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Original article

Climate variations affect the growth period of young *Tectona grandis* Linn F. in the Amazon

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ABSTRACT

Climate change is expected to increase the occurrence of severe droughts in the tropics, and little is known about its influence on tree dynamics. Tree-ring width and remote sensing tools can help understand the impacts of climate change on tree growth. We evaluated the applicability of NDVI to obtain phenological metrics (*e.g.*, start, peak, end, and length of growth season) and explored its relationship with tree-ring width of *Tectona grandis* (teak). The phenological metrics and tree-ring width were correlated with each other, and with both local (temperature, precipitation, solar insolation, Standardized Precipitation Evapotranspiration Index – SPEI) and large-scale (El Niño) climatic variables. The length of season and tree-ring width of teak were positively correlated with precipitation and negatively correlated with temperature in the initial months of the growth period. Tree-ring width was negatively correlated with El Niño events. Climate variables and length of season from the prior period were correlated with the tree-ring width of the current growing period. This study demonstrated that rather than directly affecting productivity, climate might also affect the length of the growing season, which would affect tree growth in the next season.

Keywords: Dendrochronology, El Niño, ENSO, phenological metrics, phenology, SPEI, teak, vegetation index

Introduction

The impact of climate change on forest growth and productivity is a matter of concern. The impact of these changes tends to be greater in the tropics, promoting an increase in temperature in these regions (IPCC 2014). Recent research indicates that the intensity and frequency of El Niño events tend to increase owing to climate change (Ham 2018). The El Niño-Southern Oscillation (ENSO) is an atmosphere-ocean phenomenon that occurs in the equatorial Pacific Ocean. The eastern equatorial Pacific climate varies between anomalously cold (La Niña) and warm (El Niño) periods on a timescale of 2-7 years. These swings lead to variations in rainfall and weather patterns in several parts of the world (Aceituno 1988; Foley *et al*. 2002; Collins *et al*. 2010), particularly in tropical forests,

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and can considerably affect large natural terrestrial carbon sinks, such as the Amazon rainforest.

For instance, rainfall in the Amazon is strongly driven by El Niño events. The warm phase decreases monthly precipitation and increases mean temperature. During El Niño, there is a reduction in total precipitation in the Amazon as the main convection center shifts to the central Pacific, and convection over the Amazon weakens (Foley *et al*. 2002). The event that occurred during 2015/2016 (strong event) caused a marked change in precipitation and temperature, compared to previous events (Moura *et al*. 2019). The evaluation of these changes helps understand the effects of this phenomenon on local and global scales.

Climate change can be evaluated using dendrochronology. One of the fundamentals of this method is that variations in tree-ring width are influenced by environmental variables that affect tree growth (Speer 2012). Species that have more prominent growth rings and show sensitivity in response to environmental variations are suitable for these studies.

Another important tool for verifying the climate-plant relationship is the study of phenology, given that tree-rings are produced within the vegetative period which is dependent on the phenological behavior of trees. Phenology explores the stages of the plant development cycle, such as budding, flowering, fruiting, and senescence of the leaves (Ghosh *et al*. 2019). As climate affects tree growth and development, tree phenology can be used as a climatic change indicator (Yu *et al*. 2017).

The monitoring and analysis of plants on a space-time scale can be conducted using vegetation indexes derived from remote sensing. Previous studies have demonstrated the association between the Normalized Difference Vegetation Index (NDVI) and tree-ring width in some seasons (*e.g.*, Barka *et al*. 2019). Moreover, phenological metrics derived from high-resolution NDVI data (*e.g.*, data provided by MODIS sensors) have the potential to improve the relationship between tree-ring width and climate (Bhuyan *et al*. 2017).

Data derived from satellite spectral measurements can be used to obtain information about the developmental period of this species. However, only a few programs can be used to extract and explore this information, such as TIMESAT (Eklundh & Jönsson 2017). Several researchers have used software to extract phenological metrics in homogeneous and heterogeneous areas (Heumann *et al*. 2007; Nhongo *et al*. 2017; Diêm *et al*. 2018; Ghosh *et al*. 2019). Phenological metrics are defined as the interannual changes in vegetation interpreted by spectral observation from satellite sensors, defining, for example, start of season (SOS), peak of season (POS), end of season (EOS) and length of season (LOF) (Eklundh & Jönsson 2017; Zeng *et al*. 2020).

Thus, the use of tree-ring width and phenological metrics combined with remote sensing techniques can help understand the impact of climatic change on plant growth. Furthermore, it offers a cost-effective method of assessing large forest areas (Vicente-Serrano *et al*. 2016).

Tectona grandis (teak) was the first species used for dendrochronological studies in the tropics. In 1870, Dietrich Brandis studied the growth of teak and determined the cutting cycles from tree-rings (Jiménez 2011). *T. grandis* is one of the most used species for climate reconstruction from its growth rings due to its anatomical characteristics (Lumyai & Duangsathaporn 2018; Zaw *et al*. 2020). It is a semi-ring-porous tropical hardwood with growth ring boundaries visually distinct by the variation in diameter of the vessel lumen and bands of marginal parenchyma at the limit of the growth period (Dié *et al*. 2015; Souza *et al*. 2019). It is a deciduous/semi-deciduous tree that sheds its leaves in the dry season (Pelissari *et al*. 2014). This favors well-defined temporal coverage patterns. Therefore, remote sensing temporal observations can accurately capture these changes (Ghosh *et al*. 2019).

In this context, the main objective of this study was to evaluate the applicability of NDVI in extracting phenological metrics and to examine its relationship with the tree-ring width of *Tectona grandis* Linn F. Additionally, we analyzed the sensitivity of phenological metrics and tree-ring width to climatic variables due to the occurrence of an El Niño event in the Amazon.

Materials and methods

Study area

This study was conducted in 12 teak plantations aged 12 years (2007 – 2018) in the southeastern region of the state of Pará, Brazil (Fig. 1). The plantations occupy approximately 30 hectares each. According to Köppen's classification, the climate is Tropical Aw. The mean temperatures of the coldest and warmest months are 18 and 22 °C, respectively. The precipitation in the driest month is less than 60 mm (Alvares *et al*. 2013). The site experiences lower precipitation volume from June to August (Lopes *et al*. 2013) (Fig. 2A).

In the time series evaluated, there were two strong El Niño events (2010 and 2015/2016) (Fig. 2B). During 2015 and 2016 the mean annual temperatures were 0.3 and 0.7 °C higher, respectively, compared to the mean of the entire study period.

Climatic data

For the local scale, monthly climatic data on temperature, precipitation, solar insolation, and evapotranspiration were obtained from the Instituto Nacional de Meteorologia (INMET) at the conventional station of Conceição do Araguaia – PA.

The monthly Standardized Precipitation-Evapotranspiration Index (SPEI) series were calculated. The SPEI is a multiscalar drought index based on precipitation and temperature data. It uses the monthly differences between precipitation and potential evapotranspiration

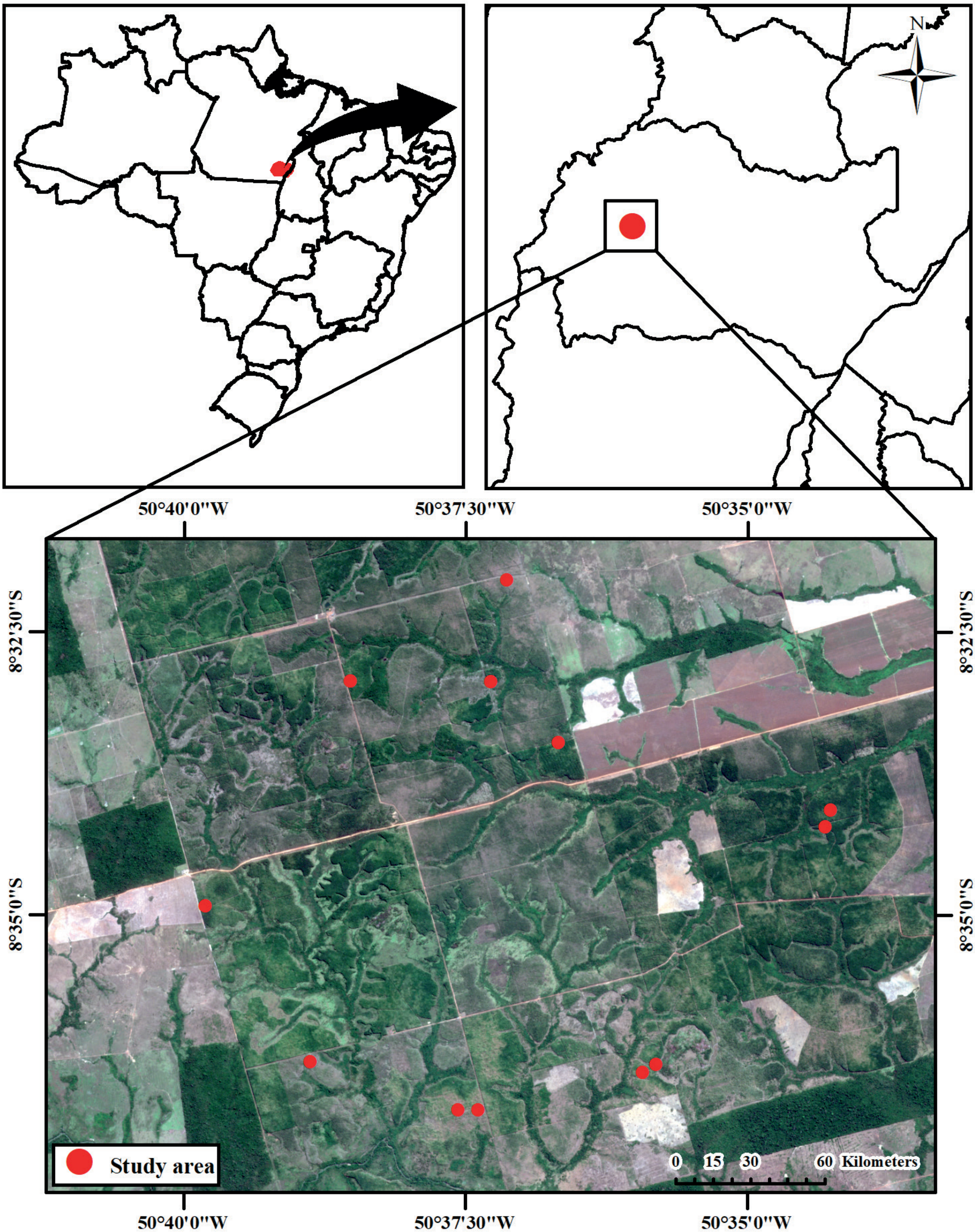

Figure 1. Map highlighting the distribution of the 12 plantations of *Tectona grandis* Linn F.

(Vicente-Serrano *et al*. 2010). The SPEI was calculated using the SPEI package in R software (ver. 4.0.2, R Development Core Team 2020) (Beguería & Vicente-Serrano 2017). For the large-scale assessment, data on sea surface temperature variations of the tropical Pacific Ocean (El Niño influence) were acquired from the National Oceanic and Atmospheric Administration (NOAA). All climate data were acquired from 2007 to 2018.

Remote sensing products and phenological metrics

Data from Normalized Difference Vegetation Index (NDVI) of the product MOD13Q1 V006 were used, with a temporal resolution of 16 days and a spatial resolution of 250 m. Tile h12v9 was applied, totaling 23 files per year.

The MODIS HDF files were downloaded from the NASA servers using the MODIStsp package in R software (ver. 4.0.2, R Development Core Team 2020) (Busetto & Ranghetti 2016). The package was also used to reproject the files into the GeoTIFF format and Datum WGS-84. The NDVI values for the areas were extracted from each pixel. All pixels were selected from the center of each plantation to ensure that they represented only *T. grandis* trees. Only good-quality pixels obtained by "MODIS quality control" were used. A linear interpolation method was used to obtain the missing pixels. These pixels, which accounted for 12.67 % of the total pixels, were mostly non-sequential, and occurred in the months with the highest rainfall intensity (February and March), owing to cloud cover. As there were two observations in each month (temporal resolution of 16 days), the interpolated data did not affect the seasonal patterns.

The NDVI was used as an indirect measure of phenology as it is an indirect measure of the vegetative period of the canopy. For each plantation, the NDVI data were organized in ASCII files, which were used to estimate phenological metrics (*e.g.*, start (SOS), peak (POS), end (EOS) and length (LOS) of the growing season) using the TIMESAT software package (ver. 3.3) (Eklundh & Jönsson 2017). TIMESAT implements three processing methods based on the least-squares of the vegetation index: asymmetric adaptive Savitzky-Golay, Gaussian, and Double Logistic. The results of each method were compared visually and statistically using the coefficient of determination (R^2). The asymmetric adaptive Savitzky-Golay method was used to estimate the phenological metrics. The method is used for

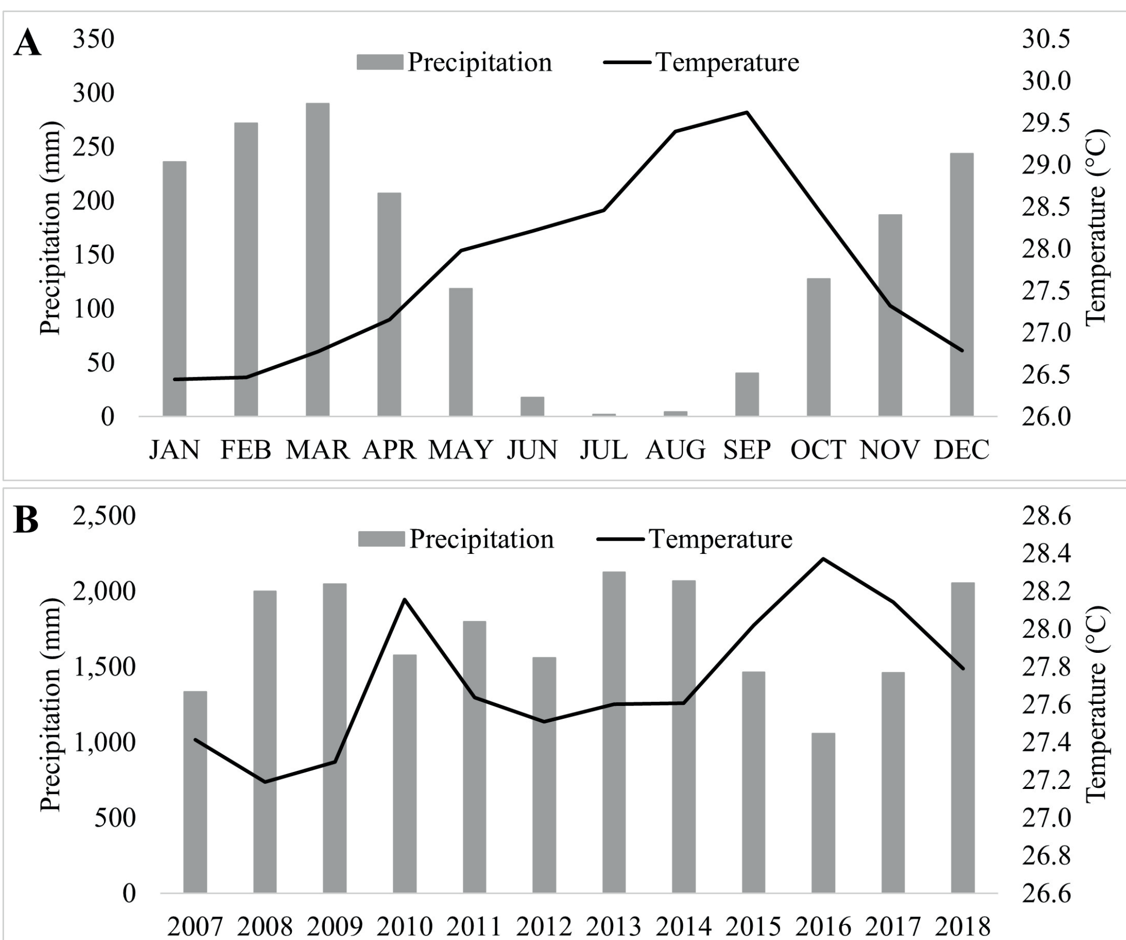

Figure 2. Average monthly (**A**) and annual (**B**) mean temperature and accumulated precipitation data of the meteorological station Conceição do Araguaia from 2007 to 2018.

smoothing noise in the NDVI time series using a weighted moving average filter (Chen *et al*. 2004).

The phenological dates of SOS and EOS were estimated using 20 % of the seasonal amplitude (Ghosh *et al*. 2019). For the analysis, we considered the mean of each phenological metric from the 12 plantations. We used the period of 2015/2016 (El Niño) as a reference to evaluate the effect of El Niño events on phenological metrics. The El Niño period was compared with 2014/2015 (pre-El Niño) and 2016/2017 (post-El Niño). The El Niño event that occurred in 2010 was not used because of the planting age, which could influence the NDVI values.

Tree-ring analysis

For tree-ring analysis, we collected five discs, from each plantation, taken at an approximate height of 0.50 m from the ground. The discs were polished with a sandpaper gradient varying between 40 and 600 grains cm^{-2} until the ring boundaries could be clearly identified. Discs were scanned at a resolution of 1,200 dpi (Epson Perfection V700 Photo). Two radial lines were laid down on each polished disc and then analyzed with Cybis CooRecorder software (version 7.8) accurate to 0.01 mm (Larsson 2014).

The quality of the cross-dating was verified using the COFECHA software (Holmes 1983). The annual growth series were fitted to a cubic spline with a 50 % frequency, with 4 years segments lagged by 2 years and a critical correlation of 0.6581 was applied. The tree-ring width was standardized using ARSTAN software (Cook & Holmes 1996), and detrended using a linear regression of any slope. The mean chronology was calculated using the averaged standardized tree-ring series (Fritts 1976).

The classic statistical parameters in dendrochronology, *i.e.*, average tree-ring width, standard deviation, mean sensitivity, and series intercorrelation were used to describe the chronology (Fritts 1976) (Tab. 1). The quality of the chronology was analyzed by the mean correlation coefficient for all possible pairings of ring width series over a common time mean correlation (*r*Bar) and the expressed population signal (EPS) (Fig. 3).

Table 1. Descriptive statistics of the chronology of *Tectona grandis*.

Mean ring width ± standard deviation (cm)	Mean sensitivity	Series intercorrelation
1.31 ± 0.639	**0.405**	**0.701**

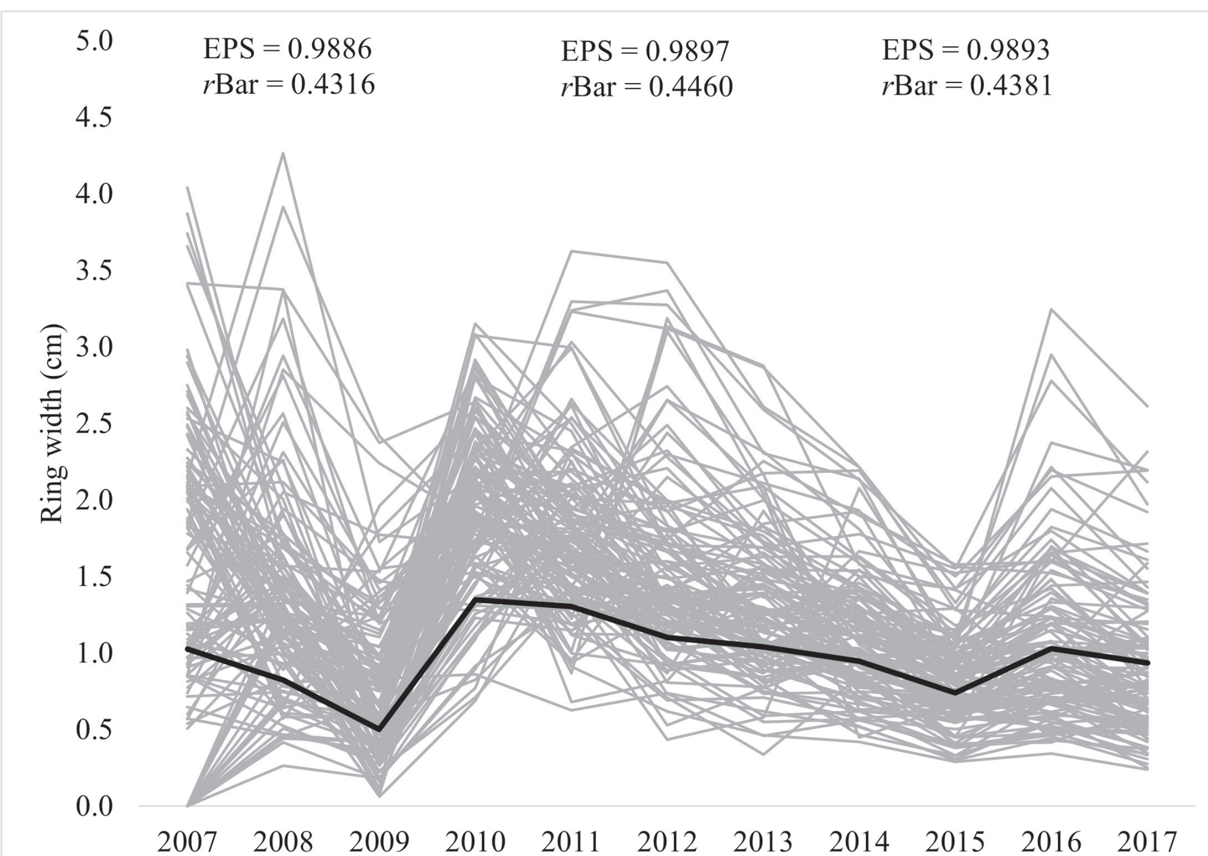

Figure 3. Mean radial growth of tree-ring chronologies (black line) and individual tree growth rate (gray lines) of *Tectona grandis*. EPS: Expressed Population Signal; *r*Bar: pairwise correlation.

Data analysis

The length of season of pre-El Niño, El Niño and post-El Niño periods were tested using analysis of variance and Tukey's post hoc test (α = 0.05). The influence of local monthly climatic variables on the length of season was tested using Pearson's correlation analysis (α = 0.05).

Ring widths were correlated with climatic variables (local) from the prior periods (May to August – dry season) and current growth periods (September to May – rainy season) by Pearson's correlation analysis (α = 0.05). To better comprehend the results, we considered the period from September to August, as the beginning of the growth season starts in September (start of the rainy season). For example, with respect to 2009, the current period runs from September 2009 to August 2010, and the prior period runs from September 2008 to August 2009.

To assess the sensitivity of tree-ring width to large-scale (ENSO) events, we conducted an annual correlation for the current and prior periods using Pearson's correlation analysis (α = 0.05). The mean annual ENSO index of the study period was considered in the analysis.

In addition, to verify the association between tree-ring width and NDVI (derived from phenology) with climatic variables (monthly), we used the Redundancy Analysis (RDA) method. The test was conducted using the vegan package in the R software (Oksanen *et al*. 2019), with 999 permutations under a full permutation model.

The association between the length of season (current and prior period) and tree-ring width was tested using Pearson's correlation analysis (α = 0.05). We used the Shapiro-Wilk test (α = 0.05) to check for data normality.

Results

Effect of climatic variables on phenological metrics

Based on the phenological metrics (2010 – 2018) extracted from TIMESAT, the start (SOS), peak (POS), and end (EOS) of growing season occurred on October 08, February 28, and August 12, respectively (Fig. 4A). The length of the growing season (LOS) was 307 days.

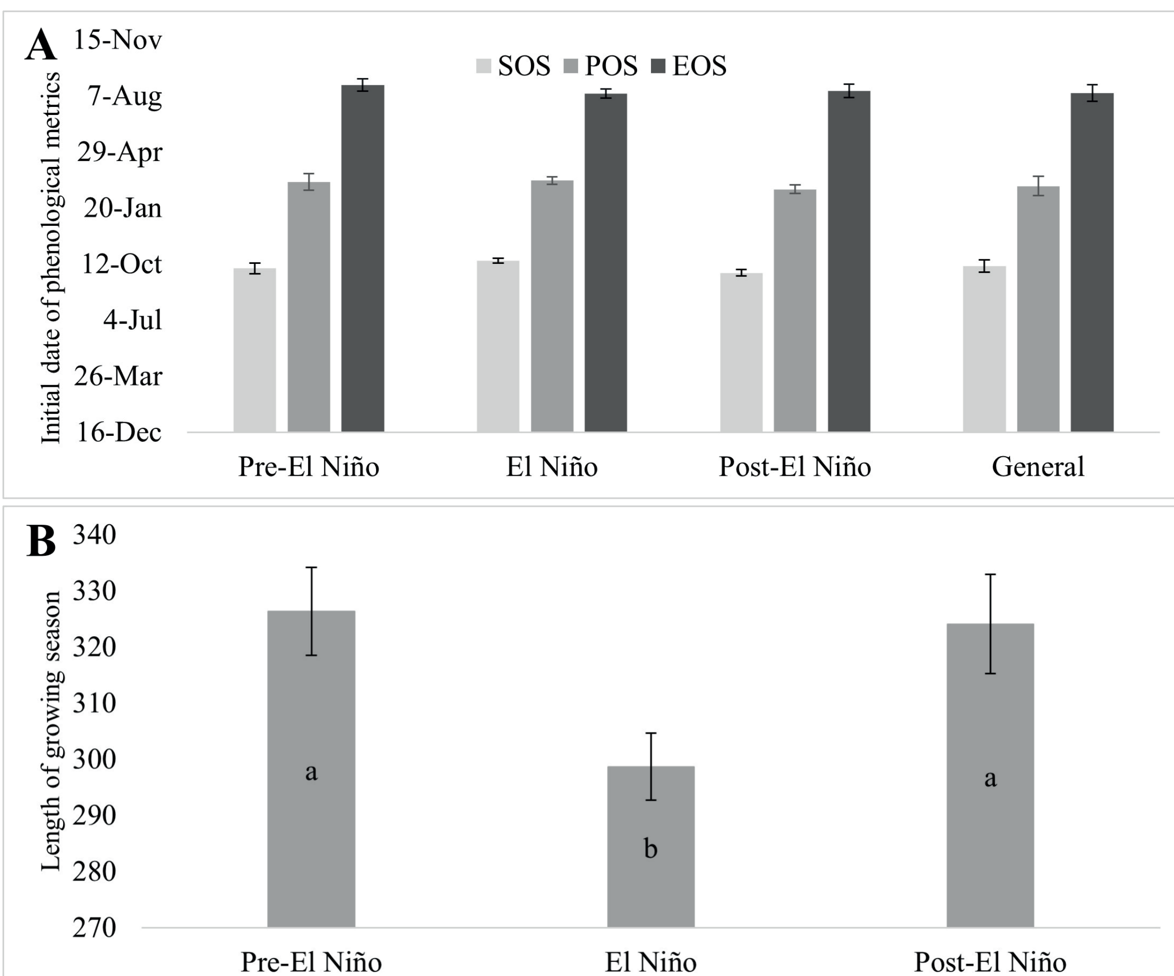

Figure 4. Phenological metrics of Start (SOS), Peak (POS), End (EOS) (**A**) and Length (LOS) (days) (**B**) of growing season of the periods Pre-El Niño, El Niño, Post-El Niño and General, based on NDVI data.

During the pre-El Niño period, the SOS occurred 14 days earlier and the EOS occurred 14 days later when compared with El Niño period (Fig. 4A). Thus, the LOS of the pre-El Niño period was 28 days longer than that of the El Niño period. During post-El Niño period, the SOS occurred 21 days earlier, the EOS occurred 5 days later (Fig. 4A), and the LOS was 26 days longer than the El Niño period. The LOS of the pre-El Niño and post-El Niño periods were statistically greater than that during the El Niño period (Fig. 4B). These results indicate that the El Niño event affects the vegetative period of teak.

Solar insolation (hours), maximum temperature, and mean temperature in September were negatively correlated with LOS (r = -0.681, p-value = 0.043; r = -0.705, p-value = 0.034; and r = -0.690, p-value = 0.039, respectively) (Fig. 5). Precipitation and SPEI, also in September, were positively correlated with LOS (r = 0.670, p-value = 0.048; and r = 0.698, p-value = 0.037, respectively) (Fig. 5). These results indicate that September (beginning of the rainy season) is a key month for the beginning of the growth period of *T. grandis* in the region.

Effect of climatic variables on tree-ring width

ENSO was negatively correlated with tree-ring width for the current period (r = -0.647, p-value = 0.031) (Fig. 6), highlighting that in the occurrence of a strong increase in the sea surface temperature of the tropical Pacific Ocean, *T. grandis* ring width reduced. For the prior period, the correlation was not significant (r = -0.051, p-value = 0.889).

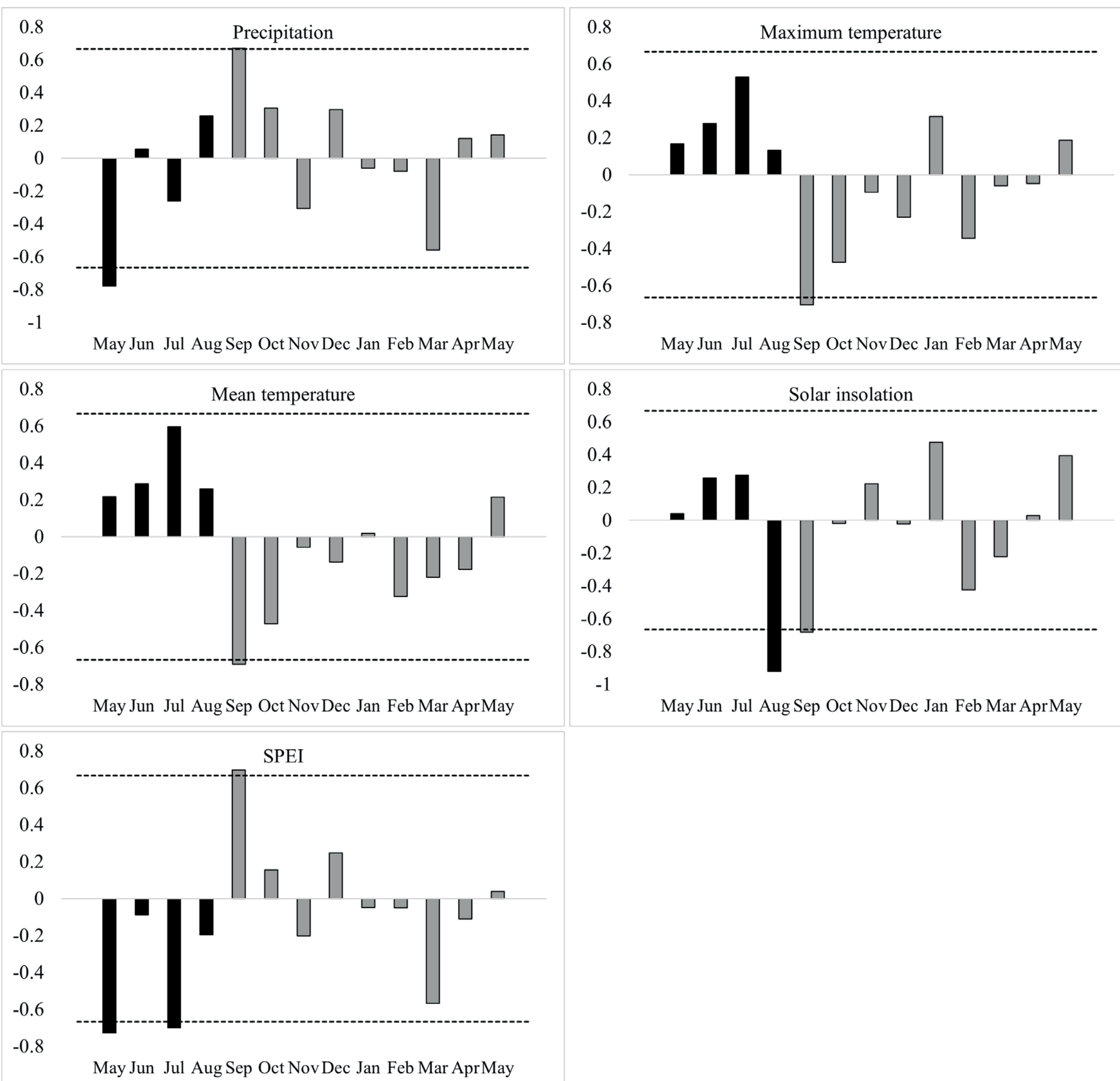

Figure 5. Correlations between climatic variables and Length of growing season of *Tectona grandis*. Dashed lines identify the 95 % confidence limits. Black and gray bars identify the prior and current growth periods, respectively.

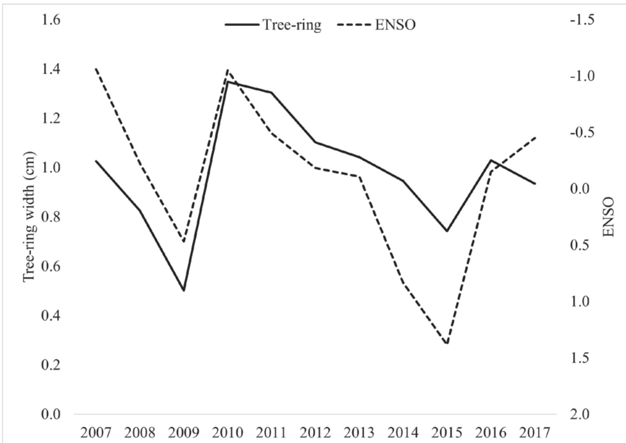

Figure 6. Tree ring width of *Tectona grandis* and El Niño - Southern Oscillation.

During the current growth period, precipitation, maximum temperature, and SPEI were not correlated with tree-ring width. However, tree-ring width was more strongly positively correlated with solar insolation in December (r = 0.636, p-value = 0.035) and negatively correlated with mean temperature in January (r = -0.660, p-value = 0.034) (Fig. 7). Our findings showed that the largest correlations occurred in the months at the beginning of the rainy season.

In prior periods, climatic variables (local) were significantly correlated with tree-ring width in May. Precipitation was negatively correlated (r = -0.619, p-value = 0.050), and the maximum temperature and solar insolation were positively correlated with tree-ring width (r = 0.643, p-value = 0.048; and r = 0.651, p-value = 0.041, respectively) (Fig. 7). These findings suggest that the increase in precipitation and decrease in solar insolation and maximum temperature in May of the prior period reduced tree-ring width during the current growth period.

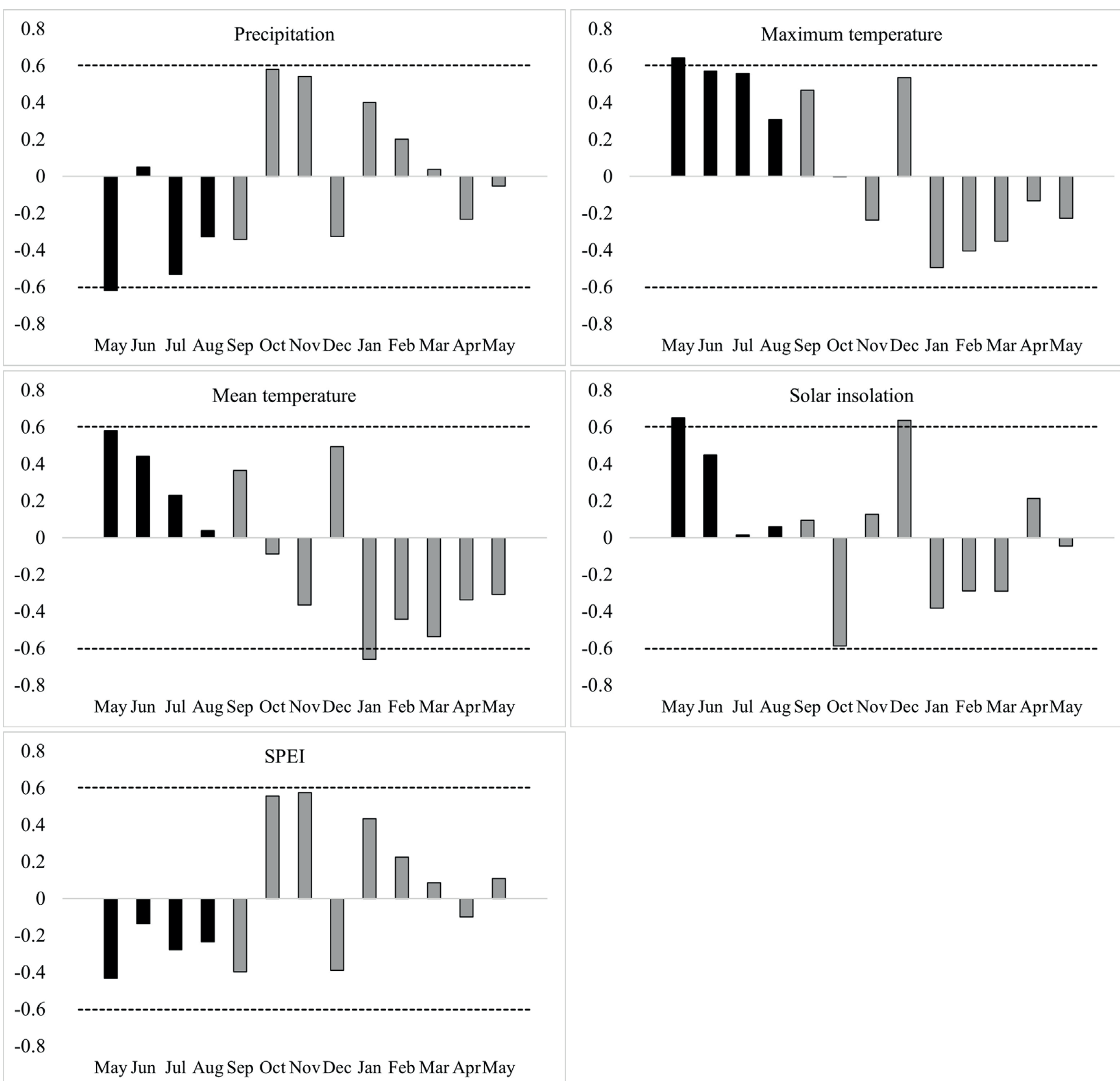

Figure 7. Correlations between climatic variables and tree-ring width of *Tectona grandis*. Dashed lines identify the 95 % confidence limits. Black and gray bars identify the prior and current growth periods, respectively.

Effect of climatic variables on phenological metrics and tree-ring width

Multivariate RDA showed a significant association (p = 0.001) between climatic and growth variables. RDA 1 and 2 accounted for 43.83 % of the data variability (Fig. 8). It also shows that tree-ring width is negatively correlated with ENSO, and to a smaller extent, is positively associated with SPEI. The results also showed that NDVI is positively correlated with precipitation, negatively correlated with solar insolation, and maximum and mean temperature and almost orthogonal with tree-ring width. These results demonstrate the influence that climatic variables might have on teak phenology.

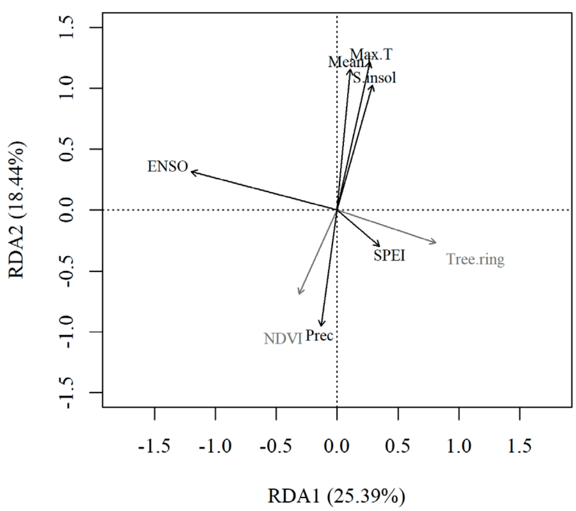

Figure 8. Ordination diagram of the redundancy analysis between NDVI and tree-ring width of *Tectona grandis* and climatic variables.

As previously demonstrated, both the LOS and tree-ring width were influenced by the El Niño event. However, the correlation between these parameters was not significant (r = 0.263, p-value = 0.494) for the current growth period. However, a correlation of -0.851 (p-value = 0.007) (Fig. 9) was observed for the prior growth period.

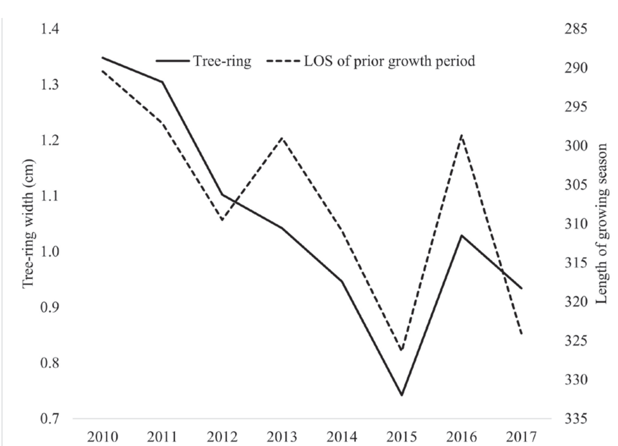

Figure 9. Tree-ring width and Length of growing season (days) of *Tectona grandis* for prior growth period.

These results showed that LOS influences tree-ring width during the prior growth period. Nevertheless, during the El Niño event, the reduction in tree-ring width was greater than in other periods (Fig. 9), indicating the influence of the event on the teak ring width during the current growth period.

Discussion

This study demonstrated the relationship between climate and growth of teak trees in the Amazon region from the perspective of climate change, which has triggered years of atypical drought in the region. El Niño events are related to global atmospheric oscillations, and their effects are more pronounced in some regions. At locations where climatic variables are less influenced by these events *T. grandis* ring width is not affected by these fluctuations (Dié *et al*. 2015).

Our results indicate the significant impact of the 2015/2016 El Niño event on the LOS of teak trees in the Amazon region, as reported in other studies (Diêm *et al*. 2018). Thus, during El Niño events there is indication that the growth period of teak trees was reduced. The event reduced the total precipitation and increased the mean temperature during the period. Such variables are known to influence the development of teak trees. Variations in cumulative precipitation and length of the rainy season influence the phenological metrics of teak trees, such as LOS (Ghosh *et al*. 2019), and consequently the tree-ring width. Our findings suggest that these climatic variables are the main drivers of teak phenology (Diêm *et al*. 2016).

Additionally, the rainy season in September affected the beginning of the growth period. *T. grandis* responds positively to the first rains by producing new leaves (Tanaka *et al*. 2015). One of the main factors associated is water availability in shallow soil horizons, which is taken up by superficial roots. Deep roots may improve resilience to inter- and intra-seasonal drought events (Clément *et al*. 2019).

El Niño event also negatively affected the tree-ring width during the current growth period. Thus, the tree-ring width of species sensitive to moisture, such as teak, can indicate drought during the El Niño events (Borgaonkar *et al*. 2010). Tree-ring studies have shown positive correlations between drought index and tree-ring width (Venegas-González *et al*. 2016; Venegas-González *et al*. 2018; Fontana *et al*. 2018; Islam *et al*. 2019). Our findings agree with those studies, indicating that greater availability of water favors an increase in teak ring width.

The association of climatic variables with length of season and tree-ring width in the prior period indicated that the prolongation of favorable growth conditions (*e.g.*, increased precipitation and SPEI, and decreased maximum temperature and solar insolation) also influenced the growth of teak during the next growth season. This could be related to the semi-deciduous phenology of teak trees. Favorable conditions may extend the canopy vegetative period and trigger physiological imbalance in teak trees during the next growing season (Venegas-González *et al*. 2016). The main function of the process of leaf drop is the recovery of nutrients before leaves detach from the perennial organs of the plant. The extent of LOS for the prior period could induce leaf drop before the completion of nutrient resorption that reduces the nutrients reserves that support growth for the current growth season (Fracheboud *et al*. 2009; Estiarte & Peñuelas 2015).

In addition, during the current growth period, solar insolation influenced *T. grandis* growth. The negative correlations between this climatic variable and tree-ring width and phenological metrics in October and September, respectively, may be related to variations in cloud cover. The greater the solar insolation at the beginning of the growth period, the lower was the precipitation (Campos & Alcantara 2016). Thus, the production of new leaves is delayed, and the growth is reduced. Furthermore, higher insolation leads to elevated leaf temperatures that can affect productivity both directly, by negatively affecting photosynthesis, reducing carbon gain, and causing irreversible thermal damage (Fauset *et al*. 2018), and indirectly, by increasing vapor pressure deficit that reduces stomatal conductance and hence inhibits carbon assimilation (Lloyd & Farquhar 2008).

Water may be the growth-limiting resource in the region during the beginning of the rainy season. For example, in December, the solar insolation was positively correlated with tree-ring width. However, during this month, there was greater water availability and leaf density. Thus, greater solar insolation/radiation on leaves favors high photosynthetic activity (Taiz *et al*. 2017). In addition, higher soil moisture allows the plant to carry out the transpiration process, and this loss of water is an important cooling mechanism for the leaves and may mitigate the negative impacts of solar radiation on tree growth under dry conditions (Taiz *et al*. 2017).

Thus, our study showed the influence of climate variables on *T. grandis* growth and the effect these changes have on its physiology. Understanding forest phenological metrics is of the utmost importance while studying the responses of plant functions in changing environments (Ghosh *et al*. 2019). The correlations between phenological metrics and climatic variables and tree-ring widths observed in this study showed the sensitivity of teak to climatic changes during the early years of development and demonstrated the potential of using remote sensing techniques combined with methods for extraction of phenological metrics to predict the growth of teak.

However, the lack of correlation between LOS and tree-ring width during the current growth period may reflect the manner in which the plant performs radiation absorption and carbon allocation (Berner *et al*. 2011). This could be explained by the way in which the plant, during the leaf period, allocates resources differently in certain situations (Vicente-Serrano *et al*. 2016). During photosynthesis, a smaller fraction is retained in the form of non-structural carbohydrates (NSC) (Vilalta *et al*. 2016). NSCs have been viewed as a reservoir pool to supply carbon for growth and respiration (Dietze *et al*. 2014). Studies have shown that for deciduous species, an increase in total NSC in wood was associated with a decrease in radial growth before leaf shedding as a response to environment changes in different growing seasons, thus allowing the plant to maintain equal growth and NSC dynamics during years with variations in water availability and solar radiation (Scartazza *et al*. 2013). Moreover, trees can use NSC reserves assimilated during the previous growth season during later periods (Dietze *et al*. 2014). Thus, future studies considering the dynamics of NSC combined with the techniques covered in this study are important to understand how this allocation occurs on *T. grandis* in response to climate change, as the intensity and frequency of El Niño events are expected to increase.

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