



Crop Production

Original Article - Edited by: Luis Eduardo Correa Antunes

Phenology of hass avocado in the Andean tropics of Caldas, Colombia

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Abstract - The objective of this study was to document and analyze the effect of climate on the phenological development of 'Hass' avocado in two contrasting zones of the Andean tropics of Caldas, located at altitudes of 1,950m and 2,400m a.s.l., respectively. A completely randomized experimental design was carried out using a five to seven year-old 'Hass' tree as experimental unit and 15 replicates on each area. Observations were conducted on lateral sylleptic shoots and their corresponding apical buds located on the eastern and western sides of each tree. The destination of the apical bud of lateral shoots was quantified, floral phenology was documented, heat units were calculated from reproductive bud stage 1 to anthesis and to harvest and root growth was followed for each study area. Air temperature, soil temperature, precipitation and photosynthetically active radiation (PAR) values were recorded over time. Differences were found in the number of apical buds of lateral shoots with reproductive and vegetative destination, flowering phenology, heat units, root growth, PAR and precipitation. Differences were found among variables evaluated at the two contrasting altitudes. There is a clear need for further ecophysiological studies on this fruit tree in tropical areas in particular.

Index terms: ecophysiology, sylleptic shoots, photosynthetically active radiation, alternate bearing, cumulative heat units.

Revista Brasileira de Fruticultura, v.44, n.5, e-252. DOI: <https://dx.doi.org/10.1590/0100-29452022252>
Received 14 Jun, 2022 • Accepted 23 Aug, 2022 • Published Sep/Oct, 2022

Fenologia do abacate hass nos trópicos andinos de Caldas, Colômbia

Resumo – Objetivou-se documentar e analisar o efeito do clima no desenvolvimento fenológico do abacateiro 'Hass' em duas zonas contrastantes dos trópicos andinos de Caldas, localizadas a 1.950m e 2.400m respectivamente. Um delineamento experimental inteiramente casualizado foi implantado usando uma árvore 'Hass' de cinco a sete anos como unidade experimental e 15 repetições em cada área. As observações foram realizadas em brotos silépticos laterais e suas gemas apicais correspondentes localizadas no lado leste e oeste de cada árvore. O destino da gema apical das brotações laterais foi quantificado, a fenologia floral foi documentada, as unidades de calor foram calculadas desde o estágio 1 da gema reprodutiva até a antese e até a colheita e o crescimento radicular foi acompanhado para cada área de estudo. Valores de temperatura do ar, temperatura do solo, precipitação e radiação fotossinteticamente ativa (PAR) foram registrados ao longo do tempo. Foram encontradas diferenças no número de gemas apicais de brotações laterais com destino reprodutivo e vegetativo, fenologia de floração, unidades de calor, crescimento radicular, PAR e precipitação. Foram encontradas diferenças entre as variáveis avaliadas nas duas altitudes contrastantes. Há uma clara necessidade de mais estudos ecofisiológicos sobre esta frutífera em áreas tropicais em particular.

Termos para indexação: ecofisiologia, brotos silépticos, radiação fotossinteticamente ativa, alternância produtiva, unidades de calor cumulativo.

Introduction

Since 2020, world avocado production has shown annual increase of 4.1% (ARIAS et al., 2018). Current estimates indicate that around 5 million tons of avocado are consumed worldwide each year (SOMMARUGA; ELDRIDGE, 2021). In Colombia, the 'Hass' cultivar corresponds to approximately 25% of the total area cultivated with avocado but it is noteworthy that the increase in the planted area is close to 73%, from 11,000 hectares in 2014 to 20,182 hectares in 2019. It is estimated that there are currently more than 30,000 hectares of 'Hass' established in the country at different regions; however, about 26% of the cultivated area is at the development stage; therefore, an increase in the annual fruit production is expected in the

coming years (MADR, 2021). Despite these figures, in order to meet market demand, it is necessary to have a consolidated knowledge base to adequately support the increase of new areas and safeguard the current ones (DÍAZ et al., 2020).

The knowledge about the genotype/environment interaction of the 'Hass' cultivar in the conditions of the Andean tropics in which Colombia is located will increase our understanding of how avocado grows and produces in these environments, and is of fundamental to promote sustainable and competitive production systems necessary to address problems such as alternate bearing, a phenomenon that implies a year of very abundant harvests ("on" year) followed by reduced ones ("off" year) and vice versa (ALCARAZ et

al., 2013). This behavior results in dramatic variations in fruit volume from year to year and translates into loss of income during low yield years (MICKELBART et al., 2012).

Recognizing that alternate production is closely related to the presence and location of fruits within the canopy and the subsequent flowering over time (ALCARAZ et al., 2013), the study of the architecture and behavior of avocado buds that generates the units that give rise to reproductive organs, and that defines the growth structure of the avocado tree, is of special importance (ARIAS et al., 2021). Thus, the objective of the present study was to follow and evaluate the phenology of 'Hass' avocado in two contrasting zones of the Andean tropics of Caldas.

Materials and methods

Plant material

The field stage was carried out between January 2020 and February 2021 in two commercial 'Hass' avocado orchards, located at 5°18' 40" N and 1,950 m a.s.l. (Aranzazu), and Villamaria at 5°01' 26" N and 2,400 m a.s.l., both with loamy textured soils. Trees are 5 to 7 years old grafted on "criollo" rootstocks from seeds planted at 6m x 6m, without irrigation system and with management based

on the ICA guidelines (Colombian Agricultural Institute) in resolutions 448 and 30021 for exporting farms (ICA, 2016).

Fifteen trees were selected on each orchard in a completely randomized experimental design (CRD). On each tree, branches of approximately 1.5 m in length were selected and marked from the middle part of the tree canopy with orientation to the eastern and western quadrants. On these selected branches, epicormic shoots and respective lateral shoots were selected and marked (SALAZAR-GARCÍA et al., 2018).

Destination of apical buds of lateral shoots

On each tree and branch with eastern and western orientation, epicormic shoots and their respective lateral shoots were marked, and the destination of their apical buds (vegetative or reproductive) was monitored over time, on each growth flush observed.

Relative intensity of lateral shoot growth.

The relative intensity of both vegetative and reproductive growth of the apical buds of sylleptic lateral shoots was determined using the following mathematical formula (ROCHA-ARROYO et al., 2011).

$$\text{Relative intensity: } \frac{\text{No. of readings} * \text{No. of reproductive or vegetative apical buds}}{100}$$

Flowering phenology

To document the flowering process, reproductive apical buds at stage '510' according to the phenological scale of Alcaraz et al. (2013) were marked in four trees and at each cardinal point. This monitoring ended when

flower anthesis occurred, determining the time elapsed between development stages.

Accumulated heat units

To quantify the accumulated heat units (AHU), the maximum and minimum temper-

atures recorded during the time between reproductive bud stage '510' and flowering '610', and from anthesis to harvest, was considered. Temperatures were obtained from automatic weather stations located on each orchard, using the following equation:

$$\text{AHU: } \left(\frac{T_{max} + T_{min}}{2} \right) - T_b$$

where $T_b = 10$

Root growth

To document the presence of new roots, random samples were monthly collected from 2 trees on each orchard, starting on the eastern quadrant. These root samples were collected under the canopy by digging 40x40x40 cm holes. As selection criterion, only light brown roots measuring ≤ 5 mm in thickness were used. Once collected, root samples were washed, dried in an oven at 70°C for 72 hours and then their dry weight was recorded using analytical scale (ROCHA-ARROYO et al., 2011).

Climatic variables

Climatic variable data were obtained from automatic weather stations located on each orchard. The variables recorded were air temperature, soil temperature, relative humidity and precipitation. Photosynthetically active radiation was periodically measured at one-hour intervals from 8:00 am to 4:00 pm using PAR MQ-303 full spectrum meter from Apogee Instruments.

Statistical analysis

Completely randomized design (CRD) was used, considering the tree as the experimental unit and replicates and subreplicates

corresponding to branches marked at each cardinal point. Results were analyzed by analysis of variance and Tukey's mean comparison ($p \leq 0.05$). The SAS statistical software (SAS Inst, Cary N.C. Version 9.4) was used.

Results and Discussion

The variables evaluated, such as destination of apical buds of lateral shoot, flowering phenology and accumulated heat units (AHU), show significant differences between locations, which confirms the fact that environmental conditions have an effect on tree growth processes. Likewise, the behavior of climatic variables such as air temperature, precipitation and solar radiation show significant changes over time in each evaluation zone.

Destination of apical buds of lateral shoots.

Shoot growth is generally monopodial and axillary buds can be proleptic (formed after a rest period of their apical meristem) or sylleptic (formed without rest period) (ALCARAZ et al., 2013; WANG et al., 2018). All lateral shoots evaluated on this research were sylleptic (Figure 1 and 2). These shoots are considered highly productive due to their flowering intensity (GARNER; LOVATT, 2016) and are more commonly observed in tropical conditions than in temperate climates (DÍAZ et al., 2020).

Observations made in this study indicate that the Aranzazu area (1,950 m) may be more productive in terms of number of flowers and fruits than the Villamaría area (2,400 m), due to the presence of statistically significant differences in the destination of reproductive apical buds of sylleptic lateral shoots in both areas under study (Figure 3).



Photo: Arias-García, 2021.

Figure 1. Proleptic and sylleptic shoot on Hass avocado trees in Caldas, Colombia.

Apical bud of growing lateral shoot with unobservable fate



Photo: Arias-García, 2021.

Figure 2. Lateral sylleptic shoot and its apical bud on Hass avocado tree.

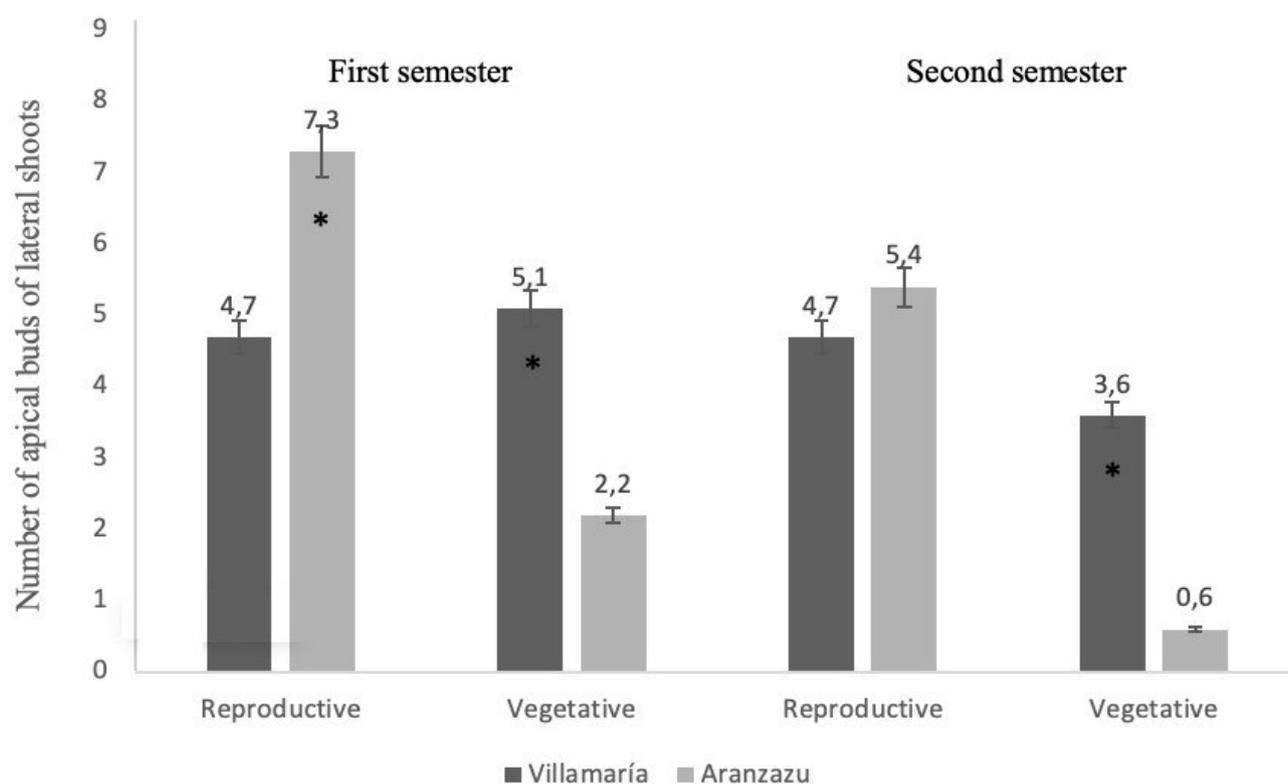


Figure 3. Destination of apical buds of lateral shoots in the first and second semester of 2021 in two contrasting areas of the Andean tropics of Caldas. Bars with asterisk denote significant differences according to the Tukey's test ($p \leq 0.05$).

Relative shoot growth intensity

The orchard located in Aranzazu (1,950 m) presented relative intensity of 76.84% of lateral shoots with reproductive destination in the first half of the year, while in the second half of the year, the relative intensity of shoots with this destination was 88.1%. The orchard located in Villamaría (2,400 m) had 47.81% of shoots with reproductive fate in the first half of the year, while in the second half of the year, the relative intensity was 43.2%. These differences are comparable to those reported by Reyes-Alemán et al. (2021), who found differences in vegetative growth in contrasting zones in different producing areas of Mexico. These results show tendency to reproductive growth over vegetative growth in the Aranzazu area and more balanced tendency between vegetative and reproductive destination in the Villamaría area.

These results might describe the productive potential of each location and support studies on lateral bud sprouting (sylleptic or proleptic) on the main axes as an important agricultural tool, since the knowledge of the tree architecture (MENZEL et al., 2014) and the manipulation of the proportion of sylleptic and proleptic buds can lead to increased productivity (GARNER; LOVATT, 2016). These results might describe the productive potential of each location and support studies on lateral bud sprouting (sylleptic or proleptic) on the main axes as an important agricultural tool, since the manipulation of the proportion of sylleptic and proleptic shoots can lead to increased productivity (GARNER; LOVATT, 2016). Likewise, increase in axillary branching could also increase photosynthetic capacity in the "on year" and thus stimulate fruit production in the "off year" (REYES-ALEMÁN et al.,

2021). Garner and Lovatt (2016), found that only shoots in terminal positions on their respective axes generally became floral, so their number indicated the floral potential of trees.

Flowering phenology

According to the phenological scale of (ALCARAZ et al., 2013) (Figure 4), the time elapsed between stage '510' (dormant reproductive buds), and stage '610' (first open flowers) was different between orchards (location), registering 110 days for anthesis in

the municipality of Aranzazu (1,950 m), and 131 days in the municipality of Villamaría (2,400 m). This is in agreement with reports by (SALAZAR-GARCÍA et al., 2018), which indicate that the timing of floral development varies according to the environmental conditions of a specific site. Decreases in temperature play an important role in the transition from the vegetative to the reproductive state (ROCHA-ARROYO et al., 2010), in addition, the floral development duration increases when temperature is lower (PATTEMORE et al., 2018).

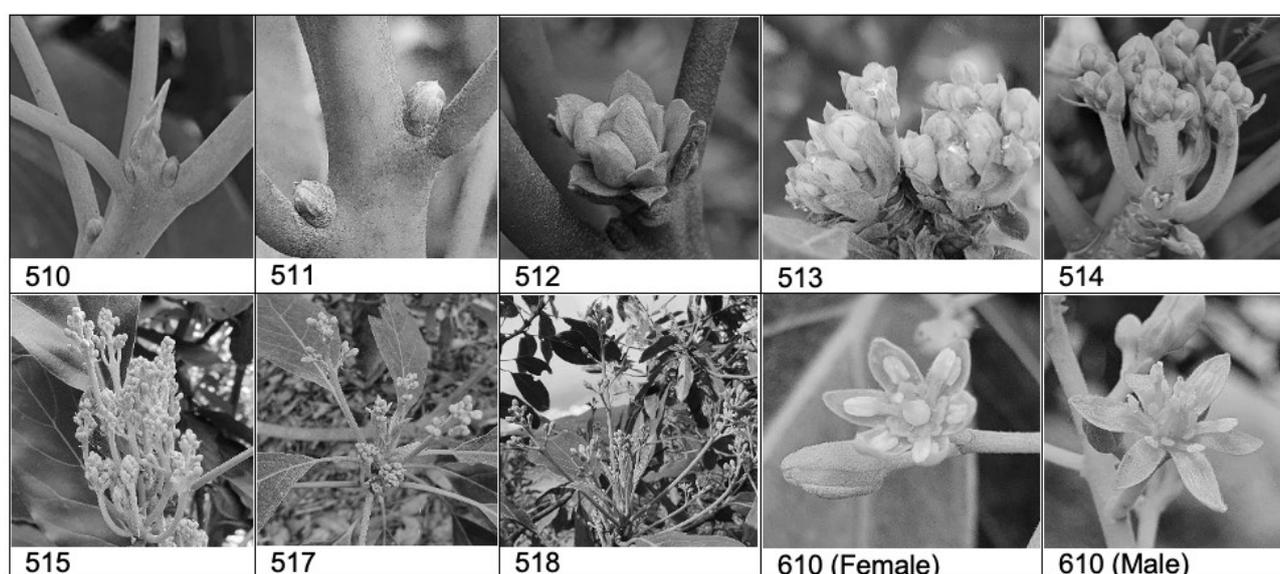


Photo: Arias-García et al., 2021.

Figure 4. Reproductive phenological scale of 'Hass' avocado in the Andean tropics of Caldas. Based on (Alcaraz et al., 2013).

Thus, the difference of 21 days to reach anthesis between orchards (location) can be explained considering the average temperature values during the observation period, since the Aranzazu area had average temperature of 21.4°C, while in Villamaría, the average temperature was 17.8°C.

Accumulated heat units (AHU)

AHU showed differences between orchards (locations). In Aranzazu (1,950 m), the amount of AHU to achieve anthesis was

1,096.55 and only 862.7 AHU (Table 1) were observed in Villamaría (2,400 m). This somewhat differs from values reported by Chávez-Bárcenas et al. (2008), who determined that trees located in semi-warm humid climate orchards require less AHU to reach anthesis than orchards located in temperate humid climate. AHU calculated for the period from flowering to harvest in both locations showed the same trend, 2,530.9 AHU for Aranzazu and 279 days until harvest while

Villamaría had 2,092.72 AHU and 355 days until harvest (Table 2). Anguiano et al; (2007), reported accumulation of 2,200 AHU per year for 'Hass' avocado, while Vargas et al., (2012) reported AHU values between 1,800

and 2,000 depending on the time of flowering, which indicates that in the Aranzazu area, the energy needs of the tree are fully satisfied, while in Villamaría, values would be below ideal optimum.

Table 1. Accumulated Heat Units (AHU) in flowering phenology in two contrasting zones of the Andean tropics of Caldas, Colombia.

Developmental stages until flowering	Days elapsed		Degree days of development (°d)	
	Villamaría	Aranzazu	Villamaría	Aranzazu
A-C	36 ± 1.02	13 ± 1.09	246.65	115.4
C-D	46 ± 1.36	61 ± 1.02	301	600.2
D-E	36 ± 1.50	22 ± 0.80	235.55	232.3
E-F	13 ± 1.54	14 ± 0.81	79.5	148.6
Total	131 ± 13.98	110 ± 22.69	862.7	1096.55

*A-C: from reproductive bud in dormancy (510), to buds near to budbreak (512). C-D: from (512) to secondary axis visible in the inflorescence (514). D-E: from (514) to yellow bud (515). E-F: from (515) to anthesis (610). ± indicates the standard deviation and data variation according to the average.

Table 2. Accumulated Heat Units (AHU) from flowering to harvest in two contrasting zones of the Andean tropics of Caldas, Colombia.

Stage of development until harvest	Days elapsed	
	Villamaría	Aranzazu
A-C	355	279
Total	2092.72	2530.9

*A-C: from flower anthesis to harvest.

These results are probably related to the difference in average temperature between locations, with Aranzazu having higher average temperature (21.4 °C), compared to Villamaría (17.8 °C).

Root growth

Root growth can occur throughout the year but be reduced at times of vegetative flush or flowering (ROCHA-ARROYO et al., 2011; MICKELBART et al., 2012), or even growth dormancy can occur (GARNER; LOVATT, 2016). The results of this research show continuous roots growth over time in both locations (Figure 5); however, higher growth is evident in the Villamaría area (2,400 m). Likewise, it is observed that for the Aranzazu area

(1,950 m), the most significant growth was observed on the second semester of the year (20.7 gr), while in the Villamaría area, the highest growth was registered in the first semester (23 gr).

Regarding the relationships between root growth, vegetative flush and flowering, it is important to mention that flowering events occurred in February and August in the Aranzazu area, and in March and September in the Villamaría area. For both areas, root growth was reduced after flowering in the first half of the year; however, in the second half of the year in the Villamaría area, root growth increased after flowering, while in Aranzazu, root growth was reduced. As for the initial vegetative flush, the apical growth

of lateral shoots began in December 2020 in both areas, and in the second semester of

2021, vegetative flush occurred near the month of June.

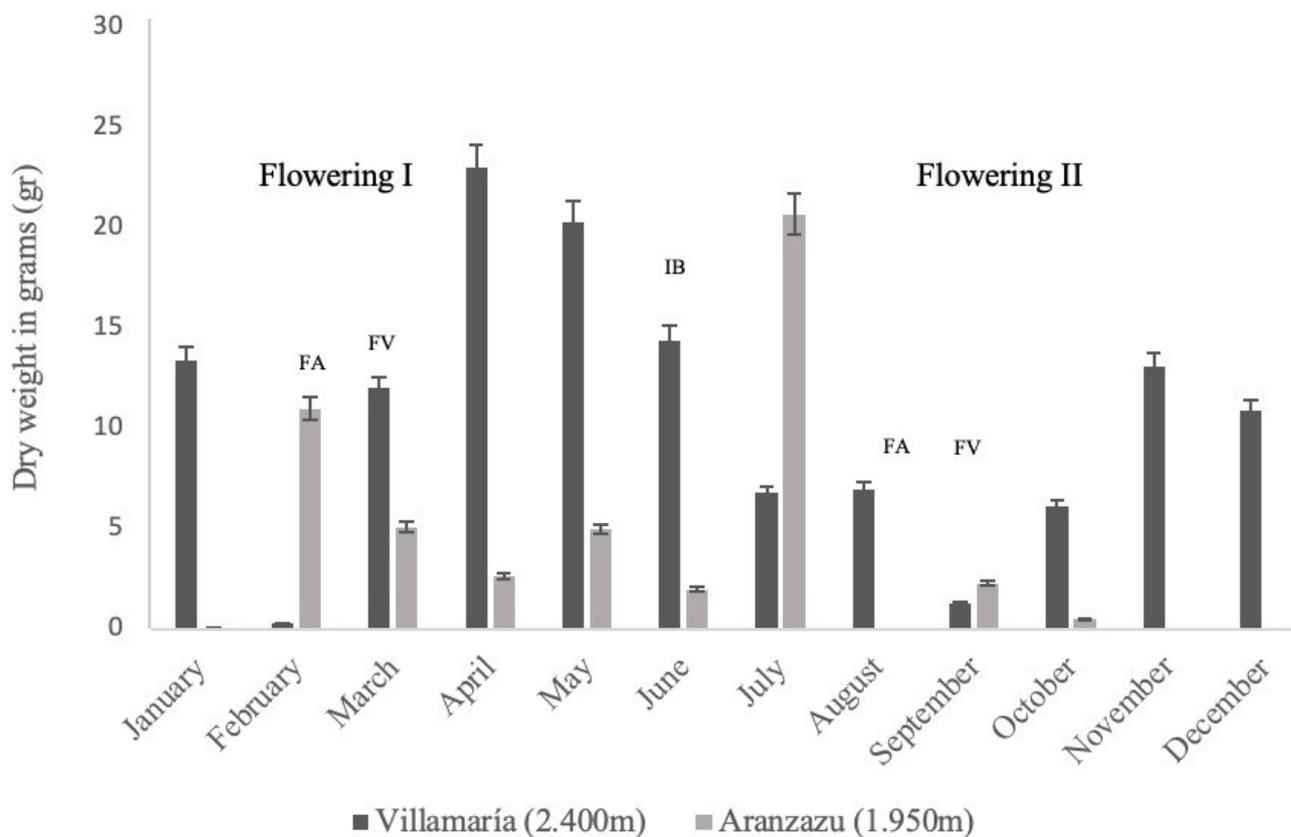


Figure 5. Root growth of 'Hass' avocado in two contrasting areas of the Andean tropics of Caldas. FA: Flowering Aranzazu FV: Flowering Villamaría IB: Initial budbreak. Initials above bars indicate the month where flowering or budbreak occurred in the different areas evaluated.

The results of this research are similar to those reported in California by Mickelbart et al. (2012), who determined that root growth flushes occurred about 30 to 60 days after shoot growth flushes; likewise, root growth was greater when shoots were not actively growing (GARNER; LOVATT, 2016). On the other hand, Rocha-Arroyo et al., (2011) concluded that in the Michoacán area (Mexico), root production occurred throughout the year, although the presence of two main root flushes that varied with climate was evident. Despite these results, Silva et al. (2017) determined that under Brazilian conditions, maximum root growth coincided with flowering and with spring and summer vegetative flushes.

The information obtained in this study allows inferring that in tropical conditions, it is usual to have distinct variations in the root growth patterns. There may be growth after flowering at some periods of the year, as well as simultaneous growth during flowering, or root growth before or after a vegetative growth flush (DÍAZ et al., 2020). This variability in growth patterns seems to be linked to changes in climate, as temperatures, precipitation and luminosity are not stable over time as they may be in Mediterranean climates. For example, in the first half of the year, when there was high precipitation, increase in root growth was observed for both areas under study; however, this behavior pattern was not repeated in the second half

of the year, despite the observation of new precipitations.

Climate conditions in both areas under study

The results obtained in this study show climatic differences between areas, which confirm the fact that climate has high influence on the vegetative and reproductive growth of avocado trees (CHUNG et al., 2022), since at level of these variables, the two areas under study also show important differences.

Air temperature

According to the Caldas-Lang climate classification, the Aranzazu area is classified as semi-humid temperate climate, while the higher elevation area of Villamaría is classified as humid cold climate (IDEAM, 2015). In

this regard, differences in minimum, mean and maximum air temperatures recorded in both areas over time are evident (Figure 6).

While the three ecological avocado cultivars offer a wide range of adaptation to air temperature (WEIL et al., 2022), for the 'Hass' cultivar in particular, Garner and Lovatt (2016) found that under the southern Australia conditions, only the coldest (17/10°C) and hottest (37/30°C) treatments restricted growth and dry matter accumulation, while Rocha-Arroyo et al. (2010) found that in California, the 'Hass' cultivar did not flower when maintained at temperatures of 30/25, 25/20 or 20/5°C (day/night), but flowered when exposed to 3-4 months of 15/10, 18/15, 20/15 and 23/18°C (day/night) respectively.

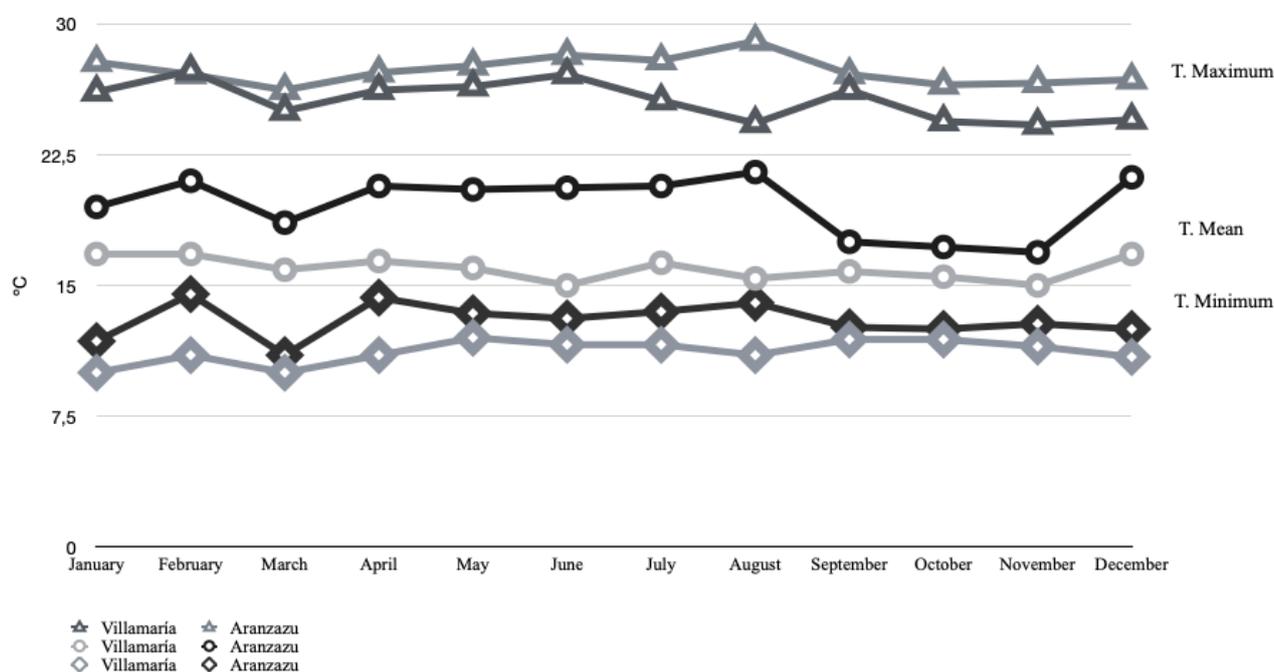


Figure 6. Maximum, mean and minimum air temperatures in the two contrasting areas of the Andean tropics of Caldas.

Air temperature data during this research do not seem to restrict tree growth in either of the two areas under study. Research carried out in Brazil determined that constant night

temperatures below 10°C can alter avocado flowering development (SOARES et al., 2002) and in California (USA), evaluations carried out on 'Hass' avocado cultivar showed that

maximum air temperatures below 15 °C reduce bee movement in the orchard (GARNER; LOVATT, 2016); however, in this area, inflorescence development is correlated with night temperature ≤ 15 °C (SALAZAR-GARCÍA et al., 2018). In the case of Aranzazu and Villamaría, night temperatures were rarely above 15°C or below 10°C, which indicates that floral development should not be affected; however, differences between one location and the other can accelerate or reduce the time of the different phenological phases, specifically the flowering time and the flower-to-fruit period.

Soil temperature

The 3 avocado cultivars, Mexican, Guatemalan and Antillean, were cultivated in different climatic regions and may show different responses to soil temperature (SILVA et al 2017). Furthermore, it has been shown that there is root growth restriction at soil temperature below 13.5°C (WEIL et al., 2022). Likewise, soil temperature ranging from 21° to 27° was better for avocado seedling

growth, but temperatures above 27° reduce growth (SILVA et al 2017).

Soil temperature levels in this study did not show strong variations in any of the areas under study (Figure 7), which results are not in agreement with those found by Rocha-Arroyo et al., (2011), where in different growing areas of Michoacán, Mexico, soil temperature variation was from 13 °C to 21 °C. The minimum temperature recorded in Villamaría was 16.4°C in November, while the highest temperature was 18.1°C in July. In Aranzazu, the minimum temperature recorded was 17°C in January, while the maximum temperature was 18.4°C in April. This information allows inferring that the soil temperature in these two areas was never below the critical minimum reported and also did not reach levels relevant to stimulate root growth. Furthermore, the maximum root growth in Villamaría occurred in April, while in Aranzazu, it occurred in July, and considering this information, there seems to be no relationship between maximum root growth and maximum soil temperature.

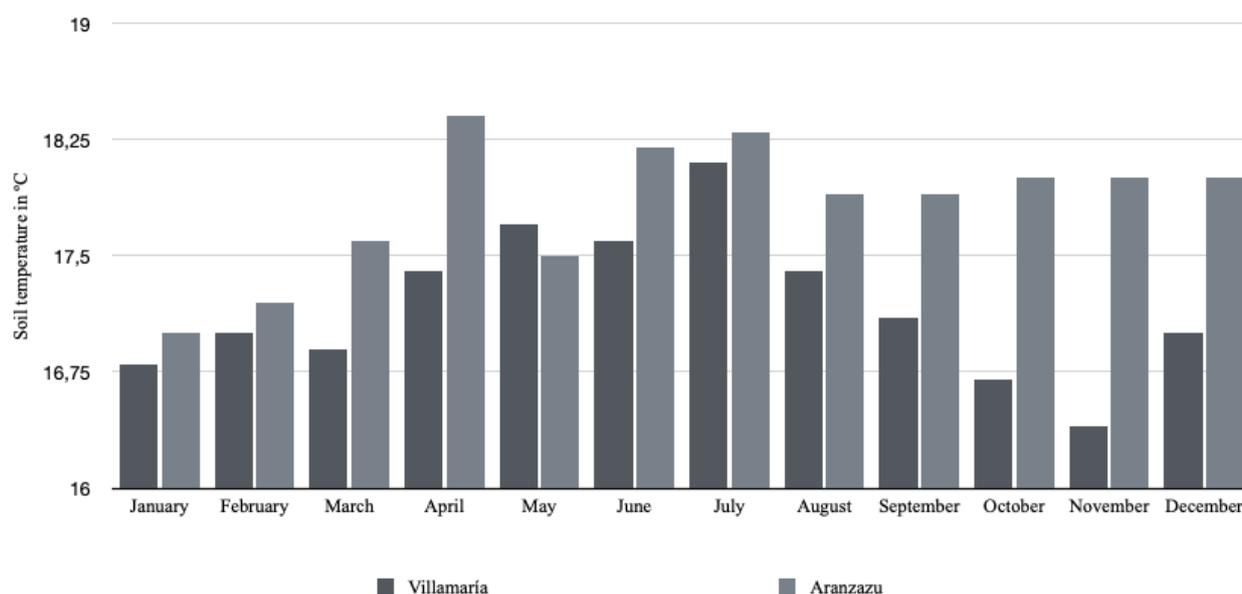


Figure 7. Soil temperature in two contrasting areas of the Andean tropics of Caldas.

Precipitation

Precipitation registered in both areas under study shows significant variations over time, although the bimodal behavior characteristic of the Andean region is preserved (RAMÍREZ; JARAMILLO, 2009). Nonetheless, precipitation of 316 mm in March for the Villamaría area is an atypical annual value in terms of precipitation (Figure 8). This demonstrates not only the intense climatic variability of the

area but also the important water supply in this central part of the country. These data contrast with what was found in a study conducted in Brazil, where in the area of the municipality of Assis Chateaubriand, state of Paraná, 1.2mm of precipitation was recorded for the month of March (CALDANA et al., 2019), which required the implementation of irrigation systems for the proper development of the avocado crop.

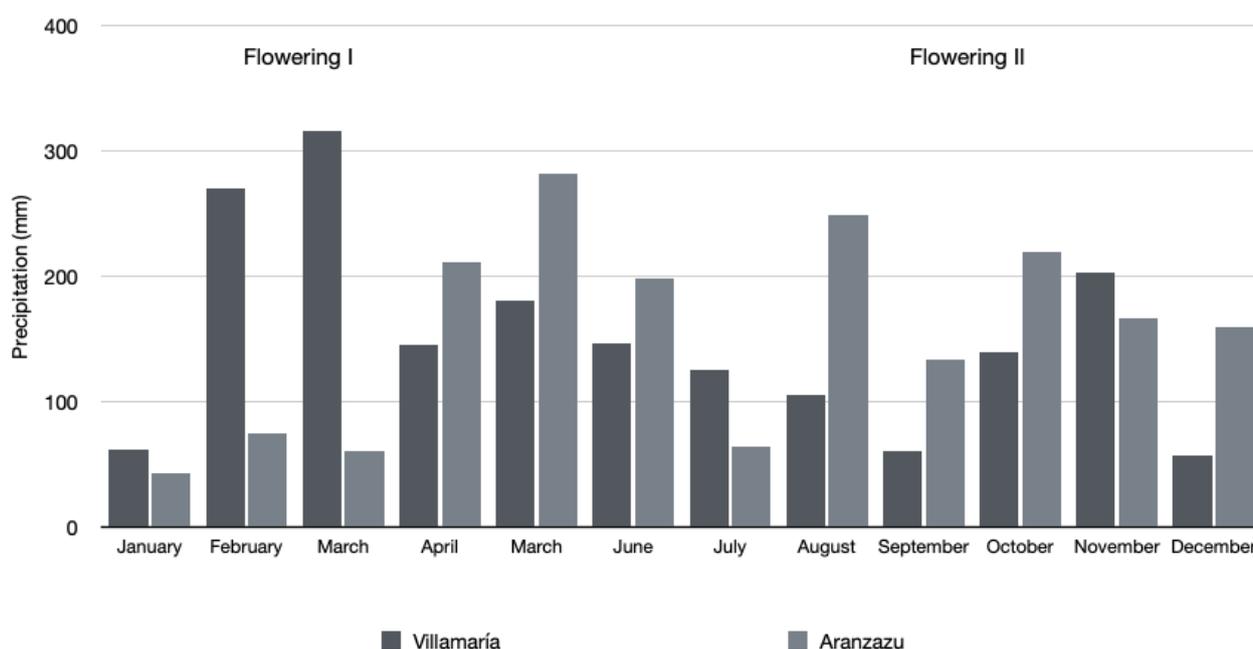


Figure 8. Precipitation in two contrasting areas of the Andean tropics of Caldas.

The two peak flowering periods recorded during the year in the two locations correspond to February-March and August-September, contrasting with high rainfall in the first semester of the year in the Villamaría area, and high precipitation in the third semester of the year in the Aranzazu area.

Silber et al. (2012) have explained which is the environmental factor that can induce flowering in avocado and reported that flower initiation can be induced by water stress. Salazar-García et al., (2018) concluded that the environmental stimulus for flowering induction was photoperiod and/or air

temperature. In contrast to the above, research carried out in the Andean tropics of Colombia showed that flowering induction occurred in some areas only at times when precipitation was reduced, while in others, flowering occurred after high precipitation (DÍAZ et al., 2020).

The results of this study have shown that several environmental factors may be associated with the floral induction of avocado under the conditions of the Andean tropics. Cloud cover may play an important role since the presence of high precipitation increases cloud cover and therefore there is a drop in

photosynthetically active radiation (PAR). In this scenario, a hypothesis that may be viable is that the avocado tree could stop vegetative growth if radiation decreased constantly, and switch to a reproductive phase that would begin with flowering induction.

Photosynthetically Active Radiation (PAR)

For both locations, the light intensity observed at different times of the year showed tendency to concentrate the highest PAR values between 11:00 am and 02:00 pm (Figure 9 A-B); however, the Villamaría area shows significant reduction in radiation after

02:00 pm, which might be due to greater presence of cloud cover if we consider that at that altitude, the presence of cloud cover in the afternoon hours is frequent. According to these results, it is important to consider that incident PAR varies according to latitude, season, planting date and plant phenology (CRUZ et al., 2021). In areas close to the equator, the length of the day does not seem to change significantly (YEANG, 2007), and as for solar radiation, Renner (2007) reported that when the sun passes directly over the equator twice a year, a bimodal cyclic change in the incoming solar radiation (insolation) is observed on these regions.

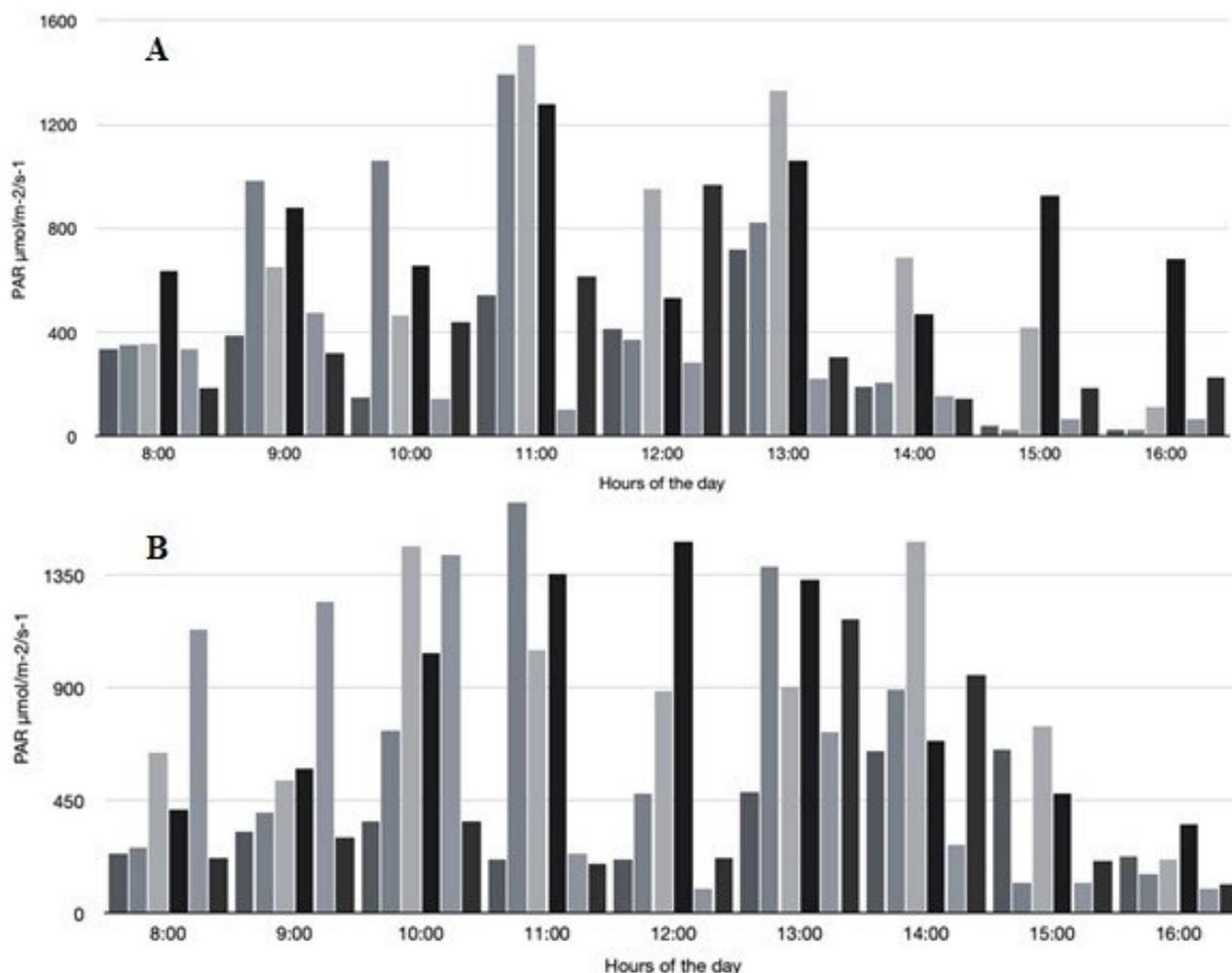


Figure 9. Photosynthetically active radiation in (A) Villamaría and (B) Aranzazu, Caldas.

The PAR values obtained in this study are high in relation to the light saturation point reported for avocado. For California, Israel

and Australia, values of 300, 500, 660 and up to 1,100 $\mu\text{mol}/\text{m}^2/\text{s}$ respectively are reported as sufficient to reach light saturation

point (WEIL et al., 2022). In this research, maximum PAR values above 2,000 $\mu\text{mol}/\text{m}^2/\text{s}$ were recorded and the average values observed were slightly less than 1,400 $\mu\text{mol}/\text{m}^2/\text{s}$ (Figure 9 A-B). This indicates very good PAR supply in areas under study and shows the opportunity to study the effect of this high solar radiation on tree physiology and productivity.

Conclusion

The Aranzazu area showed higher values of shoots with reproductive destination in their apical buds on both semesters of the year. Also, in Aranzazu (AHU 1,096.55), anthesis

occurred 21 days earlier than in Villamaría (AHU 862.7), and in Aranzazu (AHU 2,530.9), harvest occurred 76 days earlier than in Villamaría (AHU 2,092.72). For both locations, there were two important root growth peaks, and soil temperature remained within maximum and minimum ranges reported. There were differences in precipitation and air temperature in the different areas.

This study reveals the need for further research on the ecophysiology of 'Hass' avocado under the conditions of the Andean tropics, since the results obtained show differential behavior of trees compared to other latitudes where this fruit is also grown.

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