



Climate-driven Modeling of the Initial Development of Brazilian Forest Species Under Current and Future Climates

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Abstract

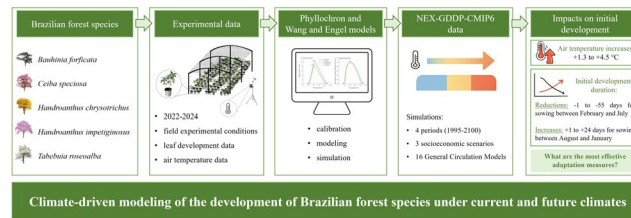
Modeling the initial development stage helps assess climate change impacts and species vulnerability under future scenarios. This study calibrated and validated two development models - the Phyllochron (Phyl) and Wang and Engel (WE) - under field conditions and identified potential alterations in the development of Brazilian forest species (*Bauhinia forficata*, *Ceiba speciosa*, *Handroanthus chrysotrichus*, *Handroanthus impetiginosus*, and *Tabebuia roseoalba*) throughout the 21st century. The Phyl and WE models estimate daily leaf appearance, which, when integrated over time, provides the duration of initial development. Field experiments conducted between 2022 and 2024 supported model calibration and validation. The best-performing model was applied to simulate development under current (1995–2014) and three future periods (2041–2060, 2061–2080, and 2081–2100) and three socioeconomic scenarios (SSP2-4.5, SSP3-7.0, and SSP5-8.5). Sixteen General Circulation Models from the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) were used. Both models accurately estimated leaf number for all species, with lower precision for development duration. The Phyl model performed better for *C. speciosa* (RMSE=1.30 leaves, 29.8 days) and *H. chrysotrichus* (1.41 leaves, 23.0 days), while the WE model performed better for *B. forficata* (1.14 leaves, 11.9 days), *H. impetiginosus* (1.50 leaves, 32.3 days), and *T. roseoalba* (1.32 leaves, 25.2 days). Projected temperature increases (+1.3 to +4.5 °C) will alter leaf emergence and development duration, with reductions (−1 to −55 days) for sowing from February to July and increases (+1 to +24 days) from August to January. Adjusting sowing schedules and controlling seedling environments are key adaptation strategies under global warming.

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Graphical Abstract

The graphical abstract presents modeling of the initial developmental stage of five Brazilian forest species (*Bauhinia forficata*, *Ceiba speciosa*, *Handroanthus chrysotrichus*, *Handroanthus impetiginosus*, and *Tabebuia roseoalba*) under present and future climate conditions. It illustrates the calibration and validation of two developmental models - Phyllochron (Phyl) and Wang and Engel (WE) - based on field experiments conducted between 2022 and 2024. The best-performing model was applied to simulate leaf emergence and the duration of initial development under current (1995–2014) and future climate scenarios (2041–2060, 2061–2080, and 2081–2100) using CMIP6 projections from sixteen global circulation models (NEX-GDDP-CMIP6) and three socioeconomic pathways (SSP2-4.5, SSP3-7.0, and SSP5-8.5). The final panel highlights projected temperature increases of +1.3 to +4.5 °C, leading to heterogeneous changes in development duration - reductions (-1 to -55 days) in seeding from February to July, and increases (+1 to +24 days) from August to January. The final panel also emphasizes that adjusting sowing schedules and controlling seedling production environments are key adaptation measures to mitigate climate change impacts on the early development of native forest species.



Highlights

- Field-calibrated Phyllochron and Wang & Engel models simulated the initial development of five Brazilian native forest species with species-specific accuracy.
- Phyllochron performed better for *Ceiba speciosa* and *Handroanthus chrysotrichus*, while Wang and Engel model performed better for *Bauhinia forficata*, *H. impetiginosus* and *T. roseoalba*.
- Developmental responses are species-specific and vary with sowing date and climate scenario.
- Projected warming of +1.3 to +4.5 °C may change initial development from –55 to +24 days among species.
- Adaptive measures such as sowing rescheduling and nursery microclimate control mitigate future thermal stress.

Keywords Climate change · Leaf appearance rate · NEX-GDDP-CMIP6 · Phyllochron · Wang and engel

Abbreviations

a	Slope of the linear regression
ALN	Accumulated leaf number on the main stem
ALNest	Estimated accumulated leaf number
ALNobs	Observed accumulated leaf number
ANOVA	Analysis of variance
b	Linear coefficient
CC	Current climate
CMIP6	Coupled model intercomparison project phase 6
EM	Emergence date
FF	Far future (2081–2100)
f(T)	Beta temperature response function
GCMs	General circulation models
IDD	Initial development duration
IDDest	Estimated initial development duration
IDDobs	Observed initial development duration
IF	Intermediate future (2061–2080)
LAR	Leaf appearance rate
LN	Leaf number

NEX-GDDP	NASA earth exchange global daily down-scaled projections
MSE	Mean square error
n	End of initial development stage date
NF	Near future (2041–2060)
Phyl	Phyllochron model
R	Replicate
r	Correlation coefficient
RCP	Representative concentration pathway
RMSE	Root mean squared error
SSP	Shared socioeconomic pathway
SD	Sowing date
Tb	Base temperature
TB	Maximum temperature
Tmax	Maximum air temperature
Tmean	Mean air temperature
Tmin	Minimum air temperature
Topt	Optimum temperature
TT	Thermal time
TTa	Accumulated thermal time

TTd Daily thermal time
WE Wang and engel model

1 Introduction

Projected temperature increases throughout the 21st century are expected to alter plant physiological and phenological processes, affecting germination, leaf emergence (Fagundes et al. 2024b; Martins et al. 2023b), flowering, and fruiting (Inouye 2022), with direct implications for forest distribution patterns (Florêncio et al. 2022; Silva et al. 2019). These impacts are particularly pronounced during the initial development stage, when seedlings exhibit greater sensitivity and lower tolerance to thermal variability (Fagundes et al. 2024b, 2025a, b; Martins et al. 2023a; Reis et al. 2021).

Beyond direct effects on plant development, temperature shifts may disrupt ecological interactions, favor the expansion of invasive species and pests (Bettioli et al. 2017; Pivello et al. 2024), and intensify habitat loss in biodiversity hotspots, such as the Atlantic Forest, Cerrado, and Caatinga, which are projected to experience reductions in area and species richness (IPCC 2023; Silva et al. 2019). Coupled, these processes amplify risks to native plant communities and ecosystem functioning.

Despite the ecological importance of native forest species, research addressing their developmental responses to climate change remains limited. This gap is largely attributed to the lack of detailed information on the phenological patterns and the absence of standardized experimental protocols, which make conducting experiments for this purpose difficult (Martins et al. 2023a; Reis et al. 2021). Furthermore, insufficient incentives, weak market regulations, and inadequate governmental support hamper the establishment and expansion of forest nurseries dedicated to native seedling production (Silva et al. 2017). This situation is further aggravated by strong market pressure favoring exotic seedling species, which generally have greater commercial appeal and profitability. Consequently, many nursery managers prioritize exotic over native species, reducing the availability of suitable seedlings and hindering the consolidation of production chains aimed at ecological restoration (Mendonça et al. 2017; Silva et al. 2015, 2017).

Progress in understanding the developmental responses of native species to climate change can support ecological restoration initiatives, biodiversity conservation, and climate-adapted forest management, in alignment with global environmental agendas (Fagundes et al. 2021; UN 2015; UNFCCC 2015). However, few studies have examined how future climates will affect the initial development of native forest species, revealing heterogeneous responses

and highlighting the need to expand species-specific investigations (Fagundes et al. 2021, 2025a, b; Reis et al. 2021).

Projecting initial development responses under future climates requires two consecutive steps. The first involves calibrating and evaluating development models, which must be performed for each species and site under current climate conditions (Fagundes et al. 2024a; Martins et al. 2022). The second involves applying climate model outputs to the previously calibrated/evaluated models (Fagundes et al. 2025a, b; Martins et al. 2023b; Reis et al. 2021).

Regarding development models, two have been successfully applied to forest species: Phyllochron (Phyl) and Wang and Engel (WE) (Fagundes et al. 2024a; Ferreira et al. 2019; Martins et al. 2022; Martins and Streck 2007). These models enable estimation of the accumulated leaf number on the main stem (ALN) and the initial development duration (IDD, in days) by relating leaf appearance rate (LAR) - a developmental variable - to air temperature functions (Fagundes et al. 2024a; Ferreira et al. 2019).

In the Phyl model, the temperature function is thermal time (TT; °C day) (Fagundes et al. 2024a; Martins et al. 2022; Martins and Streck 2007), whereas in the WE it is the beta function [$f(T)$; dimensionless] (Wang and Engel 1998). The main difference between these functions is that TT allows for various calculation methods, typically involving two linear responses to air temperature: the first between base temperature (T_b) and optimum (T_{opt}), and the second between T_{opt} and maximum (T_B) (Gilmore Junior and Rogers 1958; Martins et al. 2023a). Different TT methods may yield distinct temperature responses from the same input data (Martins et al. 2023b; Zhou and Wang 2018). Conversely, $f(T)$ represents a nonlinear relationship between air temperature and T_b , T_{opt} , and T_B (Wang and Engel 1998), aligning more closely with the thresholds (T_b , T_{opt} , and T_B), especially when air temperature is near T_b or above T_{opt} (Fagundes et al. 2024a; Martins et al. 2023a, b).

The General Circulation Models (GCMs) from the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) dataset are derived from the Coupled Model Intercomparison Project Phase 6 (CMIP6), representing a new generation of climate models with high spatial resolution due to bias correction (Thrasher et al. 2022). i.e., the NEX-GDDP-CMIP6 models are capable of projecting air temperature at a finer scale, making them suitable for assessing local climate trends (Dias et al. 2024; Fagundes et al. 2025a, b), as intended in this study. These models combine Shared Socioeconomic Pathways (SSPs) with radiative forcing scenarios (Representative Concentration Pathways, RCPs), providing a more comprehensive framework to assess Earth system responses to anthropogenic forcing (Almazroui et al. 2021; Riahi et al. 2017).

By integrating outputs from NEX-GDDP-CMIP6 climate models into properly calibrated and evaluated development models (Phyl or WE), it is possible to project the initial development dynamics in terms of ALN and IDD (Fagundes et al. 2024a; Ferreira et al. 2019; Martins et al. 2023b; Reis et al. 2021), yielding valuable insights into responses to projected temperature increases. Such information enables the design of more reliable adaptation measures to cope with future climate warming.

Several Brazilian native forest species are vulnerable and under anthropogenic pressure due to unsustainable exploitation and population decline. Among them, five species deserve special attention: *Bauhinia forficata* Link (Fabaceae; bauínia, pata-de-vaca), *Ceiba speciosa* (A. St.-Hil.) Ravenna (Malvaceae; paineira, árvore-de-paina), *Handroanthus chrysotrichus* (Mart. ex DC.; Bignoniaceae; ipê-amarelo-cascudo, ipê-dourado) Mattos *Handroanthus impetiginosus* (Mart. ex DC.) Mattos (Bignoniaceae; ipê-roxo-de-bola, pau-d'arco-roxo), and *Tabebuia roseoalba* (Ridl.) Sandwith (Bignoniaceae; ipê-branco, ipê-do-cerrado). These species have multiple uses and high ecological and economic relevance, as widely recognized by the scientific community and society (Carvalho 2003, 2006; Vieira et al. 2018).

Although development models such as Phyl and WE provide valuable information for climate-resilient forest planning and management, their application to these five native species has not yet been evaluated. Consequently, three key questions remain unanswered: (I) Are the Phyl and WE models capable of producing reliable development estimates in terms of ALN and IDD under current climate conditions? (II) How can projected air temperature increases from NEX-GDDP-CMIP6 climate models influence ALN and IDD in the five native forest species relative to the current climate? (III) If development and IDD are affected, what are the most effective adaptation measures?

This study aims to address these questions by evaluating the capacity of both Phyl and WE models to estimate ALN and IDD for the five species under experimental conditions, and by identifying developmental responses under current climate (1995–2014) and future climate (2041–2100), considering air temperature projections from multiple NEX-GDDP-CMIP6 climate models.

2 Materials and Methods

This study was conducted in two stages: (I) calibration and performance evaluation of the Phyl and WE models in describing the initial development of the forest species *B. forficata*, *C. speciosa*, *H. chrysotrichus*, *H. impetiginosus*, and *T. roseoalba*; and (II) identification of their development

responses under future climate conditions, based on air temperature projections from multiple NEX-GDDP-CMIP6 climate models.

2.1 Data and Development Model Descriptions

The initial development data used in stage I refer to the accumulated leaf number (ALN) on the main stem, measured from the emergence date (EM) to the end of the initial development stage (n), and to the initial development duration (IDD, in days). These data were obtained from open-air experiments conducted in the experimental area of the Federal University of Itajubá, Minas Gerais, Brazil (22° 24' 45" S, 45° 26' 49" W, 850 m a.s.l.), between June 2022 and January 2024. The dataset comprised 14 sowing dates (SDs) spaced approximately 30 days apart (Table 1), with the full experimental protocol described in detail by Ferreira et al. (2025).

Initial development for both models (Phyl and WE) was estimated in three sequential steps (Fig. 1): (I) calculating daily LN, obtained by summing daily leaf appearance rate (LAR) values from the emergence date (EM) to the end of the initial development stage (n) (Fig. 1, Eq. 1); (II) calculating ALN, obtained by summing LN values (Fig. 1, Eq. 6), and determining the date on which ALN reached 10 leaves (a value corresponding to the final seedling stage, as defined in preliminary experiments described in Ferreira et al. 2025); and (III) determining the IDD, given by the number of days between EM and n (Fig. 1, Eq. 7). The temperature functions of both models (TTd and $f(T)$) are shown in Fig. S1.

In the Phyl model, the daily LAR is calculated by multiplying the species-specific coefficient (a) (detailed in Fig. 1, Eq. 2) by the daily thermal time (TTd). In the WE model, LAR is calculated by multiplying the maximum daily leaf appearance rate (LAR_{max}), which is also species-specific (detailed in Fig. 1, Eq. 4), by the beta temperature response function [$f(T)$]. Both TTd and $f(T)$ incorporate daily mean temperature and species-specific thermal thresholds of development (T_b , T_{opt} , T_B), previously estimated by Ferreira (2025) for the five studied species (Table S1).

2.2 Calibration and Performance Evaluation of the Phyl and WE Models

The coefficients “ a ” (Phyl model) and LAR_{max} (WE model) were calibrated using ALN data from SD1 to SD6, following previously established procedures (Fagundes et al. 2024a; Martins et al. 2022, 2023b) (Fig. 2). The “ a ” coefficient was calibrated through a series of linear regressions between ALN and accumulated thermal time (TTa), adjusted for each forest species and SD. Subsequently, the species-specific value of “ a ” was obtained as the arithmetic

Table 1 Sowing (SD), emergence (EM), and end of the initial development stage (n) dates for the forest species *B. forficata*, *C. speciosa*, *H. chrysotrichus*, *H. impetiginosus*, and *T. roseoalba* in the experiment conducted in Itajubá, Minas Gerais, Brazil

Sowing date (SD)	<i>Bauhinia forficata</i>		<i>Ceiba speciosa</i>		<i>Handroanthus chrysotrichus</i>		<i>Handroanthus impetiginosus</i>		<i>Tabebuia roseoalba</i>	
	EM ¹	n ²	EM ¹	n ²	EM ¹	n ²	EM ¹	n ²	EM ¹	n ²
SD1 - Jun 14, 2022	Jul 08, 2022	Dec 02, 2022	Jun 29, 2022	Dec 02, 2022	Jul 15, 2022	Dec 02, 2022	Jul 18, 2022	Dec 02, 2022	Jul 12, 2022	Dec 02, 2022
SD2 - Jul 15, 2022	Aug 05, 2022	Jan 26, 2023	Jul 29, 2022	Jan 04, 2023	Aug 22, 2022	Dec 21, 2022	Aug 01, 2022	Jan 19, 2023	Aug 10, 2022	Jan 19, 2023
SD3 - Aug 16, 2022	Sep 02, 2022	Feb 22, 2023	Sep 02, 2022	Jan 12, 2023	Sep 23, 2022	Feb 02, 2023	Sep 09, 2022	Feb 02, 2023	Sep 16, 2022	Feb 15, 2023
SD4 - Sep 16, 2022	Oct 17, 2022	Feb 22, 2023	Oct 07, 2022	Feb 15, 2023	Oct 21, 2022	Feb 08, 2023	Oct 10, 2022	Mar 01, 2023	Oct 18, 2022	Feb 22, 2023
SD5 - Oct 17, 2022	Nov 01, 2022	Mar 31, 2023	Oct 27, 2022	Mar 15, 2023	Nov 07, 2022	Mar 01, 2023	Nov 01, 2022	Mar 15, 2023	Nov 07, 2022	Mar 22, 2023
SD6 - Nov 14, 2022	Nov 24, 2022	May 03, 2023	Nov 28, 2022	Jun 07, 2023	Dec 05, 2022	Apr 12, 2023	Nov 28, 2022	Jun 02, 2023	Dec 05, 2022	May 03, 2023
SD7 - Dec 16, 2022	Dec 26, 2022	May 26, 2023	Dec 23, 2022	Jun 30, 2023	Jan 02, 2023	May 10, 2023	Dec 23, 2022	Jun 07, 2023	Dec 28, 2022	May 26, 2023
SD8 - Jan 17, 2023	Jan 30, 2023	Aug 04, 2023	Jan 27, 2023	Sep 15, 2023	Feb 06, 2023	Aug 04, 2023	Feb 01, 2023	Aug 18, 2023	Feb 08, 2023	Aug 25, 2023
SD9 - Feb 15, 2023	Feb 27, 2023	Sep 08, 2023	Feb 22, 2023	Sep 01, 2023	Mar 01, 2023	Aug 18, 2023	Mar 01, 2023	Aug 25, 2023	Mar 01, 2023	Sep 08, 2023
SD10 - Mar 15, 2023	Mar 22, 2023	Sep 29, 2023	Mar 22, 2023	Oct 13, 2023	Apr 12, 2023	Sep 01, 2023	Mar 31, 2023	Sep 15, 2023	Apr 06, 2023	Sep 29, 2023
SD11 - Apr 17, 2023	May 05, 2023	Nov 17, 2023	Apr 28, 2023	Nov 17, 2023	May 02, 2023	Nov 03, 2023	May 05, 2023	Nov 10, 2023	May 10, 2023	Nov 10, 2023
SD12 - May 16, 2023	Jun 05, 2023	Nov 17, 2023	Jun 02, 2023	Nov 10, 2023	Jun 07, 2023	Nov 10, 2023	Jun 23, 2023	Nov 17, 2023	Jun 12, 2023	Nov 24, 2023
SD13 - Jun 19, 2023	Jul 07, 2023	Jan 05, 2024	Jul 07, 2023	Dec 15, 2023	Aug 07, 2023	Jan 12, 2024	Jul 28, 2023	Jan 12, 2024	Aug 04, 2023	Jan 19, 2024
SD14 - Jul 13, 2023	Aug 04, 2023	Jan 26, 2024	Aug 04, 2023	Dec 08, 2023	Aug 14, 2023	Dec 01, 2023	Aug 18, 2023	Jan 12, 2024	Aug 21, 2023	Jan 26, 2024

¹EM = emergence date, defined as the day when the seeds reached a species-specific minimum emergence percentage, ranging from 24.2 to 32.9% for *B. forficata*, 30.0 to 47.1% for *C. speciosa*, 5.4 to 5.9% for *H. chrysotrichus*, 10.4 to 26.7% for *H. impetiginosus* and 10.4 to 35.4% for *T. roseoalba*. ²n = end of the initial development stage, defined when the plants reached an average of 10 accumulated leaves on the main stem. All thresholds were established in preliminary experiments, as described in Ferreira et al. (2025).

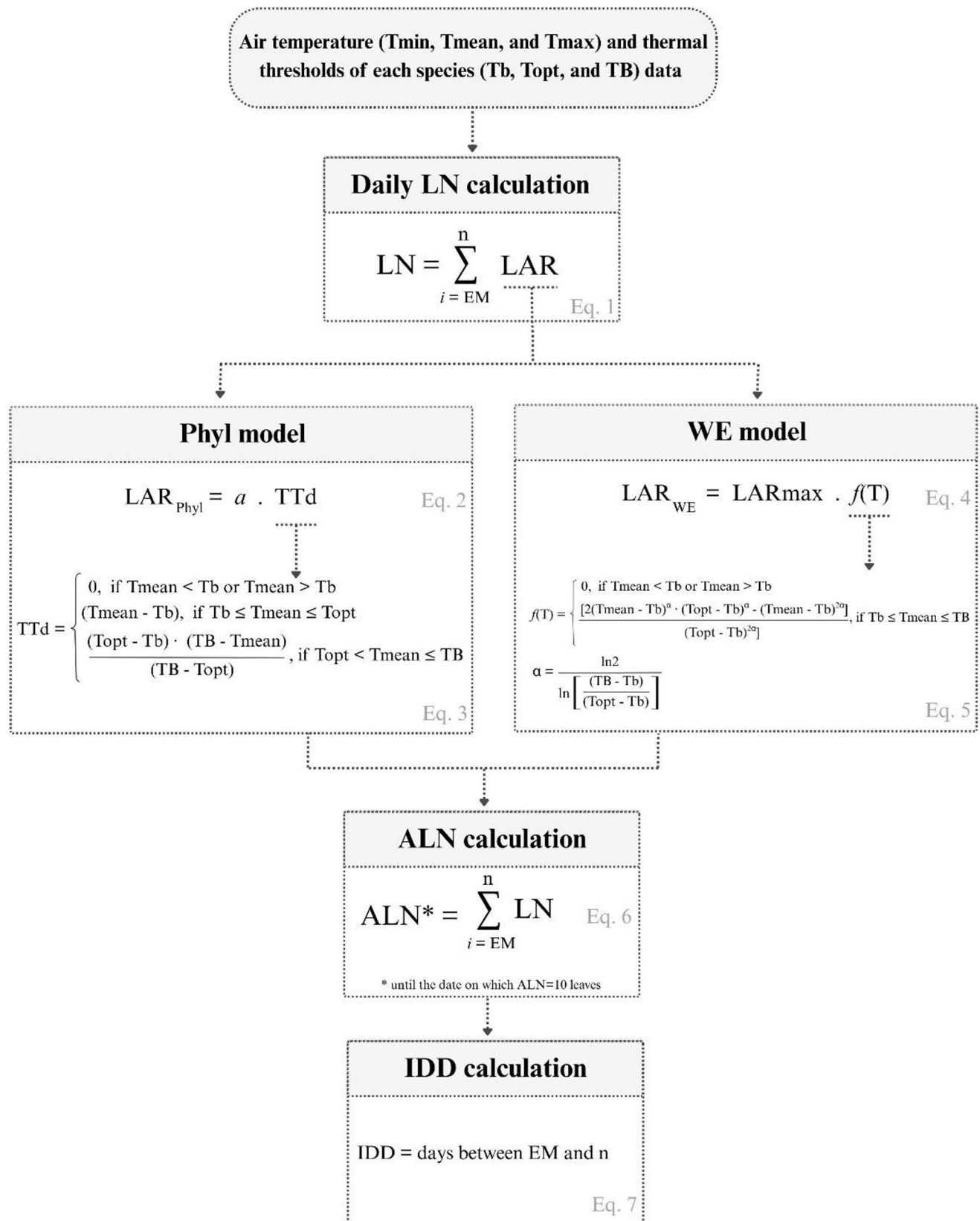


Fig. 1 Schematic representation of the steps for estimating initial development, considering accumulated leaf number (ALN) on the main stem and the initial development duration (IDD), according to the Phyllochron (Phyl) and Wang and Engel (WE) models. Adapted from Fagundes et al. (2021, 2024a). Where: EM=emergence date; n=end of initial development stage date; LAR_{Phyl} and LAR_{WE} =daily leaf appearance rate by the Phyl model and WE model (leaf day⁻¹) respectively; a =angular coefficient of the linear regression between LAR and TTd (leaf °C day⁻¹), which is species-specific and expresses the mean development rate; TTd=daily thermal time (°C day); LAR_{max} =maximum daily leaf appearance rate (leaf day⁻¹), which is species-specific; $f(T)$ =beta temperature response function (from 0 to 1); and α =coefficient of the $f(T)$; Tmean=daily mean air temperature, recorded by an automatic weather station installed in the experimental area; Tb, Topt and TB=thermal thresholds of initial development (base, optimum, and maximum temperatures, respectively).

mean of the regression slopes (Ferreira et al. 2019; Martins and Streck 2007).

The LAR_{max} was calibrated from a series of nonlinear regressions between ALN and accumulated $f(T)$, adjusted for each SD and forest species. The LAR_{max} value was taken from the regression yielding the lowest mean square error (MSE) (Fagundes et al. 2024a; Martins et al. 2023a).

The performance of both models was evaluated using independent ALN data (from SD7 to SD14) in two stages: (I) comparison between observed (ALNobs) and estimated ALN (ALNest) values; and (II) comparison between observed (IDDobs) and estimated IDD (IDDest) values by both models (Martins et al. 2022, 2023b) (Fig. 2). For stage I, model accuracy was evaluated by using the performance index (c-index), mean bias (BIAS), and root mean square error (RMSE), Levene's and Tukey's tests ($\alpha=0.05$). The c-index, BIAS, and RMSE were obtained by (Fagundes et al. 2024a; Snedecor and Cochran 1989):

$$c - index = \left[\frac{\sum (O_i - \bar{O}_i) \cdot (E_i - \bar{E}_i)}{\left\{ \left[\sum (O_i - \bar{O}_i)^2 \right] \cdot \left[\sum (E_i - \bar{E}_i)^2 \right] \right\}^{0.5}} \right] \cdot \left\{ 1 - \left[\frac{\sum (E_i - O_i)^2}{\sum (|E_i - \bar{O}_i| + |O_i - \bar{E}_i|)^2} \right] \right\} \quad (1)$$

$$BIAS = \frac{\sum_{i=1}^{nd} E_i - \sum_{i=1}^{nd} O_i}{\sum_{i=1}^{nd} O_i} \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{nd} (E_i - O_i)^2}{nd}} \quad (3)$$

where: E_i = estimated ALN values by the Phyl and WE models; $\bar{E}$ = mean ALN values estimated by the Phyl and

WE models; O_i = observed ALN values from the experiment; $\bar{O}_i$ = mean observed ALN values; nd=number of observations.

The interpretation of c-index performance follows Camargo and Sentelhas (1997): $c > 0.85$: excellent; $0.76 < c < 0.85$: very good; $0.66 < c < 0.75$: good; $0.61 < c < 0.65$: reasonable; $0.51 < c < 0.60$: poor; $0.41 < c < 0.50$: very poor; and $c \leq 0.40$: extremely poor.

Levene's test was applied to evaluate the homogeneity of variance between ALNobs and ALNest for both models. The hypotheses tested were H_0 =homogeneous variances ($p \geq 0.05$) versus H_1 =heterogeneous variances ($p < 0.05$) (Brown and Forsythe 1974):

$$W = \frac{(nd - k)}{(k - 1)} \cdot \frac{\sum_{i=1}^k N_i \left(\bar{Z}_i - \bar{Z} \right)^2}{\sum_{i=1}^k \sum_{j=1}^{N_i} \left(Z_{ij} - \bar{Z}_i \right)^2} \quad (4)$$

where: W=Levene's test value; nd=total number of observations; k=2, representing the two groups compared (ALNobs and ALNest by Phyl and WE); N_i = number of observations in the i-th group; $\bar{Z}_i$ = mean of the absolute deviations within the i-th group; $\bar{Z}$ = overall mean of all absolute deviations; $Z_{ij} = |Y_{ij} - \tilde{Y}_i|$ = the absolute deviation of each observation from the median of its group (a criterion adopted due to its greater robustness to the presence of outliers); Y_{ij} = ALN value (observed or estimated by Phyl and WE models); $\tilde{Y}_i$ = median of ALN values of the i-th group.

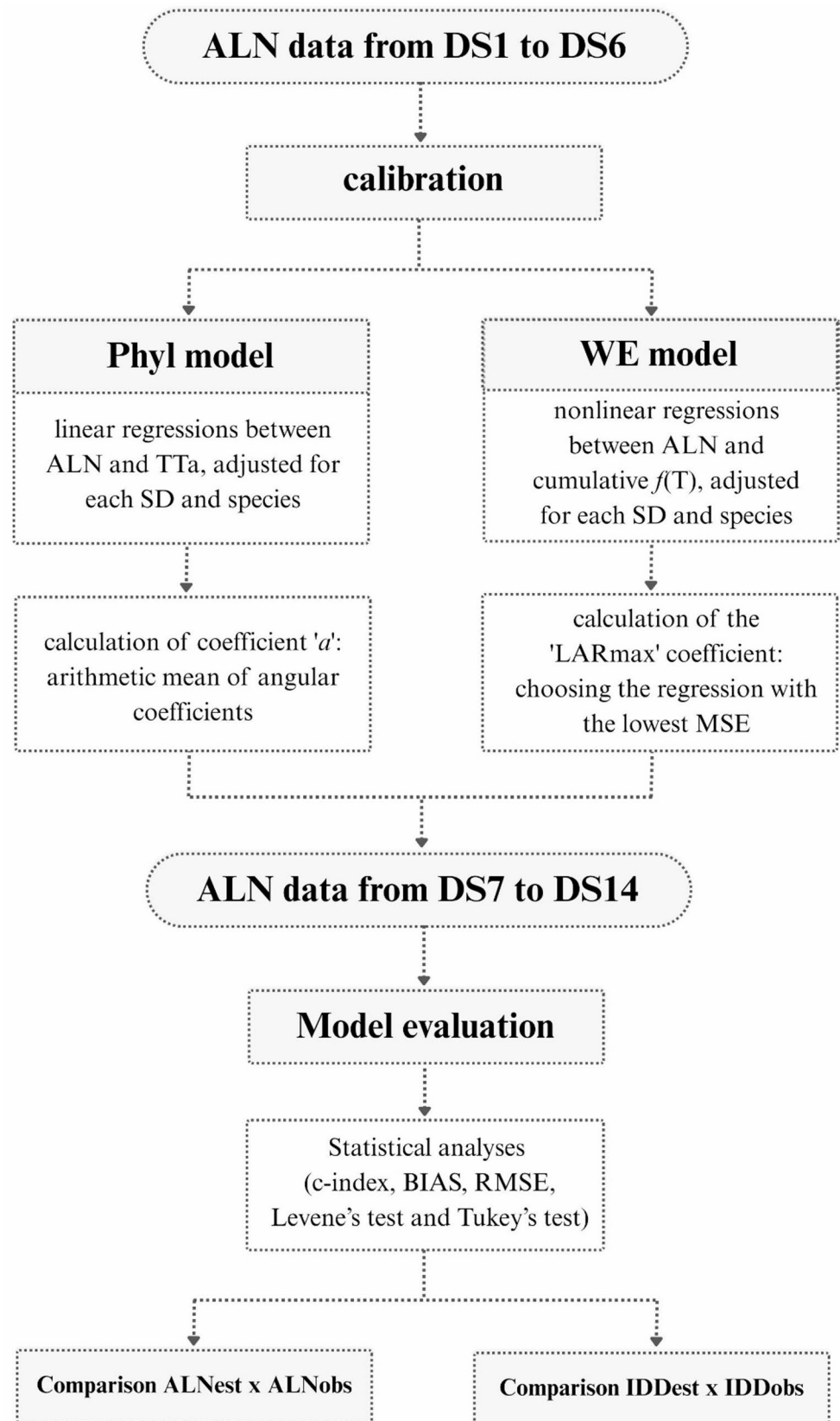
Tukey's test was used to compare the means of ALNobs and ALNest for both models. The hypotheses tested were: H_0 =ALNobs mean values do not differ from the ALNest mean (for each model and species) ($p \geq 0.05$) versus H_1 =ALNobs mean values differ from the ALNest mean ($p < 0.05$), given by (Tukey 1977):

$$\Delta = q \sqrt{\frac{MSE}{nd}} \quad (5)$$

Where: Δ = Tukey test value, $q = (2 \text{ models} - 1)$, MSE=mean square error obtained from the sum of squared differences between ALNobs and ALNest divided by the number of data; nd=number of observations.

In stage II, RMSE, BIAS, and Tukey's test were applied to IDDobs and IDDest values obtained from the Phyl and WE models.

Fig. 2 Schematic representation of the calibration and performance evaluation steps for the Phyllochron (Phyl) and Wang and Engel (WE) models
Adapted from Fagundes et al. (2024a); Martins et al. (2022, 2023b).



The model that provided the most accurate estimation of ALN, given by the highest c-index, homogeneous variance ($p \geq 0.05$), lowest BIAS and RMSE, non-significant differences in mean values ($p \geq 0.05$), and the best estimation of IDD, was considered the most suitable for describing the initial development of each species (Fagundes et al. 2024a).

2.3 Identifying the Impacts of Air Temperature Projections on IDD

The IDD was simulated for current climate (CC, 1995–2014) and projected for three future periods: near future (NF, 2041–2060), intermediate future (IF, 2061–2080), and far future (FF, 2081–2100), under three SSPs: SSP2-4.5, SSP3-7.0, and SSP5-8.5, considering the model that best described initial development under experimental conditions (detailed in 2.2). Simulations and projections were performed for each species and SD (Table 1), calculating the IDD as the number of days from EM to ALN = 10 leaves (Fagundes et al. 2024a; Martins et al. 2022).

Daily mean air temperature (Tmean) data from 16 NEX-GDDP-CMIP6 GCMs (Table S2) was extracted for the grid point nearest to Itajubá and used as input in the temperature functions, i.e., TTd (Phyl) or $[f(T)]$ (WE) (Fig. 3). This climate models are provided by the Climate Analytics Group and NASA Ames Research Center, and made available through the NASA Center for Climate Simulation (NCCS) portal (Thrasher et al. 2022) at <<https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp%3E> and have a horizontal resolution of 0.25° (latitude/longitude), suitable for local-scale studies. The selected GCMs perform well over the study region (Dias et al. 2024; Ribeiro et al. 2024).

All simulations and projections were performed for each GCM and SSP, and ensemble means were subsequently calculated. The projections were performed under three SSPs: SSP2-4.5, SSP3-7.0, and SSP5-8.5. SSP narratives and radiative forcing trajectories follow O'Neill et al. (2017).

Tmean data from climate models were validated for the CC by comparison with data provided by Xavier et al. (2016), extracted for the grid point nearest to Itajubá at a horizontal resolution of 0.25° (latitude/longitude), similar to climate models from NEX-GDDP-CMIP6. The validation procedure assessed the ability of the 16 GCMs in representing observed Tmean and, consequently, the IDD responses of the studied species. Validation procedure was performed using Pearson's correlation (r), RMSE and BIAS (Dias et al. 2024; Snedecor and Cochran 1989):

$$r = \frac{\sum (E_i - \bar{E}) \cdot (O_i - \bar{O})}{\sqrt{(\sum (E_i - \bar{E})^2 - \sum (O_i - \bar{O})^2)}} \quad (6)$$

$$\text{RMSE} = \left[\frac{\sum (E_i - O_i)^2}{nd} \right]^{0.5} \quad (7)$$

where: E_i = daily Tmean values simulated for each NEX-GDDP-CMIP6 climate model; O_i = daily Tmean values provided by Xavier et al. (2016), both from 1995 to 2014; nd = number of observations; $\bar{E}$ and $\bar{O}$ = mean values of E_i and O_i , respectively. The statistics were calculated for each climate model and the ensemble mean of all models.

Four types of BIAS were calculated based on differences between the Tmean simulated by each GCM and the observed Tmean provided by Xavier et al. (2016): monthly minimum and maximum, seasonal (DJF, MAM, JJA, and SON), and annual mean biases.

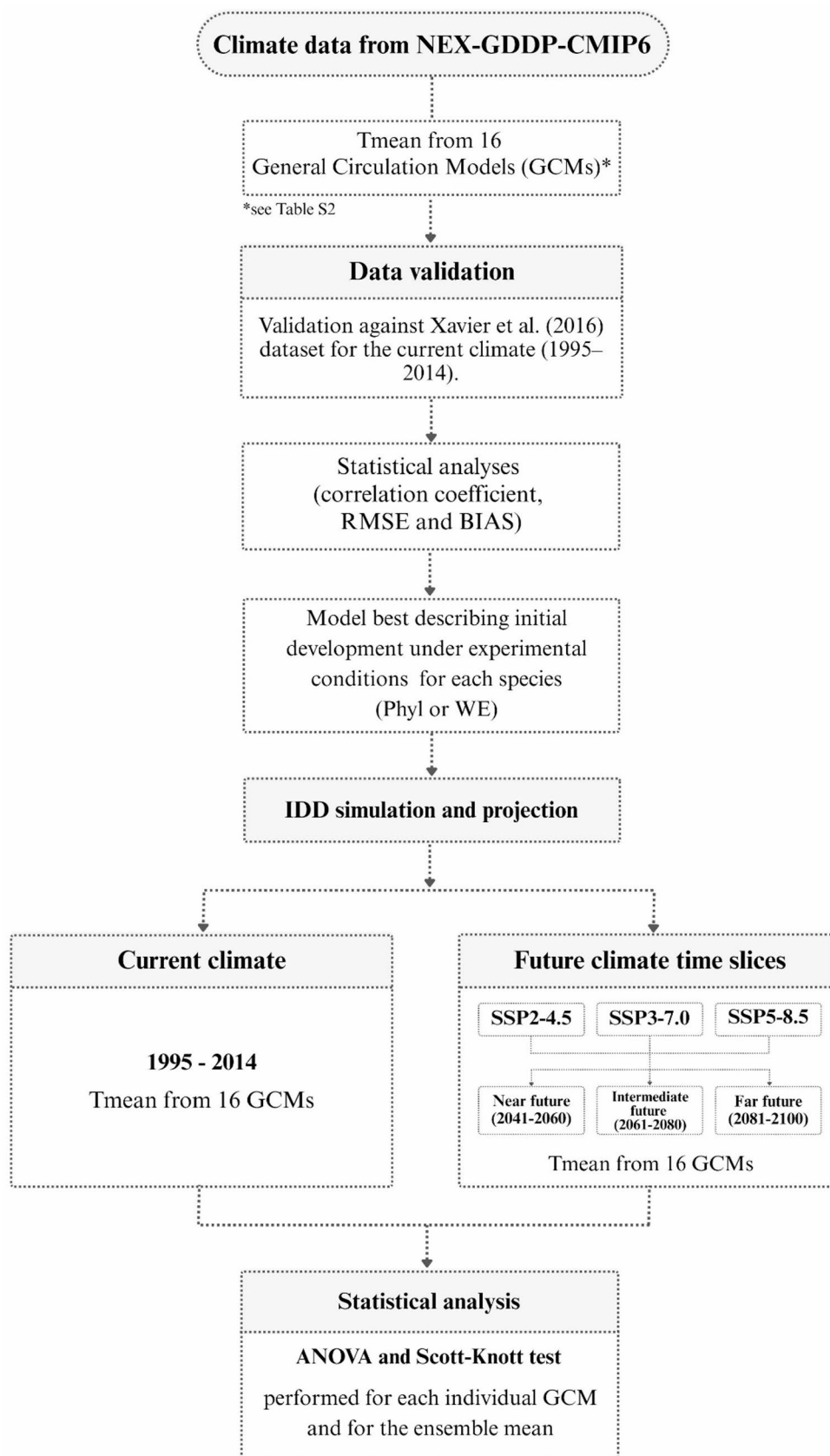
To assess the impact of projected Tmean on development, IDD data for each species were analyzed using a three-way analysis of variance (ANOVA), considering 4 periods (CC, NF, IF, FF), 3 socioeconomic scenarios (SSP2-4.5, SSP3-7.0, SSP5-8.5), and 14 Sowing dates (SD). Mean comparisons were performed using the Scott–Knott test ($p = 0.05$) (Scott and Knott 1974). Both analyses were performed using ensemble mean IDD obtained from the 16 climate models for each SSP.

3 Results

The ALN dataset used to calibrate (SD1 to SD6) and evaluate (SD7 to SD14) both models was obtained under sowing dates encompassing a wide range of weather conditions, especially air temperature. Overall, during the experimental period, air temperature ranged from 3.4 °C (absolute minimum) to 38.1 °C (absolute maximum), accumulated precipitation varied from 124.8 to 1635.4 mm SD⁻¹, global solar radiation ranged from 1.8 (minimum value) to 34.9 MJ m⁻² day⁻¹ (maximum value), and photoperiod varied from 11.6 (minimum value) to 14.3 h (maximum value) (Fig. 4). These values are consistent with the climatological means of monthly temperature, precipitation, and global solar radiation for Itajubá (Alves et al. 2020). Such variability among SDs is important, as it yields robust ALN datasets for calibrating and evaluating initial development models (Fagundes et al. 2024a; Ferreira et al. 2019; Martins et al. 2022).

Fig. 3 Schematic representation of the steps to identify the impacts of projected air temperature on IDD.

Adapted from Fagundes et al. (2024a); Martins et al. (2022, 2023b)



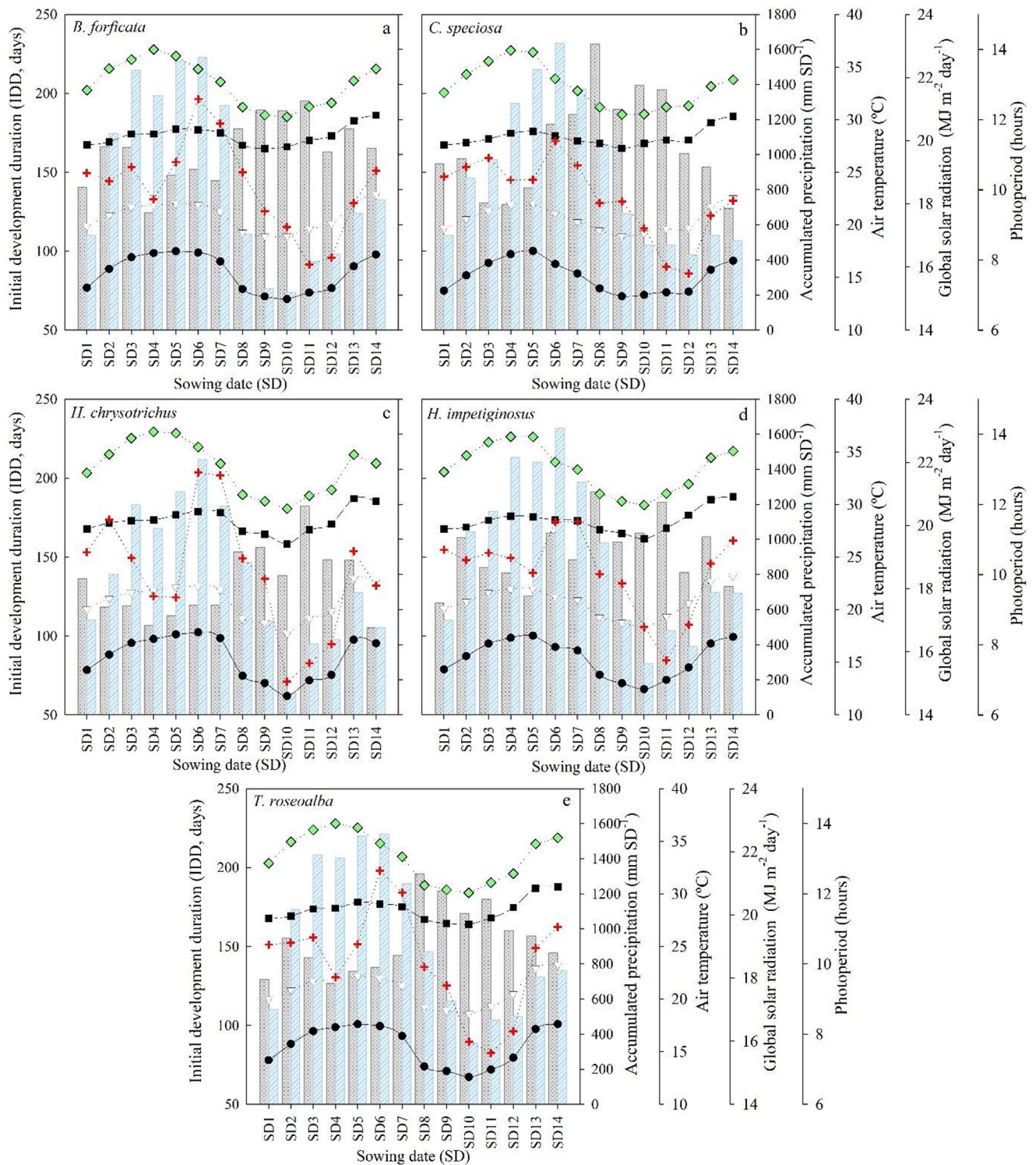


Fig. 4 Initial development duration (IDD, days), air temperature (minimum, mean and maximum, °C), accumulated precipitation (mm SD⁻¹), global solar radiation (MJ m⁻² day⁻¹) for the 14 sowing dates (SD1 to SD14) for five forest species: *B. forficata* (panel a), *C. spe-*

ciosa (panel b), *H. chrysotrichus* (panel c), *H. impetiginosus* (panel d) e *T. roseoalba* (panel e), during the experiments under open-air conditions in Itajubá, Minas Gerais, Brazil. Weather variables were recorded from an automatic weather station located at the experimental area

3.1 Calibration and Performance Evaluation of the Development Models

The calibrated coefficients ‘*a*’ (Phyl) and LARmax (WE) differed among the studied forest species (Table 2) and were statistically significant ($p \leq 0.05$). Both coefficients describe the thermal requirements for initial development. I.e., lower (higher) values of ‘*a*’ and LARmax indicate slower (faster) leaf appearance rates, resulting in longer (shorter) initial development duration (IDD, in days) (Fagundes et al. 2025a, b; Martins et al. 2022).

For example, in the Phyl model, the biological meaning of coefficient ‘*a*’ is given by its reciprocal ($1/a$), which corresponds to the thermal requirement for the appearance of a single leaf ($^{\circ}\text{C day leaf}^{-1}$) (Martins et al. 2023b; Martins and Streck 2007). Accordingly, the species required $\sim 115.1^{\circ}\text{C day}$ (*H. chrysotrichus*), $120.6^{\circ}\text{C day}$ (*C. speciosa*), $143.2^{\circ}\text{C day}$ (*T. roseoalba*), $146.6^{\circ}\text{C day}$ (*H. impetiginosus*), and $179.5^{\circ}\text{C day}$ (*B. forficata*) to emit one leaf. Thus, the total accumulated thermal time required to complete the initial development (ALN=10 leaves) ranged from $\sim 1,151^{\circ}\text{C day}$ for *H. chrysotrichus* to $\sim 1,795^{\circ}\text{C day}$ for *B. forficata*. These thermal accumulations closely matched those obtained in the experimental conditions of SD13 ($\sim 1.155^{\circ}\text{C day}$) for *H. chrysotrichus*, and SD11 ($\sim 1.683^{\circ}\text{C day}$) and SD13 ($\sim 1.685^{\circ}\text{C day}$) for *B. forficata*. Conversely, for *H. impetiginosus*, SD11 ($\sim 1.216^{\circ}\text{C day}$) and SD13 ($\sim 1.197^{\circ}\text{C day}$) exhibited lower thermal time than estimated by the phyllochron approach ($\sim 1.466^{\circ}\text{C day}$), while for *C. speciosa*, SD11 ($\sim 1.422^{\circ}\text{C day}$) exhibited higher thermal time accumulation than the phyllochron approach ($\sim 1.206^{\circ}\text{C day}$).

Regarding the WE model, the LARmax coefficient indicates the maximum leaf appearance rate in 1 day, which occurs when Tmean approaches the Topt for development (Martins et al. 2022). I.e., higher LARmax values denote faster development and shorter IDD. Using this approach, the estimated IDD (IDDest) ranged from ~ 104 days (*H. chrysotrichus*) to 168 days (*B. forficata*). Overall, the IDDest values derived from LARmax are consistent with the IDD observed (IDDobs) in SDs where there Tmean remained close to Topt. For example, for *T. roseoalba*, the IDDest = 140 days was similar to IDDobs in SD3, SD5, SD6 and SD7, which presented higher frequency ($\sim 70\%$) of days with Tmean near Topt (21.2°C). Otherwise, IDDest diverged from IDDobs in SDs where there is a higher frequency

of Tmean near Tb or TB. For example, *H. impetiginosus* exhibited IDDest = 131 days, differing from IDDobs under SD8 (191 days), SD9 (159 days), SD10 (165 days), and SD11 (185 days), which had higher frequencies of Tmean near Tb (12.6°C) or TB (42.6°C) (~ 46 cases = 26% and ~ 19 cases = 12%, respectively).

Both models accurately estimated ALN for the five studied species across nearly all SDs, with moderate to high c-index values (0.61 to 0.99), low BIAS (-0.45 to 0.78) and low RMSE (0.35 leaves to 5.2 leaves) (Table 3). Furthermore, except in SD7, SD8, and SD11 of *C. speciosa* and SD8, SD9, and SD11 of *H. chrysotrichus*, both models satisfied the assumptions of variance homogeneity and normality. Such results are desirable when selecting the most suitable development model (Fagundes et al. 2021, 2024a; Martins et al. 2022; Martins and Streck 2007).

When analyzing the behavior of estimated and observed ALN across species and SDs during initial development (Fig. 5), a tendency toward underestimation is observed for the Phyl, mainly for *B. forficata*, *H. impetiginosus*, and *T. roseoalba* (all SDs). In contrast, the WE model tended to overestimate ALN from ~ 5 leaves, mainly for *C. speciosa* (except SD14), *H. chrysotrichus* (except SD14), and *T. roseoalba* (except SD7 and SD14).

Although both models accurately estimated ALN, the WE model performed slightly better for *B. forficata*, *H. impetiginosus*, and *T. roseoalba* in most SDs, with an overall RMSE of ~ 1.14 to 1.50 leaves and a closer fit to the 1:1 line. Conversely, Phyl performed better for *C. speciosa* (global RMSE = 1.30 leaves) and *H. chrysotrichus* (global RMSE = 1.41 leaves).

Analyzing the IDD patterns (Fig. 6), exactly in the SD where ALN was underestimated (or overestimated) (Fig. 5; Table 3) there was a corresponding IDD overestimation (or underestimation), with magnitudes proportional to RMSE and BIAS values. For example, for *H. impetiginosus*, the ALN underestimation by the Phyl model across all SDs (Fig. 5, panel g) resulted in IDD overestimations ranging from +41 (SD11) to +70 days (SD12) (Fig. 6, panels e and f). Conversely, the largest ALN overestimation generated by the WE model occurred for *C. speciosa* in nearly all SDs (except SD14), leading to IDD underestimations ranging from -21 (SD12) to -105 days (SD8).

Overall, IDD estimation performance across species (and SDs) followed the same pattern observed for ALN, i.e., the WE model performed better for *B. forficata*, *H.*

Table 2 Calibrated coefficients ‘*a*’ (phyllochron model) and LARmax (Wang and Engel model) for five native forest species, in Itajubá, Minas Gerais, Brazil

Forest species	a (leaf $^{\circ}\text{C day}^{-1}$)	LARmax (leaf day^{-1})
<i>Bauhinia forficata</i>	0.005569	0.0597
<i>Ceiba speciosa</i>	0.008288	0.0811
<i>Handroanthus chrysotrichus</i>	0.008688	0.0953
<i>Handroanthus impetiginosus</i>	0.006819	0.0767
<i>Tabebuia roseoalba</i>	0.006980	0.0716

Table 3 Performance of the Phyllochron (Phyl) and Wang and Engel (WE) models in estimating accumulated leaf number (ALN) for the five native forest species in Itajubá, Minas Gerais, Brazil

Sowing date (SD)	Model	c-index ¹	BIAS	RMSE (leaves)	Levene ²	ALNobs	ALNest ³
<i>Bauhinia forficata</i>							
SD7	Phyl	0.82	-0.31	2.03	0.76 ^{ns}	6.35	4.35 ^{ns}
	WE	0.88	-0.25	1.64	0.46 ^{ns}		4.78 ^{ns}
SD 8	Phyl	0.84	-0.27	1.93	0.12 ^{ns}	6.62	4.82 [*]
	WE	0.89	-0.17	1.56	0.02 [*]		5.47 [*]
SD 9	Phyl	0.87	-0.20	1.51	0.07 ^{ns}	6.31	5.04 ^{ns}
	WE	0.89	-0.08	1.38	0.01 [*]		5.78 ^{ns}
SD 10	Phyl	0.87	-0.22	1.54	0.17 ^{ns}	6.22	4.83 [*]
	WE	0.90	-0.10	1.29	0.02 [*]		5.61 ^{ns}
SD 11	Phyl	0.93	-0.12	1.00	0.11 ^{ns}	5.25	4.61 ^{ns}
	WE	0.93	0.06	1.16	0.02 [*]		5.56 ^{ns}
SD 12	Phyl	0.89	-0.31	1.75	0.58 ^{ns}	5.60	3.88 [*]
	WE	0.96	-0.17	0.99	0.86 ^{ns}		4.65 ^{ns}
SD 13	Phyl	0.98	-0.12	0.73	0.66 ^{ns}	5.54	4.86 ^{ns}
	WE	0.99	-0.01	0.49	0.29 ^{ns}		5.47 ^{ns}
SD 14	Phyl	0.96	-0.17	1.05	0.90 ^{ns}	5.88	4.84 ^{ns}
	WE	0.98	-0.09	0.61	0.58 ^{ns}		5.37 ^{ns}
Average	Phyl	0.89	-0.22	1.44	0.42 ^{ns}	5.97	4.65 [*]
	WE	0.93	-0.10	1.14	0.28 ^{ns}		5.34 [*]
<i>Ceiba speciosa</i>							
SD7	Phyl	0.94	0.40	1.31	0.03 [*]	5.56	6.27 ^{ns}
	WE	0.82	0.78	2.92	0.00 [*]		7.76 ^{ns}
SD 8	Phyl	0.76	0.40	2.81	0.00 [*]	5.17	7.21 ^{ns}
	WE	0.61	0.78	5.02	0.00 [*]		9.18 [*]
SD 9	Phyl	0.98	0.00	0.58	0.87 ^{ns}	6.01	5.99 ^{ns}
	WE	0.90	0.27	2.10	0.06 ^{ns}		7.64 ^{ns}
SD 10	Phyl	0.87	0.30	1.87	0.06 ^{ns}	4.82	6.27 ^{ns}
	WE	0.71	0.67	3.88	0.00 [*]		8.06 [*]
SD 11	Phyl	0.92	0.24	1.55	0.04 [*]	4.73	5.87 ^{ns}
	WE	0.76	0.64	3.62	0.00 [*]		7.74 [*]
SD 12	Phyl	0.98	-0.09	0.58	0.81 ^{ns}	5.03	4.60 ^{ns}
	WE	0.94	0.22	1.45	0.13 ^{ns}		6.12 ^{ns}
SD 13	Phyl	0.98	0.01	0.44	0.76 ^{ns}	5.19	5.25 ^{ns}
	WE	0.93	0.26	1.61	0.30 ^{ns}		6.56 ^{ns}
SD 14	Phyl	0.93	-0.20	1.26	0.30 ^{ns}	5.48	4.36 ^{ns}
	WE	0.99	-0.03	0.35	0.95 ^{ns}		5.05 ^{ns}
Average	Phyl	0.92	0.13	1.30	0.36 ^{ns}	5.25	5.73 ^{ns}
	WE	0.83	0.45	2.62	0.18 ^{ns}		7.26 [*]
<i>Handroanthus chrysotrichus</i>							
SD7	Phyl	0.96	-0.20	1.33	0.81 ^{ns}	5.68	4.55 ^{ns}
	WE	0.92	0.15	1.25	0.25 ^{ns}		6.53 ^{ns}
SD 8	Phyl	0.87	-0.15	1.64	0.03 [*]	7.07	5.98 ^{ns}
	WE	0.76	0.23	3.08	0.00 [*]		8.68 ^{ns}
SD 9	Phyl	0.88	-0.17	1.60	0.04 [*]	6.84	5.64 [*]
	WE	0.80	0.19	2.70	0.00 [*]		8.14 ^{ns}
SD 10	Phyl	0.91	-0.23	1.44	0.75 ^{ns}	6.10	4.68 ^{ns}
	WE	0.93	0.11	1.50	0.03 [*]		6.73 ^{ns}
SD 11	Phyl	0.89	0.03	1.39	0.00 [*]	5.67	5.85 ^{ns}
	WE	0.68	0.53	4.05	0.00 [*]		8.65 ^{ns}
SD 12	Phyl	0.92	-0.08	1.02	0.14 ^{ns}	5.40	4.98 ^{ns}
	WE	0.81	0.35	2.69	0.00 [*]		7.32 ^{ns}
SD 13	Phyl	0.97	-0.06	0.67	0.32 ^{ns}	5.91	5.55 ^{ns}
	WE	0.84	0.33	2.62	0.01 [*]		7.86 ^{ns}

Table 3 (continued)

Sowing date (SD)	Model	c-index ¹	BIAS	RMSE (leaves)	Levene ²	ALNobs	ALNest ³
SD 14	Phyl	0.79	-0.36	2.18	0.53 ^{ns}	5.84	3.75*
	WE	0.95	-0.09	0.89	0.40 ^{ns}		5.30 ^{ns}
Average	Phyl	0.90	-0.15	1.41	0.33 ^{ns}	6.06	5.12*
	WE	0.84	0.22	2.35	0.09 ^{ns}		7.40 ^{ns}
<i>Handroanthus impetiginosus</i>							
SD7	Phyl	0.84	-0.32	2.13	0.55 ^{ns}	6.45	4.36*
	WE	0.95	0.02	1.13	0.07 ^{ns}		6.56 ^{ns}
SD 8	Phyl	0.79	-0.29	2.10	0.10 ^{ns}	6.78	4.81*
	WE	0.84	0.10	2.16	0.00*		7.48 ^{ns}
SD 9	Phyl	0.67	-0.40	2.89	0.65 ^{ns}	7.10	4.25*
	WE	0.88	-0.07	1.59	0.01*		6.60 ^{ns}
SD 10	Phyl	0.78	-0.34	2.03	0.85 ^{ns}	5.84	3.85*
	WE	0.91	0.03	1.35	0.01*		6.03 ^{ns}
SD 11	Phyl	0.76	-0.33	2.08	0.07 ^{ns}	5.97	4.01*
	WE	0.84	0.10	2.08	0.00*		6.57 ^{ns}
SD 12	Phyl	0.81	-0.37	2.20	0.20 ^{ns}	5.70	3.59*
	WE	0.99	-0.01	0.42	0.43 ^{ns}		5.64 ^{ns}
SD 13	Phyl	0.84	-0.26	1.59	0.34 ^{ns}	5.85	4.34*
	WE	0.86	0.12	1.78	0.00*		6.55 ^{ns}
SD 14	Phyl	0.68	-0.45	3.18	0.68 ^{ns}	6.92	3.77*
	WE	0.91	-0.17	1.49	0.10 ^{ns}		5.76 ^{ns}
Average	Phyl	0.77	-0.34	2.27	0.43 ^{ns}	6.32	4.12*
	WE	0.90	0.02	1.50	0.08 ^{ns}		6.40 ^{ns}
<i>Tabebuia roseoalba</i>							
SD7	Phyl	0.90	-0.25	1.51	0.67 ^{ns}	5.78	4.33 ^{ns}
	WE	0.97	-0.04	0.65	0.38 ^{ns}		5.54 ^{ns}
SD 8	Phyl	0.92	-0.13	1.12	0.12 ^{ns}	6.04	5.26 ^{ns}
	WE	0.86	0.16	1.97	0.00*		7.03 ^{ns}
SD 9	Phyl	0.92	-0.18	1.24	0.17 ^{ns}	6.07	5.00 ^{ns}
	WE	0.89	0.10	1.67	0.00*		6.70 ^{ns}
SD 10	Phyl	0.88	-0.24	1.46	0.36 ^{ns}	5.73	4.38*
	WE	0.91	0.05	1.39	0.01*		5.99 ^{ns}
SD 11	Phyl	0.89	-0.19	1.27	0.14 ^{ns}	5.27	4.26*
	WE	0.87	0.16	1.73	0.00*		6.12 ^{ns}
SD 12	Phyl	0.90	-0.23	1.38	0.61 ^{ns}	5.39	4.13*
	WE	0.94	0.06	1.04	0.07 ^{ns}		5.70 ^{ns}
SD 13	Phyl	0.93	-0.17	1.12	0.69 ^{ns}	5.96	4.96 ^{ns}
	WE	0.95	0.08	1.03	0.07 ^{ns}		6.40 ^{ns}
SD 14	Phyl	0.86	-0.31	2.01	0.99 ^{ns}	6.32	4.37*
	WE	0.96	-0.10	1.07	0.13 ^{ns}		5.70 ^{ns}
Average	Phyl	0.90	-0.21	1.39	0.47 ^{ns}	5.82	4.59*
	WE	0.92	0.06	1.32	0.08 ^{ns}		6.15 ^{ns}

¹ Performance criteria for the c-index: $c \geq 0.85$: excellent; $0.76 < c < 0.85$: very good; $0.66 < c < 0.75$: good; $0.61 < c < 0.65$: reasonable; $0.51 < c < 0.60$: poor; $0.41 < c < 0.50$: very poor and $c \leq 0.40$: extremely poor (Camargo and Sentelhas 1997). ² P-value = Levene test probability that compares variance between observed accumulated leaf number (ALNobs) and estimated (ALNest) for each model. The null hypothesis (ns) for the Levene test assumes homogeneous variances ($p \geq 0.05$) and the alternative hypothesis (*) assumes heterogeneous variances ($p < 0.05$). ³ Tukey's test, which compares the means between observed accumulated leaf number (ALNobs) and estimated (ALNest) for each model. The null hypothesis (ns) for the Tukey test is that the means are not different from each other ($p \geq 0.05$), and the alternative hypothesis (*) is that the means are different ($p < 0.05$).

impetiginosus, and *T. roseoalba*, while Phyl was better for *C. speciosa* and *H. chrysotrichus*. However, both models showed larger errors (higher RMSE) in IDD than in ALN estimation, with IDD biases (underestimates or

overestimates) proportional to ALN deviations (Table 3). For example, the largest ALN overestimations for *C. speciosa* in SD7 and SD8 lead to the largest IDD underestimations by Phyl (-28 and -56 days) and WE (-65 and -105

Fig. 5 Estimated accumulated leaf number (ALNest) versus observed (ALNobs) by the Phyllochron (Phyl) and Wang and Engel (WE) models for *Bauhinia forficata* (panels a and b), *Ceiba speciosa* (panels c and d), *Handroanthus chrysotrichus* (panels e and f), *Handroanthus impetiginosus* (panels g and h), and *Tabebuia roseoalba* (panels i and j). The solid line is the 1:1 line

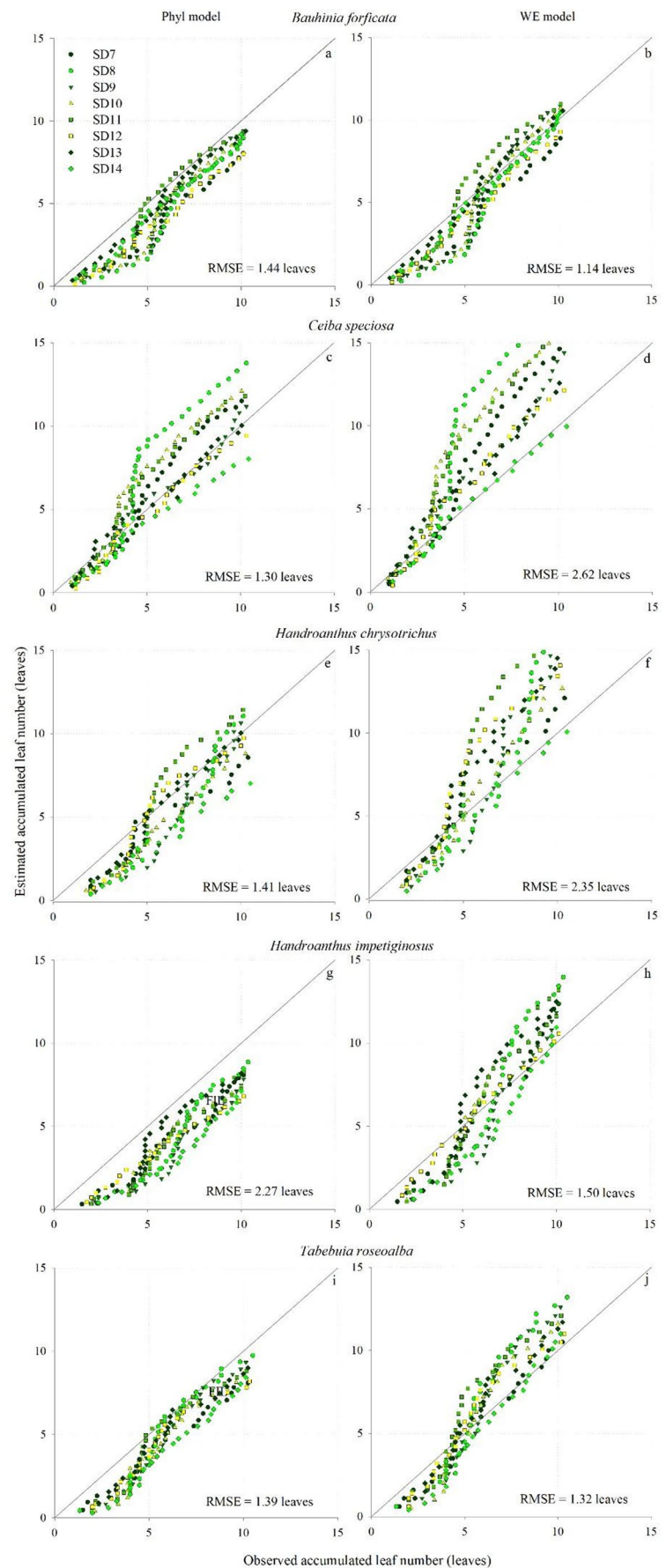
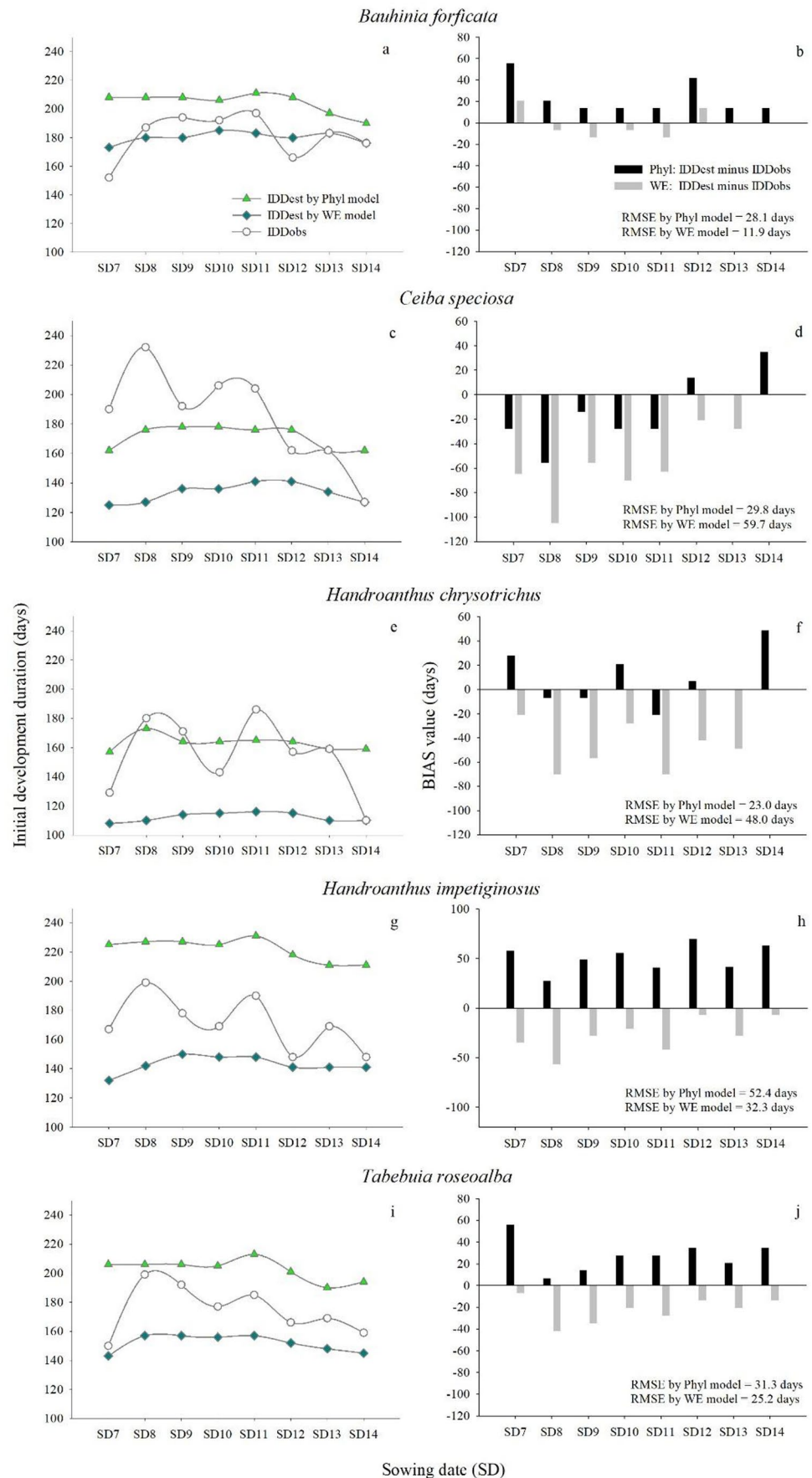


Fig. 6 Initial development duration (IDD; days) from sowing dates 7 to 14 for *Bauhinia forficata* (panels a and b), *Ceiba speciosa* (panels c and d), *Handroanthus chrysotrichus* (panels e and f), *Handroanthus impetiginosus* (panels g and h), and *Tabebuia roseoalba* (panels i and j). BIAS value is given by the difference between estimated IDD (IDDest) and observed (IDDobs) values from the Phyl and WE models



days). On the contrary, smallest ALN underestimation for *H. chrysotrichus* in SD12 by Phyl produced the smallest IDD overestimation (+7 days).

Errors in IDD estimation result from the cumulative propagation of ALN errors, which is a common feature in forest species development models (Fagundes et al. 2021, 2024a; Martins et al. 2022, 2023a). There is still no established criterion defining acceptable IDD error limits for forest species (Fagundes et al. 2021; Martins et al. 2022; Reis et al. 2021). In this study, Phyl model generated the smallest overall errors for *C. speciosa* (RMSE=1.30 leaves and 29.8 days) and *H. chrysotrichus* (RMSE=1.41 leaves and 23.0 days), while WE model generated the smallest errors for *B. forficata* (RMSE=1.14 leaves and 11.9 days), *H. impetiginosus* (RMSE=1.50 leaves and 32.3 days), and *T. roseoalba* (RMSE=1.32 leaves and 25.2 days). Therefore, the Phyl model was selected to assess development responses, in terms of IDD, under future climate conditions for *C. speciosa* and *H. chrysotrichus*, and the WE model for *B. forficata*, *H. impetiginosus*, and *T. roseoalba*.

3.2 Validation, simulation, and Projections of Tmean and IDD

The sixteen NEX-GDDP-CMIP6 climate models and the ensemble mean accurately represent the monthly, seasonal, and annual patterns of Tmean for the CC (Fig. 7) ($r > 0.97$, RMSE < 0.79 °C, and BIAS from -0.85 to +1.84), highlighting IPSL-CM6A-LR ($r = 0.99$, RMSE = 0.56 °C, mean annual BIAS = +0.04), MPI-ESM1-2-LR ($r = 0.99$, RMSE = 0.59 °C, mean annual BIAS = -0.05), and NorESM2-LM ($r = 0.99$, RMSE = 0.59 °C, mean annual BIAS = +0.04).

Therefore, Tmean data from each NEX-GDDP-CMIP6 climate model were used as inputs in the TTd (from the Phyl model) to simulate (CC) and project (NF, IF, FF in the three SSPs) the IDD of *C. speciosa* and *H. chrysotrichus*, and in the $f(T)$ (from the WE model) to *B. forficata*, *H. impetiginosus*, and *T. roseoalba*.

The ensemble of NEX-GDDP-CMIP6 models projects a gradual and continuous increase in Tmean for Itajubá throughout the 21st century, ranging from ~+1.3 °C in the near future (NF, SSP2-4.5) up to ~+4.5 °C in the far future (FF, SSP5-8.5) (Fig. 8). These projections are consistent with previous studies conducted for Itajubá using different

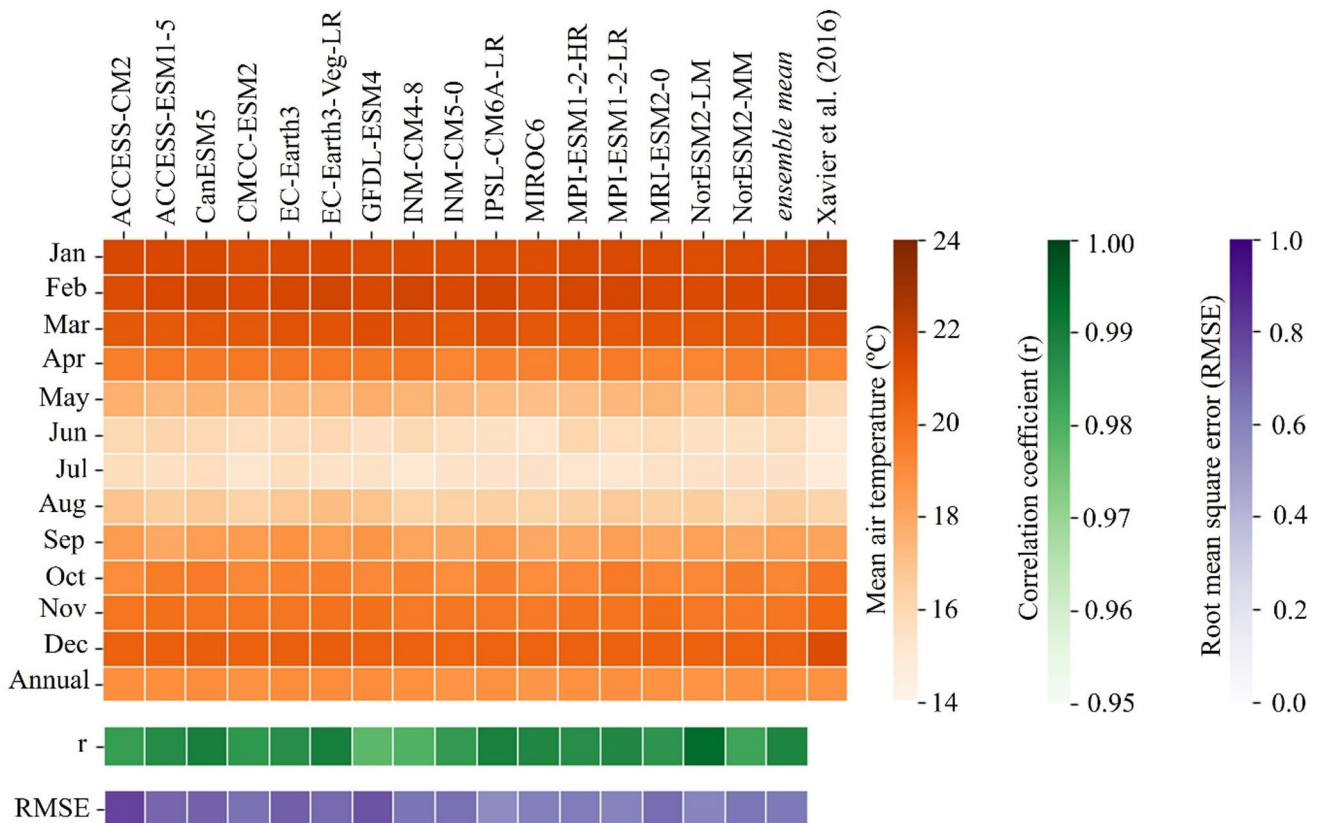


Fig. 7 Monthly and annual cycle of mean air temperature (Tmean; °C) simulated by the sixteen General Circulation Models (GCMs) from the NEX-GDDP-CMIP6 dataset, ensemble mean, and observed data provided by Xavier et al. (2016) for the current climate (1995–2014)

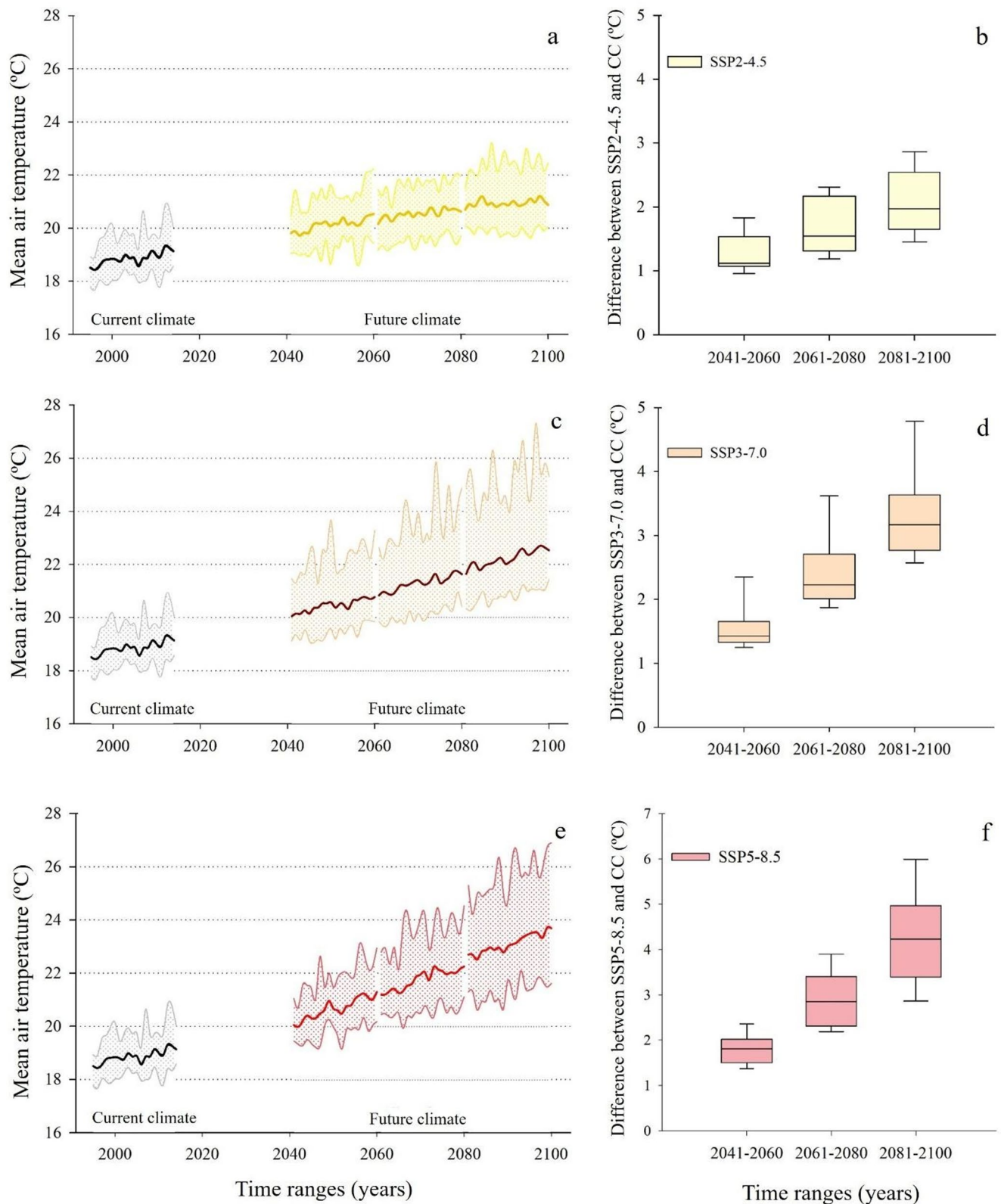


Fig. 8 Temporal variation in simulated mean air temperature for the current climate (CC=1995–2014) and projected for the future climate (near future=2041–2060; intermediate=2061–2080; far=2081–2100) in Itajubá, derived from 16 climate models under three socioeconomic scenarios: SSP2-4.5 (panel a), SSP3-7.0 (panel c), and SSP5-8.5 (panel e). Bold lines (black, orange, brown, and red) represent the

ensemble mean of the climate models. Gradient-colored lines (gray, yellow, orange, and red) represent each GCM. Boxplot represents the differences between future (NF, IF, and FF) and current climate (CC) within each SSP (panel b - SSP2-4.5, panel c - SSP3-7.0, and panel f - SSP5-8.5)

climate models, temporal scales and CMIP generations. For instance, Fagundes et al. (2025a), based on 13 NEX-GDDP-CMIP6 models, Fagundes et al. (2021), based on 8 NEX-GDDP-CMIP5 models, and Alves et al. (2020), using a regional climate model (RegCM4/CMIP5), reported projected increases from ~ 1.1 °C (in NF and SSP2-4.5) to 5 °C (FF and RCP8.5).

Tmean projections will affect IDD patterns throughout the 21st century, with varying magnitudes of change across species, SDs, and SSPs (Fig. 9; Table 4). When analyzing the IDD projections by species (and SD), period, and SSP (Fig. 9), three distinct response patterns emerge: (I) increased Tmean may accelerate LAR, leading to faster leaf appearance, earlier completion of the initial development phase, and consequently, a shorter IDD; (II) reduced LAR and extend IDD; or (III) LAR and IDD remain virtually unchanged. Furthermore, the magnitudes of IDD changes vary across species, SD, and climate models, with a predominant pattern toward situation I, mainly for *C. speciosa* and *H. chrysotrichus* in the FF and SSP5-8.5 (Fig. 9).

The lowest inter-model variability in IDD, in terms of standard deviation, was observed in the NF (and in SD3 to SD7) for *B. forficata*, *H. impetiginosus*, and *T. roseoalba*. Conversely, the highest variability was observed in the FF, mainly for *C. speciosa* and *H. chrysotrichus* (in SD2, SD3, and SD4). This variability likely reflects inherent uncertainties in climate model predictability (Fagundes et al. 2021; Martins et al. 2023a). However, the use of multiple NEX-GDDP-CMIP6 models provides a broader coverage of potential outcomes, thereby reducing uncertainty in future IDD projections (Fagundes et al. 2021, 2025a, b; Florêncio et al. 2019; Martins et al. 2023a; Reis et al. 2021). Accordingly, ANOVA and mean comparisons (Table 4) were performed using the ensemble mean IDD values derived from all 16 climate models.

ANOVA revealed a significant interaction among periods (CC, NF, IF, and FF) and socioeconomic scenarios (SSP 2-4.5, 3-7.0, and 5-8.5) and SDs ($p \leq 0.05$) for all five species studied. This indicates differences in magnitude and relative influence of each main factor on IDD across species. For all species, SD exerts the greatest influence on IDD (F-test values between 1856 and 3257), followed by periods (F-test values between 97.2 and 398) and scenarios (F-test values between 5.2 and 131) (Table S4). Despite inter-model variability, IDD is projected to be most susceptible to interannual variations in Tmean among SDs, consistent with observations for *L. ferrea* (Fagundes et al. 2021), *C. antisiphilitica*, *P. regnellii* (Fagundes et al. 2025a) and *B. orellana* (Reis et al. 2021).

When analyzing the IDD projections by SD, a greater reduction (-1 to -55 days) can be observed, mainly under FF and SSP5-8.5. Regardless of species, the largest IDD

reductions occur between SD8 and SD12, corresponding to simulations conducted between February and June/July. Conversely, increases of +1 to +24 days are projected mainly for SD2 to SD7, corresponding to simulations from August to January, under FF (SSP3-7.0 and SSP5-8.5) (Fig. 9; Table 4).

Except for *H. chrysotrichus*, most species exhibit IDD reductions across the majority of SDs, with magnitudes varying across periods (NF to FF) and SSPs. *B. forficata* and *C. speciosa* showed similar patterns of IDD change across SDs, with reductions projected in SD1, SD2, SD8 to SD13, comprising simulations conducted from January to June, and increases in SD3 to SD6 (September to December), across all periods under SSP5-8.5 (Fig. 9; Table 4). *H. impetiginosus* and *T. roseoalba* display similar patterns, with IDD reductions (-1 to -25 days) in SD1, SD2, SD8 to SD13, and increases (+1 to +7 days) in SD3 to SD7 (September to January simulations). For *H. chrysotrichus*, all three situations (I, II and III) are projected throughout the 21st century under the three SSPs. I.e., IDD reductions in SD1 and SD8 to SD12 (February to July simulations), IDD increases in SD2 to SD7, SD13, and SD14 (August to January simulations), and no change in SD3 (IF-SSP2-4.5) and SD7 (IF-SSP5-8.5).

Across periods and scenarios, the tendency for IDD reduction (or increase) becomes more pronounced in the far time slice and under scenarios with higher radiative forcing (Fig. S2). As an example, for *C. speciosa*, the largest IDD increases in the FF were projected under SSP3-7.0 (+6 to +8 days) and SSP5-8.5 (+3 to +15 days), while the largest decreases are projected under SSP3-7.0 (-3 to -51 days) and SSP5-8.5 (-10 to -55 days), compared to SSP2-4.5 (-2 to -39 days).

When comparing species, *B. forficata* appears least impacted by Tmean projections, with the smallest change, i.e., the smallest reduction (-1 to -16 days) and increase (+1 to +6 days) of IDD, followed by *T. roseoalba* (-23 to +7 days) and *H. impetiginosus* (-25 to +7 days). Otherwise, *C. speciosa* and *H. chrysotrichus* exhibited the largest IDD changes, indicating greater sensitivity to projected increases in Tmean. For *C. speciosa*, larger (less intense) IDD reductions are projected, ranging from -1 (NF and SSP2-4.5) to -55 days (FF and SSP5-8.5), along with smaller increases (up to +15 days) in IDD (Table 4). In contrast, *H. chrysotrichus* showed smaller reductions, from -1 (NF and SSP2-4.5) to -44 days (FF and SSP5-8.5), and slightly larger increases (up to +23 days).

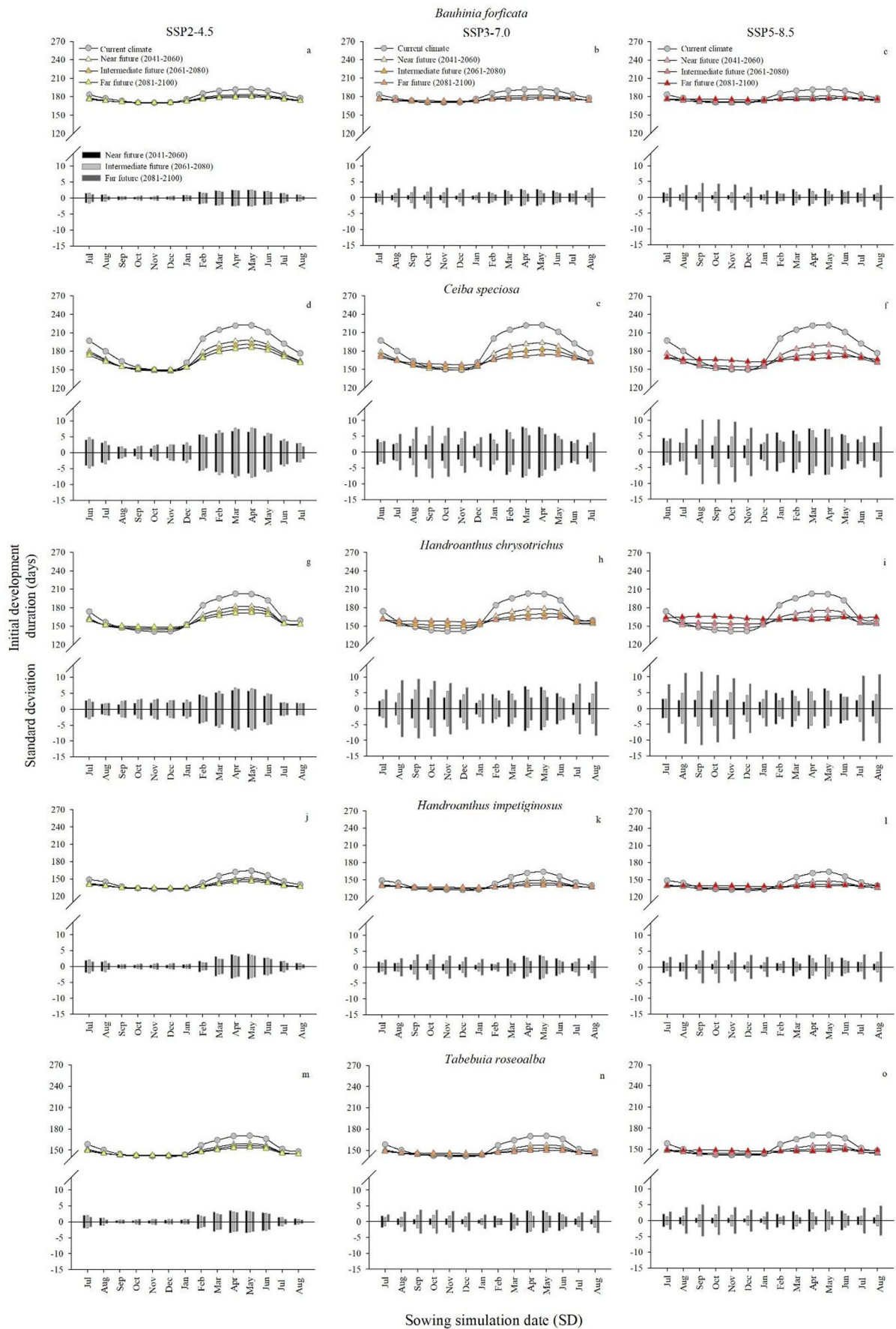


Fig. 9 Initial development duration (IDD, in days) across sowing dates for *Bauhinia forficata* (panels a, b and c), *Ceiba speciosa* (panels d, e and f), *Handroanthus chrysotrichus* (panels g, h and i), *Handroanthus impetiginosus* (panels j, k and l) and *Tabebuia roseoalba* (panels m, n and o) simulated for the current climate (1995–2014), and projected for the near (2041–2060), intermediate (2061–2080), and far (2081–2100) future under three socioeconomic scenarios (SSP2–4.5, SSP3–7.0, and SSP5–8.5). Vertical bars refer to the standard deviation of the IDD of the 16 NEX-GDDP-CMIP6 climate models for the near (black), intermediate (light gray), and far future (dark gray)

4 Discussion

Since IDD depends on daily thermal accumulation, which is metabolically regulated by plants to occur within thermal thresholds (T_b , T_{opt} , and T_B) (Bahuguna and Jagadish 2015; Ferreira et al. 2019; Martins et al. 2023b), any modification in T_{mean} changes TT_d (Phyl) and $f(T)$ (WE) and, consequently, affects LAR and IDD (Fagundes et al. 2021, 2024a; Martins et al. 2023a, b; Martins and Streck 2007). Therefore, the reductions in IDD simulated in SDs with milder temperature projections (January to July), even under warmer scenarios (FF and SSP5–8.5) (Fig. 9; Table 4), may have resulted from an increased frequency of projected T_{mean} values close to the T_{opt} of the studied forest species (20.3 °C to 21.5 °C). For example, for *C. speciosa*, considering the SDs with the largest IDD reductions, ~141 days (85.5%) in SD8, ~124 days (74.2%) in SD9, and ~119 days (71.2%) in SD10 exhibited projected T_{mean} values near T_{opt} (21 °C). At optimal temperatures, TT_d (Eq. 3) and $f(T)$ (Eq. 5) reach their maximum values, and LAR approaches LAR_{max} (Fagundes et al. 2024a; Martins et al. 2023a, b; Reis et al. 2021), accelerating seedling development and thereby reducing IDD (from –1 to –55 days).

The reduction in IDD in SD8 to SD13 may be advantageous for all five species, as a faster development rate may enhance competitive ability and seedling survival in the field (Martins et al. 2023b; Reis et al. 2021), while also promoting the acquisition of tolerance to cope with subsequent increases in T_{mean} (Fagundes et al. 2021; Reis et al. 2021). The beneficial effect of optimal temperatures on initial development under projected T_{mean} increases has been observed in tropical forest species such as *Anadenanthera peregrina* (L.) Speg. (Fagundes et al. 2021), *Bixa orellana* L. (Reis et al. 2021), *Cybistax antisiphilitica* (Mart.) Mart. and *Platycamus regnellii* Benth (Fagundes et al. 2025a), which are native to Brazil, and *Psidium guajava* L. (Reis et al. 2021), native to South America. Despite these benefits, increases in T_{mean} more commonly result in IDD increases.

On the other hand, in warmer scenarios (FF and SSP5–8.5) and sowing dates (SD3 = September to SD6 = December), an increase in IDD was projected for all species, corresponding to periods where temperature projections are most extreme for Itajubá, reaching up to 6 °C in September in FF (Alves et

al. 2020). The increase in IDD may be associated with more frequent occurrences of projected T_{mean} (Fig. 8) closer to the T_B of the species (~40 °C). At supraoptimal temperatures (> T_{opt}), TT_d and $f(T)$ approach zero, reducing LAR relative to LAR_{max} , and thereby increasing IDD (Fagundes et al. 2025a, b; Martins et al. 2022, 2023a; Martins and Streck 2007; Reis et al. 2021). Delays in initial development due to supraoptimal temperatures have also been reported in other forest species, including *Citharexylum myrianthum* Cham. (Reis et al. 2021), *Libidibia ferrea* (Mart. ex Tul.) LP Queiroz (Fagundes et al. 2021), both native to Brazil, and exotic commercial species such as *Corymbia citriodora* (Hook.) (K.D. Hill & L.A.S. Johnson) and *Eucalyptus urophylla* (S.T. Blake) (Martins et al. 2023b).

These contrasting responses between increases and decreases in the IDD have direct implications for forest restoration and ecosystem functioning. For instance, species (and SDs) in which IDD increases with rising T_{mean} may experience more days under stressful conditions, such as heat waves and drought events (Fagundes et al. 2025a, b). Moreover, from ecological and functional perspectives, the combined effects of increasing T_{mean} and heterogeneous precipitation regimes can reshape interspecific competition, natural regeneration process, and successional dynamics when higher leaf development no longer coincides with periods of higher water availability (Ruiz-Díaz et al., 2024). This phenological mismatch has been identified as a central mechanism driving restoration planting failure under future climate conditions, particularly in tropical ecosystems, where delays or advances in the leaf phenophase directly affect photosynthesis (Ferreira et al. 2025), plant water balance, and biotic interactions during the establishment phase (Anderegg et al. 2020).

Uncertainties in IDD projections may arise due to (I) limitations in climate model predictability (Fagundes et al. 2021) and (II) the ability of models to simulate IDD (Fagundes et al. 2024a; Florêncio et al. 2019; Martins et al. 2022). To minimize item I, we considered a set (and ensemble) of multiple climate models from NEX-GDDP-CMIP6, following recommendations by Dias et al. (2024); Fagundes et al. 2025a, b; Thrasher et al. (2022). The error related to item II may be associated with cumulative errors in ALN estimation, especially above 5 leaves (Fig. 5), which resulted in errors of 11.9 days (*B. forficata*) to 32.3 days (*H. impetiginosus*) by the WE model, and ~26 days (*C. speciosa* and *H. chrysotrichus*) by the Phyl model.

Overestimation (underestimation) of ALN by the Phyl and WE models led to underestimation (overestimation) of IDD across SDs. ALN overestimation arises from increasing LAR over time, accelerating the development cycle and, consequently, reducing IDD (Fagundes et al. 2021; Martins et al. 2023b; Martins and Streck 2007). This may occur due

to (Fagundes et al. 2021, 2024a; Ferreira et al. 2019; Martins et al. 2022): (I) the lower ability of models to capture development in colder SDs ($T_{\text{mean}} \cong T_b$), and (II) limited model capacity to simulate lower LAR values caused by slower germination speed or declining seed viability over time. Conversely, ALN underestimations may result from reduced LAR under T_{mean} conditions close to T_b (or T_b) (Martins et al. 2022; Martins and Streck 2007).

Practical issues related to seed viability loss over time, especially for *H. impetiginosus* (in SD7 and SD8), may have reduced the emergence speed, germination, and LAR, contributing to the lower accuracy of Phyl (RMSE = ~2.3 leaves and 52.4 days) and WE (RMSE = ~1.50 leaves and 32.3 days). To minimize further damage to seed viability in the studied species, strict storage protocols were followed to maintain conditions closer to ideal (cold chamber, $T_{\text{mean}} \sim 2.9\text{--}5.0\text{ }^{\circ}\text{C}$ and relative humidity ~50.0%) (Fowler and Martins 2001). In addition, seeds were collected in two or more dispersal periods (Table 1).

Similar ALN and IDD patterns predicted by Phyl and WE were observed for the initial development of *P. guajava* (Ferreira et al. 2019), *C. myrianthum* (Martins et al. 2022), (*A. peregrina* (Fagundes et al. 2021), *C. antisiphilitica*, and *P. regnellii* (Fagundes et al. 2024a). Errors of 1.5 to 4 leaves in ALN estimate and 5.9 to 29.1 days in IDD estimate are common for native forest species (Fagundes et al. 2024a; Martins et al. 2022), with tolerable maximum IDD errors of 30–35 days (Fagundes et al. 2021, 2024a). Therefore, errors associated with item II were minimal for (*B. forficata* with the WE model (RMSE = 1.14 leaves and 11.9 days), within expected ranges for *H. chrysotrichus* by the Phyl model (RMSE = 1.41 leaves and 23 days) and *T. roseoalba* by the WE (RMSE = 1.32 leaves and 25.2 days), and close to tolerable levels for (*C. speciosa* (by the Phyl, RMSE = 1.30 leaves and 29.8 days) and *H. impetiginosus* (by the WE, RMSE = 1.50 leaves and 32.3 days). Therefore, uncertainties in projected IDD for *C. speciosa* and *H. impetiginosus* under future climate remain evident in this study.

All stages of this study, including calibration of coefficients (a and LARmax), model evaluation, and selection of the most accurate model, provide important practical insights and are necessary to identify climate projection impacts on development (Fagundes et al. 2024a; Martins et al. 2022; Reis et al. 2021). For example, the values of ' a ' and 'LARmax' (Table 2) are used to compare thermal requirements and development patterns among forest species (Martins et al. 2023b; Martins and Streck 2007). Accordingly, *C. speciosa* ($1/a \sim 121\text{ }^{\circ}\text{C day leaf}^{-1}$ and LARmax = 0.0811 leaf day $^{-1}$) and *H. chrysotrichus* ($1/a = 115\text{ }^{\circ}\text{C day leaf}^{-1}$ and LARmax = 0.0953 leaf day $^{-1}$) emit leaves faster and require fewer days to complete initial development compared to *B. forficata* ($1/a = 179.5\text{ }^{\circ}\text{C day leaf}^{-1}$ and LARmax = 0.0597

leaf day $^{-1}$), *H. impetiginosus* ($1/a = 147.0\text{ }^{\circ}\text{C day leaf}^{-1}$ and LARmax = 0.0767 leaf day $^{-1}$) and *T. roseoalba* ($1/a = 143\text{ }^{\circ}\text{C day leaf}^{-1}$ and LARmax = 0.0716 leaf day $^{-1}$).

Although not yet widely adopted in forest nurseries, coefficients ' a ' and 'LARmax' represent promising alternatives to replace less precise methods, such as visual assessments, or even destructive techniques, like the Dickson quality index (Dickson et al. 1960; Fagundes et al. 2021; Martins et al. 2023b). Beyond providing more consistent estimates of initial development, these coefficients facilitate determination of IDD and identification of critical stages for silvicultural practices, including hardening, acclimatization in nursery conditions, and final transplantation (Fagundes et al. 2024a). For example, species with higher a and LARmax values, such as *C. speciosa* and *H. chrysotrichus*, complete this phase more quickly than slower-developing species like *B. forficata*. I.e., allowing nurserymen to schedule transplantation or acclimation when seedlings exhibit optimal vigor and field adaptability. This approach mitigates premature planting (seedlings insufficiently developed) and delayed planting (excessive elongation or quality reduction), thereby reducing post-transplant losses and improving survival.

This aspect is particularly relevant for native species, often used in restoration projects, where seed availability is limited, and each individual holds significant ecological value (Silva et al. 2015, 2017). Furthermore, in a context of global warming, projecting species-specific thermal requirements enhances the ability to select genotypes resilient to environmental variations, supporting adaptation and mitigation measures (Fagundes et al. 2025a, b; Reis et al. 2021). In this study, *B. forficata*, *T. roseoalba*, and *H. impetiginosus* were the least impacted by increases in T_{mean} , exhibiting comparatively smaller changes in IDD. Therefore, these species emerge as suitable candidates for forest restoration initiatives in the study region and in areas with climatic conditions similar to Itajubá. Moreover, integrating these models into nursery management raises seedling quality standards and enhances the efficiency of long-term forest restoration and biodiversity conservation programs.

4.1 Adaptive Measures To Address the Impacts of Temperature Projections on the Initial Development

The species studied are important representatives of the Brazilian flora that simultaneously face threats arising from climatic and anthropogenic pressures (Lima et al. 2024; Silva et al. 2019). *H. impetiginosus* and *T. roseoalba* are classified as near threatened, while *H. chrysotrichus* is listed as vulnerable by the IUCN (2021), mainly due to unsustainable logging practices and population decline. Moreover, habitat loss, exacerbated by forest fires, agricultural expansion, and

Table 4 Comparison of means for the initial development duration (IDD, in days) for *Bauhinia forficata*, *Ceiba speciosa*, *Handroanthus chrysotrichus*, *Handroanthus impetiginosus* and *Tabebuia roseoalba*, based on simulations for the current climate (CC=1995–2014) and the projections for the future climate (NF=2041–2060, IF=2061–2080 and FF=2081–2100) across 14 simulated sowing dates and three socioeconomic scenarios (SSP 2-4.5, SSP3-7.0, and SSP5-8.5) for Itajubá, Minas Gerais, Brazil

Sowing simulation date (SD)		CC	SSP2-4.5			SSP3-7.0			SSP5-8.5		
			NF	IF	FF	NF	IF	FF	NF	IF	FF
<i>Bauhinia forficata</i>											
SD1		183.2	Ed	177.6	De2	176.7	Eb3	175.6	Dal	177.1	Eb1
SD2		177.2	Dc	173.6	Cal	173.4	Dal	172.9	Cal	173.7	Dal
SD3		173.1	Bb	171.2	Bal	171.2	Bal	171.4	Ba2	171.5	Bal
SD4		170.2	Aa	169.7	Aal	170.0	Aal	170.4	Aa1	170.2	Aal
SD5		169.9	Aa	169.6	Aal	169.8	Aal	170.2	Aa1	169.9	Aal
SD6		170.6	Aa	170.0	Aal	170.1	Aal	170.4	Aa1	170.3	Aal
SD7		175.8	Cc	173.0	Cal	172.4	Cal	172.2	Cal	172.7	Cal
SD8		185.0	Fd	178.6	Ec3	177.0	Eb2	175.9	Da2	177.8	Fc2
SD9		189.5	Gd	181.8	Fc3	179.8	Fb3	178.1	Ea3	180.5	Gc2
SD10		191.3	Hd	182.9	Gc3	180.8	Gb3	178.8	Ea3	181.5	Hc2
SD11		192.1	Hd	183.4	Gc3	181.4	Gb3	179.4	Fa3	182.1	Hc2
SD12		189.3	Gd	181.6	Fc3	180.0	Fb3	178.4	Ea2	180.8	Gc2
SD13		183.1	Ed	177.7	De2	176.8	Eb3	175.6	Dal	177.2	Eb2
SD14		177.3	Dc	173.7	Cal	173.5	Dal	172.9	Cal	173.8	Dal
<i>Ceiba speciosa</i>											
Sowing simulation date (SD)		CC	SSP2-4.5			SSP3-7.0			SSP5-8.5		
			NF	IF	FF	NF	IF	FF	NF	IF	FF
SD1		196.5	Gd	180.0	Gc3	176.9	Gb3	173.3	Fa2	177.9	Gc2
SD2		180.0	Ec	166.0	Eb2	164.9	Eb2	162.6	Dal	165.3	Eb2
SD3		163.4	Cc	155.0	Cal	154.8	Cal	155.0	Bal	155.8	Cal
SD4		153.5	Bb	149.5	Bal	150.3	Bal	151.5	Aa1	151.2	Ba2
SD5		149.9	Ab	147.7	Aal	148.8	Aal	150.2	Ab1	149.2	Aa2
SD6		149.6	Ab	147.4	Aal	148.3	Aal	149.9	Ab1	148.8	Aa2
SD7		162.9	Cc	153.9	Cal	153.5	Cal	154.0	Bal	154.4	Cal
SD8		201.7	Hd	178.5	Gc3	172.2	Fb3	169.1	Ea2	175.6	Fc2
SD9		215.6	Jd	191.1	Hc3	184.4	Hb3	179.0	Ga3	186.3	Hc2
SD10		222.4	Kd	196.2	Ic3	189.5	Ib3	183.3	Ia3	191.2	Jc2
SD11		222.6	Kd	198.0	Ic3	191.7	Jb3	185.7	Ja3	193.3	Kc2
SD12		211.2	Id	190.6	Hc3	186.0	Hb3	181.1	Ha3	187.3	Ic2
SD13		191.5	Fd	176.1	Fc2	173.7	Fb3	170.2	Eal	174.5	Fc2
SD14		176.5	Dc	163.3	Db1	163.0	Db2	160.6	Cal	163.1	Dal
<i>Handroanthus chrysotrichus</i>											
Sowing simulation date (SD)		CC	SSP2-4.5			SSP3-7.0			SSP5-8.5		
			NF	IF	FF	NF	IF	FF	NF	IF	FF
SD1		173.8	Hd	162.9	Fb1	161.7	Fb2	159.8	Eal	162.2	Fb1
SD2		156.5	Ec	151.0	Cal	151.6	Cal	151.9	Cal	152.2	Cal
SD3		148.0	Ca	147.0	Bal	148.4	Bal	150.2	Bb1	148.9	Ba2

Table 4 (continued)

Bauhinia forficata																					
SD4	143.1	Ba	145.1	Ab1	147.0	Ac1	149.1	Ad1	147.1	Ab2	151.8	Ac2	158.2	Bd2	147.7	Ab2	154.5	Ac3	165.6	Cd3	
SD5	141.4	Aa	144.4	Ab1	146.4	Ac1	148.5	Ad1	146.5	Ab2	151.2	Ac2	157.6	Ad2	147.1	Ab2	153.9	Ac3	164.6	Bd3	
SD6	141.9	Aa	144.7	Ab1	146.4	Ac1	148.5	Ad1	146.8	Ab2	150.8	Ac2	156.7	Ad2	147.3	Ab2	153.4	Ac3	162.4	Ad3	
SD7	154.1	Db	150.5	Ca1	150.6	Ca1	151.5	Ca1	151.4	Ca1	153.0	Bb2	156.8	Ac2	151.3	Ba1	154.4	Ab2	161.3	Ac3	
SD8	185.1	Id	168.2	Gc3	163.5	Gb2	161.3	Fa1	166.1	Gb2	160.7	Dal	159.6	Ba1	163.6	Eb1	159.6	Ba1	160.8	Aa1	
SD9	196.2	Kd	176.3	Hc3	170.9	Ba3	166.8	Ga2	172.9	Hc2	165.4	Eb2	161.3	Ca1	170.5	Fc1	162.7	Cb1	160.4	Aa1	
SD10	203.5	Ld	181.6	Ic3	176.1	Ib3	170.8	Ia3	177.6	Ic2	168.9	Fb2	162.4	Ca2	174.7	Gc1	164.5	Dbl	159.6	Aa1	
SD11	202.7	Ld	182.0	Ic3	176.8	Ib3	171.7	Ia3	178.1	Ic2	170.0	Fb2	163.7	Da2	175.3	Gc1	165.5	Dbl	161.0	Aa1	
SD12	192.2	Jd	176.0	Hc3	172.4	Hb3	168.6	Ha2	173.5	Hc2	168.2	Fb2	164.2	Dal	171.3	Fb1	164.9	Dal	164.2	Ba1	
SD13	162.0	Gc	154.4	Ea1	154.8	Ea1	153.8	Dal	155.1	Ea1	155.7	Ca1	158.2	Bb2	154.5	Ca1	155.8	Aa1	163.3	Bb3	
SD14	159.5	Fc	152.7	Dal	153.3	Dal	152.9	Dal	153.6	Dal	155.1	Cb2	158.4	Bc2	153.1	Ca1	155.5	Ab2	164.4	Bd3	
Handroanthus impetiginosus																					
Sowing simulation date (SD)		CC	SSP2-4.5				SSP3-7.0				SSP5-8.5										
			NF	IF	FF	IF	FF	IF	NF	IF	FF	IF	FF	NF	IF	FF	IF	FF	NF	IF	
SD1	148.6	Hd	141.9	Fc2	141.0	Eb3	139.6	Da2	141.4	Ecl	140.0	Db2	139.0	Ca1	141.0	Ecl	138.9	Ca1	140.0	Bb2	
SD2	144.4	Fc	139.1	Eb1	138.7	Db2	137.6	Ca1	138.9	Dbl	138.1	Ca1	138.2	Ba1	138.5	Dal	137.6	Ba1	139.8	Bb2	
SD3	136.6	Cb	134.4	Ba1	134.5	Ba1	134.7	Aa1	134.8	Ba1	135.5	Aa2	137.3	Ab2	134.6	Ba1	136.0	Ab2	140.1	Bc3	
SD4	133.6	Ba	133.2	Aa1	133.6	Aa1	134.1	Aa1	133.8	Aa1	135.0	Ab2	137.4	Ac2	133.8	Aa1	135.9	Ab3	140.3	Bc3	
SD5	132.6	Aa	132.8	Aa1	133.3	Ab1	133.9	Ab1	133.4	Ab1	134.8	Ac2	137.0	Ad2	133.5	Aa1	135.6	Ab3	139.7	Bc3	
SD6	132.2	Aa	132.7	Aa1	133.1	Ab1	133.7	Ab1	133.3	Ab1	134.5	Ac2	136.8	Ad2	133.4	Ab1	135.4	Ac3	139.2	Ad3	
SD7	133.2	Ba	133.1	Aa1	133.4	Aa1	133.9	Aa1	133.6	Aa1	134.6	Ab2	136.5	Ac2	133.7	Aa1	135.4	Ab3	138.7	Ac3	
SD8	143.5	Ec	137.9	Db2	136.8	Ca1	136.5	Ba1	137.3	Ca1	136.4	Ba1	136.7	Ba1	136.8	Ca1	136.6	Aa1	137.9	Ab2	
SD9	155.3	Id	144.9	Gc3	142.2	Fb3	140.6	Ea2	143.5	Fc2	140.0	Db2	138.6	Ba1	142.4	Fc1	139.3	Cb1	138.3	Aa1	
SD10	162.2	Jd	149.9	Ic3	146.9	Hb3	144.2	Ga3	148.1	Hc2	143.4	Eb2	140.1	Da2	146.8	Hc1	141.5	Dbl	138.6	Aa1	
SD11	164.2	Kd	151.4	Ic3	148.5	Ib3	145.4	Ha3	149.6	Ic2	144.7	Fb2	140.8	Da2	148.0	Ic1	142.3	Dbl	138.9	Aa1	
SD12	156.0	Id	146.8	Hc3	145.2	Gb3	142.8	Fa2	145.9	Gc2	143.0	Eb2	140.8	Dal	145.0	Gbl	141.2	Dal	140.6	Ba1	
SD13	145.5	Gc	139.8	Eb1	139.3	Db2	138.0	Ca1	139.5	Dbl	138.8	Ca2	138.4	Ba1	139.0	Dbl	137.8	Ba1	140.1	Bc2	
SD14	139.9	Db	136.3	Ca1	136.2	Ca1	135.8	Ba1	136.5	Ca1	136.5	Ba1	137.4	Ab2	136.1	Ca1	136.4	Aa1	139.6	Bb3	
Tabebuia roseoalba																					
Sowing simulation date (SD)		CC	SSP2-4.5				SSP3-7.0				SSP5-8.5										
			NF	IF	FF	IF	FF	IF	NF	IF	FF	IF	FF	NF	IF	FF	IF	FF	NF	IF	
SD1	158.2	Fd	151.4	Gc2	150.4	Gb3	148.8	Ea1	150.8	Gc1	149.3	Db2	148.2	Ca1	150.3	Fb1	148.1	Ca1	148.9	Ba1	
SD2	150.1	Dc	146.0	Dal	145.9	Dal	145.2	Ca1	146.2	Dal	145.9	Ba1	146.5	Ba2	145.8	Dal	145.6	Ba1	148.5	Bb3	
SD3	144.6	Bb	143.0	Ba1	143.2	Ba1	143.5	Aa1	143.4	Ba1	144.3	Ab2	146.2	Bc2	143.3	Ba1	144.9	Ab2	149.0	Bc3	
SD4	142.2	Aa	142.0	Aa1	142.4	Aa1	143.0	Aa1	142.6	Aa1	143.8	Ab2	146.0	Bc2	142.6	Aa1	144.6	Ab3	148.7	Bc3	
SD5	141.6	Aa	141.8	Aa1	142.2	Aa1	142.7	Ab1	142.3	Aa1	143.6	Ab2	145.7	Ac2	142.4	Aa1	144.4	Ab3	148.2	Bc3	
SD6	141.7	Aa	141.8	Aa1	142.2	Aa1	142.7	Aa1	142.3	Aa1	143.4	Ab2	145.4	Ac2	142.4	Aa1	144.2	Ab3	147.6	Ac3	
SD7	143.9	Bb	142.9	Ba1	142.9	Ba1	143.3	Aa1	143.1	Ba1	143.8	Aa2	145.3	Ab2	143.2	Ba1	144.3	Aa2	147.2	Ab3	
SD8	157.4	Fc	149.9	Fb3	148.0	Fa2	147.3	Dal	149.1	Fb2	146.8	Ca1	146.5	Ba1	148.1	Eb2	146.5	Ba1	147.0	Aa1	
SD9	164.6	Gd	154.5	Hc3	151.9	Hb3	150.3	Fa2	153.1	Hc2	149.6	Db2	147.8	Ca1	152.1	Gc1	148.7	Cb1	147.3	Aa1	

Table 4 (continued)

<i>Bauhinia forficata</i>																				
SD10	170.0	Id	158.4	Jc3	155.7	Jb3	153.0	Ha3	156.7	Jc2	152.3	Eb2	149.0	Da2	155.4	Ic1	150.3	Db1	147.4	Aa1
SD11	170.6	Id	159.0	Jc3	156.3	Jb3	153.5	Ha3	157.3	Jc2	153.0	Eb2	149.6	Da2	156.0	Ic1	150.9	Db1	148.0	Aa1
SD12	165.8	Hd	156.4	Ic3	154.4	Ib3	152.3	Ga2	155.4	Ic2	152.1	Eb2	149.7	Da1	154.2	Hc1	150.4	Db1	149.3	Ba1
SD13	151.5	Ec	147.0	Eb1	146.7	Eb1	145.9	Ca1	147.0	Ea1	146.4	Ca1	146.8	Ba2	146.6	Da1	146.0	Ba1	148.5	Bb3
SD14	147.9	Cc	144.7	Ca1	144.7	Ca1	144.4	Ba1	145.0	Ca1	145.2	Ba1	146.3	Bb2	144.6	Ca1	145.2	Aa1	148.6	Bb3

*For details of simulated sowing dates, see Table 1. Means followed by the same uppercase letter in the column (sowing dates), lowercase letter in the row (CC – current climate, NF – near future, IF – intermediate future, and FF – far future), and number in the row (socioeconomic scenarios SSP2-4.5, SSP3-7.0, and SSP5-8.5) do not differ from each other by the Scott-Knott test at 5% probability. The initial development duration (IDD) values were obtained for each General Circulation Model (GCM), and the data in the table (original data) refer to the mean IDD values. As IDD data did not follow the normality assumption by the Shapiro-Wilk test ($p < 0.05$), they were transformed by Ln prior to analyses (Fagundes et al. 2021; Reis et al. 2021). Letters (A–L; a–d) and numbers (1–3) were arranged in ascending order of IDD.

conversion of natural areas into pasturelands (Silva et al. 2019), has further contributed to the decline of these and other species, such as the *B. forficata* and *C. speciosa*.

Given the vulnerability of these species and the potential impacts of temperature increases on their initial development, a comprehensive literature review was conducted to identify the most effective adaptation measures for nursery cultivation. Because the species' responses throughout the 21st century vary across SDs, adaptation measures should be tailored to each response.

For SDs where increases in IDD are projected, especially between SD2 and SD7 (August to January), adjustments in sowing dates and regulation of the nursery microclimate are recommended. This regulation can be achieved through artificial control of temperature, humidity, and light (Costa and Streck 2018; Fagundes et al. 2025a, b; Florêncio et al. 2019; Reis et al. 2021). Furthermore, nursery management practices should be optimized to ensure that seedlings reach adequate vigor for commercialization, including: (I) use of larger-volume containers; (II) application of controlled-release fertilizers; (III) higher frequency of phytosanitary treatments, such as insecticides and fungicides; and (IV) intensification of irrigation (Costa and Streck 2018; Fagundes et al. 2025a, b; Florêncio et al. 2022; Reis et al. 2021).

Conversely, for SDs where IDD reductions are projected, especially between SD8 and SD12 (February and June/July), changes in sowing date or container size are unnecessary, as the species tend to develop faster in these SDs. However, it is still recommended to apply controlled-release fertilizers, increase irrigation frequency, and intensify insecticide and fungicide applications (Fagundes et al. 2025a, b; Martins et al. 2023b; Reis et al. 2021).

Artificial microclimate regulation may be achieved by using 50% shading screen coupled with irrigation (Costa and Streck 2018; Reis et al. 2021), aiming to reduce leaf temperature and evapotranspiration losses. However, both measures can increase seedling production costs (Fagundes et al. 2025a). Since projected increases in Tmean across all SDs (Fig. 8) will raise evaporative demand, irrigation requirements in Itajubá may reach at least 9 mm day⁻¹ in far future (Alves et al. 2020). However, increased irrigation may also heighten susceptibility to foliar diseases and root rot, mainly of fungal origin (Lopes and Michereff 2018; Martins et al. 2023b). In seedlings of *B. forficata*, *C. speciosa*, *H. chrysotrichus*, *H. impetiginosus*, and *T. roseoalba* cultivated in nurseries, occurrences of *Corynespora cassicola* (target leaf spot), *Apiosporaria guaranitica* (brown blotch), and *Oidium* spp. (powdery mildew) have been reported (Carvalho 2003, 2006; Moreira and Arco-Verde 1998). Therefore, effective control of these pathogens becomes essential, with the application of broad-spectrum fungicides, such as from

strobilurin, triazole, and sulfur chemical groups (Andrade 2009; Nohra et al. 2021; Viana et al. 2018). Nonetheless, this measure implies additional costs, impacting nursery profitability and seedling marketability (Fagundes et al. 2025a, b).

Regarding disease and pest management, regardless of whether increases or decreases in IDD are projected, control strategies should be intensified, as rising temperatures favor pest proliferation and increase plant vulnerability to outbreaks and infestations (Delgado-Baquerizo et al. 2020; Martins et al. 2022). Under heat-stress conditions, seedlings of *B. forficata*, *C. speciosa*, *H. chrysotrichus*, *H. impetiginosus*, and *T. roseoalba* cultivated in nurseries are particularly susceptible to attacks from pests such as *Aleurothrixus* spp. (whitefly), *Coccus* spp. (mealybug), *Toxoptera* spp. (aphid), *Trioza tabebuiae* (ipê psyllid), *Oligonychus* spp. (mites); *Bradysia* spp., *Sciara* spp., and *Scythropochroa* spp. (fungus gnats), *Agrotis ipsilon*, *Nomophila* spp., *Spodoptera* spp. (caterpillars), *Gryllus* spp. (cricket) and *Neocurtilla* spp. (mole cricket) (Carvalho 2003, 2006; Lemes and Zanuncio 2021). Controlling these pests is crucial, as most of these insect species serve as hosts for plant-pathogenic viruses (Lemes and Zanuncio 2021). As biological control strategies, the introduction of potential natural enemies, such as predators or parasitoids (Florêncio et al. 2022; Lemes and Zanuncio 2021), or increasing the frequency of broad-spectrum insecticide and acaricide applications, particularly those belonging to the quinolizidine alkaloid (plant-derived) and ketoenol chemical groups (Andrade 2009; Andrade et al. 2020).

Lastly, species selection for future plantations can be guided by species-specific thermal thresholds and requirements, providing a basis for climate-adaptive restoration measures. In this context: (I) species with higher T_{opt} and broader thermal tolerance ranges should be prioritized in regions projected to experience more intense warming; (II) combining species with distinct thermal thresholds and development patterns can reduce ecological risks associated with mismatches between IDD and the onset of the rainy season; and (III) projections of IDD can support operational decisions related to nursery water allocation, acclimation protocols, and the timing of outplanting, thereby enhancing restoration success under future climate conditions.

All the aforementioned adaptation measures are applicable to forest nurseries and provide practical guidance for climate decision-making under global warming (Fagundes et al. 2025a, Florêncio et al. 2022; Martins et al. 2023b).

5 Conclusion

Both models - Phyllochron and Wang and Engel – accurately estimated accumulated leaf number (ALN) for all five species. However, cumulative errors in ALN estimation led to less precise estimations of initial development duration. Phyllochron model performed better for *C. speciosa* (RMSE = 1.30 leaves and 29.8 days) and *H. chrysotrichus* (RMSE = 1.41 leaves and 23.0 days), while Wang and Engel model performed better for *B. forficata* (RMSE = 1.14 leaves and 11.9 days), *H. impetiginosus* (RMSE = 1.50 leaves and 32.3 days), and *T. roseoalba* (RMSE = 1.32 leaves and 25.2 days).

Projected air temperature increases over the 21st century (ranging from ~1.3 °C in the near future (2041–2060) to 4.5 °C in the far future (2081–2100)) will modify the development and initial development duration of the five forest species, with varying magnitudes of change depending on species, sowing dates, periods, and socioeconomic scenarios. Among these factors, sowing date exerts the strongest influence on the initial development duration across all species. Sowing dates from August to January in the Southern Hemisphere are projected to increase the initial development duration, whereas sowing dates from February to June/July may shorten the initial development duration.

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Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

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References

- Almazroui M, Islam MN, Saeed F, Saeed S, Ismail M, Ehsan MA, Diallo I, O'Brien E, Ashfaq M, Martínez-Castro D, Cavazos T, Cerezo-Mota R, Tippet MK, Gutowski WJ Jr, Alfaro EJ, Hidalgo HG, Vichot-Llano A, Campbell JD, Kamil S, Rashid IU, Sylla MB, Stephenson TS, Taylor M, Barlow M (2021) Projected changes in temperature and precipitation over the united States, central America, and the Caribbean in CMIP6 GCMs. *Earth Syst Environ* 5:1–24. <https://doi.org/10.1007/s41748-021-00199-5>
- Alves AMMR, Martins FB, Reboita MS (2020) Balanço hídrico climático Para Itajubá-MG: cenário atual e projeções climáticas. *Rev Bras Climatol* 26:712–732. <https://doi.org/10.5380/abclima.v26i0.70387>
- Anderegg WRL, Trugman AT, Badgley G, Anderson CM, Bartuska A, Ciais P, Cullenward D, Field CB, Freeman J, Goetz SJ, Hicke JA, Huntzinger D, Jackson RB, Nickerson J, Pacala S, Randerson JT (2020) Climate-driven risks to the climate mitigation potential of forests. *Science* 368:eaaz7005. <https://doi.org/10.1126/science.aaz7005>
- Andrade JS (2009) Acaricidas para o manejo de *Tetranychus urticae* em mamoeiro: toxicidade e resistência no norte do Espírito Santo. Master's Dissertation, Universidade Estadual do Norte Fluminense Darcy Ribeiro, Campos dos Goytacazes, Brazil
- Andrade DJ, Rocha CM, Matos STS, Zanardi OZ (2020) Oxymatrine-based Bioacaricide as a management tool against *Oligonychus ilicis* (McGregor) (Acari: Tetranychidae) in coffee. *Crop Prot* 134:105182. <https://doi.org/10.1016/j.cropro.2020.105182>
- Bahuguna RN, Jagadish KSV (2015) Temperature regulation of plant phenological development. *Environ Exp Bot* 111:83–90. <https://doi.org/10.1016/j.envexpbot.2014.10.007>
- Bettiol W, Hamada E, Angelotti F, Auad AM, Ghini R (2017) Aquecimento global e problemas Fitossanitários. Embrapa Meio Ambiente, Brasília, p 488. <https://www.alice.cnptia.embrapa.br/alice/handle/doc/1077623>
- Brown MB, Forsythe AB (1974) Robust tests for the equality of variances. *J Am Stat Assoc* 69:364–367. <https://doi.org/10.2307/2285659>
- Camargo AP, Sentelhas PC (1997) Avaliação do desempenho de diferentes métodos de estimativa Da evapotranspiração potencial no Estado de São Paulo, Brasil. *Rev Bras Agrometeorol* 5:89–97
- Carvalho PER (2003) Espécies arbóreas brasileiras. Embrapa Informação Tecnológica, Embrapa Florestas, Colombo. Coleção Espécies Arbóreas Brasileiras 1:1039. <https://www.alice.cnptia.embrapa.br/alice/handle/doc/305634>
- Carvalho PER (2006) Espécies arbóreas brasileiras. Embrapa Informação Tecnológica, Embrapa Florestas, Colombo, Coleção Espécies Arbóreas Brasileiras 2:627. <https://www.alice.cnptia.embrapa.br/alice/handle/doc/305634>
- Costa DB, Streck NA (2018) Duração Da Fase de Mudanças Em Eucalipto simulada Em cenários de aumento de temperatura. *Ciênc Florest* 28:12631279. <https://doi.org/10.5902/1980509833378>
- Delgado-Baquerizo M, Guerra CA, Cano-Díaz C, Egidi E, Wang JT, Eisenhauer N, Singh BK, Maestre FT (2020) The proportion of soil-borne pathogens increases with warming at the global scale. *Nat Clim Chang* 10:550–554. <https://doi.org/10.1038/s41558-020-0759-3>
- Dias CG, Martins FB, Martins MA (2024) Climate risks and vulnerabilities of the Arabica coffee in Brazil under current and future climates considering new CMIP6 models. *Sci Total Environ* 907:167753. <https://doi.org/10.1016/j.scitotenv.2023.167753>
- Dickson A, Leaf A, Hosner JF (1960) Quality appraisal of white Spruce and white pine seedling stock in nurseries. *Chron* 36:10–13. <https://doi.org/10.5558/tfc36010-1>
- 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>
- Fagundes FFA, Martins FB, Reis FYS, Costa HF (2024a) Modeling the initial development dynamics for two native Brazilian forest tree species. *Forestry* 97:295–308. <https://doi.org/10.1093/forestry/cpad044>
- Fagundes FFA, Martins FB, Reis FYS, Costa HF (2024b) Predicting temperature ranges for the initial development of two native Brazilian tree species using multiple sowing dates. *Ecol Manage* 562:121912. <https://doi.org/10.1016/j.foreco.2024.121912>
- Fagundes FFA, Martins FB, Aquila G, Saldanha GW (2025a) Forest seedling development of two Brazilian native species under global warming: assessments, adaptation measures and financial implications. *Forestry: An International Journal of Forest Research*, cpaf065. <https://doi.org/10.1093/forestry/cpaf065>
- Fagundes FFA, Martins FB, Torres RR, Marraffon VHA (2025b) Global warming levels (1.5–4°C) and water availability for Eucalyptus plantations based on High-resolution CMIP6 models. *Earth Syst Environ*. <https://doi.org/10.1007/s41748-025-00916-497:295-308>
- Ferreira MC (2025) Comportamento fenológico e modelagem do desenvolvimento de espécies florestais: clima atual e futuro. Thesis, Universidade Federal de Itajubá, Itajubá, Brazil
- Ferreira MC, Martins FB, Florêncio GWL, Pasin LAAP (2019) Cardinal temperatures and modeling of vegetative development in guava. *Rev Bras Eng Agric Ambient* 23:819–825. <https://doi.org/10.1590/1807-1929/agriambi.v23n11p819-825>
- Ferreira MC, Martins FB, Costa HF (2025) Phenological description for the initial development stage of five Brazilian native forest species according to BBCH scale. *Ann Appl Biol*. <https://doi.org/10.1111/aab.70071>
- Florêncio GWL, Martins FB, Ferreira MC, Pereira RAA (2019) Impacts of Climatic changes on the vegetative development of Olive crops in Minas Gerais. *Rev Bras Eng Agric Ambient* 23:641–647. <https://doi.org/10.1590/1807-1929/agriambi.v23n9p641-647>
- Florêncio GWL, Martins FB, Fagundes FAF (2022) Climate change on Eucalyptus plantations and adaptive measures for sustainable

- forestry development across Brazil. *Ind Crops Prod* 188:115538. <https://doi.org/10.1016/j.indcrop.2022.115538>
- Fowler JAP, Martins EG (2001) Manejo de Sementes de espécies Florestais. Embrapa Florestas, Colombo, p 76. <http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/289390>
- Gilmore Junior EC, Rogers JS (1958) Heat units as a method of measuring maturity in corn. *Agron J* 50:611–615. <https://doi.org/10.2134/agronj1958.00021962005000100014x>
- Inouye DW (2022) Climate change and phenology. *WIREs Clim Change* 13:e764. <https://doi.org/10.1002/wcc.764>
- Intergovernmental Panel on Climate Change [IPCC] (2023) Summary for policymakers. In: Lee H, Romero J (eds) Climate change 2023: synthesis report. Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change [Core writing team. IPCC, Geneva, Switzerland, pp 1–34. <https://doi.org/10.59327/IPCC/AR6-9789291691647.001>
- International Union for Conservation of Nature [IUCN] (2021) The IUCN Red List of Threatened Species. <https://www.iucnredlist.org>
- Lemes PG, Zanuncio JC (2021) Novo Manual de Pragas Florestais Brasileiras. Instituto de Ciências Agrárias, Universidade Federal de Minas Gerais 996. https://www.ipef.br/publicacoes/novo-manual-de-pragas-florestais-brasileiras/Novo_Manual_de_Pragas_Florestais_Brasileiras.pdf
- Lima RAF, Dauby G, Gasper AL, Fernández EP, Vibrans AC, Oliveira AA, Prado PI, Souza VC, Siqueira MF, Steege H (2024) Comprehensive conservation assessments reveal high extinction risks across Atlantic forest trees. *Science* 383:219–225. <https://doi.org/10.1126/science.abq509>
- Lopes UP, Michereff SJ (2018) Desafios do Manejo de doenças radiculares causadas Por Fungos. EDUFRRPE, Recife, p 208. <https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1095701/1/LivroCORRIGIDODesafiosManejoDoencasRadiculares.pdf>
- Martins FB, Streck NA (2007) Aparecimento de folhas Em Mudanças de Eucalipto estimado Por dois modelos. *Pesq Agropec Bras* 42:1091–1100. <https://doi.org/10.1590/S0100-204X200700080005>
- Martins FB, Ferreira MC, Florêncio GWL (2022) Agrometeorological models for predicting seedlings development of two native forest species. *Sci Agric* 79:e20200192. <https://doi.org/10.1590/1678-992X-2020-0192>
- Martins FB, Ferreira MC, Fagundes FFA, Florêncio GWL (2023a) Thermal and photoperiodic requirements of the seedling stage of three tropical forest species. *J Res* 34:209–220. <https://doi.org/10.1007/s11676-022-01530-0>
- Martins FB, Florêncio GWL, Ferreira MC, Fagundes FFA, Freitas CH (2023b) Predicting seedling development for two commercial forest species under current and future climates: a multi-model assessment. *Ecol Manage* 537:120929. <https://doi.org/10.1016/j.foreco.2023.120929>
- Mendonça GC, Chichorro JF, Mendonça AR, Guimarães LAOP (2017) Avaliação silvicultural de Dez espécies Nativas Da Mata Atlântica. *Ciênc Florest* 27:277–290. <https://doi.org/10.5902/1980509826466>
- Moreira MAB, Arco-Verde MF (1998) Controle de pragas e doenças em viveiros florestais. Embrapa Roraima 5. <https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/688479/1/cot00198vivmar.pdf>
- Nouhra G, Poloni NM, Pereira FD, Goes A (2021) Eficiência de trifloxistrobina e tebuconazole, Em formulação comercial, associados a fungicidas protetores no controle Da Mancha Marrom de Alternária Em Tangor “Murcott. *Summa Phytopathol* 47:122–125. <https://doi.org/10.1590/0100-5405/245415>
- O'Neill BC, Krieger E, Ebi KL, Kemp-Benedict E, Riahi K, Rothman DS, van Ruijven BJ, van Vuuren DP, Birkmann J, Kok K, Levy M, Solecki W (2017) The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob Environ Change* 42:169–180. <https://doi.org/10.1016/j.gloenvcha.2015.01.004>
- Pivello VR, Rocha RM, Vitule JRS, Braga RR, Brown GG, Castro CF, Cruz Neto CC, Franco AS, Heringer G, Magalhães ALB, Miranda RJ, Mormul RP, Oliveira I, Saulino HHL, Silva Matos DM (2024) Capítulo 4: Impactos de espécies exóticas invasoras sobre as Contribuições da Natureza para as Pessoas (CNP), o Desenvolvimento Sustentável e a boa qualidade de vida. In: Dechoum MS, Junqueira AOR, Orsi ML (eds) Relatório Temático sobre Espécies Exóticas Invasoras, Biodiversidade e Serviços Ecossistêmicos. Editora Cubo, São Carlos 133–184. <https://doi.org/10.4322/978-65-00-87228-6.cap4>
- 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>
- Riahi K, van Vuuren DP, Krieger E, Edmonds J, O'Neill BC, Fujimori S, Bauer N, Calvin K, Dellink R, Fricko O, Lutz W, Popp A, Cuaresma JC, Emmerling J, Ebi K, Hasegawa T, Havlik P, Humpenöder F, da Silva LA, Smith S, Stehfest E, Bosetti V, Eom J, Gernaat D, Masui T, Rogelj J, Streffer J, Drouet L, Krey V, Luderer G, Harmsen M, Takahashi K, Baumstark L, Doelman JC, Kainuma M, Klimont Z, Marangoni G, Lotze-Campen H, Obersteiner M, Tabeau A, Tavoni M (2017) The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Glob Environ Change* 42:153–168. <https://doi.org/10.1016/j.gloenvcha.2016.05.009>
- Ribeiro AF, Martins FB, Santos DF, Torres RR, Fagundes FFA (2024) Suitable areas for temperate fruit trees in a Brazilian hotspot area: changes driven by new IPCC scenarios. *Eur J Agron* 155:127110. <https://doi.org/10.1016/j.eja.2024.127110>
- Ruiz-Díaz S, Pérez de Molas LF, Benítez-León E, Bohlman S, Broadbent EN (2024) Bioclimatic predictors of forest structure, composition and phenology in the Paraguayan dry Chaco. *J Trop Ecol* 40:e1. <https://doi.org/10.1017/S0266467423000329>
- Scott AJ, Knott M (1974) A cluster analysis method for grouping means in the analysis of variance. *Biometrics* 30:507–512
- Silva APM, Marques HR, Santos TVMN, Teixeira AMC, Luciano MSF, Sambuichi RHR (2015) Diagnóstico da Produção de Mudanças Florestais Nativas no Brasil. IPEA. <https://repositorio.ipea.gov.br/entities/publication/9537be0e-3086-4a8a-950f-2769a2d1f4bd>
- Silva APM, Schweizer D, Marques HR, Teixeira AMC, Santos TVM, Sambuichi RHR, Badari CG, Gaudare U, Brancalion PHS (2017) Can current native tree seedling production and infrastructure Meet an increasing forest restoration demand in Brazil? *Restor Ecol* 25:509–515. <https://doi.org/10.1111/rec.12470>
- Silva JMC, Rapini A, Barbosa LCF, Torres RR (2019) Extinction risk of narrowly distributed species of seed plants in Brazil due to habitat loss and climate change. *PeerJ* 7:e7333. <https://doi.org/10.7717/peerj.7333>
- Snedecor GW, Cochran WG (1989) Statistical methods. Iowa State University, Ames, p 503
- Thrasher B, Wang W, Michaelis A, Melton F, Lee T, Nemani R (2022) NASA global daily downscaled Projections, CMIP6. *Sci Data* 9:262. <https://doi.org/10.1038/s41597-022-01393-4>
- Tukey JW (1977) Exploratory data analysis. Addison-Wesley, Reading, p 688
- United Nations Framework Convention on Climate Change [UNFCCC] (2015) COP 21 Climate Agreement. <https://unfccc.int/resource/docs/2015/cop21/eng/109r01.pdf>
- United Nations [UN] (2015) Transforming our world: the 2030 agenda for sustainable development. UN, Nova York. <https://sdgs.un.org/2030agenda>

- Viana FMP, Cardoso JE, Martins MVV, Ootani MA (2018) Enxofre versus acibenzolar-s-methyl no controle do oídio do Cajueiro. *Summa Phytopathol* 44:400–401. <https://doi.org/10.1590/0100-5405/188409>
- Vieira RF, Camillo J, Coradin L (2018) Espécies nativas da flora brasileira de valor econômico atual ou potencial: plantas para o futuro: Região Centro-Oeste. Ministério do Meio Ambiente. Secretaria de Biodiversidade 1.160. <https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1073295/especies-nativas-da-flora-brasileira-de-valor-economico-atual-ou-potencial-plantas-para-o-futuro-regiao-centro-oeste>
- Wang E, Engel T (1998) Simulation of phenological development of wheat crops. *Agric Syst* 58:1–24. [https://doi.org/10.1016/S0308-521X\(98\)00028-6](https://doi.org/10.1016/S0308-521X(98)00028-6)
- Xavier AC, King CW, Scanlon BR (2016) Daily gridded meteorological variables in Brazil (1980–2013). *Int J Climatol* 36:2644–2659. <https://doi.org/10.1002/joc.4518>
- Zhou G, Wang Q (2018) A new nonlinear method for calculating growing degree days. *Sci Rep* 8:10149. <https://doi.org/10.1038/s41598-018-28392-z>

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