
| *C. speciosa* | -0.73$^{ns}$ | 0.37 | -0.05$^{ns}$ | 0.19 | 0.66 |
| *S. terebinthifolia* | -1.65$^{ns}$ | 0.82 | 0.11$^{ns}$ | 0.75 | 0.06 |
| Species | DD = a + bTm | | | | |
| | a | p-value ($H_0$: a = 0) | b | p-value ($H_0$: b = 0) | $r^2$ |
| *H. heptaphyllus* | 3839.12$^{ns}$ | 0.65 | -115.69$^{ns}$ | 0.75 | 0.06 |
| *T. roseoalba* | -3940.29$^{ns}$ | 0.26 | 194.29$^{ns}$ | 0.22 | 0.61 |
| *C. speciosa* | 2736.97$^{ns}$ | 0.81 | 1.46$^{ns}$ | 0.99 | 0.00 |
| *S. terebinthifolia* | 1077.96$^{ns}$ | 0.92 | -2.41$^{ns}$ | 0.10 | 0.00 |

Estimated base temperature (TB) values were 50.3 ºC for *H. heptaphyllus*, 53.2 ºC for *T. roseoalba*, 57.6 ºC for *C. speciosa*, and 52.6 ºC for *S. terebinthifolia.* As determined by ANOVA ($p \geq 0.05$), a significant interaction was detected between the studied species and sowing date for the phyllochron values. Differences in phyllochron values were observed between the times for *H. heptaphyllus* and *S. terebinthifolia*, whereas no difference was found among sowing dates for *T. roseoalba* and *C. speciosa* (Scott-Knott test). The lowest phyllochron values for *H. heptaphyllus* occurred during SD3, SD7, SD9, and SD10, whereas for *S. terebinthifolia* they occurred during E2, E5, E6, E7, and E10 (Table 7). The Topt values for *H. heptaphyllus, T. roseoalba, C. speciosa*, and *S. terebinthifolia* were obtained using the arithmetic mean of the mean air temperatures of the sowing dates with the lowest phyllochron values. The Estimated Topt values were 25.7ºC for *H. heptaphyllus*, 24.2°C for *T. roseoalba*, 24.8°C for *S. terebinthifolia*, and 22.7°C for *C. speciosa*.

Table 7
Comparison of Mean Phyllochron Values (ºC day per leaf) for Four Forest Species Across Ten Sowing Dates. The table displays a comparison of means for phyllochron values across ten sowing dates for the four forest species. Means marked with the same lowercase letter within a column (representing the sowing date) and uppercase letter within a row (representing the forest species) indicate no statistically significant differences between them, as determined by the Scott-Knott test ($p \geq 0.05$).

| Sowing date | *H. heptaphyllus* | *T. roseoalba* | *C. speciosa* | *S. terebinthifolia* | Mean |
|---|---|---|---|---|---|
| E1 | 103.56aA | 128.08aA | 131.09aA | 104.35bA | 117.69b |
| E2 | 194.70aA | 127.27aA | 175.38aA | 148.58aA | 162.35a |
| E3 | 84.18bB | 128.54aA | 145.95aA | 110.67bA | 117.74b |
| E4 | 109.20aA | 114.99aA | 150.74aA | 121.25bA | 122.44b |
| E5 | 143.76aA | 155.01aA | 100.51aA | 142.59aA | 138.47b |
| E6 | 115.09aB | 130.03aB | 246.22aA | 204.22aA | 177.25a |
| E7 | 122.71bA | 117.76aA | 159.92aA | 132.10aA | 129.70b |
| E8 | 149.43aA | 120.38aA | 148.41aA | 148.93bA | 142.15b |
| E9 | 75.64bB | 128.88aA | 135.90aA | 90.32bA | 108.96b |
| E10 | 81.20bB | 124.94aA | 175.31aA | 145.54aA | 130.68b |
| Mean | 122.51C | 127.39B | 154.82A | 134.86B | |

The *H. heptaphyllus* displayed the lowest phyllochron value among the forest species examined (Table 7) at a value of 122.5°C day leaf-1. Conversely, the *C. speciosa* displayed the highest phyllochron value at 154.8°C day·leaf$^{-1}$, signifying that it requires a greater degree of energy accumulation to produce a leaf, leading to slower seedling development. The adjusted linear regressions between the NL and DD, computed by using the three cardinal temperatures previously mentioned for each forest species, showed an adjusted coefficient of determination greater than 0.75 ($R^2$ adj > 0.75) with slope coefficients that were statistically significant ($p < 0.05$). This outcome indicates a positive and direct linear connection between the number of leaves and thermal sum (Fig. 4).
The phyllochron value exhibited substantial variability among the examined forest species, as indicated by the non-overlapping notched boxplot, signifying significant differences in medians. Notably, *C. speciosa* demonstrated the highest phyllochron value, followed by *T. roseoalba* and *S. terebinthifolia*. Conversely, *H. heptaphyllus* displayed the lowest phyllochron value (Fig. 5 and Table 5).

## DISCUSSION

The results of our experiment revealed that the Tn, Tm, and Tx values exceeded those reported in previous studies with similar objectives for various species, such as *Psidium guajava* L. (Ferreira et al. 2019a), *Citharexylum myrianthum* Cham., *Bixa orellana* L. (Ferreira et al. 2019b), *Caesalpinia ferrea* Mart. ex. Tul. var. leiostachya Benth, *Anadenanthera macrocarpa* (Benth), Brenan (Silva et al. 2020), *Eucalyptus* sp. (Martins and Streck 2007; Freitas et al. 2017), and olive trees (Souza and Martins 2014). These studies employed similar methods for estimating the cardinal temperatures and observed wider temperature variations, ranging from 3.6°C to 34.6°C (Silva et al. 2020a), 2.3°C to 35.7°C (Ferreira et al. 2019a), and − 3.7°C to 32°C (Souza and Martins2014), resulting in thermal amplitudes of approximately 30°C (between the absolute minimum and maximum air temperature). In contrast, our study exhibited a thermal amplitude of around 20°C.

A study conducted by Monteiro et al. (2014) with *Hymenolobium petraeum*, *Parkia pendula*, *Anadenanthera pavonina*, and *Cassia fistula* presented temperature variations similar to our study, confirming the applicability of most of the methods employed to estimate Tb and the phyllochron approach to Topt. Literature reports Tb ranging from 10.0°C to 12.9°C and Topt ranging from 17.3°C to 25.1°C for perennial species (Ferreira et al. 2019a; Lima and Silva 2008; Martins et al. 2007; Monteiro et al. 2014), which aligns closely with the range found in our study.

In general, the methods used in our study were effective in estimating Tb, except for CR and RD, which produced Tb values outside the expected range (> 20°C) for T. rosealba. While the Tb values for the other forest species examined fell within the expected range, the slope coefficient for the linear regression between RD and Tm was found to be insignificant (Table 3). The relative development method relies on the correlation between Tm and RD (RD = 100/N) to estimate Tb. Thus, higher RD values are expected during periods of higher mean temperatures. However, the mean temperature values considered in Tb estimation using sowing dates exhibited limited variation (~ 2°C). As cautioned by Yang et al. (1995), extrapolating the regression line in such cases poses a limitation to the comparative development method, leading to a tendency of RD to approach zero. This can result in inaccurate basal temperature readings when temperature variation is minimal.

The RC method was employed to associate the number of days required for leaf emergence with Tm. It is generally expected that as temperature increases, the accumulated number of days for leaf emergence remains relatively constant. Although the slope coefficients for *H. heptaphyllus* and *T. roseoalba* did not support the null hypothesis (H0: b = 0; p-value > 0.05), the values deviated significantly from zero, indicating a higher Tb for *H. heptaphyllus* (positive slope coefficient) and a lower Tb for T. roseoalba (negative slope coefficient).

Regarding Tb, our method established higher thresholds compared to those estimated for other perennial species, including *Parkia pendula* (Monteiro et al. 2014), *Corymbia citriodora*, and *Eucalyptus urophylla* (Freitas et al. 2017), *Citharexylum myrianthum*, *Bixa orellana*, *Libidibia ferrea*, *Anadenanthera macrocarpa* (Silva et al. 2020), *Ceiba speciosa*, and *Psidium guajava* (Ferreira et al. 2019a), with values ranging from 36.5°C to 46.4°C.

In conclusion, our experiment demonstrated higher Tn, Tm, and Tx values compared to previous studies for various species. The temperature variations observed in our study were relatively lower, resulting in a narrower thermal amplitude. The methods employed for estimating Tb proved effective, except for CR and RD, which produced unexpected Tb values for *T. rosealba*. The RC method provided insights into the relationship between Tm and the number of days for leaf emergence, highlighting the contrasting Tb values for *H. heptaphyllus* and *T. roseoalba*. These findings contribute to the current understanding of cardinal temperatures and their implications for the growth and development of forest species. It is important to note that our study aligns with the established ranges of Tb and Topt reported in the literature for perennial species.

The limitations of our study include the restricted temperature variation during the estimation of Tb using sowing dates, leading to potential inaccuracies in the basal temperature readings. The extrapolation of the regression line in cases of minimal temperature variation can further impact the accuracy of the relative development method. These limitations highlight the need for caution when applying these estimation methods in experiments with low temperature variability.

Overall, our study contributes to the knowledge of cardinal temperatures and their estimation methods for forest species. Further research is warranted to validate these findings and explore additional factors that may influence the growth and development of these species under varying temperature conditions. Such investigations will enhance our understanding of the physiological responses and adaptive mechanisms of forest species to temperature fluctuations, facilitating more accurate predictions and management strategies in the face of changing climate conditions.

Additionally, future studies could also investigate the potential interactions between cardinal temperatures and other environmental factors, such as light intensity, humidity, and soil moisture, to gain a more comprehensive understanding of the growth and development processes.

The results obtained from this study suggest that the four forest species examined in this study are well-suited to high-temperature conditions, which is consistent with their occurrence in Brazil (Lohmann 2020a; Lohmann 2020b; Carvalho-Sobrinho 2020; Silva-Luz et al. 2020). These regions are known to experience high daily mean air temperatures (Alvares et al. 2013). Studies projecting temperature increases and modeling the growth of tropical species under future climates have reported the potential for changes in specific leaf area and leaf lifespan, depending on the season (Reis et al. 2021; Fagundes et al. 2021), particularly in species with limited thermal amplitude.

The TB values obtained in this study were influenced by experimental conditions, but certain constraints were observed in the operation of the TB techniques at different temperatures. The slightly elevated TB values found in our investigation compared to other perennial species (Martins et al. 2014; Freitas et al. 2017; Ferreira et al. 2019a, b; Silva et al. 2020) may be attributed to the narrow range of Tn, Tm, and Tx values between the two sowing dates used in the TB estimation, similar to the duration (in days) (Table 3).

The measured Topt values for the analyzed species (ranging from 22.5°C to 26.0°C) were comparable to those reported for *Anadenanthera macrocarpa* (Topt = 23°C) (Silva et al. 2020a), *Hymenolobium petraeum* (Topt = 24.9°C), Parkia pendula (Topt = 25.1°C), *Adenanthera pavonina* (Topt = 24.4°C), and Cassia fistula (Topt = 24.9°C) (Monteiro et al. 2014). These values were also higher than those reported for other forest species such as *Citharexylum myrianthum*, *Bixa orellana* (Ferreira et al. 2019b), *Caesalpinia ferrea* (Silva et al. 2020a), *Psidium guajava* (Ferreira et al. 2019a), *Corymbia citriodora*, and *Eucalyptus urophylla* (Freitas et al.2017), which ranged from 17.1°C to 20.7°C.

The average phyllochron values for the species in our study were statistically significant ($p \leq 0.05$). However, there was limited variation between the sowing dates, with no significant difference observed for *T. roseoalba* and *C. speciosa*. This lack of difference may be attributed to the minimal variation in Tm during the experimental period, as it was close to the Topt. The species exhibited differences in leaf emergence speed according to the sowing dates, with higher phyllochron values observed in the sowing dates with intermediate temperatures for *S. terebinthifolia* (SD5 and SD6) and higher Tm for *H. heptaphyllus* (SD2 and SD8). These findings align with previous studies that reported similar trends in *H. heptaphyllus* and *S. terebinthifolia*, with *H. heptaphyllus* displaying a higher phyllochron and an inverse relationship with Tm, while *S. terebinthifolia* exhibited faster maturation and a lesser phyllochron, with less reliance on daily mean temperatures (Monteiro et al. 2014). This suggests that *H. heptaphyllus* requires a lower degree of energy accumulation (in degree days) to produce a leaf on the main stem, resulting in faster leaf generation and seedling development, as reported by Martins et al. (2023). The lower Tb estimated for *S. terebinthifolia* compared to other forest species may contribute to greater thermal accumulation under similar environmental conditions (Fagundes et al. 2021; Freitas et al. 2017; Martins et al. 2023).

## CONCLUSIONS

Our findings highlight the importance of considering temperature variability and its effects on *Handroanthus heptaphyllus, Tabebuia roseoalba, Ceiba speciosa*, and *Schinus terebinthifolia*. Deviations from their optimal temperature ranges, as revealed by our observations of Topt, Tb, and TB values, could severely affect their growth and survival, particularly under climate change scenarios. The variations in cardinal temperature values among species have implications for their phenology, growth, and overall adaptation to different environmental conditions. The methods employed in our study proved effective in estimating cardinal temperatures, although certain limitations exist for specific species. This knowledge contributes to the broader field of plant physiology and can inform management and conservation efforts for forest ecosystems. Thus, careful management and monitoring of these plant species are imperative to ensure their long-term viability. Consequently, our research highlights the thermal requirements of these plant species, allowing for the development of suitable models that require cardinal temperatures as inputs.

## Declarations

**Acknowledgements:** The authors thank the Fundação de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ) for providing the scholarship to the 1st author, under the guidance of Dr. Marcel Carvalho Abreu (ICb_2019/2 – E-26/200.823/2020 (256001)). The authors also thank the Natural Resources Institute at the Federal University of Itajubá for providing subsidies for translating this article.

**Author contributions**: Lais Mello Araújo: data curation, formal analysis, investigation, methodology, software, roles/writing – original draft and writing. Fabrina Bolzan Martins: formal analysis, methodology and software, supervision, validation, visualization, roles/writing – original draft and writing – review & editing. Gustavo Bastos Lyra: formal analysis, methodology and software, supervision, validation, visualization, roles/writing – original draft and writing – review & editing. José Carlos Arthur Junior: methodology, supervision, validation, visualization, roles/writing – original draft and writing – review & editing. Emanuel José Gomes Araújo: methodology, supervision, validation, visualization, roles/writing – original draft and writing – review & editing. Rodolfo Cesar Real de Abreu: formal analysis, methodology and software, supervision, validation, visualization, roles/writing – original draft and writing – review & editing. Marcel Carvalho Abreu: study concept and design, data curation, formal analysis, investigation, methodology, software, supervision, validation, visualization, roles/writing – original draft and writing – review & editing.

**Competing interests:** The corresponding author on behalf of all the authors of this manuscript, declare that there are no competing interests. The authors declare they have no financial interests.

**Data Availability**: The data that support the findings of this study are available from the corresponding author upon reasonable request.

## References


1. Abreu MC, Martins FB, Freitas CH, Pereira RAA, Melloni EGP (2015) Valores limitrofes para transpiração, desenvolvimento e crescimento de *Corymbia citriodora* (Hook.) K.D. Hill & L.A.S. Johnson em resposta à deficiência hídrica no solo. Rev Árvore 39:841–852. https://doi.org/10.1590/0100-67622015000500007
2. Abreu MC, Soares AAV, Freitas CH, Martins FB (2022) Transpiration and growth responses by *Eucalyptus* species to progressive soil drying. J For Res 33:1529–1543. https://doi.org/10.1007/s11676-021-01448-z
3. Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLM, Sparovek G (2013) Köppen's climate classification map for Brazil. Meteorol Z 22:711–728. https://doi.org/10.1127/0941-2948/2013/0507
4. Arnold CY (1959) The Determination and Significance of the Base Temperature in a Linear Heat Unit System. Am Soc Hortic Sci 74:430–445
5. Bartz AC, Muttoni M, Alberto CM, Streck NA, Machado GA, Giacomeli R, Helgueira DB, Moura DS (2017) Thermal time in sprinkler-irrigated lowland rice. Pesqui Agropecu Bras 52:475–484. https://doi.org/10.1590/S0100-204X2017000700001
6. Calzavara AK, Bianchini E, Mazzanatti T, Oliveira HC, Stolf-moreira R, Pimenta JA (2015) Morphoanatomy and ecophysiology of tree seedlings in semideciduous forest during high-light acclimation in nursery. Photosynthetica 53:597–608. https://doi.org/10.1007/s11099-015-0151-0
7. Carvalho-Sobrinho JG (2020) Ceiba in Flora do Brasil 2020 [WWW Document]. Jard. Botânico do Rio Janeiro
8. Contin DR, Habermann E, Alves VM, Martinez CA (2020) Effect of different irradiance levels on anatomy and growth of two Malvaceae species during two seasons. Rev Bras Bot 43:257–269. https://doi.org/10.1007/s40415-020-00609-4
9. Costa DB, Streck NA (2018) Duração da fase de mudas em eucalipto simulada em cenários de aumento de temperatura. Ciência Florest 28:1263–1270. https://doi.org/10.5902/1980509833378
10. Endres L, Câmara CA, Ferreira VM, Silva JV (2010) Morphological and photosynthetic alterations in the Yellow-ipe, *Tabebuia chrysotricha* (Mart. Ex DC.) Standl., under nursery shading and gas exchange after being transferred to full sunlight. Agrofor Syst 78:287–298. https://doi.org/10.1007/s10457-009-9235-9
11. Fagundes FFA, Reis FYS, Martins FB (2021) A model for predicting the initial development of two native forest species under current and future climates. Environ Exp Bot 192:104662. https://doi.org/10.1016/J.ENVEXPBOT.2021.104662
12. Farias VD, Costa DL, Souza PJ, Takaki A, Lima MJ (2015) Temperaturas basais e necessidade térmica para o ciclo de desenvolvimento do feijão-caupi. Enciclopédia Biosf 11(21):1781
13. Ferreira MC, Martins FB, Florêncio GWL, Pasin LAAP (2019a) Cardinal temperatures and modeling of vegetative development in guava. Rev Bras Eng Agrícola e Ambient 23:819–825. https://doi.org/10.1590/1807-1929/agriambi.v23n11p819-825
14. Ferreira MC, Martins FB, Florêncio GWL, Silva JPGC, Pasin LAAP (2019b) Cardinal temperatures and thermal requirements for the initial development of two Brazilian native species. Pesqui Agropecu Bras 54:e00525. https://doi.org/10.1590/S1678-3921.PAB2019.V54.00525
15. Florêncio GWL, Martins FB, Ferreira MC, Pereira RAA (2019) Impacts of climatic changes on the vegetative development of olive cultivars. Rev Bras Eng Agric e Ambient 23:641–647. https://doi.org/10.1590/1807-1929/agriambi.v23n9p641-647
16. Freitas CH, Martins FB, Abreu MC (2017) Cardinal temperatures for the leaf development of *Corymbia citriodora* and *Eucalyptus urophylla* seedlings. Pesqui Agropecu Bras 52:283–292. https://doi.org/10.1590/S0100-204X2017000500001
17. Gay APC, Santos DS, Vieira EA (2017) Effects of zinc excess on antioxidant metabolism, mineral content and initial growth of *Handroanthus heptaphy*llus (Mart. ex DC.) Mattos and *Tabebuia roseoalba*. (Ridl) Sandwith Environ Exp Bot 144:88–99. https://doi.org/10.1016/j.envexpbot.2017.09.006
18. Gonçalves JLM, Santarelli EG, Manara MP, Stape JL (2000) Produção de mudas de espécies nativas: substrato, nutrição, sombreamento e fertilização, in: Gonçalves JLM, Benedetti V. (Eds.). Nutrição e Fertilização Florestal. Piracicaba, pp. 309–350
19. IPCC (2013) The physical science basis (AR5). Contribution of working group I to the fifth assessment report. Cambridge, United Kingdom and New York, NY, USA
20. Lima EP, Silva EL (2008) Temperatura base, coeficientes de cultura e graus-dia para cafeeiro arábica em fase de implantação. Rev Bras Eng Agric e Ambient 12:266–273. https://doi.org/10.1590/s1415-43662008000300007
21. Lima PR, Horbach MA, Dranski JAL, Ecco M, Malavasi MM, Malavasi UC (2014) Avaliação Morfofisiológica em Mudas de *Handroanthus heptaphyllus* (Mart. ex DC.) Mattos Durante a Rustificação. Floresta e Ambient 21:316–326. https://doi.org/10.1590/2179-8087.058813
22. Lin J, Zhang R, Hu Y, Song Y, Hänninen H, Wu J (2019) Interactive effects of drought and shading on *Torreya grandis* seedlings: physiological and growth responses. Trees 33:951–961. https://doi.org/10.1007/s00468-019-01831-8
23. Lohmann LG (2020a) *Handroanthus* in Flora do Brasil 2020 [WWW Document]. Jard. Botânico do Rio Janeiro
24. Lohmann LG (2020b) *Tabebuia* in Flora do Brasil 2020 [WWW Document]. Jard. Botânico do Rio Janeiro
25. Lucas DDP, Streck NA, Bortoluzzi MP, Trentin R, Maldaner IC (2012) Base temperature for node appearance and plastochron of watermelon plant. Rev Cienc Agron 43:288–292. https://doi.org/10.1590/s1806-66902012000200011

26. Marangoni JA, Pinto JVC, Kassuya CAL, Oliveira Junior PC, Santos SM, Cardoso CAL, Silva RMMF, Silva ME, Machado CD, Manfron J, Formagio ASN (2023) Geographical variation in the chemical composition, anti-inflammatory activity of the essential oil, micromorphology and histochemistry of *Schinus terebinthifolia* Raddi. J Ethnopharmacol 301:115786. https://doi.org/10.1016/j.jep.2022.115786
27. Martins FB, Silva JC, Streck NA (2007) Estimating base temperature for leaf appearence rate and the phyllochron in two eucaliptus species during seedling phase. Rev Arvore 31:373–381. https://doi.org/10.1590/s0100-67622007000300002
28. Martins FB, Ferreira MC, Florêncio GWL (2022) Agrometeorological models for predicting seedlings development of two native forest species. Sci Agric 79(4):e20200192. https://doi.org/10.1590/1678-992X-2020-0192
29. Martins FB, Ferreira MC, Fagundes FFA, Florêncio GWL (2023) Thermal and photoperiodic requirements of the seedling stage of three tropical forest species. J For Res 34:209–220. https://doi.org/10.1007/s11676-022-01530-0
30. Martins FB, Streck NA (2007) Leaf appearance in seedlings of *Eucalyptus* estimated by two models. Pesqui Agropecu Bras 42:1091–1100. https://doi.org/10.1590/s0100-204x2007000800005
31. Monteiro EB, Silva CC, Silva AC, Souza AP (2014) Estimating Emission of Leaves Seedlings Forest in Different Shading Levels, at Conditions of Transition Amazon-Cerrado, Brazil. Am J Plant Sci 05:2330–2341. https://doi.org/10.4236/ajps.2014.515247
32. Posse R, Valani F, Souza C, Posse S, Sales R, Oliveira E, Quartezani W, Leite M (2018) Basal Temperature and Thermal Constant for the Production of Cacao Tree Seedlings. J Exp Agric Int 25:1–16. https://doi.org/10.9734/JEAI/2018/43321
33. Reis FYS, Martins FB, Torres RR, Florêncio GWL, Cassemiro JM, Monteiro VFC, Ferreira MC (2021) Climate change impact on the initial development of tropical forest species: a multi-model assessment. Theor Appl Climatol 145:533–547. https://doi.org/10.1007/s00704-021-03646-5
34. Santos DL, Sugahara VY, Takaki M (2005) Efeitos da luz e da temperatura na germinação de sementes de *Tabebuia serratifolia* (Vahl) Nich, *Tabebuia chrysotricha* (Mart. ex DC.) Standl. e *Tabebuia roseo-alba* (Ridl) Sand - Bignoniaceae. Ciência Florest 15(1):87–92. https://doi.org/10.5902/198050981826
35. Sharratt BS, Sheaffer CC, Baker DG (1989) Base temperature for the application of the growing-degree model to field-grow alfafa. F Crop Res 21:95–102. https://doi.org/10.1016/0378-4290(89)90045-2
36. Silva-Luz C, Pirani JR, Pell SK, Mitchell JD (2020) Anacardiaceae in Flora do Brasil 2020. [WWW Document]. Jard. Botânico do Rio Janeiro
37. Silva LV, Reis FYS, Martins FB, Cassemiro JM (2020) Desenvolvimento Vegetativo de *Cesalpinea ferrea* e *Anadenanthera macrocarpa*: I-Estimativa das Temperaturas Cardinais. Rev Bras Meteorol 35(1):23–33. https://doi.org/10.1590/0102-7786351006
38. Sinclair TR, Gilbert RA, Perdomo RE, Shine JM, Powell G, Montes G (2004) Sugarcane leaf area development under field conditions in Florida, USA. F Crop Res 88:171–178. https://doi.org/https://doi.org/10.1016/j.fcr.2003.12.005
39. Souza PMB, Martins FB (2014) Estimativa da temperatura basal inferior para as cultivares de oliveira Grappolo e Maria da Fé. Rev Bras Meteorol 29:307–313. https://doi.org/10.1590/S0102-77862014000200013
40. Torres RR, Benassi RB, Martins FB, Lapola DM (2021) Projected impacts of 1.5 and 2°C global warming on temperature and precipitation patterns in South America. Int J Climatol 42(3):1597–1611. https://doi.org/https://doi.org/10.1002/joc.7322
41. Wergifosse L, André F, Goosse H, Boczon A, Cecchini S, Ciceu A, Collalti A, Cools N, D'andrea E, De Vos B, Hamdi R, Ingerslev M, Knudsen MA, Kowalska A, Leca S, Matteucci G, Nord-Larsen T, Sanders TGM, Schmitz A, Termonia P, Jnard M (2022) Simulating tree growth response to climate change in structurally diverse oak and beech forests. Sci Total Environ 806(Part 2):150422. https://doi.org/10.1016/j.scitotenv.2021.150422
42. Yang S, Logan J, Coffey DL (1995) Mathematical formulae for calculating the base temperature for growing degree days. Agric For Meteorol 74:61–74. https://doi.org/10.1016/0168-1923(94)02185-M

## Figures

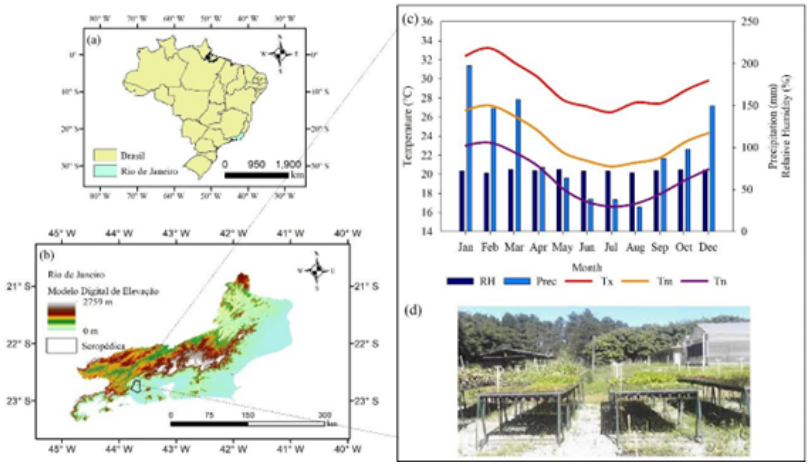


**Figure 1**

Forest Nursery "Luiz Fernando de Oliveira Capellão" Location and Experiment Details. (a) Location of the Rio de Janeiro State, Brazil. (b) Location of Seropédica city. (c) Average climatological mean (1981-2010) air temperatures - maximum (Tx), mean (Tm), and minimum (Tn) - relative humidity (RH), and precipitation (Prec) in Seropédica. (d) Benches used for placing the seedlings at the forest nursery.

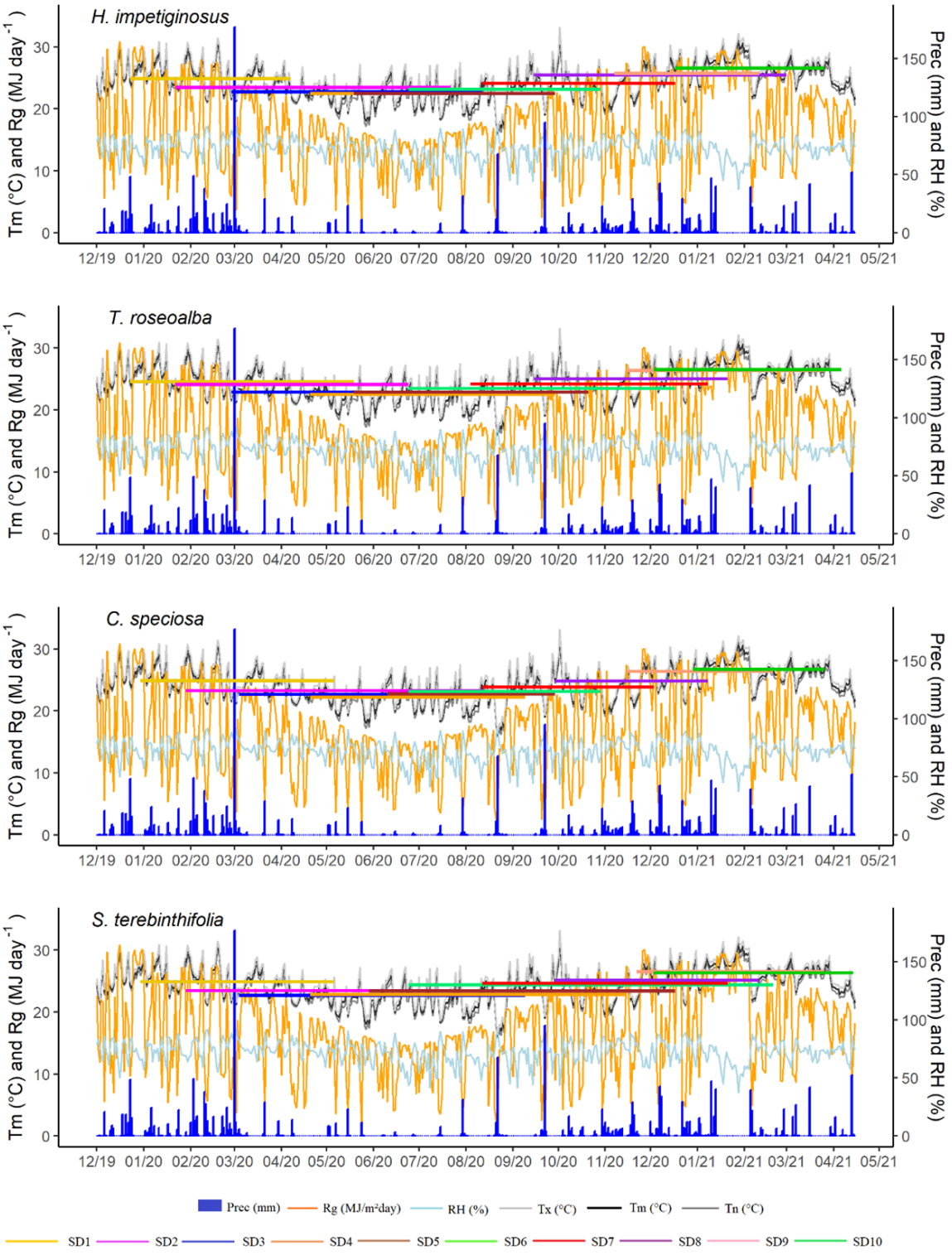


**Figure 2**

The maximum (Tx, °C), mean (Tm, °C), and minimum (Tn, °C) air temperatures, relative humidity (RH,%), precipitation (mm), global radiation (Rg. MJ/$m^2$dia) and the duration of the seedling phase throughout the course of the experiment (SD1-SD10).

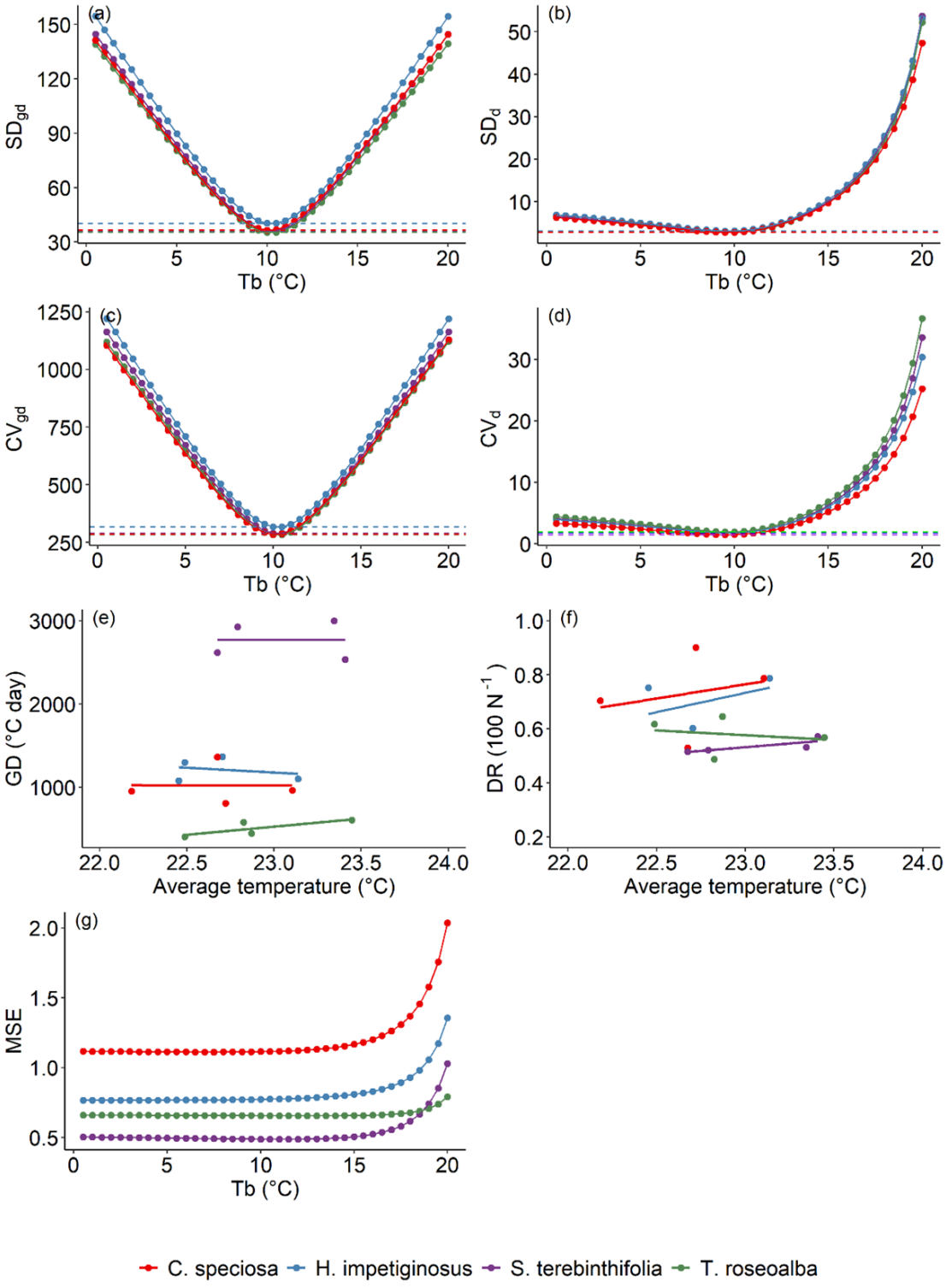


**Figure 3**

Methods utilized for estimating the base temperature (Tb) for *H. heptaphyllus*, *T. roseoalba*, *C. speciosa*, and *S. terebinthifolia*. These methods include: (a) the least standard deviation in degree days, (b) the least standard deviation in days, (c) the coefficient of variation in degree days, (d) the coefficient of variation in days, (e) the regression coefficient, and (f) the relative development. The parameter N denotes the number of days corresponding to each sowing date.

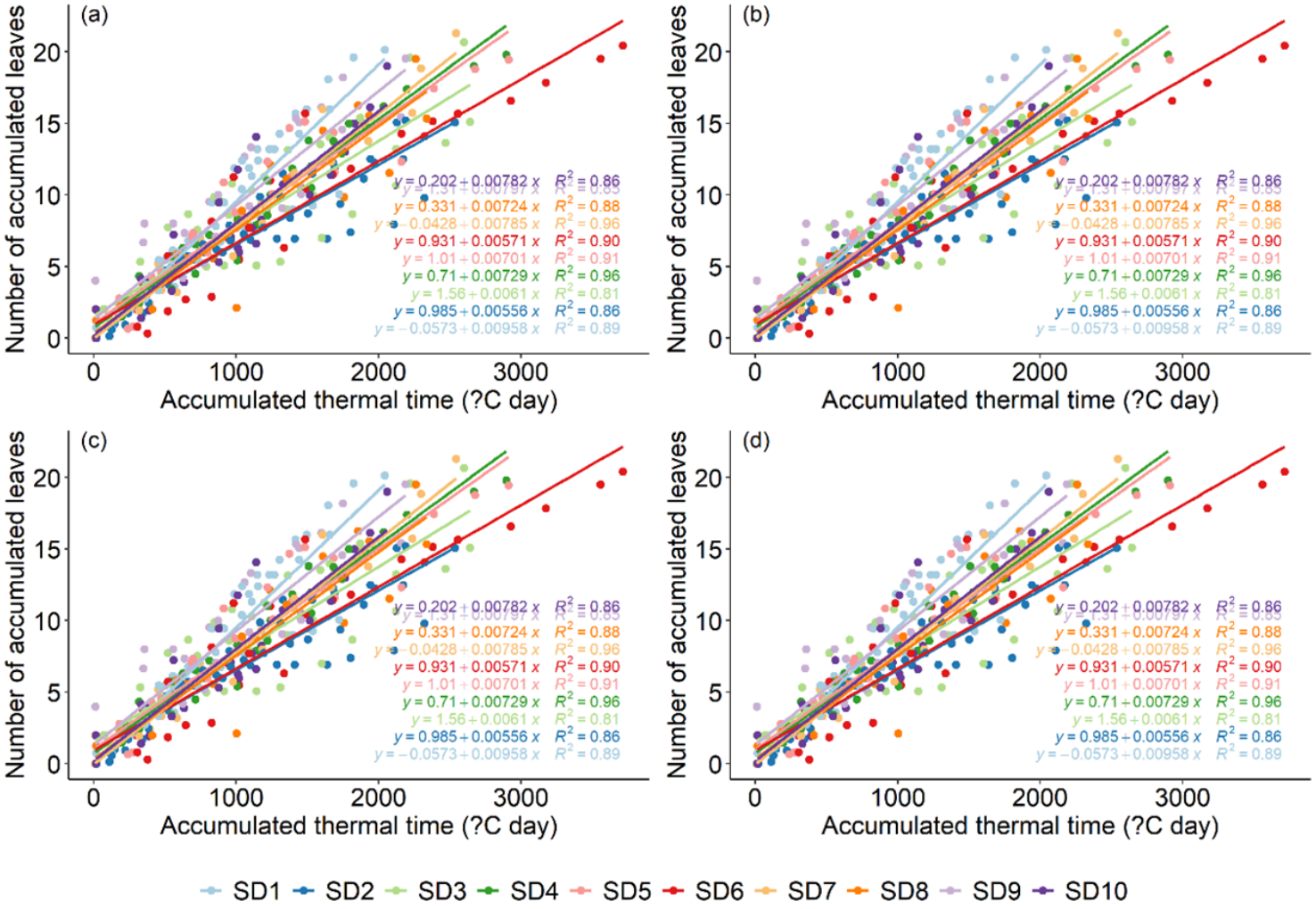


**Figure 4**

Accumulated number of leaves versus accumulated degree days were calculated for the following forest species: (a) *H. heptaphyllus*, (b) *T. roseoalba*, (c) *C. speciosa*, and (d) *S. terebinthifolia*.

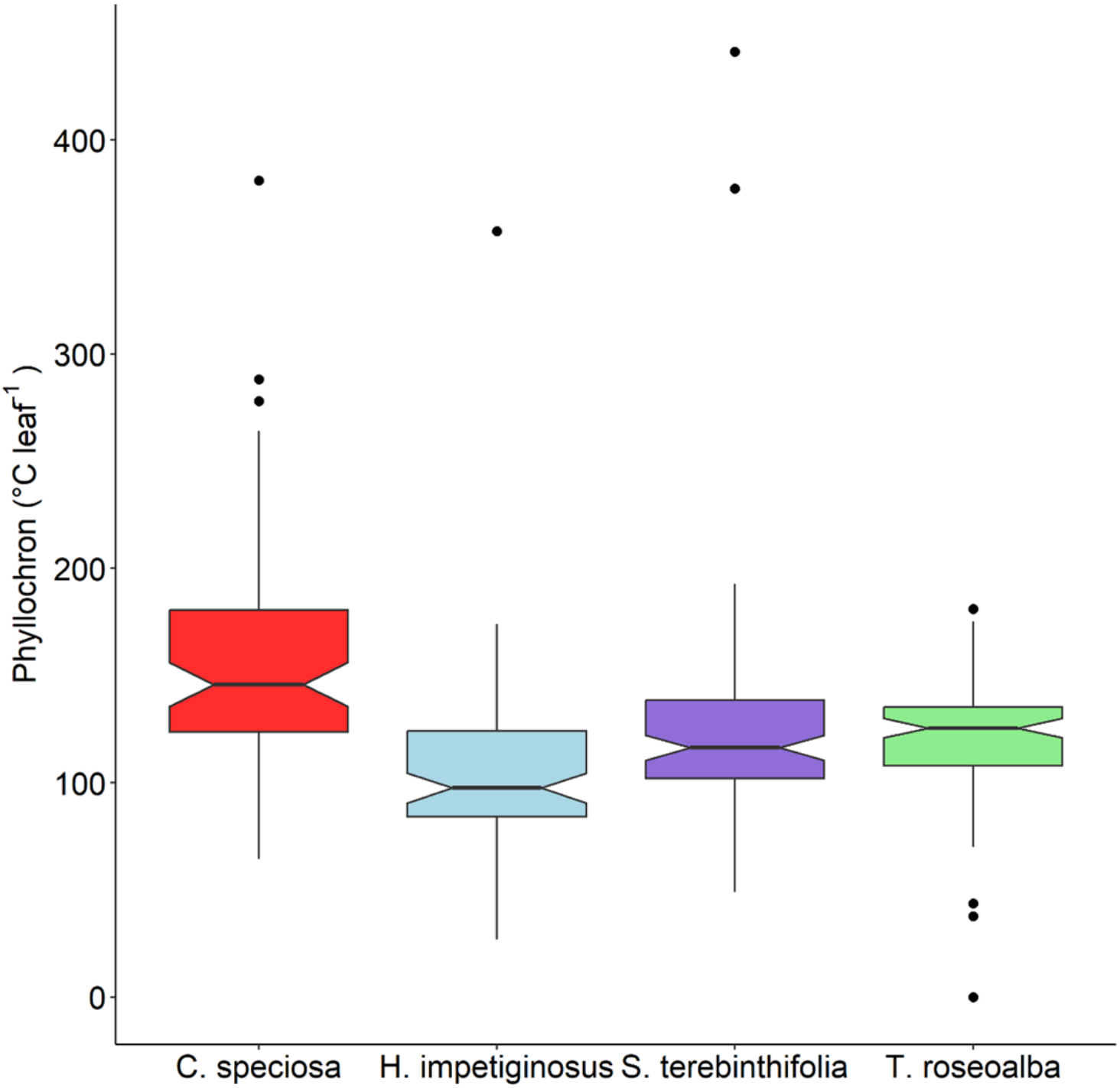


**Figure 5**

The boxplot of the phyllochron values for *H. heptaphyllus*, *T. roseoalba*, *C. speciosa,*and *S. terebinthifolia.*