International Journal of Biometeorology
https://doi.org/10.1007/s00484-019-01693-2

ORIGINAL PAPER

Arabica coffee fruits phenology assessed through degree days, precipitation, and solar radiation exposure on a daily basis

Paula Cristina da Silva Angelo[1] · Iran Bueno Ferreira[2] · Carlos Henrique Siqueira de Carvalho[3] · José Braz Matiello[4] · Gustavo Hiroshi Sera[5]

Received: 20 June 2018 / Revised: 8 February 2019 / Accepted: 11 February 2019
© ISB 2019

Abstract

Knowledge regarding reproductive cycle duration is important in terms of scheduling harvests and estimating coffee cultivars adaptability. Nine *Coffea arabica* cultivars were evaluated during two successive reproductive cycles. Dates of occurrence of the major blossoms, and the green and ripe fruits, on 64 branches for each cultivar, were registered during each reproductive cycle. These dates were used to calculate the duration of the fruit development (blossom to green) and ripening (green to ripe) phases, the quantities of degree days, precipitation, and solar radiation accumulated throughout each phase, and also degree days, precipitation, and radiation on a daily basis, all of which are novelties in coffee research. The differences between cultivars and reproductive cycles were tested by ANOVA. Cultivars were grouped in clusters according to the above-cited variables. Principally, the daily quantities of degree days and precipitation determined the differences between reproductive cycles and coffee cultivars during development phases. Early and very early cultivars accumulated high numbers of degree days.day^{-1}, in periods of relatively good water availability, with high exposure to solar radiation. Late cultivars accumulated less degree days.day^{-1} and were exposed to lower amounts of daily solar radiation and longer periods of water scarcity. Regarding the fruit ripening phase, cultivars were principally distinguished by degree days and solar radiation on a daily basis. Two of the coffee cultivars were classified or confirmed as early and very early and another three as late and very late. One cultivar, Siriema, displayed an interesting conjugation of early and intermediate characteristics.

Keywords Flowering · Fruit maturation · Thermal time · Adaptability

Iran Bueno Ferreira in memoriam

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00484-019-01693-2) contains supplementary material, which is available to authorized users.

✉ Paula Cristina da Silva Angelo
paula.angelo@embrapa.br

1 Embrapa Café - Instituto Agronômico do Paraná (IAPAR), Londrina, PR, Brazil

2 Fundação Procafé Alameda do Café, no. 1000 Vila Verônica CEP, Varginha, MG 37086-423, Brazil

3 Embrapa Café - Fundação Procafé, Varginha, MG, Brazil

4 Fundação Procafé, Varginha, MG, Brazil

5 Instituto Agronômico do Paraná (IAPAR), Londrina, PR, Brazil

Introduction

The characterization of coffee cultivars regarding the reproductive cycle is important to schedule harvesting. Start dates and the duration of the reproductive cycles are, among others, developmental processes strongly responsive to environmental conditions (Camargo and Camargo 2001; Morais et al. 2008), which influence the plants' adaptability.

Environmental data and data on plant developmental processes can be integrated by the use of variables such as the "thermal time", which is the sum of the daily mean temperatures from which the base temperature has been subtracted, counting days from the start to end of the developmental process of interest. The base temperature is reached when the described process stops (Nátrová and Nátr 1991). Thermal time as a concept is the result of a research effort to better describe plant physiology and phenology and is expressed in degree days (see "Material and methods" for the formula).

Despite its utility, thermal time is seldom applied to study coffee plants. More frequently, authors have reported thermal

Published online: 21 March 2019

times concerning entire reproductive cycles (meaning blossoming to ripe fruits) for Arabica (Pezzopane et al. 2008; Bardin-Camparotto et al. 2012) or Robusta (*C. canephora*) coffees (Souza et al. 2017).

However, regarding reproductive cycle organization, Arcila-Pulgarín et al. (2002) divided coffee fruit development into six principal stages and fruit ripening into another four stages. Pezzopane et al. (2003) defined seven different phases from pinhead fruits to overripe fruits. Morais et al. (2008) distinguished six growth/development stages according to fruit size and five ripening stages. Camargo and Camargo (2001) recognized fruit development and ripening phases as distinguishable processes, which, in general, take place under different seasonal conditions in the year. Indeed, there are already some reports regarding the use of thermal times to describe distinct phases in the reproductive cycle of Arabica coffees (Petek et al. 2009; Carvalho et al. 2014).

Herein, coffee fruit development and ripening phases are described using thermal times, and accumulated precipitation and solar radiation, subsequently divided by the number of days necessary for the different cultivars to accomplish each of these two phenological phases, during two reproductive cycles. The division by the number of days spent in each phase was introduced in the calculations to enhance the value of genetic and physiological differences between the cultivars. The analyses were performed, principally, to characterize recently recommended cultivars, contributing to schedule the harvests. The results here reported aim to enrich the limited collection of similar data available for coffee plants, and to allow comparisons between cultivars and locations, while physiological analyses are expected for the near future.

Material and methods

Biological material *Coffea arabica* cultivars Catucaí Amarelo 24/137 (item 4, registered as Catucaiam 24137), Acauã Novo (item 5, Sarchimor × *C. arabica* cv. Mundo Novo, registered as Acuãnovo), Palma III (item 11, Catimor × *C. arabica* cv. Catuaí), Sabiá (item 12, Catimor × *C. arabica* cv. Acaiá, registered as Sabiá Tardio), Catucaí Vermelho 785/15 (item 18, registered as Catucaí 785/15), Guará (item 22, selection from Catucaís Vermelhos 20/15), Arara (item 24, natural hybrid of Sarchimor Amarelo 1669-20 × *C. arabica* cvs. Catuaí or Icatu Amarelos), Catuaí Vermelho IAC 144 (item 29), and Siriema (item 34, clone 13/36, group VC4. *C. arabica* × *C. racemosa* backcrossed to *C. arabica*) were evaluated during 2015/2016 and 2016/2017, when the plants went through their fourth and fifth reproductive cycles. Catuaís were obtained by breeding *C. arabica* cv. Mundo Novo × cv. Caturra. Catucaís originated as Icatu (*C. arabica* × *C. canephora* $2n = 44$, backcrossed to *C. arabica*) × *C. arabica* cv. Catuaí progenies. Sarchimors and Catimors were obtained by breeding Timor hybrids (*C. arabica* × *C. canephora* natural hybrids, $2n = 44$) to *C. arabica* cv. Vila Sarchi or Caturra, respectively. All evaluated cultivars are self-compatible plants that display $2n = 44$ chromosomes and are *C. arabica* variants. Regarding resistance to the coffee leaf rust caused by *Hemileia vastatrix,* item 29 is susceptible, items 4, 18, and 12 are moderately resistant, and items 5, 22, 24, and 34 are moderately to strongly resistant (Matiello et al. 2016). In addition, item 34 is resistant to the leaf miner *Leucoptera coffeella*. Regarding the sizes of dry seeds, items 4, 5, 18, 22, 29, and 34 are intermediate, item 24 is big, and item 12 has small-sized seeds. Further information regarding the genetic background of the cultivars can be found in Matiello et al. (2016). Collections of data were conducted in the farm managed by the Procafé Foundation, in Varginha, MG (21°34’ S and 45°24’ W, altitude 970 m, block 88), in four randomized blocks of six plants per cultivar, spaced 3.5 × 0.7 m apart. Conventional nutrient and weed management were applied to the experimental plot. Chemical treatments to control diseases and irrigation were not applied.

Data collected and calculations At the time of flower bud emission (which indicates that the reproductive phase is in process), four out of the six plants per cultivar per block had four branches in the upper third part, pointing to four different geographic quadrants, tagged with alphanumeric codes. Tagging took place at the beginning of each reproductive cycle. The experiment was visited weekly or every 2 weeks. Dates for blossoms, and the occurrence of green and ripe fruits (FL, M1, and M3 stages from Morais et al. 2008) in the majority of the rosettes in the apical/distal nodes (nodes formed in the immediately preceding period of vegetative growth) of the tagged branches were registered. All data below refer to the flowers and fruits in these apical/distal branch nodes. When two or three consecutive blossoms took place in the same branch during the same reproductive cycle, only the dates of occurrence of the major ones were used for the calculations and analyses. Flowers and pinhead fruits from previous or subsequent minor blossoms in the same nodes were eliminated from the branches manually (Pezzopane et al. 2012). These procedures ensured the evaluation of offspring coming exclusively from the major blossom event on each tagged branch. The “green fruit” stage was registered only for dates when the complete absence of liquid endosperm in some sectioned fruits was verified (Pezzopane et al. 2003). Dates for the occurrence of the “ripe fruit” stage were registered when the surface of the majority of fruits changed color from green to yellow “amarelo” or red “vermelho”. Days from the major blossom up to the occurrence of green fruits were included in the fruit-ripening phase. Days from the occurrence of green fruits up to the occurrence of ripe fruits were included in the fruit-ripening phase. The thermal time was calculated as (sum of (maximal daily temperature + minimal daily temperature)/2–10.5 °C) for the fruit development phase and for the fruit-ripening phase, in each of the two cycles. The endmost value in the formula is the base temperature (Pezzopane et al. 2008; Petek et al. 2009). Values for the entire reproductive cycles (from blossom to ripe fruits) were estimated from the values calculated for the two above-cited phenological phases. In addition to the thermal time, for each tagged branch, the accumulation of degree days, millimeters of rain, and solar radiation were calculated on a daily basis as follows: degree days per day (DDPD) = thermal time for fruit development/number of days for fruit development; precipitation accumulated per day (PPD) = precipitation accumulated in the development phase/number of days for fruit development; solar radiation per day (SRPD) = solar radiation accumulated in the development phase/number of days for fruit development, and so on, for each phase in each reproductive cycle. Meteorological data were taken from the Automated Meteorological Stations maintained by the National Institute of Meteorology—INMET (http://www.inmet.gov.br/index.php?r=estacoes/estacoesAutomaticas) and the Procafé Foundation (http://fundacaoprocafe.com.br), at the same experimental farm. The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Statistics Ranks of data and medians for the numbers of days to accomplish each phenological phase, DDPD, PPD, and SRPD, and the thermal time were calculated for the 64 (approximately) tagged branches of each coffee cultivar, in each reproductive cycle. ANOVA on ranks and Dunn's test were applied to search for significant differences between the two reproductive cycles and among the nine cultivars. ANOVA on ranks statistic H is computed by ranking all the observations from the smallest to the largest without regard for the group. The average values for the ranks for each group are computed and compared. If H is large, the variability between the average ranks is larger than expected from random variability. Inferior and superior tails of the box plots represent the 75th percentile and the 25th percentiles, respectively. Dunn's test was chosen for differences among cultivars and between cycles because the sample sizes were not the same (Systat 2010). The analyzed variables were the following: (1) for the fruit development phase, (a) the number of days, DDPD, PPD, and SRPD calculated for each reproductive cycle independently and (b) for both cycles, using data from both cycles together; (2) for the fruit-ripening phase, the number of days, DDPD, PPD, and SRPD calculated using data from both cycles together; and (3) for entire reproductive cycles, the values for the same variables were estimated by the values of the two phenological phases, calculated using the data sets for both reproductive cycles together. Medians for DDPD, PPD, and SRPD calculated as described in 1a, 1b, 2, and 3 above (five data sets per variable) were used to produce matrices of Euclidean distances and to cluster the cultivars in circular trees according to the distances, using the neighbor-joining method. The trees produced for the three variables were subsequently subjected to consensus calculation analysis to produce a final tree for the three variables together. The clusters preserved in the final tree were those displaying frequencies above 50% (e.g., 2/3) of all possible clusters in the three original trees. To test these consensus clusters, data in the registries referring to 847 plant branches, which had been indexed according to the cultivar codes for the ANOVAs, were reindexed according to the clusters in the consensus tree and subjected to discrimination analyses. These analyses were tested for statistical significance using Bartlett's test. SigmaPlot version 11.2 (Systat Software Inc. 2010), BioEstat (Ayres 2015), and PHYLIP (Felsenstein 2009) were used to perform all abovementioned analyses.

Results

Three different blossom periods and the fruits produced by flowers in each of these blossom periods were observed separately during each reproductive cycle. For the first cycle (2015/2016), there was a flower blossom between September 4th and 23rd reaching 215 tagged branches; another blossom was registered for 66 branches on October 10th; the final blossom occurred between November 1st and 11th for 172 tagged branches. For the second reproductive cycle (2016/2017), blossom was registered for 55 branches between August 14th and September 14th, a significant blossom took place between October 5th and 13th reaching 387 branches, and flowers on the 15 last branches, very late, opened between October 22nd and December 10th. It should be noted that none of these last branches had produced flowers before this. During this last reproductive cycle, in fact, some branches produced a relatively reduced number of flowers and glomerules (coffee inflorescences).

Medians for the evaluated variables, as well as the number of branches (*N*) included in the median calculations, are provided in Table 1. Cultivars, designated by their codes in the experimental field (Table 1, COD columns), are ranked according to the median values in ascending order. The displacement of cultivars to superior or inferior positions in the ranks, from phase to phase and cycle to cycle, were imputed for differences in their reactions to environmental conditions and are discussed below.

Fruit development phase

During the first reproductive cycle, the fruit development phase was evaluated on 453 tagged branches. The fruits on these branches reached the green fruit stage in periods from 121 to 199 days after blossoming, starting on 20 September 2015 and finishing on 6 May 2016, counting thermal times from 1594 to 2623 degree days. The subsequent fruit development phase was evaluated on 457 tagged branches, which produced green fruits in periods ranging from 123 to 217 days,

Table 1 Number of days, degree days (DDPD), precipitation (PPD), solar radiation (SRPD) accumulated per day, and thermal times calculated for the coffee fruits development phase (blossom to green fruits), ripening phase (green to ripe fruits), and for the whole reproductive cycles (blossom to ripe fruits), in N branches of nine Arabica coffee cultivars (COD), during 2015/2016 and 2016/2017, in Varginha, MG

BLOSSOM			TO		GREEN		FRUITS	GREEN TO RIPE			BLOSSOM TO RIPE	
2015/2016			2016/2017			2015/2016		AND	2016/2017		TOGETHER	
COD*	N	MEDIAN	COD	N	MEDIAN	COD	MEDIAN	COD	N	MEDIAN	COD	MEDIAN
NUMBER OF DAYS TO ACCOMPLISH BOTH PHASES AND REPRODUCTIVE CYCLES												
5	54	150.00	**18**		157.00	**5**	150.00	**18**	89	49.00	**18**	220.00
12	46	164.00	**5**	43	159.00	**4**	168.00	**34**	115	56.00	**5**	221.00
29	53	165.00	**4**	51	168.00	**12**	168.00	**4**	104	59.50	**34**	227.00
4	57	171.00	**29**	53	168.00	**29**	168.00	**29**	111	62.00	**4**	227.50
11	41	171.00	**34**	61	168.00	**18**	171.00	**22**	86	64.50	**29**	230.00
34	57	171.00	**22**	57	172.00	**34**	171.00	**12**	105	70.00	**22**	237.50
24	54	173.50	**12**	51	174.00	**22**	173.00	**5**	89	71.00	**12**	238.00
18	64	174.50	**24**	58	181.00	**24**	175.00	**24**	108	71.50	**24**	246.50
22	27	178.00	**11**	50	194.50	**11**	178.00	**11**	93	76.00	**11**	254.00
DDPD – DEGREE DAYS ACCUMULATED PER DAY (degree ºC - days/day)												
24	54	13.14	**11**	50	12.44	**22**	12.64	**11**	93	8.98	**11**	11.58
11	41	13.15	**22**	57	12.51	**11**	12.72	**24**	108	9.44	**24**	11.85
5	54	13.16	**12**	51	12.58	**12**	12.72	**12**	105	9.85	**12**	11.91
12	46	13.17	**18**		12.58	**34**	12.76	**5**	89	10.45	**22**	12.10
22	27	13.21	**24**	58	12.58	**24**	12.78	**29**	111	10.67	**5**	12.20
29	53	13.21	**34**	61	12.62	**29**	12.91	**22**	86	11.18	**29**	12.32
34	57	13.21	**4**	51	12.64	**5**	13.12	**34**	115	11.22	**4**	12.43
4	57	13.21	**5**	43	12.64	**4**	13.20	**4**	104	11.44	**34**	12.49
18	64	13.22	**29**	53	12.64	**18**	13.21	**18**	89	12.24	**18**	13.18
PPD – PRECIPITATION PER DAY (mm/day)												
22	27	6.52	**11**	50	4.27	**22**	4.79	**11**	93	1.54	**11**	3.73
4	57	6.53	**22**	57	4.41	**11**	4.92	**12**	105	1.64	**24**	3.85
18	64	6.53	**18**		4.46	**12**	4.92	**24**	108	1.64	**22**	3.95
34	57	6.53	**24**	58	4.54	**24**	5.02	**5**	89	1.80	**12**	3.98
24	54	6.66	**12**	51	4.64	**34**	5.06	**29**	111	1.83	**34**	4.10
11	41	7.04	**34**	61	4.74	**29**	5.74	**34**	115	1.87	**29**	4.37
29	53	7.04	**4**	51	4.79	**5**	6.41	**4**	104	1.93	**5**	4.87
12	46	7.21	**5**	43	4.79	**4**	6.44	**22**	86	2.01	**4**	5.15
05	54	7.44	**29**	53	4.79	**18**	6.52	**18**	89	2.40	**18**	5.64
SRPD – SOLAR RADIATION ACCUMULATED PER DAY (W/m2/day)												
5	54	9513.13	**18**		11865.79	**5**	9804.24	**24**	108	7177.66	**24**	9211.23
11	41	9532.57	**22**	57	11959.53	**4**	9817.58	**11**	"	7200.29	**12**	9540.20
12	46	9532.57	**11**	50	11978.67	**18**	9817.58	**12**	105	7719.62	**11**	9808.38
24	54	9538.90	**4**	51	12027.93	**29**	10067.46	**5**	!"	7977.88	**29**	9855.50
29	53	9738.38	**5**	43	12027.93	**24**	11569.32	**29**	111	8315.68	**34**	9930.90
4	57	9776.68	**24**	58	12306.86	**22**	11611.92	**22**	86	8981.45	**18**	10045.24
22	27	9776.68	**34**	61	12306.86	**11**	11804.43	**34**	115	9179.75	**4**	10151.44
34	57	9776.68	**12**	51	12348.41	**34**	11893.39	**4**	104	9352.47	**5**	10288.50
18	64	9817.58	**29**	53	12348.41	**12**	11931.06	**18**	!"	9581.71	**22**	11062.40
THERMAL TIME (degree ºC- days)												
5	54	1973.80	**18**		1945.60	**5**	1973.80	**18**	89	638.50	**5**	2695.85
12	46	2155.75	**5**	43	2025.55	**4**	2122.90	**34**	115	638.50	**4**	2827.30
29	53	2190.80	**4**	51	2119.05	**22**	2152.40	**24**	108	652.38	**29**	2833.38
11	41	2245.75	**29**	53	2122.90	**29**	2155.53	**11**	93	661.95	**12**	2833.60
4	57	2260.85	**34**	61	2122.90	**12**	2155.75	**12**	105	677.85	**34**	2835.35
34	57	2260.85	**22**	57	2133.20	**34**	2196.85	**29**	111	677.85	**22**	2874.45
24	54	2283.75	**12**	51	2187.15	**18**	2260.85	**4**	104	704.40	**18**	2899.35
18	64	2306.10	**24**	58	2253.93	**24**	2269.05	**5**	89	722.05	**24**	2921.43
22	27	2351.35	**11**	50	2421.98	**11**	2278.80	**22**	86	722.05	**11**	2940.75

**COD* is the code for the coffee cultivars 4 Catucaí Amarelo 24/137, 5 Acauã Novo, 11 Palma III, 12 Sabiá, 18 Catucaí Vermelho 785/15, 22 Guará, 24 Arara, 29 Catuaí Vermelho IAC 144 and 34 Siriema from 24 August 2016 to 11 May 2017, counting thermal times from 1579 to 2634 degree days (Table 1).

The data above lead to the presumption that the development phases of the two reproductive cycles were quite similar. However, significant differences ($p \leq 0.05$) were found for the thermal times, precipitation, and solar radiation accumulated during the fruit development phases in different cycles without regard of the cultivars (Fig. 1). The only exception was for the duration, in days (1st cycle = 171 and 2nd cycle = 168 days; $p = 0.53$; Fig. 1d), most likely because variability between the cultivars masked the differences between the cycles. For some cultivars, the duration of the fruit development phases in the 1st cycle diverged from that in the 2nd cycle ($H = 86.85$; $p \leq 0.001$): Palma III (11), Sabiá (item 12), and Arara (24) besides Acauã Novo (item 5) and Catucaí 144 (item 29) displayed longer development phases in 2016/2017 than in 2015/2016. On the contrary, Catucaís 24/137 and 785/15 (items 4 and 18) displayed shorter development phases in 2016/2017 than in 2015/2016. These results mean that there was an interaction between the factors "cultivar" and "reproductive cycle".

Thermal time ($H = 46.01$; 1st cycle = 2260.85 and 2nd cycle = 2122.90 degree days; $p \leq 0.05$; Fig. 1a), and principally, degree days per day (DDPD) differed between cycles (H = 677.68; median of 1st cycle = 13.21 and 2nd cycle = 12.58 degree days.day^{-1}; $p \leq 0.05$; Fig. 2a). Indeed, although the differences in days between the fruit development phases in the two reproductive cycles were not significant, the divergence became significant when the analysis was performed for thermal times ($H = 46.01$) and, as expected, became still more meaningful when DDPDs ($H = 677.68$) were compared. Early cultivars displayed higher thermal times for 2015/2016 than for 2016/2017, significantly ($p \leq 0.05$) higher for items 4, 18, and 34 in addition to item 22.

Precipitation accumulated during development phases ($H = 684.90$; 1st cycle = 1160.30 and 2nd cycle = 805.20 mm; $p \leq 0.05$; Fig. 1b) and precipitation accumulated per day (PPD) also differed ($H = 683.85$; 1st cycle = 6.53 and 2nd cycle = 4.64 mm.day^{-1}; $p \leq 0.05$; Fig. 2c). Solar radiation followed the trend and differed between cycles ($H = 497.26$; 1st cycle = 1.67×10^6 and 2nd cycle = 2.10×10^6 W.m^{-2}; $p \leq 0.05$; Fig. 1c) as did the accumulation of solar radiation per day (SRPD, $H = 677.88$; 1st cycle = 9770.91 and 2nd cycle = 12,138.57 W.m^{-2}.day^{-1}; $p \leq 0.05$; Fig. 2e).

Dunn's tests (Fig. 2b–f) were performed using data from the fruit development phases of both reproductive cycles together, in order to value registries from more than one reproductive cycle as capable to produce a more reliable characterization of the cultivars and to facilitate comparison to results concerning the fruit-ripening phase (Figs. 2b–f and 3b–f). Catucaí 24/137 (item 4) and 785/15 (18) did not differ from each other and both differed from Palma III (item 11) and Arara (24). Catuaí 144 (29), on the other hand, could not be distinguished from the other cultivars (Figs. 2b, d, and f).

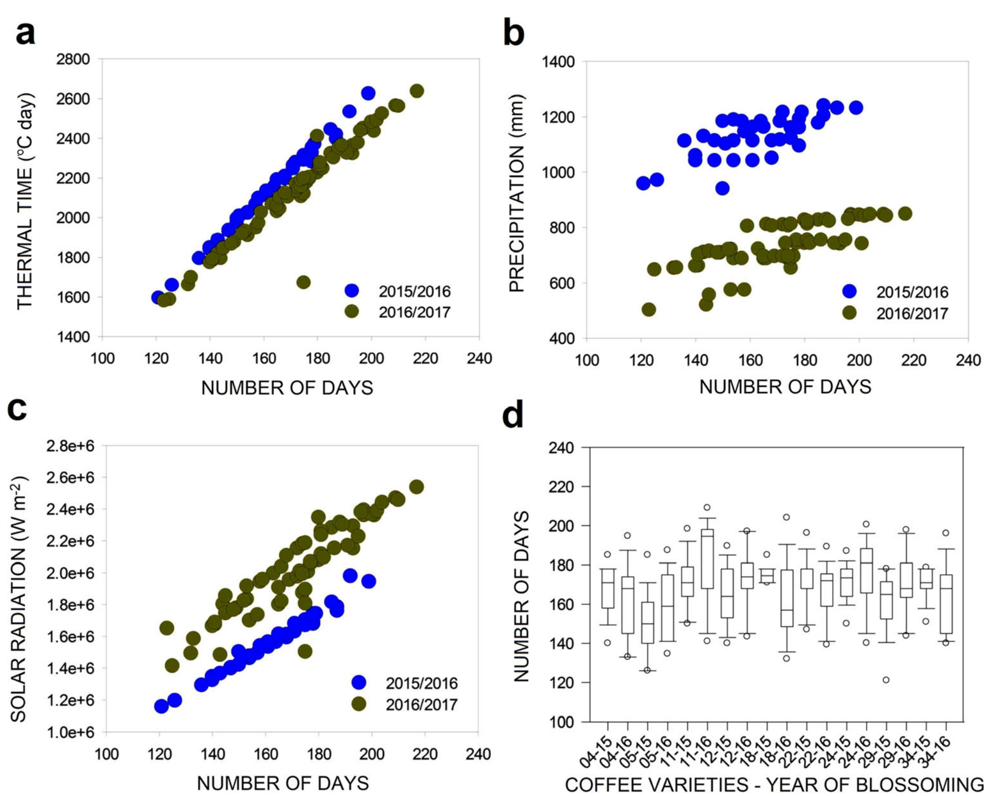
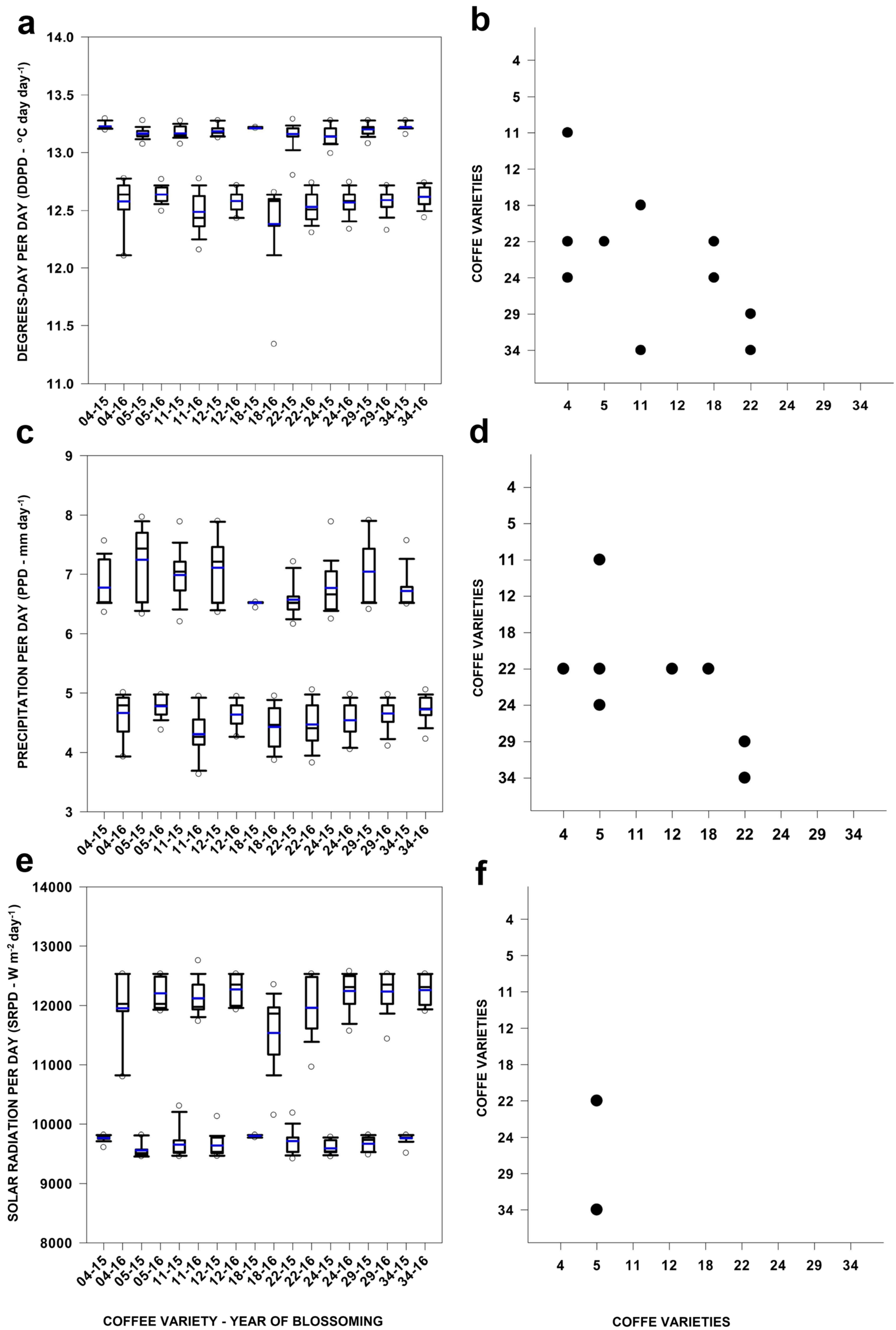


Fig. 1 Thermal time (**a**), precipitation (**b**), and solar radiation (**c**) accumulated by plants of nine Arabica coffee cultivars during the fruit development phase in 2015/2016 and 2016/2017, in Varginha, MG. Points in **a**, **b**, and **c** represent branches, tagged and evaluated during each cycle. The numbers of days to accomplish the transition from blossoming to green beans are represented in (**d**) as ranks of data per cultivar and reproductive cycle. The first pair of numbers in the X labels indicates the code of the cultivar. The second pair of numbers indicates the year of blossom. (4) Catucaí Amarelo 24/137, (5) Acauã Novo, (11) Palma III, (12) Sabiá, (18) Catucaí Vermelho 785/15, (22) Guará, (24) Arara, (29) Catuaí Vermelho IAC 144, and (34) Siriema


a
b
c
d
e
f
DEGREES-DAY PER DAY (DDPD - °C day day-1)
PRECIPITATION PER DAY (PPD - mm day-1)
SOLAR RADIATION PER DAY (SRPD - W m-2 day-1)
COFFE VARIETIES
04-15 04-16 05-15 05-16 11-15 11-16 12-15 12-16 18-15 18-16 22-15 22-16 24-15 24-16 29-15 29-16 34-15 34-16
4 5 11 12 18 22 24 29 34
COFFEE VARIETY - YEAR OF BLOSSOMING
COFFE VARIETIES

◀**Fig. 2** Ranks of data concerning the fruit development phase for nine Arabica coffee cultivars in two reproductive cycles in Varginha, MG. Degree days *DDPD* (**a**), precipitation *PPD* (**c**), and solar radiation *SRPD* (**e**) accumulated per day are displayed. Medians are black bars and means are blue bars inside the boxes. Reproductive cycles 2015/2016 and 2016/2017 and also cultivars differed for these three variables. **b**, **d**, and **f** are Dunn's Test results for DDPD, PPD, and SRPD regarding both cycles together, respectively. Intercepts (points) in the graph planes represent significant differences between the pair of cultivars indicated by their codes in the X and Y axes. A high number of points in the graph plane indicate good discriminatory capacity for the variable. The first pair of numbers in the X labels indicates the code of the cultivar. The second pair of numbers indicates the year of blossoming. (4) Catucaí Amarelo 24/137, (5) Acauã Novo, (11) Palma III, (12) Sabiá, (18) Catucaí Vermelho 785/15, (22) Guará, (24) Arara, (29) Catuaí Vermelho IAC 144, and (34) Siriema

Fruit-ripening phase

During the fruit-ripening phase in 2015/2016, 486 branches were evaluated, and fruits reached the ripe stage between 28 and 118 days after the occurrence of green fruits, on dates ranging from 17 February to 27 July 2016, with thermal times ranging from 373 to 1155 degree days. The corresponding phase in 2016/2017 was evaluated on 414 tagged branches, cherries occurred from the 29th to the 117th day after registering green fruits, in the period between 14 February and 02 August 2017, with thermal times ranging from 297 to 1185 degree days. Differences in the number of branches (branches per cultivar, *N* in Table 1) evaluated for each phase and each cycle were due to the loss of leaves leading to the death of branches' tips (particularly in 2016/2017), unauthorized withdrawal of fruits and tags from the branches and some mistaken or unreadable registries.

For the ripening phases, DDPDs, PPDs, and SRPDs regarding different reproductive cycles did not differ from each other significantly and all the analyses were performed for datasets comprising both cycles simultaneously (Fig. 3a, c, and e). Coffee fruits are climacteric (Gaspari-Pezzopane et al. 2012), and their ripening phase can be more responsive to endogenous signals than to environmental conditions. This contributes to explain why statistically significant differences between the two analyzed reproductive cycles, concerning DDPDs, PPDs, and SRPDs for the ripening phases, were not detected. This result was opposite to that referring to the fruit development phases (Figs. 2a, c, and e), when divergences between cycles for the same three variables were observed and some analyses were performed separately.

The Catucaís (items 4 and 18), in particular, accumulated higher DDPDs (Fig. 3a and b) and ripened with higher values for PPD (Fig. 3c and d) and SRPD (Figs. 3e and f). The contrary was observed for late cultivars such as Palma III (item 11) and Arara (item 24).

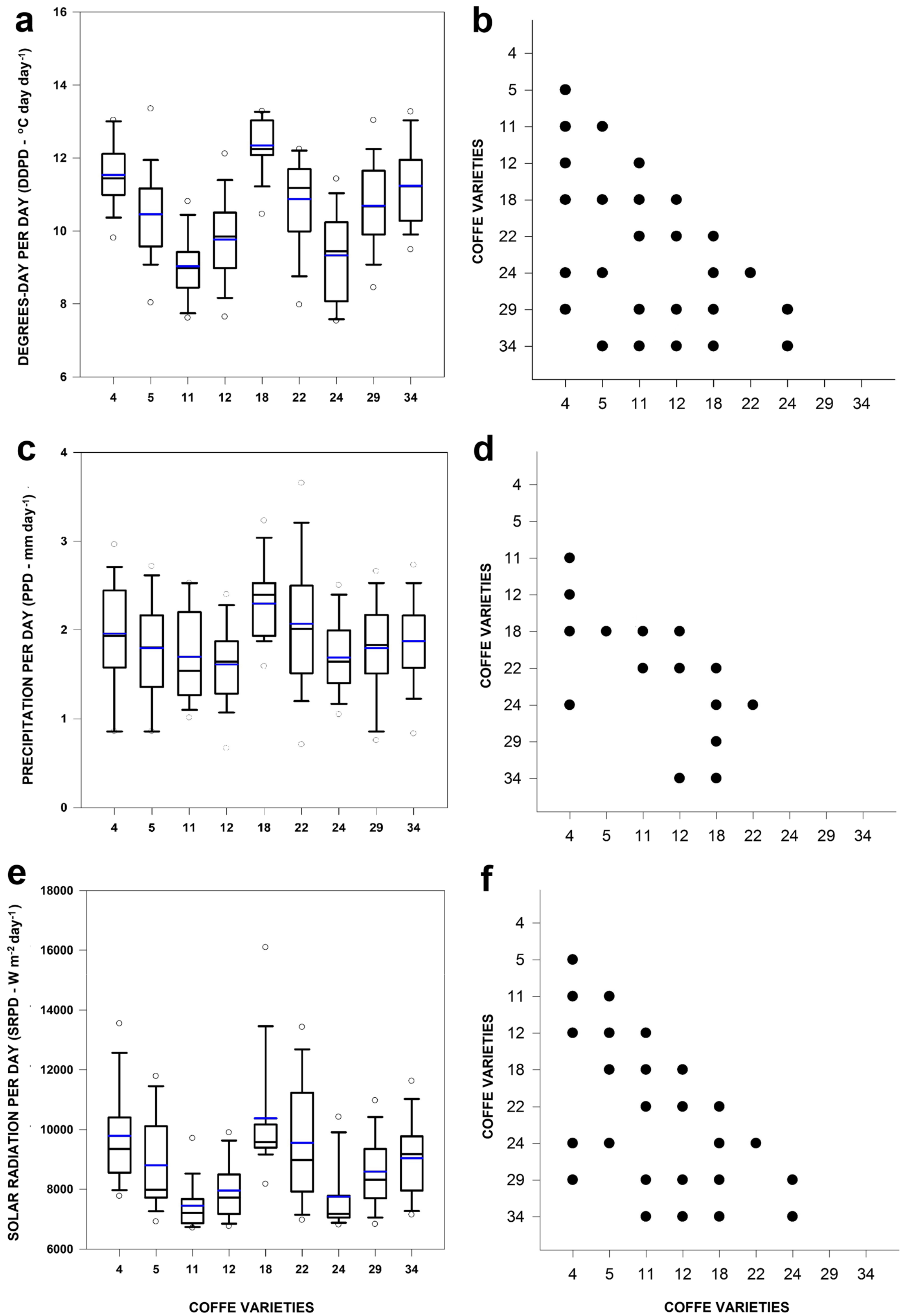
Clustering

For clustering, the data sets mentioned above regarding different phenological phases and different reproductive cycles were simultaneously assessed in order to assemble a single tree per variable and finally, a single consensus tree for DDPDs, PPDs, and SRPDs, referring to both phenological phases and both reproductive cycles.

The number of days is most likely to be the variable more often used to describe the duration of phenological phases and was chosen to introduce clustering, despite not being included in the subsequent analyses. Thus, when considering both reproductive cycles simultaneously, the number of days to accomplish the fruit development phase, ripening phase and entire cycles (Fig. 4a and Fig. S1) Catucaís 24/137 (item 4) and 785/15 (18) and Siriema (34) became settled in two different clusters. Catucaí 785/15 (18) and Siriema (34) did not differ in the number of days to accomplish the fruit-ripening phase, but 785/15 (18) was different ($p \leq 0.05$) from 24/137 (4). In addition, 24/137 (item 4) fruits required a relatively low number of days to develop and ripen, while the other two (items 18 and 34) ripened in a very short period of time. For these reasons, based only on the number of days, Catucaí 785/15 (18) and Siriema (34) were classified as very early and Catucaí 24/137 (4) as an early cultivar. Nevertheless, when DDPD, PPD, and SRPD were analyzed, Siriema (34) became detached from the "very early" cluster and would be better classified as intermediate (see below).

In the other extreme of the same circular tree based on the duration (in days) of the different phases (Fig. 4a), Palma III (item 11) did not differ from Arara (24), and as a cluster of very late cultivars, they became different from all the other clusters (Fig. S1). The closest neighbor to this very late cluster was Sabiá (12), which due to its relatively shorter development phase differed from Palma III (11) and became placed in a different branch of the circular tree. Sabiá (12) also differed from the early cultivars (items 4, 18, and 34) that ripen faster (Figs. 4a and S1) and was classified as a late cultivar.

Among the intermediate cultivars, Acauã Novo (item 5) was the only cultivar displaying fast-developing and slow-ripening fruits (Table 1). This cultivar differed from all the others in the development phase, and regarding the entire cycle, it differed not only from the very early cultivars 18 and 34 but also from the very late ones 11 and 24 (Figs. 4a and S1) and was classified as intermediate. However, Acauã Novo was affected by unauthorized harvesting of fruits and branches in one of the experimental blocks that were probably exposed to higher solar radiation because the plants were in the outermost positions of the experimental field. Additional cycles should be observed to establish a more accurate classification for item 5. Catuaí 144 (item 29) also spent an intermediary number of days in the development and ripening phases, during both cycles. It differed from Palma III (11) regarding


a
DEGREES-DAY PER DAY (DDPD - °C day day-1)
16
14
12
10
8
6
4
5
11
12
18
22
24
29
34
b
COFFE VARIETIES
c
PRECIPITATION PER DAY (PPD - mm day-1)
d
e
SOLAR RADIATION PER DAY (SRPD - W m-2 day-1)
18000
16000
14000
12000
10000
8000
6000
f
COFFE VARIETIES

◀**Fig. 3** Ranks of data concerning the fruit-ripening phase for nine Arabica coffee cultivars in two reproductive cycles in Varginha, MG. Degree days *DDPD* (**a**), precipitation *PPD* (**c**), and solar radiation *SRPD* (**e**) accumulated per day are displayed. Medians are black bars and means are blue bars inside the boxes. Reproductive cycles 2015/2016 and 2016/2017 did not differ but cultivars are statistically different for these three variables. **b**, **d**, and **f** are Dunn's Test results for DDPD, PPD, and SRPD regarding both cycles together, respectively. Intercepts (points) in the graph planes represent significant differences between the pair of cultivars indicated by their codes in the X and Y axes. A high number of points in the graph plane indicates good discriminatory capacity for the variable. (4) Catucaí Amarelo 24/137, (5) Acauã Novo, (11) Palma III, (12) Sabiá, (18) Catucaí Vermelho 785/15, (22) Guará, (24) Arara, (29) Catuaí Vermelho IAC 144, and (34) Siriema

ripening and the entire cycle, and it differed from Arara (item 24) for all the phenological phases and also from Catucaí 785/15 (18) in regard of ripening (Fig. S1), and it was classified as intermediate. Finally, Guará (item 22) did not differ from Acauã Novo (5) regarding the ripening phase and did not differ from Catuaí 144 (item 29) or Sabiá (item 12) in terms of ripening and the entire cycle and could be classified as intermediate or late (Figs. 4a and S1). Analyses of DDPDs, PPDs, and SRPDs supported the classification of Guará (22) as an intermediate cultivar.

Circular trees produced with DDPDs (Fig. 4b), PPDs (Fig. 4c), and SRPDs (Fig. 4d) were used to establish a consensus tree (Fig. 4e). Clusters defined by consensus were tested through analyses of discrimination. For such analyses, data referring to each reproductive cycle were taken separately, avoiding the occurrence of two clouds of symbols related to the development phases for each cultivar, as depicted in Fig. 1. Symbols representing the branches of Catucaí 24/137 (item 4, cluster 2) and Catucaí 785/15 (item 18, cluster 1) became superimposed and mostly restricted to the right side of the graph planes (Fig. 4f and g), but some distinction was maintained and subclouds of symbols representing these two cultivars can be observed, particularly during 2015/2016 (Fig.

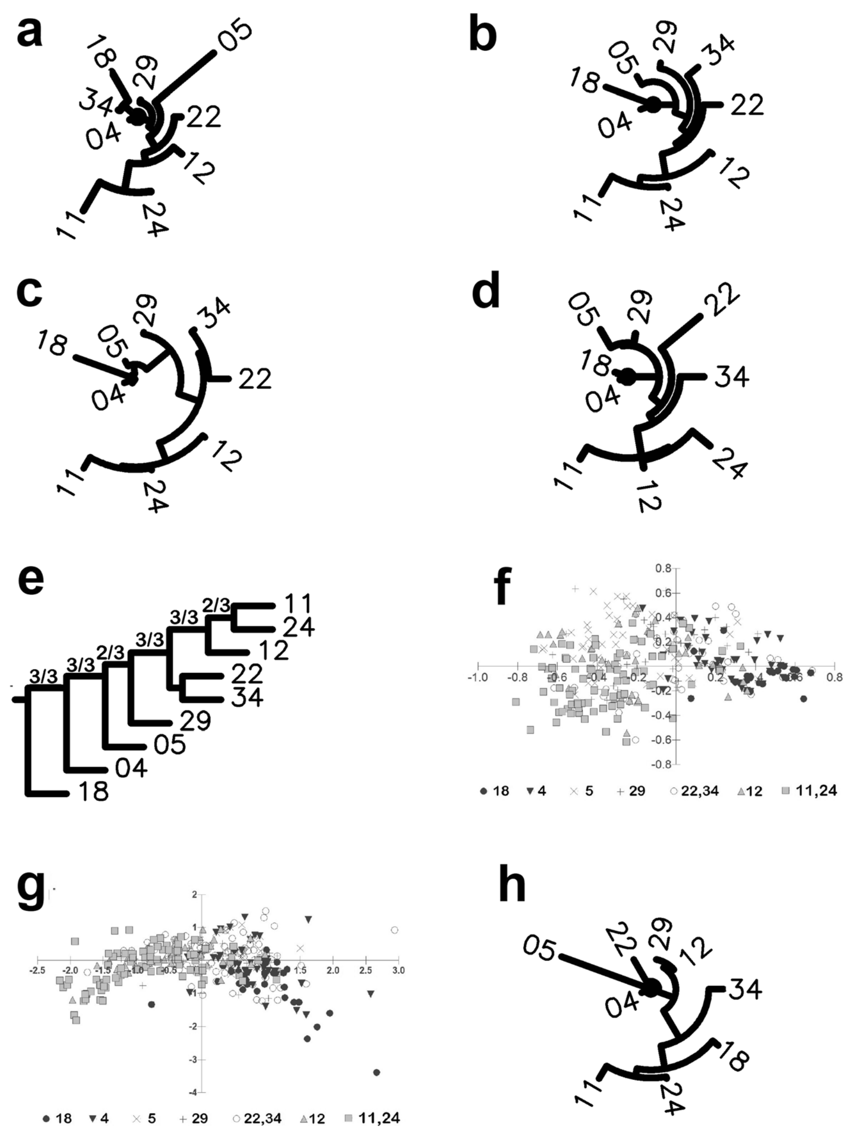


Fig. 4 Clusters of Arabica coffee cultivars produced according to the number of days (**a**), DDPDs (**b**), PPDs (**c**), and RSPDs (**d**) accumulated during the fruit development and ripening phases of two reproductive cycles in Varginha, MG. Values used for clustering by the number of days were those for cycles 2015/2016 and 2016/2017 taken together. The tree in (**e**) is a consensus among the trees in (**b**, **c**, and **d**) and the numbers above the subtrees represent the frequency of a subtree preserved in the consensus. The clusters in (**e**) were tested through analyses of discrimination and the resulting graphs are depicted in (**f**) and (**g**), for 2015/2016 and 2016/2017, respectively. The tree in (**h**) was produced with values for thermal times. (4) Catucaí Amarelo 24/137, (5) Acauã Novo, (11) Palma III, (12) Sabiá, (18) Catucaí Vermelho 785/15, (22) Guará, (24) Arara, (29) Catuaí Vermelho IAC 144, and (34) Siriema

4f). Catucaí 24/137 (item 4, cluster 2) and Catucaí 785/15 (item 18, cluster 1) are very early and early cultivars regarding the duration of the cycles (Fig. 4a), and they diverged in the consensus tree (Fig. 4e), partially at least, due to the differences in DDPDs and PPDs calculated for the ripening phase (Fig. 3b and d). These two cultivars (items 4 and 18) were more similar to each other than Siriema (item 34) regarding SRPD in the 2016/2017 cycle (Fig. 2e), and Siriema diverged from Catucaí 785/15 (item 18, cluster 1) regarding all three variables during the ripening phase (Fig. 3b, d, and f).

By their turn, symbols representing branches of Sabiá (item 12, cluster 6) and Palma III and Arara (items 11 and 24, cluster 7), late and very late cultivars, principally occupied the left side of the planes (Fig. 4f and g) and are harder to distinguish from each other. Symbols representing clusters intermediate to these extremes, including Siriema and Guará (items 22 and 34), were distributed all over the graph planes. Discrimination between the clusters in the consensus tree (Fig. 4e) was statistically significant ($\Phi = 442.43$ and 316.73 for 2015/2016 and 2016/2017, respectively; DF = 36; $p \leq 0.05$).

The circular tree based on thermal times (Fig. 4h) was clearly different from those produced for other variables (Fig. 4a–d); the earliest cultivar Catucaí 785/15 (item 18) and very late cultivars such as Palma III (11) and Arara (24) became closest neighbors.

Discussion

The thermal times calculated in the present work for entire reproductive cycles (Table 1, rightmost columns) are similar to those previously reported. Pezzopane et al. (2012) revealed that the ideal time to harvest Catuaí Vermelho 144 and Obatã Amarelo IAC 1669-20 (this last cultivar is a selection among Sarchimors) fruits correspond to the maximal accumulation of sucrose, at the transition from cane-green to ripe, which takes place, respectively, around 221 days and 2840 degree days or 249 days and 3090 degree days after blossom in Campinas, State of São Paulo. Similar numbers of days and similar thermal times were taken by Catuaí 144 (item 29) and Arara (item 24, which has Sarchimor Amarelo 1669-20 in its background as well) fruits to reach the ripe-bean stage in Varginha (Table 1). Petek et al. (2009) reported that to accomplish the entire reproductive cycles (blossoming to ripe fruits), 223.6 days and 2762 degree days for Catucaí 785/15, and 243.6 days and 2935 degree days for Obatã Amarelo IAC 1669-20 were necessary in Londrina, State of Paraná, corresponding to items 18 and comparable to item 24 in Varginha, respectively (Table 1). Information on thermal times was not available for the other cultivars, and reports on thermal times are even scarcer for coffee plants cultivated in the State of Minas Gerais (however, see additional data regarding Catuaí 144 (item 29) below).

While the thermal times agreed with previously reported calculations, the relationships between the variables calculated on a daily basis, used here for the first time, were intriguing and deserve closer examination. The correlation coefficient (R) was 0.510 ($p \leq 0.05$) among registries for daily solar and mean daily temperatures recorded for the period from January 2015 to October 2017. For the same period, the correlation between precipitations and the mean daily temperatures was 0.114 and not significant. Therefore, the mean daily temperatures were principally related to the solar radiation incidence. Thus, how can it be that the DDPDs for the fruit development phase, as a quantity based on thermal time, were higher during the 2015/2016 cycle (Fig. 2a), when lower values for accumulated solar radiation were registered (Fig. 1c)? And why did this relationship become inverted in 2016/2017, when lower DDPDs were calculated for a period of higher accumulation of solar radiation?

The answers to these questions were found in the reactions of the plants to the climate. For different reasons, during the development phase, DDPDs calculated for early and late cultivars were higher in 2015/2016 than in 2016/2017, despite solar radiation records displaying the opposite pattern. The numbers of days necessary to conclude fruit development did not differ between reproductive cycles, as mentioned above, but it differed among cultivars. DDPD values, in turn, differed between cycles and also among cultivars. Early cultivars displayed higher thermal times for 2015/2016 than for 2016/2017. This difference was a consequence of the temperatures being above the historical series registered throughout the 2015/2016 summer season, including April 2016 (Fundação Procafé n.d.-a). The division of significantly higher thermal times in 2015/2016 by a similar number of days registered for both cycles, caused DDPD values to be higher in 2015/2016 than in 2016/2017 for early cultivars. Opposite to the early cultivars, late cultivars, such as 11, 12, and 24, required a significantly higher number of days to accomplish the fruit development phase in 2016/2017 than in 2015/2016. Thus, in this case, the division of thermal time values that did not differ from cycle to cycle by a significantly higher number of days observed in 2016/2017 forced DDPDs in this last cycle to fall below those calculated for 2015/2016 for late cultivars (Fig. 2a).

Despite the environmental signals being the same for all evaluated plants while cultivated in the same experimental spot, signal perception, and transduction are complex and involve a huge number of metabolic pathways. The proteins activated to trigger fruit development and ripening can display structural polymorphisms, and the relative amounts of transcripts accumulated during a specific phenological phase can differ among cultivars and from cycle to cycle (Gaspari-Pezzopane et al. 2012), resulting in distinguishable phenotypes. Therefore, by reporting DDPDs (and precipitation and solar radiation on a daily basis), we intend to place together the usefulness of data on the numbers of days and on thermal times, to better characterize, classify, and distinguish the cultivars.

Nátrová and Nátr (1991) recognized the lower variability found in thermal times as being advantageous to describe plant phenology when compared to the highly variable registers obtained for numbers of days, in general. The advantage was perceived most likely because the number of days in each phase can be directly influenced by environmental and also physiological conditions. Besides that, influences of environmental and physiological nature interfering with the amounts of days counted for a phenological process to be accomplished are beyond comprehension when the corresponding meteorological data are not reported. On the other hand, as cited above, thermal time can buffer the differences, e.g., when two cultivars that diverge in terms of numbers of days necessary to accomplish a same long-term phenological process happen to accumulate similar thermal times. This phenomenon was observed when unusual registers for the mean daily temperatures occurred while different phenological phases of the long-term coffee reproductive cycle were running in different cultivars. In this context, separate analyses and interpretation of observations concerning independent phenological phases could improve the discriminatory power of thermal times. The evaluation of two independent phases per reproductive cycle is not a novelty for coffee plants (Petek et al. 2009; Carvalho et al. 2014), which are frequently included in the same wide class when the duration of the entire reproductive cycle is analyzed (Aguiar et al. 2004).

Catucaí 785/15 (item 18), for instance, which was positioned in the middle of the rank for the fruit development phase calculated for both cycles together, ripened faster than Catucaí 24/137 (item 4) and Siriema (34), and eventually became classified as the earliest cultivar with respect to the entire reproductive cycle (Table 1). Carvalho et al. (2014) registered similar results in Uberlândia, State of Minas Gerais; Catuaí Vermelho IAC 15 displayed the highest value for the thermal time calculated from blossom to cane-green fruits and the lowest thermal time for the subsequent phase when the fruits became ripe. For Catuaí 144, corresponding to item 29 in the present work, registries for thermal times regarding phenological phases are different, while the thermal time calculated for the entire reproductive cycle is quite similar, reaching 2811 degree days in Uberlândia (Carvalho et al. 2014) and 2833 degree days in Varginha (Table 1).

The circular tree produced with thermal time data referring simultaneously to both cycles and both phenological phases (Fig. 4h) can only be properly interpreted if the numbers of days necessary to accumulate the represented thermal times are made available because thermal times calculated for earliest and latest cultivars, such as Catucaí 785/15 (item 18) and Palma III and Arara (items 11 and 24), were similar for entire reproductive cycles evaluated for two consecutive years (Table 1, last column), and these data were also used for clustering. In turn, the distinction among cultivars became clearer when based on DDPDs (Fig. 4b), despite the datasets on DDPDs used to cluster the cultivars referred to the same phenological phases/periods of time as the datasets on thermal times used to cluster the cultivars by thermal times (Fig. 4h).

In general, early cultivars, particularly Catucaís (items 18 and 4), began the reproductive cycle earlier in the year and developed faster, being reliant upon the water from the rainy periods that trigger blossoming to accelerate initial fruit expansion. Catucaí 24/137 (item 4) and Catucaí 785/15 (18) diverged most likely due to the differences in DDPDs and PPDs in the ripening phase (Fig. 3a–d). In addition, for Catucaí 785/15 (item 18), the uniformity verified for blossoming dates, with a significant number of plant branches displaying flowers in anthesis simultaneously, determined the almost invariably narrow amplitude of the ranks of data, which was unpaired by Catucaí 24/137 (item 4) or Siriema (34).

The Siriema transposition to intermediate clusters in those trees (Fig. 4b–e) indicated that, during two successive reproductive cycles, fruits on the tagged branches in plants of this cultivar reached the green and ripe stages accumulating lower DDPDs, PPDs, and SRPDs (Fig. 3d) than Catucaís 24/137 and 785/15 (items 4 and 18), becoming closer to the intermediate and late cultivars (Fig. 3d), and yet, the number of days that Siriema took to accomplish both phenological phases was very similar to that recorded for these other two cultivars (Fig. 4a). Andreazi et al. (2017) reported that *C. racemosa* contributed to Arabica coffee reproductive cycles being accomplished more rapidly and progenies originated from that interspecific hybridization by backcrosses and selections developed earlier than their Arabica recurrent genitors. Nevertheless, Siriema began the reproductive cycles and displayed major blossoms slightly later when compared with the Catucaís during the years of observation. In addition, some of the unique characteristics that probably supported the reactions observed in Siriema, such as disease resistances that can reduce the loss of leaves, were introgressed from *C. racemosa* (Medina-Filho et al. 1977; Sureshkumar et al. 2010).

Late cultivars, such as Palma III (item 11) and Arara (24), spent more days developing, as well as ripening fruits. It is probable that a higher percentage of green fruits, arriving later in the year as a consequence of the later starting point and the prolonged development phase, become exposed to the relatively milder solar radiation of the autumn and take more days to ripen. Morais et al. (2006) demonstrated the influence of solar interception through shadowing to increase the extension of the reproductive cycle while arresting coffee fruit ripening. As a consequence of longer development phases, late cultivars need to tolerate longer periods of water scarcity while maintaining carbon fixation as high as early cultivars in order to be productive. Although Arara (item 24) has only recently been cultivated commercially, it produced 32.9 sacks of 60 kg/ha compared with 28 sacks of 60 kg/ha for a selection of Catucaí 24/137, as the average production of the first six harvests when cultivated in 3.5 m × 1.2 m spatial distribution, in Varginha, MG (Fundação Procafé n.d.-b).

Conclusions

The results of the evaluations through the use of thermal times in the State of Minas Gerais, Brazil, contributed information to the very few similar reports available. The analyses became enriched by the inclusion of traditionally cultivated (such as the Catucaís and Catuaí) and recently released cultivars (as Arara, Siriema, Guará, Acauã, and Sabiá). Catucaís 785/15 (item 18) and 24/137 (item 4) were classified as early cultivars, as expected. Accomplishing the entire reproductive cycles in 220 to 227.5 days, respectively, these genotypes accumulated degree days per day rapidly, as well as more millimeters of rain per day, besides being exposed to higher amounts of solar radiation per day. On the other hand, the very late and late cultivars, such as Palma III (item 11), Arara (item 24), and Sabiá (item 12), accomplished reproductive cycles in 238 to 254 days, accumulating degree days slowly—even 1.6 degree days per day less than the earliest Catucaí 785/15. Their fruits developed in periods of relatively lower solar radiation, but they needed to interact with longer periods of low water availability.

DDPD (degree days per day = thermal time/number of days), a variable introduced in the present work, may be useful for future evaluation of coffee cultivars. While thermal times are valued because they can buffer part of the variability facilitating comparisons and numbers of days can vary considerably from year to year and in different locations for the same cultivar, DDPDs balance the characteristics of the two measurements.

DDPDs better distinguished the cultivars in both phenological phases. Thus, DDPDs and PPDs and DDPDs and RSPDs can be considered to be the most interesting variables to distinguish cultivars in development and ripening phases, respectively.

Acknowledgments The authors are thankful to the Embrapa Café Research Program for the financial support (SEG number 02.13.02.017.00.04) and for the fellowships to Juliano de Carli and Isabella Esteves Couto that contributed to collect data. Authors are also grateful to Dr. Heverly Morais and the reviewers, who read the manuscript and encouraged submission.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Aguiar ATDE, Guerreiro-Filho O, Maluf MP, Gallo PB, Fazuoli LC (2004) Caracterização de cultivares de Coffea arabica mediante utilização de descritores mínimos. Bragantia 63:179–192. http://www.scielo.br/pdf/brag/v63n2/21367.pdf. Accessed 15 Oct 2014

Andreazi E, Carducci FC, Sera T, Pereira CTM, Junior VM, Carvalho FG, Shigueoka LH, Santos WGD, Fonseca ICDB, Sera GH (2017) Ciclo precoce de maturação e produtividade em genótipos de café derivados de C1195-5-6-2. Coffee Sci 12:575–582 http://www.coffeescience.ufla.br/index.php/Coffeescience/article/view/1375

Arcila-Pulgarín J, Buhr L, Bleiholder H, Hack H, Meier U, Wicke H (2002) Application of the extended BBCH scale for the description of the growth stages of coffee (Coffea spp.). Annual Applied Biology 141: 19–27. https://onlinelibrary.wiley.com/doi/10.1111/j.1744-7348.2002.tb00191.x. Accessed 13 Nov 2014.

Ayres M (2015) BIOSTAT version:5 http://www.bioestat.software.informer.com

Bardin-Camparotto L, Camargo MBPD, Moraes JFLD (2012) Época provável de maturação para diferentes cultivares de café arábica para o Estado de São Paulo. Ciência Rural 42:549–599 http://www.scielo.br/pdf/cr/v42n4/a9612cr5899.pdf

Camargo AP, Camargo MBP (2001) Definição e esquematização das fases fenológicas do cafeeiro arábica nas condições tropicais do Brasil. Bragantia 60:65–68 http://www.scielo.br/pdf/brag/v60n1/a08v60n1.pdf

Carvalho HDP, Camargo RD, Gomes MWDN, Souza MFD (2014) Classificação do ciclo de desenvolvimento de cultivares de cafeeiro através da soma térmica. Coffee Sci 9:237–244 http://www.coffeescience.ufla.br/index.php/Coffeescience/article/view/623

Felsenstein J (2009) PHYLIP (Phylogeny Inference Package) version 3.695. http://www.evolution.genetics.washington.edu/phylip.html

Fundação Procafé. (n.d.-a) Boletim de Avisos do Sul de Minas. http://www.fundacaoprocafe.com.br/estacao-e-avisos/sul-de-minas/boletim-de-aviso. Accessed monthly from September-2014 to December-2017

Fundação Procafé (n.d.-b). www.fundacaoprocafe.com.br/sites/efault/files/publicacoes/pdf/38 cbpc%20 NovasVariedades Saulo.pdf, accessed in August-4th, 2018)

Gaspari-Pezzopane CD, Bonturi N, Filho OG, Favarin JL, Maluf MP (2012) Gene expression profile during coffee fruit development, identification of candidate markers for phenological stages. Pesq Agrop Brasileira 7:974–982 http://seer.sct.embrapa.br/index.php/pab/article/view/12387

Matiello JB, Santinato R, Almeida SR, Garcia AWR (2016) Variedades de Café. In: Cultura de Café no Brasil: manual de recomendações. Futurama, São Paulo, pp 61–100

Medina-Filho HP, Carvalho A, Medina DM (1977) Germoplasma de *Coffea racemosa* e seu potencial no melhoramento do caffeiro. Bragantia 36:XLIV–XLVI http://www.scielo.br/pdf/brag/v36n1/41.pdf

Morais H, Caramori PH, Ribeiro AMDA, Gomes JC, Koguishi MS (2006) Microclimatic characterization and productivity of coffee plants grown under shade of pigeon pea in southern Brazil. Pesq Agrop Brasileira 41:763–770 http://seer.sct.embrapa.br/index.php/pab/article/view/7204

Morais H, Caramori PH, Koguishi MS, Ribeiro AMDA (2008) Escala fenológica detalhada da fase reprodutiva de *Coffea arabica*. Bragantia 67:257–260 http://www.scielo.br/pdf/brag/v67n1/a31v67n1.pdf

Nátrová Z, Nátr L (1991) The utilization of degree days for the characterization of developmental stages of 26 winter wheat cultivars. Biologia Plantarum (Praha) 33:417–429 https://link.springer.com/article/10.1007/BF02897693

Petek MR, Sera T, Fonseca ICDB (2009) Exigências climáticas para o desenvolvimento e maturação dos frutos de cultivares de *Coffea arabica*. Bragantia 68:169–181 http://www.scielo.br/pdf/brag/v68n1/a18v68n1.pdf

Pezzopane JRM, Júnior MJP, Thomaziello RA, Camargo MBPD (2003) Escala para avaliação de estádios fenologicos do cafeeiro arábica. Bragantia 62:499–505 http://www.scielo.br/pdf/brag/v62n3/v62n3a15.pdf

Pezzopane JRM, Júnior MJP, Camargo MBPD, Fazzuoli LC (2008) Exigência térmica do café arábica cv. Mundo Novo no subperíodo florescimento colheita. Ciência e Agrotecnologia 32:1781–1786 http://www.scielo.br/pdf/cagro/v32n6/v32n6a16.pdf

Pezzopane JRM, Salva TDJG, Lima VBD, Fazuoli LC (2012) Agrometeorological parameters for prediction of the ripening period of Arabica coffee cultivars. Int J Biometeorol 56:843–851 https://link-springer-com.ez298.periodicos.capes.gov.br/article/10.1007/s00484-011-0486-6

Souza CAD, Rocha RB, Alves EA, Espindula MC, Ramalho AR, Teixeira AL, Ferrão MAG (2017) Componentes genéticos do desenvolvimento e do desenvolvimento e maturação de frutos de *Coffea canephora* Pierre ex A. Froehner Coffee Sci 12:355–364 http://www.Coffeescience.ufla.br/index.php/Coffeescience/article/view/1295

Sureshkumar V, Prakash N, Mohanan K (2010) A study of *Coffea racemosa* x *Coffea canephora* var. *robusta* hybrids in relation to certain critically important characters. Int J Plant Breed Genet 4:30–35 http://docsdrive.com/pdfs/academicjournals/ijpbg/2010/30–35.pdf

Systat Software Inc (2010) Kruskall-Wallis ANOVA on ranks. In: SigmaPlot statistics user's guide. Systat, San Jose – CA, pp 147–161