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**Corresponding author:**
Anderson Prates Coelho;
Email: anderson.coelho@unesp.br



# Agronomic performance of Arabica coffee cultivars for the low-altitude region

Vinícius Augusto Filla, Anderson Prates Coelho, Orlando Ferreira Morello, Fábio Tiraboschi Leal, João Paulo Leme Donadelli, Bruno Moura Coimbra, Pedro Afonso Couto Júnior, Stefany Silva de Souza, Jordana de Araújo Flôres and Leandro Borges Lemos

São Paulo State University (Unesp), School of Agricultural and Veterinary Sciences, Jaboticabal, Via de Acesso Prof. Paulo Donato Castellane, s/n, km 5, 14884-900, São Paulo, Brazil

## Abstract

Temperature increase may cause some regions in the world to become marginal or unsuitable for Arabica coffee cultivation, due to either heat and/or marked water deficit. The feasibility of sustainable coffee production in these regions promotes good opportunity of income and value addition for rural producers within an expanding market. This study aimed to identify short-stature Arabica coffee cultivars with the best agronomic and qualitative performance in a low-altitude region. The experiment was located in northeastern São Paulo state, Brazil, at 565 m above sea level. During the experimental period (2014–2018) the average annual and November temperatures were 23.0 and 24.3°C, respectively, with an average annual water deficit of 109 mm. The experimental design was randomized blocks, with four replicates, and the treatments consisted of 17 short-stature cultivars. The cultivars Catuaí Amarelo IAC 62, Catuaí Vermelho IAC 99, IAC Ouro Amarelo, Obatã IAC 1669-20, Obatã IAC 4739, Tupi IAC 1699-33, IAC 125 RN and IPR 100 stood out in terms of yield, reaching approximately 50 bags/ha. The appropriate choice of Arabica coffee cultivar in a low-altitude region may result in yield increment of up to 74%. The cultivars Catuaí Vermelho IAC 99, Tupi IAC 1699-33 and IAC 125 RN produced grains with the best quality and highest hundred-grain weight, processing yield and percentage of grains retained on sieve 17. Therefore, it is possible for an Arabica coffee cultivar to have high yield and high grain and beverage quality in a low-altitude region, promoting production alternatives for farmers.

## Introduction

Coffee is one of the most consumed beverages in the world, with Arabica being the most produced and consumed worldwide, due to the particular chemical characteristics of its grains, which produce a beverage with better sensory attributes, in addition to being a functional food and beneficial to human health (Melo Pereira *et al*., 2020). Global production of coffee involves approximately 25 million farmers, most of whom are small producers (Waller *et al*., 2007). The Americas have a remarkable relevance in the production of the grain, accounting for 57% of the coffee marketed in the world, with Brazil occupying a prominent position (FAO, 2020) as the largest producer and the second largest consumer of Arabica coffee (ICO, 2021*a*, 2021*b*).

The production of specialty coffees is an alternative for producers to increase their income and diversify their agricultural production (Teles and Behrens, 2020). In recent years, the growing demand for specialty coffees offers opportunities for good financial returns for small producers. In this sense, associating high yield with excellent beverage qualities promotes greater value addition to the commodity. In addition to the social and economic benefits, sustainable management of coffee cultivation can promote environmental benefits, as the crop has great potential to mitigate or reverse negative impacts of climate, becoming a 'carbon sink' (Noponen *et al*., 2013, 2017).

There are two main objectives in coffee cultivation: obtaining high yields to meet the growing internal and external demand, and obtaining grains with high quality for the production of specialty coffees (Romano *et al*., 2022). Both are influenced by genetic factor and the environment, especially by air temperature and rainfall which are closely related to altitude (Rolim *et al*., 2020). Lower altitudes and higher temperatures influence the coffee crop cycle and beverage quality (Oliveira Aparecido et al., 2018; Rolim *et al*., 2020), in addition to agricultural practices, post-harvest processing and storage (Barbosa *et al*., 2019; Barrios-Rodriguez *et al*., 2021).

The ideal environment for Arabica coffee cultivation is characterized by mild temperatures, with optimal range from 18 to 21°C, and the crop develops well in equatorial regions at altitudes above 1000 m (Rena and Maestri, 1987). However, due to the increase in world demand for coffee, its cultivation can migrate to less suitable regions, with high temperatures and low altitudes, in order to meet the growing demand. In addition, due to the increase in the average temperature of the earth in recent decades, some regions that were coffee producers currently have restrictions on cultivation due to high temperatures (Morello *et al*., 2020).

The main limitations in marginal regions are higher temperatures and water deficit. However, these difficulties are not a factor that prevents sustainable coffee production (Teixeira *et al*., 2015; Morello *et al*., 2020). Cultivation is feasible and high yields can be obtained by cultivars more adapted to regions with high temperatures (Teixeira *et al*., 2015; Carvalho *et al*., 2022*a*). Although the climate variable is considered the most influential in coffee production, technological advancement and greater use of new technologies by producers are the main factors that will promote increased production and yield (Ferreira *et al*., 2019).

There are several alternatives to mitigate the impact of climate factors in less suitable regions, such as the cultivation of shaded coffee, high planting density, use of irrigation and use of more heat-tolerant cultivars (WeldeMichael and Teferi, 2020). Among these alternatives, the adoption of commercial cultivars more tolerant to high temperatures can allow satisfactory yields to be obtained in marginal regions, in addition to generating information for the development of new cultivars by breeding programmes. It is also worth mentioning that this alternative would be the most practical and fast, since cultivars available in the market would be used. There are 139 cultivars of Arabica coffee registered in Brazil (Brasil, 2022), however there is a lack of information on the performance of these genotypes in low-altitude regions (Teixeira *et al*., 2015; Souza *et al*., 2019; Morello *et al*., 2020).

Based on the hypothesis that coffee cultivars have different agronomic and qualitative responses in a marginal region for cultivation due to high temperatures, the objective of this study was to identify short-stature Arabica coffee cultivars with the best agronomic and qualitative performance in low-altitude regions.

## Materials and methods

### Experimental area description and weather characterization

The experiment was conducted in Jaboticabal, state of São Paulo, Brazil, in an experimental area near the coordinates 21°14′30.23″ S, 48°17′51.66″ W (central point of the area) and altitude of 565 m (Fig. 1). The climate is classified as Aw (humid tropical with rainy season in summer and dry winter), according to Köppen's climate classification (Alvares *et al*., 2013). According to the Brazilian classification, the soil of the experimental area was classified as *Latossolo Vermelho eutroférrico* (Santos *et al*., 2018), which corresponds to Oxisol in the American classification (Soil Survey Staff, 2014). The soil has a clayey texture, with clay, silt and sand contents of 533, 193 and 274 g/kg, respectively.

Based on average data from 1971 to 2014 (measurements of the weather station at the university began in 1971), the average annual temperature ($T_{avg}$) of the region was 22.3°C, the average temperature of November ($T_n$) was 24°C and the annual rainfall was 1417 mm. The data were obtained at a weather station located 1.5 km from the experimental area. It is noteworthy that for Agricultural Zoning of Climate Risk of coffee in Brazil, the temperature in November is one of the most relevant, a time that coincides with the flowering/beginning of fruit growth. These average data presented here point to a limitation to coffee cultivation in this region, which is the thermal restriction. $T_{avg}$ is within the range of restriction, according to the criteria of Pinto *et al*. (2001), between 22 and 23°C. $T_n$ is at the limit adopted by the Agricultural Zoning of Climate Risk (*Zoneamento Agrícola de Risco Climático* – ZARC), of 24°C (Brasil, 2011). The classification of the region would change from 'suitable', according to Pinto *et al*. (2001), to 'marginal with thermal restriction'.

The temperature and rainfall data of the first four coffee seasons, period of this study, are presented in Fig. 2. The average temperatures between the first and fourth seasons were 23.0, 23.1, 22.7 and 23.0°C, respectively, while the average temperature for November was 24.4, 24.8, 23.9 and 23.9°C, respectively. The accumulated precipitation in the first, second, third and fourth harvests was 1218, 1974, 1301 and 762 mm, respectively.

The average annual water deficit of Jaboticabal between 1971 and 2000 was 56 mm (Fig. 3(*a*)), with no water restriction for cultivation, according to the criteria used in agroclimatic zoning of coffee (Pinto *et al*., 2001; Brasil, 2011). However, during the experimental period (2013–2018), the average annual water deficit was 109 mm (Fig. 3(*a*)), within the range from 100 to 150 mm, characterizing water restriction, so water supply by irrigation was indicated (Matiello, 2008). The water balance was carried out according to the methodology described by Thornthwaite and Mather (1955).

### Experimental design and treatments

The experimental design was randomized blocks, with four replicates, and the treatments consisted of 17 short-stature Arabica coffee cultivars (Supplementary Table 1). The seedlings were produced in a system of tubes with artificial substrate based on coconut fibre, peat and slow-release fertilizer and planted in the field when they had five pairs of leaves. At the time of field planting, the seedlings were 5 months old.

Each experimental plot consisted of a 4-metre-long coffee row, with eight plants, at spacing of 0.50 m between plants and 3.5 m between rows. The cultivar Acauã was used along the entire border of the experiment. Throughout the experiment, *Urochloa ruziziensis* was sown broadcast between the rows in order to form vegetation cover on the soil surface, avoiding erosion.

The seedlings were planted in April 2013. The first harvest was carried out between April and May 2015. The present study encompasses the first four coffee seasons, from 2015 to 2018. In the experimental area, a drip irrigation system was used, with pressure-compensating emitters spaced 0.50 m apart, with service pressure of 150 kPa and flow rate of 1.6 l/h. The irrigation interval was 7 days, with a water depth of 15–20 mm per week throughout the dry season. In dry spells during the rainy season, the system was also activated. From July to the first half of August, irrigation was suppressed to promote anthesis (Lima *et al*., 2021).

In the four seasons, the soil of the experimental area was subjected to fertility analysis (Raij *et al*., 2001) (Supplementary Table 2). According to Raij *et al*. (1997), there was no need for liming or gypsum application before, as base saturation was above 70% and aluminium saturation was low (almost 0%), indicating ideal conditions for coffee growth in Brazil. Soil tillage was carried out by subsoiling, plowing and harrowing in September and October 2012. Liming, gypsum application and mineral fertilization for production (after planting) were performed as recommended by Raij *et al*. (1997). It is worth mentioning that organic fertilization was carried out in all agricultural years, using cattle manure as source, in the amount of 10 t/ha, applied in August. Agricultural gypsum was also applied in October 2016 at a dose of 2 t/ha, aiming at the supply of Ca and S, as

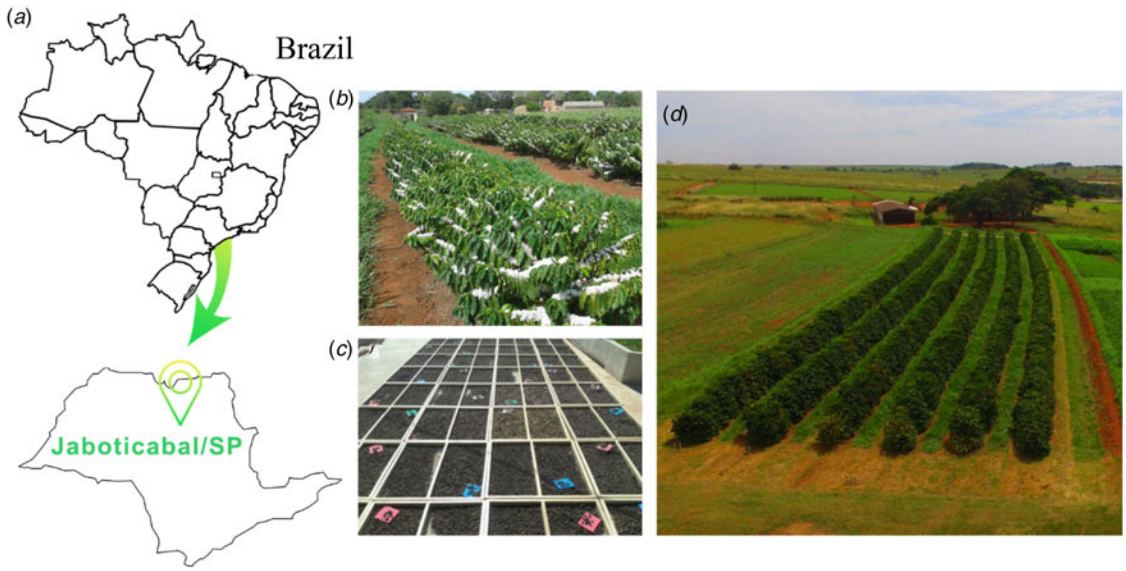


**Figure 1.** Geographical location of the experimental area to evaluate the quantitative and qualitative performance of the 17 short-stature *Coffea arabica* cultivars (*a*); (b) anthesis in the first season; (c) coffee samples drying in full sun on trays; (d) aerial view of the experiment in the fourth season.

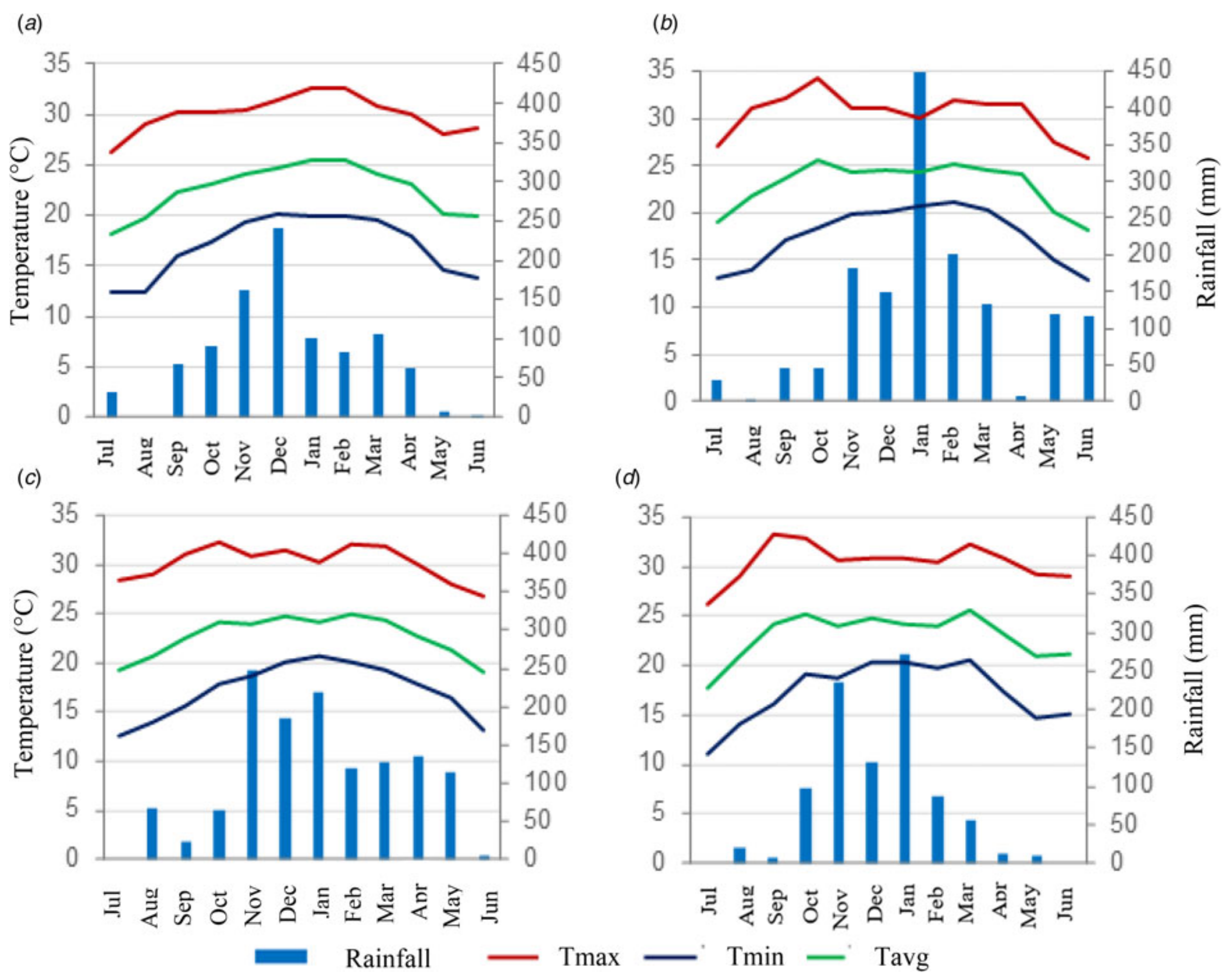


**Figure 2.** Average data of maximum, minimum and average temperature ($T_{max}$, $T_{min}$, $T_{avg}$) and rainfall. (a) 1st season (2014/2015); (b) 2nd season (2015/2016); (c) 3rd season (2016/2017); (d) 4th season (2017/2018).

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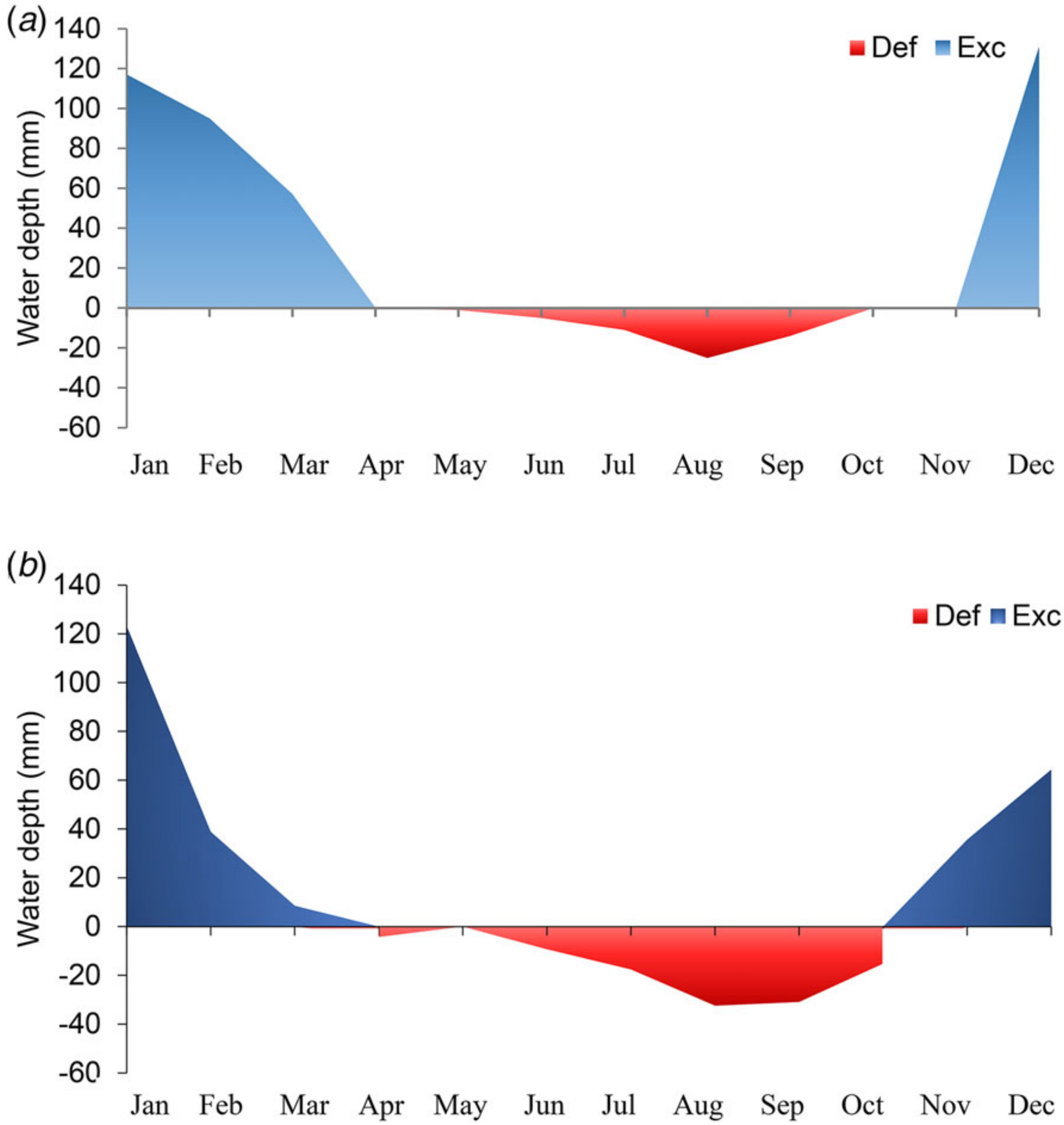


**Figure 3.** Climatological water balance (a) from 1971 to 2000 and (b) during the experimental period from 2013 to 2018. Def: water deficit; Exc: water surplus.

well as the improvement of the soil environment in subsurface to favour root growth. Regarding the mineral fertilization for production, doses within the range of 350–450 kg/ha of N, 80–100 kg/ha of $P_2O_5$ and 300–350 kg/ha of $K_2O$ were applied. Nutrients (N, Zn, Mn, Ca, B, Cu, Mo) were also supplied by foliar fertilization, in 4–6 applications per agricultural year. These application ranges of fertilizer rates and spraying occurred depending on the two-year period of coffee production and the pressure of pests and diseases in each year. After 2018, the coffee was pruned and harvested two more times. These data after 2018 were used in another study with a new approach to skeleton pruning in Arabica coffee grown in low-altitude region.

### Field and laboratory evaluations

Plant height was measured with a graduated ruler, from the ground to the apical meristem. Crown diameter (cm) was measured from the end of the branches farthest from the plant and perpendicular to the planting row. For the degree of fruit maturation (%), 1 l (standard methodology for coffee) of coffee was collected in each plot and used for classification and quantification of green, cane-green, cherry, raisin and dry fruits, as described in Pezzopane *et al.* (2012). After harvesting and homogenizing the fruits, the total volume of coffee harvested in each plot was measured, and 10 L of raw coffee were collected and put to dry in the sun on a concrete terrace. After drying, the dried coffee beans were processed. From the weight of raw coffee bean, obtained after processing and moisture correction to 12.5% (wet basis), the yield (in bags of 60 kg of processed coffee per hectare) and the processing yield (% of coffee beans relative to dried coffee beans) were estimated.

The coffee beans, 1 l of each plot, were placed on a set of sieves arranged in the following order: round sieve 17 (flat berry bean), round sieve 15 (flat berry bean), oblong sieve 10 (peaberry bean),

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round sieve 13 (flat berry bean) and bottom (sticks, stones, broken grains, among others). After sieving, the mass of grains retained on each sieve was quantified and the percentages of grains by size and shape contained in each sieve and sample were determined. In the same sample collected for classification by size and shape, black, immature and sour grains were selected and weighed to establish the percentages of these defects. Four samples of 100 grains, flat berry type, were selected and counted in each plot. The average of the samples was used to establish the hundred-grain weight (HGW).

Sensory analysis was performed following an adaptation of the methodology of the Specialty Coffee Association (SCA) (Lingle, 2011), by a specialty coffee taster (QGrader), qualified and certified by the Coffee Quality Institute (CQI). The coffee roasting level corresponded to 58 points on the Agtron scale for the whole bean and 63 points for the ground bean. In each evaluation, five cups of coffee representative of each experimental plot were tasted, and a sensory analysis session was performed for each replicate, totaling three replicates for each treatment.

### Statistical analysis

The data were subjected to outlier analysis by the generalized ESD test (Rosner, 1983) and it was checked whether the assumptions of the analysis of variance (ANOVA) including normality of residuals, by the Levene test (Levene, 1960) and homogeneity of variances, by the Jarque–Bera test (Jarque and Bera, 1980) were met. When one of the assumptions was violated, the data were transformed to meet the requirements of ANOVA. Data were analysed using one-factor ANOVA (one-way ANOVA). When the $F$ test was significant ($P < 5\%$), the Scott–Knott clustering test was performed to compare the means. The analyses were carried out using SpeedStat® software (SPEED Stat, UFV, Viçosa, Brazil).

Due to the dependency structure of the variables analysed, multivariate exploratory analysis by principal components (Hair *et al.*, 2009) was applied in order to plot the distribution of the Arabica coffee cultivars in two dimensions and group the variables into new latent variables (principal components).

Production and qualitative variables of coffee beans were used for the multivariate analysis. Prior to the analysis, all variables were standardized, generating null mean and unit variance. The number of principal components was chosen according to Kaiser's criterion, using those with eigenvalues above 1.0 (Kaiser, 1958). The eigenvalues were extracted from the covariance matrix of the original variables. Variables with scores close to or higher than 0.600 were considered relevant for the explanation within each principal component (Romano *et al.*, 2022).

To identify the cultivars with specific characteristics, ellipses covering the values of the $X$ and $Y$ axes, ranging from −1.96 to 1.96, were plotted. These values refer to the $Z$ value of the normal distribution; values lower than −1.96 and higher than 1.96 indicate points with specific characteristics at 5% probability level. Thus, it was possible to identify the cultivars with specific characteristics for each principal component, as performed by Romano *et al.* (2022). Multivariate statistical analyses were performed using Statistica® software, version 7.0 (StatSoft, Tulsa, USA).

## Results

Significant differences were found for the morphological attributes, including plant height (PH) and crown diameter (CrD) increment (Table 1). For PH, the largest increases between the first and second seasons were obtained for the cultivars ObV, ObA and Sacr, with a variation of 1.14–1.27 m. The highest increment between the seasons for CrD was obtained by the IAC cultivars (SH3, CA62, CV99, OrV and OrA) and the cultivar IPR100 (Table 1).

Differences in fruit maturation between cultivars were obtained in all years (Supplementary Table 3). The average percentage of green fruits (G) ranged from 17.7 to 22.3% between seasons, with an overall mean of 22%. The overall mean of cherry (C) and raisin + dry (R + D) fruits was 44 and 23.9%, respectively (Supplementary Table 4).

The average processing yield (PY) among the four seasons ranged from 42.4 to 50.2%, with an overall mean of 46.7% (Table 1). Among the IAC cultivars, CA99, OrV, OrA, IPR100 and Sabiá were in the group with the highest PY. Considering all cultivars, the overall mean was 10.9 g. The average HGW of the seasons was between 9.6 and 12.3 g. The cultivars that produced the lightest grains were Catiguá and PBr, with means of 9.6 and 9.9 g, respectively.

Differences in yield between cultivars were obtained in all seasons, highlighting the genotypic and phenotypic expression differences in this environment (Table 2). In the 1st season, several cultivars reached high yields. IAC cultivars had yields above 40 bags/ha, except for SH3 (32.2 bags/ha) and ObA (24.1 bags/ha). The other cultivars of this institution produced between 42 and 52 bags/ha.

In the 3rd season, Catiguá and Sacramento were in the least productive group, with about 30 bags/ha. ObV and PBr were the most productive, with approximately 60 bags/ha. In the 4th season, all IAC cultivars were in the most productive group (Table 2), with yields between 54.2 (CA62) and 77.1 bags/ha (OrA). Among the other cultivars, only IPR100 was in this group, with 55.7 bags/ha. The two groups with the lowest yields were composed of the cultivars Catiguá, Oeiras, PBr, Sacr and Sabiá Tardio. Catiguá and Sacr also had the lowest PY and low HGW (Table 1).

The variation of yield among the four seasons per cultivar can be better visualized in Fig. 4. The cultivars with the lowest variation between years were IPR100, IPR103 and Sabiá Tardio, indicating greater yield stability.

Yield increments in each season were observed for the cultivars SH3, Catiguá and Sacr (Fig. 4). The cultivar PBr showed wide oscillation between seasons, producing about 50% less after a high yield. Oeiras and PBr also had biennial production in all seasons. Despite the low yield in the 1st season, ObA showed an increase from the next season, doubling its yield (48.4 bags/ha), maintaining it in the 3rd season (45.9 bags/ha), and reaching 69.6 bags/ha in the 4th season, with an overall mean of 47 bags/ha. The highest yields were obtained in the 4th season for most cultivars.

The percentage of grains retained on sieves with the largest openings is presented in Supplementary Table 5. As observed for PY and yield, the size and type of grains may vary according to the agricultural year. The lowest mean values for S17 (17.7% and 28.6%) were obtained in the 1st and 4th seasons. When evaluating the retention of small grains (Supplementary Table 6), greater retention was observed in the 1st season compared to the others, with an average of 22.2% of S13 grains, a value 116% higher than the overall mean (10.13%).

The percentage of peaberry beans is presented in Supplementary Table 7. Flat berry beans come from well-developed cherries, but the coffee plant can also produce some beans with a round shape, called peaberry. This type results from the fertilization of only one of the eggs of the coffee cherry,

**Table 1.** Plant height (PH) and crown diameter (CrD) increment (m), processing yield (PY) and hundred-grain weight (HGW) of Arabica coffee cultivars on average of the fourth seasons

| Cultivar | Breeding program | PH (m) increment | CrD (m) | PY (%) mean | HGW (g) |
|---|---|---|---|---|---|
| SH3 | IAC | 1.09 b | 0.66 a | 45.6 c | 10.9 e |
| CA62 | | 1.07 b | 0.55 a | 47.3 b | 10.5 f |
| CA99 | | 1.11 b | 0.54 a | 49.5 a | 11.3 d |
| OrV | | 1.07 b | 0.58 a | 50.2 a | 10.6 f |
| OrA | | 1.11 b | 0.70 a | 49.5 a | 10.5 f |
| ObV | | 1.14 a | 0.40 b | 47.2 b | 11.0 e |
| ObA | | 1.19 a | 0.36 b | 43.7 d | 10.8 e |
| Tupi | | 1.07 b | 0.33 b | 45.8 c | 11.6 c |
| IAC125 | | 1.04 b | 0.30 b | 46.3 c | 12.3 a |
| Catiguá | EPAMIG | 1.11 b | 0.49 b | 43.9 d | 9.6 h |
| Oeiras | | 0.99 b | 0.38 b | 44.7 c | 10.9 e |
| PBr | | 1.04 b | 0.45 b | 46.2 c | 9.9 h |
| Sacr | | 1.27 a | 0.43 b | 42.4 d | 11.0 e |
| IPR99 | IAPAR | 1.06 b | 0.36 b | 47.4 b | 11.9 b |
| IPR100 | | 1.08 b | 0.69 a | 48.8 a | 10.7 f |
| IPR103 | | 1.04 b | 0.50 b | 47.3 b | 10.1 g |
| Sabiá | PROCAFÉ | 0.94 b | 0.36 b | 48.8 a | 11.3 d |
| F | | 4.07** | 2.77** | 18.1** | 51.6** |
| CV (%) | | 6.71 | 31.45 | 2.17 | 1.75 |
| Mean | | 1.08 | 0.48 | 46.7 | 10.9 |

SH3: IAC Catuaí SH3; CA62: Catuaí Amarelo IAC 62; CV99: Catuaí Vermelho IAC 99; OrV: IAC Ouro Verde; OrA: IAC Ouro Amarelo; ObV: Obatã IAC 1669-20; ObA: IAC Obatã 4739; Tupi: Tupi IAC 1669-33; IAC125: IAC 125 RN; Catiguá: Catiguá MG1; Oeiras: Oeiras MG 6851; PBr: Pau-Brasil MG1; Sacr: Sacramento MG1; IPR99: IPR 99; IPR100: IPR 100; IPR103: IPR 103; Sabiá: Sabiá Tardio. Means followed by the same letter do not differ from each other by the Scott–Knott test at 5% probability level. *Significant at 5% probability level. **Significant at 1% probability level.

leading to a round bean instead of two flat-sided beans. In coffee classification, peaberry beans are not considered defects, but rather anomalies.

The cultivars that produced the highest average percentage of peaberry beans were PBr and Sacr (13 and 13.8%, respectively), followed by CA62 (10.6%), Tupi (11.6%) and Catiguá (10.2%). The percentage of the main grain defects (BIS – black, immature and sour beans) also differed among cultivars in all seasons (Supplementary Table 7).

Two principal components (PC) were relevant to explain 66.22% of the variability of the data, corresponding to 37.6% for PC1 and 28.6% for PC2 (Fig. 5). The relevant variables – with eigenvalues close to or above 0.600 (Romano *et al.*, 2022) – for the first PC were HGW, S17, S15, S13, PY and YLD. Variables with equal signs are directly correlated with each other, and variables with opposite signs are inversely correlated. Therefore, HGW, S17, PY and YLD were directly correlated that the higher the HGW, S17 or PY, the higher the grain yield. The variables S15, S13 and Peaberry were inversely proportional to the abovementioned attributes (Table 3). The larger the amount of grains of lower sieve and peaberry grains, the smaller the amount of large grains, PY and HGW, and consequently the lower the yield.

For PC2, the relevant variables were the percentage of peaberry beans and the green + cane-green (G + CG), cherry (C) and raisin + dry (R + D) degrees of fruit maturity. C and R + D fruits were directly correlated with each other and inversely correlated with the immature fruits (Table 3).

It was possible to identify cultivars with the best performance for agronomic and qualitative attributes with the PC analysis (Fig. 5). The cultivars with specific characteristics for the two PCs are located outside the ellipse. For PC1, the cultivars with the best agronomic performance were those from Tupi, CV99 and IAC125, characterized by higher production of larger beans, with higher S17, HGW, PY, higher yields and lower amounts of beans of the peaberry type and of lower sieve. Among the three cultivars, IAC125 stood out, located farther to the right in the biplot. ObV and ObA are located below the ellipse due to the high percentage of green fruits and lower amount of S17 beans, but also stood out for their high yields.

The opposite side contained the cultivars with the worst performances, PBr, Sacr and Catiguá (Fig. 5). Although it is recommended to cultivate these materials under the same conditions considered suitable for planting cultivars of the Catuaí group, their performance was significantly lower compared to the cultivars of this group. Even the cultivar Sacr, which showed excellent vegetative development (Table 1), and which is characterized by high vegetative vigour and high yield in the first seasons, showed poor performance in the region of Jaboticabal.

In PC2, the cultivars with specific characteristics were ObV and ObA, with a higher percentage of immature fruits (G + CG)

**Table 2.** Grain yield of Arabica coffee cultivars in the first four seasons (2015, 2016, 2017, 2018)

| | | Grain yield (bags/ha) | | | | |
|---|---|---|---|---|---|---|
| Cultivar | Breeding programme | 1st Season | 2nd Season | 3rd Season | 4th Season | Mean |
| SH3 | IAC | 32.2 b | 40.1 a | 43.1 c | 59.1 a | 43.6 b |
| CA62 | | 48.0 a | 28.4 b | 53.4 b | 54.2 a | 46.0 a |
| CV99 | | 47.6 a | 31.5 b | 44.8 c | 71.2 a | 48.8 a |
| OrV | | 43.1 a | 41.1 a | 35.2 d | 59.9 a | 44.8 b |
| OrA | | 44.9 a | 37.5 a | 36.0 d | 77.1 a | 48.9 a |
| ObV | | 51.9 a | 26.4 b | 56.5 a | 61.6 a | 49.1 a |
| ObA | | 24.1 c | 48.4 a | 45.9 c | 69.6 a | 47.0 a |
| Tupi | | 42.0 a | 45.6 a | 50.3 b | 62.8 a | 50.2 a |
| IAC125 | | 44.6 a | 28.3 b | 46.2 c | 68.2 a | 46.8 a |
| Catiguá | EPAMIG | 13.6 d | 24.7 b | 29.5 d | 48.5 b | 29.1 d |
| Oeiras | | 38.9 b | 17.9 b | 45.0 c | 37.0 b | 34.7 c |
| PBr | | 41.4 a | 22.1 b | 59.6 a | 26.2 b | 37.3 c |
| Sacr | | 16.3 d | 23.4 b | 33.2 d | 33.9 b | 26.7 d |
| IPR99 | IAPAR | 41.4 a | 36.3 a | 52.8 b | 30.3 b | 40.2 b |
| IPR100 | | 45.5 a | 53.0 a | 52.4 b | 55.7 a | 51.6 a |
| IPR103 | | 32.8 b | 44.0 a | 44.1 c | 45.6 b | 41.6 b |
| Sabiá | PROCAFÉ | 39.0 b | 32.3 b | 36.9 d | 38.7 b | 36.7 c |
| F | | 18.72** | 6.00** | 17.04** | 7.89** | 13.72** |
| CV | | 17.0 | 24.2 | 9.3 | 20.1 | 9.4 |
| Mean | | 38.1 | 34.2 | 45.0 | 52.9 | 42.5 |

SH3: IAC Catuaí SH3; CA62: Catuaí Amarelo IAC 62; CV99: Catuaí Vermelho IAC 99; OrV: IAC Ouro Verde; OrA: IAC Ouro Amarelo; ObV: Obatã IAC 1669-20; ObA: IAC Obatã 4739; Tupi: Tupi IAC 1669-33; IAC125: IAC 125 RN; Catiguá: Catiguá MG1; Oeiras: Oeiras MG 6851; PBr: Pau-Brasil MG1; Sacr: Sacramento MG1; IPR99: IPR 99; IPR100: IPR 100; IPR103: IPR 103; Sabiá: Sabiá Tardio. Means followed by the same letter do not differ from each other by the Scott–Knott test at 5% probability level. *Significant at 5% probability level. **Significant at 1% probability level.

and defects (BIS). The greater amount of defects is related to the greater presence of fruits with green beans, which contribute to increasing the percentage of BIS beans. Conversely, the percentage of more mature fruits (C and R + D) was relevant, and Tupi stood out (Fig. 5).

Regarding beverage quality, the sensory analysis of the cultivars confirmed the hypothesis about the possibility of producing specialty coffees in the region of Jaboticabal (Table 4). Only OrA did not achieve the specialty beverage score, being slightly inferior, with 79 points, classified as fine cup, or 'hard to better'.

## Discussion

The increase in the global average temperature in recent decades (Rounce *et al*., 2023) has promoted deep changes in cultivation in some crops, such as Arabica coffee (Malhi *et al*., 2021; Richardson *et al*., 2023). Regions that were previously traditional and suitable for the cultivation of Arabica coffee began to be classified as marginal or unsuitable for its cultivation (Camargo, 2010; Volsi *et al*., 2019). This can be exemplified by the change in coffee cultivation in Brazil, where the state of São Paulo was the largest national producer but currently Arabica coffee cultivation has migrated to the state of Minas Gerais, in regions of higher altitude (>900 m) and with milder temperatures.

To revive coffee cultivation in these regions and generate other cultivation possibilities for producers to diversify their income, this study evaluated the adaptation of 17 short-stature coffee cultivars in a region with low altitude and high temperature. This study may help producers, technicians and breeders in the development of cultivars that are more tolerant to heat, with genotypes capable of facing climate change in the coming decades with greater yield associated with improved quality. To this end, variables related to the growth, yield and quality of Arabica coffee were evaluated.

It should be noted that Agricultural Zoning of Climate Risks does not prohibit the production of Arabica coffee in regions marginal to cultivation, it only indicates the risk of production in a given location. The fact that the region is considered high risk or even marginal does not mean that production cannot occur, but rather that there is a certain risk for the producer that must be taken into account. Furthermore, small annual losses can lead to significant damage for the producer in the long term. In this way, several strategies can be used to mitigate these risks and promote greater production stability and safety.

Some management practices can be adopted to minimize the risks of Arabica coffee production in regions marginal to cultivation. Among them, irrigation, cultivation of cover crops in coffee inter rows, application of anti-stress products, balanced and adequate fertilization, spacing, among others, in addition to cultivar choice itself (Camargo, 2010) stand out. It is known that there are Arabica coffee cultivars that are more tolerant to heat (Kahsay *et al*., 2023), therefore, the use of these genotypes would help

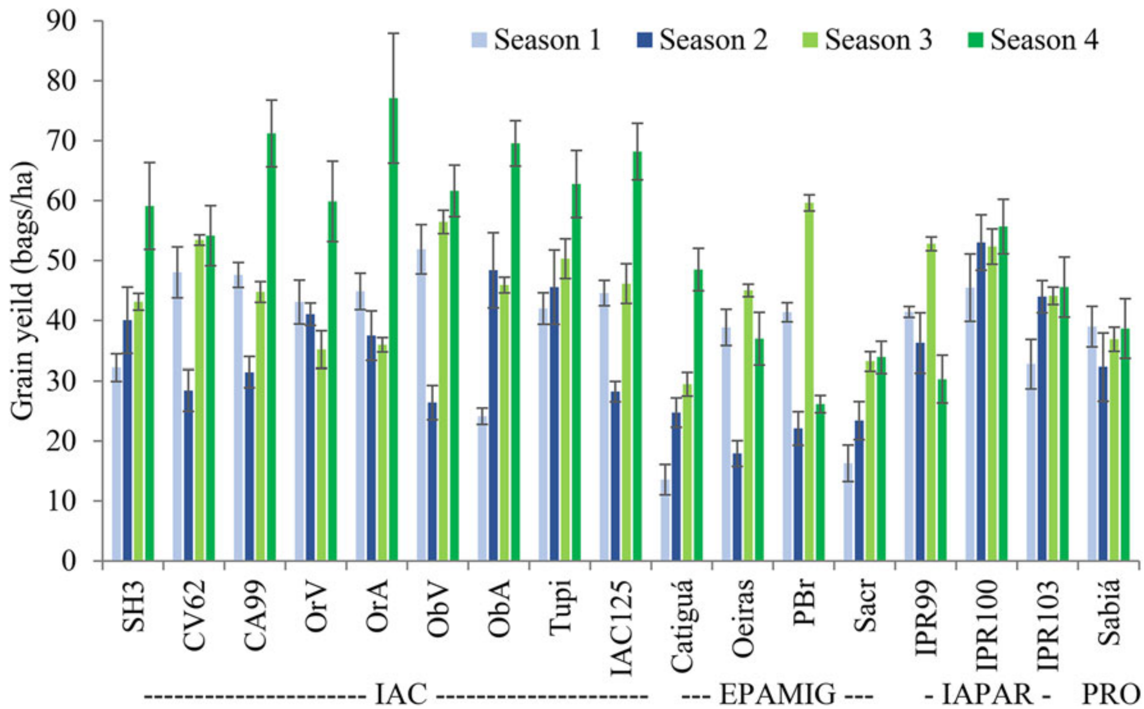


**Figure 4.** Average grain yield of short-stature Arabica coffee cultivars in the first four seasons. SH3: IAC Catuaí SH3; CA62: Catuaí Amarelo IAC 62; CV99: Catuaí Vermelho IAC 99; OrV: IAC Ouro Verde; OrA: IAC Ouro Amarelo; ObV: Obatã IAC 1669-20; ObA: IAC Obatã 4739; Tupi: Tupi IAC 1669-33; IAC125: IAC 125 RN; Catiguá: Catiguá MG1; Oeiras: Oeiras MG 6851; PBr: Pau-Brasil MG1; Sacr: Sacramento MG1; IPR99: IPR 99; IPR100: IPR 100; IPR103: IPR 103; Sabiá: Sabiá Tardio. PRO: Procafé. Error bar indicates mean standard error.

reduce production risks in marginal regions and optimize resources. In this context, the present study aims to elucidate and recommend these genotypes under Brazilian conditions, promoting greater security for producers.

The differences in coffee tree growth variables (PH and CrD increment) among cultivars may be attributed to the genetic variability between the genotypes studied, since they were developed by different breeding programmes in Brazil. The cultivars ObV, ObA and Sacramento showed the highest growth in PH increment, due to their high vegetative vigour (Carvalho *et al.*, 2022*b*).

The higher percentage of green fruits in the last two seasons may be related to the higher rainfall in the months of August

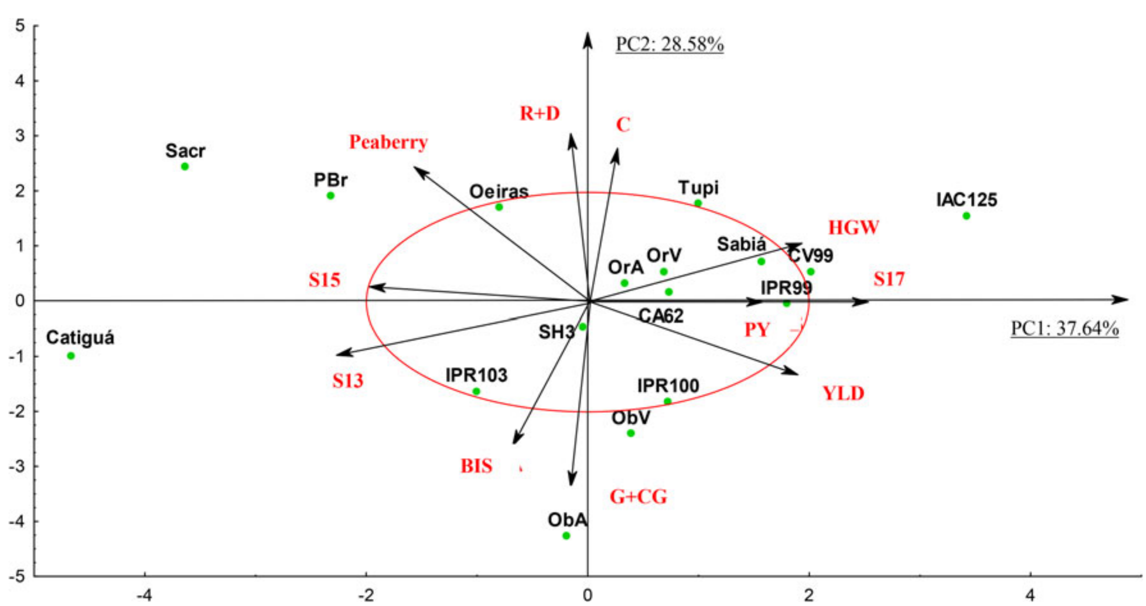


**Figure 5.** Biplot of the principal components to evaluate the dispersion of the average agronomic and qualitative attributes in the first four seasons of 17 Arabica coffee cultivars. Jaboticabal, SP, Brazil. SH3: IAC Catuaí SH3; CA62: Catuaí Amarelo IAC 62; CV99: Catuaí Vermelho IAC 99; OrV: IAC Ouro Verde; OrA: IAC Ouro Amarelo; ObV: Obatã IAC 1669-20; ObA: IAC Obatã 4739; Tupi: Tupi IAC 1669-33; IAC125: IAC 125 RN; Catiguá: Catiguá MG1; Oeiras: Oeiras MG 6851; PBr: Pau-Brasil MG1; Sacr: Sacramento MG1; IPR99: IPR 99; IPR100: IPR 100; IPR103: IPR 103; Sabiá: Sabiá Tardio.

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**Table 3.** Factor loadings of the variables in the principal components

| Variables | PC1 | PC2 |
|---|---|---|
| HGW | **0.744** | 0.262 |
| S17 | **0.978** | −0.020 |
| S15 | **−0.737** | 0.049 |
| Peaberry | **−0.596** | **0.640** |
| S13 | **−0.861** | −0.260 |
| PY | **0.613** | −0.017 |
| BIS | −0.267 | **−0.707** |
| G + CG | −0.066 | **−0.920** |
| C | 0.102 | **0.723** |
| R + D | −0.043 | **0.771** |
| YLD | **0.726** | −0.360 |

PC1, principal component; HGW, hundred-grain weight; S17, flat berry beans retained on sieve 17; S15, flat berry beans retained on sieve 15; S13, flat berry beans retained on sieve 13; PY, processing yield; BIS, black, immature and sour beans; G + CG, green and cane-green fruits; C, cherry fruits; R + D, raisin and dry fruits; YLD, grain yield of the first four seasons. The values highlighted in red represent the relevant variables in each principal component with a score close to or above 0.600.

preceding the 3rd and 4th seasons, advancing flowering. Fruit maturation is genetically controlled, but this characteristic is greatly influenced by the edaphoclimatic conditions of the region of cultivation, especially temperature and water availability (Osorio Pérez *et al*., 2023).

**Table 4.** Beverage score of the 17 short-stature Arabica coffee cultivars

| Cultivar | Breeding programme | Beverage score |
|---|---|---|
| SH3 | IAC | 81.5 |
| CA62 | | 80 |
| CV99 | | 81.5 |
| OrV | | 81.5 |
| OrA | | 79 |
| ObV | | 81 |
| ObA | | 83 |
| Tupi | | 80.5 |
| IAC125 | | 81.5 |
| Catiguá | EPAMIG | 81.5 |
| Oeiras | | 81 |
| PBr | | 82 |
| Sacr | | 81 |
| IPR99 | IAPAR | 82.5 |
| IPR100 | | 80 |
| IPR103 | | 80 |
| Sabiá | PROCAFÉ | 82 |

SH3: IAC Catuaí SH3; CA62: Catuaí Amarelo IAC 62; CV99: Catuaí Vermelho IAC 99; OrV: IAC Ouro Verde; OrA: IAC Ouro Amarelo; ObV: Obatã IAC 1669-20; ObA: IAC Obatã 4739; Tupi: Tupi IAC 1669-33; IAC125: IAC 125 RN; Catiguá: Catiguá MG1; Oeiras: Oeiras MG 6851; PBr: Pau-Brasil MG1; Sacr: Sacramento MG1; IPR99: IPR 99; IPR100: IPR 100; IPR103: IPR 103; Sabiá: Sabiá Tardio. Means followed by the same letter do not differ from each other by the Scott–Knott test at 5% probability level. *Significant at 5% probability level. **Significant at 1% probability l. Beverage score based on the SCA scale (Speciality Coffee Association).

Fruits in the senescence phase are more susceptible to the action of fermenting microorganisms, which produce alcohols and acids that can depreciate the aroma and flavour of the beverage if fermentation occurs for a longer time (Mesquita *et al*., 2016). To reduce the probability of occurrence of undesirable fermentation, cultivars with a longer cycle, such as ObV and ObA, would be appropriate to prevent harvest from coinciding with some rains that may sporadically occur in May. In addition, the choice of cultivars with different maturation times on the same farm promotes better harvest management and processing (Medina Filho *et al*., 2008).

Temperatures in the experimental area are higher than in regions of higher altitude, accelerating the maturation process. In the state of São Paulo, coffee can ripen up to 2–3 months earlier compared to regions with milder temperatures, such as in producing regions in the state of Minas Gerais (Oliveira Aparecido *et al*., 2018). In these regions, harvest is concentrated in the months from June to August, while in the present study almost all cultivars were suitable to be harvested in May, including materials classified as late.

Considering the state of São Paulo, there are also differences in cycle duration between the different regions. In higher regions, such as Alta Mogiana, where altitudes are higher than 800 m, maturation occurs after May, while in regions with low altitudes, such as the central-western region of the state, at less than 600 m, the cycle is shorter (Bardin-Camparotto *et al*., 2012). Higher temperatures, for reducing the grain growth period, cause less accumulation of photosynthates, reducing the potential for beverage quality (Oliveira Aparecido *et al*., 2018).

Although the production of good quality beverage is positively correlated with altitude (Rolim *et al*., 2020), low altitude is not an insurmountable obstacle for Arabica coffee producers in these regions with higher temperatures. In addition to climate, the intrinsic potential of the cultivar, crop management, and post-harvest processing influence beverage quality (Barbosa *et al*., 2019; Barrios-Rodriguez *et al*., 2021). Therefore, choosing cultivars with greater adaptability to environments located at lower altitudes, associated with good agronomic practices and adequate processing, grain selection and storage, can result in the production of coffee lots with superior quality even in these regions.

Most cultivars in the present study were within the appropriate range of processing yield for Arabica coffee, which is 45–55% (Krug *et al*., 1965). The cultivars with means below the recommended range were ObA, Catiguá, Oeiras and Sacr, whose means ranged from 42.4 to 44.7%. The PY parameter establishes the amount required for filling a bag of coffee. PY is an indication of coffee quality used by cooperatives and coffee processing industries, as well as by the farmer, because the higher the PY, the larger the amount of raw coffee.

The values found for yield demonstrate that it is possible to obtain yields similar to those observed in traditional regions of cultivation, despite the low altitude. Carvalho *et al*. (2022*a*) also obtained maximum yields similar to those found in the present study for the 1st coffee season in a region with lower altitude (25 m altitude), even for the cultivar ObA. These results demonstrate the high adaptation of coffee cultivars to regions with higher temperatures. The least productive cultivars were Catiguá (13.6 bags/ha) and Sacr (16.3 bags/ha). In the other seasons, these cultivars also remained among the ones with the worst performance.

IPR99, developed by IAPAR, produced grains with an average weight of 11.9 g, slightly lower than the value found for IAC125

(12.3 g). Both cultivars are characterized by the production of large grains (Carvalho *et al*., 2022*b*).

Using the Scott–Knott mean test, four groups of means were established for yield across the four seasons. In the first group, yield ranged from 46.0 to 51.6 bags/ha, in the second group from 40.2 to 44.8 bags/ha, in the third from 34.7 to 37.3 bags/ha and in the fourth from 26.7 to 29.1 bags/ha. Considering the average of the four seasons, the group with IAC cultivars was the most productive. Most cultivars produced 46–50.2 bags/ha, except for SH3 and OrV, with slightly lower performance (close to 44 bags/ha), but still above the average (42.5 bags/ha). In the other groups, only IPR100 was among the most productive, reaching 51.6 bags/ha. IPR99 and IPR103 performed well, with 40.2 and 41.6 bags/ha, respectively. These values are well above the average yields of Brazil (less than 25 bags/ha) and São Paulo state (22.4 bags/ha) and are similar to that of the region with more 'technified' producers, 45.1 bags/ha (Conab, 2022). The average yield for irrigated coffee plantations is within the range of 40–50 bags/ha (Sakai *et al*., 2015). Based on the average of the four seasons, among the 17 cultivars, the 12 cultivars of the two superior statistical groups were within or above this range.

The IAC's breeding centre for Arabica coffee cultivars is located in a region which is approximately 700 m above sea level (Campinas, SP), while the other institutes are located in regions which are more than 900 m above sea level. Thus, the superiority of IAC cultivars for yield compared to the cultivars from the other research and breeding institutes can be explained by the greater similarity between the climate of the region of the present study and that of the IAC's breeding centre where most of the cultivars were developed.

In the average of the four seasons, the cultivars of the superior group (letter of mean 'a') reached an average yield of 48.6 bags/ha, while in the inferior group (letter of mean 'd') the value was 27.9 bags/ha. This demonstrates that, on average, the appropriate choice of Arabica coffee cultivar in a low-altitude region may result in up to 74% yield increase as was observed in the present study. When considering the most contrasting cultivars (IPR100 and Sacr), this difference reaches 93%. In regions with higher altitude and greater suitability for coffee cultivation in Minas Gerais, IPR103 and Sabiá also showed adaptability and stability, regardless of the environment (Carvalho *et al*., 2013).

The cultivar with the highest value of large grains (four seasons average) was IAC125, with 49.4% of grains retained on S17. This cultivar has characteristics of oblong fruits and large grains, with average sieve of 17 (Fazuoli *et al*., 2018*b*), which favours the retention of grains on sieves with larger openings. CA62, CV99, IPR99 and Sabiá also showed high production of S17 grains, close to 40%. The inferior group was composed of Catiguá, PBr and Sacr, which also showed low performance for PY, HGW and YLD. The cultivars Catiguá, Sacr, PBr and Oeiras MG 6851 produced 27–48% less than the most productive cultivars.

Coffee is a commodity that allows the addition of value according to its quality, and the attributes evaluated include its size and shape. Grain size is one of the elements that influence price, because larger grains have higher commercial value (Leroy *et al*., 2006). Lots with greater unevenness of grains result in lower quality and price. Larger grains roast more slowly, while small grains roast quickly (Hoffmann, 2018). Grain size and shape, depending on the cultivar, influence the quality of the beverage (Luna González et al., 2019), and larger grains are preferable for export.

In all seasons, the average values of peaberry were close to 10%, being at the limit of the range considered normal. The range of peaberry beans considered acceptable in sales contracts on the stock exchange is up to 10% (BMF – BM&FBOVESPA, 2006); for the production of certified seeds, it is up to 12% (Guimarães *et al*., 2002). PBr and Sacr produced above the limit mentioned, reaching values higher than 15%. In Carmos de Minas, at 1231 m altitude, a region suitable for cultivation, percentages of peaberry beans between 10 and 20% were also obtained for the cultivars Catiguá, Sacr and PBr, exceeding these parameters (Silva *et al*., 2016).

The high percentage of peaberry beans may indicate deficiency in fertilization, related not only to the genetic factor, but also to nutrition and climatic factors, such as low humidity during flowering in warm regions (Matiello *et al*., 2020). As peaberry beans have a lower weight when compared to two flat berry beans, a high percentage in the production of these grains is not desired. In addition, the mixture of flat berry beans with peaberry beans compromises the coffee roasting process. However, lots with small peaberry beans can get higher scores compared to lots with flat berry beans (Soares *et al*., 2019).

The overall mean of BIS defects was about 8%. Tupi, IAC125, Oeiras and Sabiá had a lower percentage of BIS beans in the overall mean (5.4–6.1%). Black, immature and sour beans are considered the worst defects of coffee, as they affect the appearance, colour and type of the beverage, and reducing these defects should be one of the main goals for the production of superior quality coffee (Mesquita *et al*., 2016).

According to the PCA, the cultivars that presented the highest values for attributes related to the agronomic and qualitative performance of Arabica coffee, such as HGW, S17, PY and YLD, were IAC125, Tupi and CV99. These cultivars were related to these attributes and presented specific characteristics, being located outside the average of the other cultivars (outside the ellipse of the normal distribution).

On the other hand, cultivars such as Catiguá, Sacr and PBr stood out for their agronomic performance below the average of the other cultivars. In the biplot graph, these cultivars are located in the opposite direction to the variables that demonstrate the agronomic and qualitative performance of the Arabica coffee and outside the average of the cultivars (outside the ellipse). The multivariate analysis corroborated and complemented the results of the univariate analysis, so it can be used in breeding programmes to identify materials with superior characteristics for these and other attributes (Romano *et al*., 2022), being also a useful tool in the selection of commercially available cultivars.

Sixteen cultivars had scores equal to or above 80, according to the methodology of the Specialty Coffee Association (SCA), and the beverages were classified as specialty coffee, within the 'very good' category (SCAA, 2015). The cultivar with the highest score was ObA, with 83 points, similar to the scores presented by the breeders who developed this cultivar (Fazuoli *et al*., 2018*a*, 2018*b*).

Although higher temperatures accelerate the maturation process compared to regions with higher altitude, lower temperatures and lower solar radiation, it was possible to obtain good quality beverages in a marginal region for Arabica coffee cultivation. The results prove that it is possible to combine high grain production with good technological quality and the capacity to obtain specialty beverages in regions of lower altitude.

## Conclusion

We found that short-stature Arabica coffee cultivars showed differences in agronomic and qualitative performance in a region

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marginal to cultivation. The cultivars of the 'IAC' breeding programme: CA62, CV99, OrA, ObV, ObA, Tupi and IAC125, together with IPR100, were those with the highest yield, close to 50 bags/ha. Among them, CV99, Tupi and IAC125 produced grains with the best quality, making it possible to associate high yields with quality of grains and beverage of Arabica coffee in a region of low altitude and high temperatures. Finally, the appropriate choice of the Arabica coffee cultivar for low-altitude region may result in yield gains of up to 74%, generating production alternatives for farmers.

**Supplementary material.** The supplementary material for this article can be found at https://doi.org/10.1017/S0021859624000674.

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**Ethical standards.** Not applicable.

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## References

**Alvares CA, Stape JL, Sentelhas PC, Gonçalves JDM and Sparovek G** (2013) Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift* **22**, 711–728.

**Barbosa IDP, Oliveira ACBD, Rosado RDS, Sakiyama NS, Cruz CD and Pereira AA** (2019) Sensory quality of *Coffea arabica* L. genotypes influenced by postharvest processing. *Crop Breeding and Applied Biotechnology* **19**, 428–435.

**Bardin-Camparotto L, Camargo MBPD and Moraes JFLD** (2012) Época provável de maturação para diferentes cultivares de café arábica para o Estado de São Paulo. *Ciência Rural* **42**, 594–599.

**Barrios-Rodriguez YF, Cordoba-Salazar GA, Bahamón-Monje AF and Gutiérrez-Guzmán N** (2021) Effect of roast degree, preparation method, and variety in the sensory and chemical characteristics of coffee (*Coffea arabica*): a mid-infrared spectrum analysis. *Coffee Science* **16**, e161964.

**BMF – BM&FBOVESPA** (2006) *Contrato Futuro de Café Arábica*. 6 p.

**Brasil** (2011) Ministério da Agricultura, Pecuária e Abastecimento. *Programa Nacional de Zoneamento Agrícola de Risco Climático*. Café. Available at https://www.gov.br/agricultura/pt-br/assuntos/riscos-seguro/programa-nacional-de-zoneamento-agricola-de-risco-climatico/portarias/safra-vigente/sao-paulo (Accessed 4 November 2024).

**Brasil** (2022) Ministério da Agricultura, Pecuária e Abastecimento. *Registro Nacional de Cultivares*. Available at https://sistemas.agricultura.gov.br/snpc/cultivarweb/cultivares_registradas.php (Accessed 4 November 2024).

**Camargo MBPD** (2010) The impact of climatic variability and climate change on Arabic coffee crop in Brazil. *Bragantia* **69**, 239–247.

**Carvalho AM, Botelho CE, Ferreira AD, Teramoto ET, Lima AE, Junior FSM and Guerreiro Filho O** (2022*a*) Initial vegetative and reproductive development of coffee cultivars in Vale do Ribeira Paulista. *Semina: Ciências Agrárias* **43**, 961–972.

**Carvalho CHS, Bartelega L, Sera G, Matiello J, Almeida SR, Santinato F and Hotz A** (2022*b*) *Catálogo de cultivares de café arábica*. Brasília, DF: EMBRAPA Café, 115p.

**Carvalho GR, Botelho CE, Rezende JCD, Ferreira AD, Cunha RLD and Pedro FC** (2013) Performance of F4 arabic coffee progenies before and after framework pruning. *Coffee Science* **8**, 33–42.

**Conab** (2022) *Acompanhamento da safra brasileira: café – Safra* 2022–4° Levantamento. Available at: https://www.conab.gov.br/info-agro/safras/café (Accessed 4 November 2024).

**FAO** (2020) *Faostat statistical database*. FAO. Available at: https://www.fao.org/faostat/en/#data/QCL (Accessed 4 November 2024).

**Fazuoli LC, Braghini MT, Silvarolla MB, Gonçalves W, Mistro JC, Gallo PB and Guerreiro Filho O** (2018*a*) IAC obatã 4739-dwarf Arabic coffee cultivar with yellow fruits and resistant to leaf rust. *Crop Breeding and Applied Biotechnology* **18**, 330–333.

**Fazuoli LC, Braghini MT, Silvarolla MB, Gonçalves W, Mistro JC, Gallo PB and Guerreiro Filho O** (2018*b*) IAC 125 RN-A dwarf coffee cultivar resistant to leaf rust and root-knot nematode. *Crop Breeding and Applied Biotechnology* **18**, 237–240.

**Ferreira WP, Ribeiro Júnior JI and Fátima Souza C** (2019) Climate change does not impact on *Coffea arabica* yield in Brazil. *Journal of the Science of Food and Agriculture* **99**, 5270–5282.

**Guimarães RJ, Mendes ANG and Souza CAS** (2002) Noções de processamento pós colheita, secagem e beneficiamento de café. In Guimarães RJ, Mendes ANG and Souza CAS (eds), *Cafeicultura*. Lavras: UFLA, pp. 294–300.

**Hair JF, Black WC, Babin BJ, Anderson RE and Tatham RL** (2009) *Análise Multivariada de Dados (Multivariate Data Analysis)*, 6th Edn. Porto Alegre: Bookman, 536p.

**Hoffmann J** (2018) *The World Atlas of Coffee: From Beans to Brewing – Coffees Explored, Explained and Enjoyed*, 2nd Edn. London: Octopus, 272p.

**ICO – International Coffee Organization** (2021*a*) Trade Statistics Tables. *World coffee consumption*. Available at https://ico.org/resources/trade-statistics-tables/ (Accessed 4 November 2024).

**ICO – International Coffee Organization** (2021*b*) ICO Coffee Development Report 2020. Available at https://www.ico.org/documents/cy2020-21/ed-2357e-cdr-2020.pdf (Accessed 4 November 2024).

**Jarque CM and Bera AK** (1980) Efficient tests for normality, homoscedasticity and serial independence of regression residuals. *Economics Letters* **6**, 255–259.

**Kahsay GA, Turreira-Garcia N, Ortiz-Gonzalo D, Georget F and Bosselmann AS** (2023) New coffee varieties as a climate adaptation strategy: empirical evidence from Costa Rica. *World Development Sustainability* **2**, 100046.

**Kaiser HF** (1958) The varimax criterion for analytic rotation in factor analysis. *Psychometrika* **23**, 187–200.

**Krug CA, Malavolta E, Moraes FRP, Dias RA, Carvalho A, Monaco LC, Franco CM, Bergamin J, Heinrich WO, Abrahão J, Rigitano A, Souza OF and Fava JFM** (1965) *Cultura e adubação do cafeeiro*. São Paulo: Instituto Brasileiro de Potassa, 277p.

**Leroy T, Ribeyre F, Bertrand B, Charmetant P, Dufour M, Montagnon C, Marraccini P and Pot D** (2006) Genetics of coffee quality. *Brazilian Journal of Plant Physiology* **18**, 229–242.

**Levene H** (1960) *Robust Tests for Equality of Variances. Contribution to Probability and Statistics*. Stanford: Stanford University Press, pp. 278–292.

**Lima AA, Santos IS, Torres MEL, Cardon CH, Caldeira CF, Lima RR, Davies WJ, Dodd IC and Chalfun-Junior A** (2021) Drought and re-watering modify ethylene production and sensitivity, and are associated with coffee anthesis. *Environmental and Experimental Botany* **181**, 104289.

**Lingle TR** (2011) *The Coffee Cupper´s Handbook: Systematic Guide to the Sensory Evaluation of Coffee´s Flavor*, 4th Edn. Long Beach: Specialty Coffee Association of America, 66p.

**Luna González A, Macías Lopez A, Taboada Gaytan OR and Morales Ramos V** (2019) Cup quality attributes of Catimors as affected by size and shape of coffee bean (*Coffea arabica* L.). *International Journal of Food Properties* **22**, 758–767.

**Malhi GS, Kaur M and Kaushik P** (2021) Impact of climate change on agriculture and its mitigation strategies: a review. *Sustainability* **13**, 1318.

**Matiello J** (2008) Critérios para a escolha da cultivar de café. In *Cultivares de café: origem, características e recomendações*, **1**. Brasília: EMBRAPA Café, pp. 157–226.

**Matiello JB, Santinato R, Garcia AWR, Almeida SR and Fernandes DR** (2020) *Cultura do café no Brasil*. Manual de Recomendações. Rio de Janeiro e Varginha: MAPA/Fundação Procafé. 716p.

**Medina Filho HP, Bordignon R and Carvalho CD** (2008) Desenvolvimento de novas cultivares de café arábica. In *Cultivares de café: origem características e recomendações*. Brasília: Embrapa Café, pp. 79–101.

**Melo Pereira GV, Carvalho Neto DP, Júnior AIM, Prado FG, Pagnoncelli MGB, Karp SG and Soccol CR** (2020) Chemical composition and health properties of coffee and coffee by-products. *Advances in Food and Nutrition Research* **91**, 65–96.

**Mesquita CD, Rezende JD, Carvalho JS, Fabri Júnior MA, Moraes NC, Dias PT and Araújo WG** (2016) *Manual do café: colheita e preparo* (*Coffea arabica* L.). Belo Horizonte: EMATER-MG, pp. 1–56. Available at http://www.sapc.embrapa.br/arquivos/consorcio/publicacoes_tecnicas/livro_colheita_preparo.pdf (Accessed 4 November 2024).

**Morello OF, Mingotte FLC, Leal FT, Coelho AP, Salvador Neto A and Lemos LB** (2020) Agronomic performance, postharvest and indirect selection of *Coffea arabica* L. cultivars for high-temperature regions. *Revista Brasileira de Ciências Agrárias* **15**, e7722.

**Noponen MRA, Góngora C, Benavides P, Gaitán A, Hayward J, Marsh C, Stout R and Wille C** (2017) Environmental sustainability—farming in the Anthropocene. In *The Craft and Science of Coffee*. London: Academic Press, pp. 81–107.

**Noponen MRA, Healey JR, Soto G and Haggar JR** (2013) Sink or sourced the potential of coffee agroforestry systems to sequester atmospheric CO2 into soil organic carbon. *Agriculture, Ecosystems & Environment* **175**, 60–68.

**Oliveira Aparecido LE, Rolim GDS, Moraes JRDSCD, Valeriano TTB and Lense GHE** (2018) Maturation periods for *Coffea arabica* cultivars and their implications for yield and quality in Brazil. *Journal of the Science of Food and Agriculture* **98**, 3880–3891.

**Osorio Pérez V, Matallana Pérez LG, Fernandez-Alduenda MR, Alvarez Barreto CI, Gallego Agudelo CP and Montoya Restrepo EC** (2023) Chemical composition and sensory quality of coffee fruits at different stages of maturity. *Agronomy* **13**, 341.

**Pezzopane JRM, Salva TDJG, Lima VB and Fazuoli LC** (2012) Agrometeorological parameters for prediction of the maturation period of Arabica coffee cultivars. *International Journal of Biometeorology* **56**, 843–851.

**Pinto HS, Zullo Junior J, Assad ED, Brunini O, Alfonsi RR and Coral G** (2001) Zoneamento de riscos climáticos para a cafeicultura do estado de São Paulo. *Revista Brasileira de Agrometeorologia* **9**, 495–500.

**Raij B, Fernandes DR, Oliveira EG and Malavolta E** (1997) Café. In Raij B, Cantarella H, Quaggio JA and Furlani AMC (eds), *Recomendações de adubação e calagem para o Estado de São Paulo*, 2nd Edn. Campinas: IAC, pp. 97–101, (Boletim Técnico, 100).

**Raij BV, Andrade JC, Cantarella H and Quaggio JA** (2001) *Análise química para avaliação da fertilidade de solos tropicais*. Campinas, São Paulo, Brasil: Instituto Agronômico, 285p.

**Rena AB and Maestri M** (1987) Ecofisiologia do cafeeiro. In Castro PRC, Ferreira SO and Yamada T (eds), *Ecofisiologia da Produção Agrícola*. Piracicaba: Associação Brasileira para Pesquisa da Potassa e do Fosfato, pp. 119–147.

**Richardson D, Kath J, Byrareddy VM, Monselesan DP, Risbey JS, Squire DT and Tozer CR** (2023) Synchronous climate hazards pose an increasing challenge to global coffee production. *PLoS Climate* **2**, e0000134.

**Rolim GS, Oliveira Aparecido LE, Souza PS, Lamparelli RAC and Santos ER** (2020) Climate and natural quality of *Coffea arabica* L. drink. *Theoretical and Applied Climatology* **141**, 87–98.

**Romano LS, Giomo GS, Coelho AP, Filla VA and Lemos LB** (2022) Characterization of Yellow Bourbon coffee strains for the production of differentiated specialty coffees. *Bragantia* **81**, e2222.

**Rosner B** (1983) Percentage points for a generalized ESD many-outlier procedure. *Technometrics* **25**, 165–172.

**Rounce DR, Hock R, Maussion F, Hugonnet R, Kochtitzky W, Huss M, Berthier E, Brinkerhoff D, Compagno L, Copland L, Farinotti D, Menounos B and McNabb RW** (2023) Global glacier change in the 21st century: every increase in temperature matters. *Science (New York, N.Y.)* **379**, 78–83.

**Sakai E, Barbosa EAA, Carvalho Silveira JM and Matos Pires RC** (2015) Coffee productivity and root systems in cultivation schemes with different population arrangements and with and without drip irrigation. *Agricultural Water Management* **148**, 16–23.

**Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumbreras JF, Coelho MR and Cunha TJF** (2018) *Sistema brasileiro de classificação de solo*, 5th Edn. Brasília, DF: Embrapa, 356p.

**SCAA** (2015) *SCAA Protocols*. Irvine, CA: Cupping Specialty Coffee, 10p.

**Silva VA, Rezende JCD, Carvalho AMD, Carvalho GR, Rezende TT and Ferreira AD** (2016) Recuperação de cultivares de café submetidas ao esqueletamento aos quatro anos e meio de idade. *Coffee Science* **11**, 55–64.

**Soares PV, Kannen V, Jordao Junior AA and Garcia SB** (2019) Coffee, but neither decaffeinated coffee nor caffeine, elicits chemoprotection against a direct carcinogen in the colon of Wistar rats. *Nutrition and Cancer* **71**, 615–623.

**Soil Survey Staff** (2014) *Soil Taxonomy*, 12th Edn. Washington, DC: USDANRCS, Washington, DC, USA.

**Souza CAD, Teixeira AL, Torres JD, Silva CA, Espindula MC and Rocha RB** (2019) Adaptability and stability of *Coffea arabica* lines in the Western Amazon. *Coffee Science* **14**, 240–249.

**Teixeira AL, Souza FDF, Pereira AA, Oliveira ACBD and Rocha RB** (2015) Selection of arabica coffee progenies tolerant to heat stress. *Ciência Rural* **45**, 1228–1234.

**Teles CRA and Behrens JH** (2020) The waves of coffee and the emergence of the new Brazilian consumer. In Almeida LF and Spers EE (eds), *Coffee Consumption and Industry Strategies in Brazil*. Sawston: Woodhead Publishing, pp. 257–274.

**Thornthwaite CW and Mather JR** (1955) *The Water Balance*. Centerton, NJ: Drexel Institute of Technology – Laboratory of Climatology, 104p. (Publications in *Climatology*, vol. VIII, n.1).

**Volsi B, Telles TS, Caldarelli CE and Camara MRGD** (2019) The dynamics of coffee production in Brazil. *PLoS ONE* **14**, e0219742.

**Waller JM, Bigger M and Hillocks RJ** (2007) World coffee production. In *Coffee Pests, Diseases and Their Management*. Wallingford: CABI, pp. 17–33.

**WeldeMichael G and Teferi D** (2020) The impact of climate change on coffee (*Coffea arabica* L.) production and genetic resources. *International Journal of Research Studies in Agricultural Sciences* **5**, 26–34.