Adaptability and stability of conilon coffee in areas of high altitude

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ABSTRACT. In view of the predicted models of global climate change and differences in prices and production costs, there is increased interest in *Coffea canephora* cultivation in areas of high altitude. However, this species is sensitive to low temperatures, where genotypes vary regarding adaptation/tolerance mechanisms, demonstrating genotype x environment interaction. The aim of this study was to evaluate the stability and adaptability of *C. canephora* varieties in high-altitude areas. The experiments were carried out in February 2004, in Bom Jesus do Itabapoana, Rio de Janeiro State, Brazil, at an altitude of 725 m. Four clonal varieties (EMCAPA 8111, EMCAPA 8121, EMCAPA 8131, and EMCAPA 8151) and five harvests (2006 to 2010) were used. The experimental design was randomized blocks with four treatments and six plots, with 12 plants in each plot and spaced 2.5 x 1.2 m. Adaptability and stability parameters were determined using methods based on

nonparametric analysis and analysis of variance. The results showed that the EMCAPA 8131 had the best performance according to stability and adaptability parameters and may be promising for high-altitude regions.

Key words: *Coffea canephora*; Low temperatures; Agronomic performance

INTRODUCTION

In recent years, global consumption of *Coffea canephora* has been increasing at the rate of 3.25% per year versus 2.58% for *C. arabica*, and moreover, price indicators of *C. canephora* have increased, while being reduced for *C. arabica* (IOC, 2014). Still, according to the latest report of the Intergovernmental Panel on Climate Change (IPCC) of 2014, global temperature is predicted to increase by 3.7° to 4.8°C by 2100, and in this scenario, *C. canephora* cultivation may increase. Assad et al. (2004) analyzed the impact of climate change on *C. arabica* in the São Paulo, Minas Gerais, Paraná, and Goiás states and observed that an increase of 1° to 3°C already causes reductions in the suitable area for cultivation in these regions, if genetic characteristics are maintained. In this context, *C. canephora* cultivation in these areas could be presented as an option for the farmer.

Generally, *C. canephora* shows satisfactory growth rates when grown in areas where the minimum temperature is above 17°C and the maximum is less than 34°C (Partelli et al., 2013). When grown in areas with low temperatures, it shows a drop in net photosynthetic rate and lower photosystem II efficiency (Partelli et al, 2009). However, when exposed to low temperatures gradually, *C. canephora* has defense/acclimation mechanisms that may enable adjustments to these conditions with different capabilities among cultivars (Ramalho et al., 2014).

Coffee regions have different climatic conditions, and the responses of cultivars differ in different environments due to genotype x environment interaction (Cucolotto et al., 2007). Methods classifying genotypes according to their stability and adaptability are more suitable to study this interaction in a greater number of environments (Regitano Neto et al., 2013), and thus increase the reliability of the recommendations.

Models that evaluate adaptability and stability have been applied to coffee (Corrêa et al., 2006; Botelho et al., 2010; Nascimento et al., 2010; Rodrigues et al., 2013). However, they have not been applied to *C. canephora* in areas of high altitude for the selection of genotypes with favorable agronomic characteristics (mostly grain yield) for these conditions.

Adaptability shows the ability of genotypes to respond to environment stimulus, and stability refers to the ability of genotypes to show highly predictable performance against environmental changes (Regazzi and Cruz, 1997).

Various methods are available for the analysis of adaptability and stability. The method proposed by Eberhart and Russell (1966) uses simple linear regression, where the dependent variable (usually grain yield) is expressed in terms of an environmental index that measures the quality of environments assessed, or based on nonparametric statistics (Lin and Binns, 1988). Other methods as proposed by Plaisted and Peterson (1959) and Annicchiarico (1992) based on analysis of variance to estimate the adaptability and stability parameters may have low accuracy (Cruz, 2013), but may be easy to interpret and can be applied with a smaller number of environments (Cargnelutti Filho et al., 2007).

Thus, the aim of this study was to estimate the stability and adaptability parameters for grain yield of *C. canephora* in areas of high altitude by different statistical methods.

MATERIAL AND METHODS

The experiments were carried out in February 2004, in Bom Jesus do Itabapoana, northwestern Rio de Janeiro State, Brazil, at an altitude of 725 m, on Oxisol soil. The climate is characterized as Aw, according to the Köppen classification, with a hot and rainy season and another dry and cool season, showing typical tropical climate, with an average temperature of 22°C and average rainfall of 1601 mm.

The study consisted of four treatments, namely the genotypes of the clonal varieties designated EMCAPA 8111, EMCAPA 8121, EMCAPA 8131, and EMCAPA 8151. EMCAPA 8111 is composed of vegetative propagation clones and early ripening. EMCAPA 8121 is also composed of vegetative propagation clones but mid ripening. EMCAPA 8131 is composed of vegetative propagation clones but late ripening. EMCAPA 8151 (seeds), also known as Robusta Tropical, results from a combination of elite clones.

The experimental design was randomized blocks, with six plots, and 12 plants in each plot and spaced 2.5 x 1.2 m. Before planting, the analysis and correction of soil pH and fertilizing was performed. The seedlings of four varieties were six months old when planted, having been grown from seeds and cuttings of orthotropic shoots.

The harvest of 2006, 2007, 2008, 2009, and 2010 were performed between May and July, according to the maturity time of each variety. The volume of coffee cherries harvested was transformed to bags/ha using the scale of 320 L coffee cherries per 60 kg sack, accounting for grain yield.

Methods based on nonparametric analysis (Lins and Binns, 1988; Kuang, 1988) and analyses of variance (Plaisted and Peterson, 1959; Eberhart and Russell, 1966; Annicchiarico, 1992) to obtain stability and adaptability parameters were used. The environment was represented by the grain yield in different harvests.

The Lin and Binns (1988) method estimates the stability and adaptability of behavior in a single parameter, Pi, which is estimated by Equation 1:

$$\text{Pi} = \frac{\sum_{j=1}^{n}\left(X_{ij} - M_j\right)^2}{2n} \qquad \text{(Equation 1)}$$

where X_{ij} is the grain yield of the cultivar *i* in environment *j*, *Mj* is the maximal response observed among all cultivars in environment *j*, and *n* is the number of environment. Thus, varieties with lower Pi value have more adaptability and stability.

The method proposed by Plaisted and Peterson (1959) quantifies the relative contribution of each genotype for genotype x environment interaction and identifies those with best stability, obtained by Equation 2:

$$\theta_i = \frac{1}{g-1}\left[\sum_{i'}\left(\hat{\sigma}^2_{ga_{ii'}}\right)\right] \ (\text{i} \neq \text{i}'). \qquad \text{(Equation 2)}$$

As $d^2_{ii'}$ is the squared Euclidean distance between genotypes *i* and *i*', and based on the behavior of these in environment *a*; therefore:

$$d_{ii'}^2 = \sum_j \left(Y_{ij} - Y_{i'j} \right)^2 \; (j = 1, 2, ..., a). \qquad \text{(Equation 3)}$$

Thus, it is estimated that:

$$SQ\,(G_{ii} \times A) = \frac{r}{2}\,[d_{ii'}^2 - \frac{1}{a} - \left(Y_{ij} - Y_{i'j}\right).^2 \qquad \text{(Equation 4)}$$

and

$$\hat{\sigma}_{ga_{ii'}}^2 = \frac{\left[\dfrac{SQ\left(G_{ii'} \times A\right)}{(a-1)}\right] - QMR}{r} \qquad \text{(Equation 5)}$$

Accordingly, the relative contribution of each cultivar for interaction is estimated by expression 6:

$$\theta_i(\%) = \frac{100\,\theta_i}{g\,\hat{\sigma}_{ga_{ii'}}^2} \qquad \text{(Equation 6)}$$

Using the method of Kuang (1988), we proceeded with the ranking of varieties in ascending order based on the estimators i obtained according to Plaisted and Peterson (1959). The following varieties were classified in descending order based on average grain yield. The values of each classification were then summed, obtaining the sum of the ranking, where the summed lower values were described as the most stable and productive varieties.

The Eberhart and Russell (1966) method is based on the following linear regression model:

$$Y_{ij} = \beta_{oi} + \beta 1_{i Ij} + \delta_{ij}, + \varepsilon_{ij} \qquad \text{(Equation 7)}$$

where Y_{ij} is the average grain yield of cultivar i in environment j, β_{oi} equals the overall average grain yield of cultivar i, $\beta 1_i$ corresponds to the linear regression coefficient, whose estimate is the cultivar response i to environment variation j, and Ij is the environmental index encoded. The deviations from the regression are represented by δ_{ij}, and ε_{ij} is the average experimental error. Varieties with $\beta 1_i = 1$ have general adaptability, and $\beta 1_i > 1$ and $\beta 1_i < 1$ show specific adaptability to favorable and unfavorable environments, respectively. The stable varieties exhibit no significant regression deviations, since this estimate is related to the prediction of variety in relation to the linear regression model.

The stability parameter according to the Annicchiarico (1992) method is given by Equation 8:

$$\omega_i = \mu_i - I_{(1-\alpha)}\,.S_i \qquad \text{(Equation 8)}$$

where ω_i is the confidence index (%), μ_i is the average percentage of variety i, I is the percentile (1 - α) of the cumulative normal distribution function, and S_i is the standard deviation of the percentage values. Varieties with higher ω_i have less chance of being indicated. The simi-

larity between varieties in relation to methods was calculated by the coincidence index (CI), where $CI = I/N$, with I beginning with the number of times that the variety appears in the same position in the ranking for the different methods and N being the total number of methods. The adaptability and stability parameters were obtained by the Genes software (Cruz, 2013).

RESULTS AND DISCUSSION

The residual mean squares (Table 1) obtained from the analyses of individual variance (by environment) for grain yield (kg/ha) showed a ratio of the highest to the lowest values of 11.375, allowing the inclusion of all environments in the analysis of variance (Regazzi and Cruz, 1997).

Table 1. Individual analyses of variance of grain yield (in bags of 60 kg/ha) for the five harvests (environments) of four *Coffea canephora* varieties in areas of high altitude in the Rio de Janeiro State, Brazil.

Environment	MS Block	MS Variety	MS Residue	F
1	19.24871	376.12619	18.44731	20.3892
2	31.49134	524.93788	11.741	44.7098
3	120.55859	1526.53034	111.96625	13.6338
4	14.61104	175.85444	29.46776	5.9677
5	119.6139	2385.80288	133.55675	17.8636
d.f.	5	3	15	

According to the combined analysis of variance (Table 2), the varieties, environments (grain yield) and varieties x environment interactions showed a significant effect, justifying the use of methods that rank the varieties according to adaptability and stability. The high significance of the environments was probably related to coffee biannuality, which is attributed to the depletion of reserves of the plants in years with high grain yields, decreasing the following production due to a decreased growth of primary branches (DaMatta et al., 2007).

Table 2. Summary of joint analysis of variance for grain yield (bags of 60 kg/ha) in five harvests (environments) for four *Coffea canephora* varieties in areas of high altitude in the Rio de Janeiro State, Brazil.

SV	d.f.	MS
Blocks	5	147.8021
Variety	3	3389.0098*
Environment	4	20610.7599**
Var x Env	12	400.0605**
Residue	95	56.4873
Total	119	
Average	36.34	
CV (%)	20.68	

* and **Significant at 1 and 5% probability, respectively.

Average grain yield and stability parameter (general Pi) based on nonparametric analysis according to Lin and Binns (1988), as well as the decomposition of parameters, are presented in Table 3. Generally, the smaller the Pi value, the lower the deviation will be in relation to the maximum grain yield for each environment. Thus, stability is necessarily related to higher grain yield (Daher et al., 2003). Thus, it is possible to observe that the best variety was EMCAPA 8131, followed by EMCAPA 8121, EMCAPA 8151, and EMCAPA 8111.

Pi decomposition in favorable and unfavorable environment improves this method (Carneiro, 1998). The decomposition of the stability parameter proposed by Lin and Binns (1988) in part due to favorable environments (those with higher average than the overall average) and unfavorable environments (whose averages are below the overall average), allows the understanding of the response of genotypes to changes in ambient conditions. In the favorable environment, the ranking of the best were EMCAPA 8131, 8151, 8121, and 8111, and in the unfavorable environment, they were EMCAPA 8131, 8121, 8151, and 8111 (Table 3). Considering the Pi estimates together, it can be observed that EMCAPA 8131 stood out, which also had a better average grain yield as the method provided.

Table 3. Estimates of stability and adaptability parameters obtained by Lin and Binns (1988) methodology and grain yield (bags of 60 kg/ha) of four *Coffea canephora* varieties assessed in five harvests in areas of high altitude in the Rio de Janeiro State, Brazil.

Varieties	Average	General Pi	Favorable Pi	Unfavorable Pi
Emcapa 8111	24.19[c]	423.18	858.87	132.71
Emcapa 8121	37.30[b]	127.79	248.62	47.24
Emcapa 8131	49.92[a]	0	0	0
Emcapa 8151	33.94[b]	165.92	225.96	125.89

Means followed by the same letter do not differ by the Tukey test at 5% probability.

According to the Plaisted and Peterson (1959) method, the more stable varieties were, in ascending order, EMCAPA 8121, 8151, 8131, and 8111 (Table 4). However, it can be observed that the variety that produced the most, i.e., EMCAPA 8131 (Table 3), did not show a suitable stability value. This fact was observed by Vilhegas et al. (2001) working with corn genotypes and Daher et al. (2003) working with *Pennisetum purpureum* Schum genotypes. According to Cargnelutti Filho et al. (2007), cultivars indicated by the Plaisted and Peterson (1959) method are associated with greater stability apart from average grain yield and adaptability to favorable and unfavorable environments.

Table 4. Estimate of stability parameters proposed by Plaisted and Peterson (1959) methodology for grain yield (bags of 60 kg/ha) for four *Coffea canephora* varieties assessed in five harvests in areas of high altitude in the Rio de Janeiro State, Brazil.

Varieties	θ_i	θ_i (%)
Emcapa 8111	93.78	35.25
Emcapa 8121	45.31	17.01
Emcapa 8131	74.10	27.85
Emcapa 8151	52.85	19.86

To improve the interpretation of the parameters of the Plaisted and Peterson (1959) method, since it is based on the analysis of variance and thus cannot highlight the most promising varieties, Kuang (1988) developed a method to distinguish stable and productive varieties. The varieties that show the lowest sum of the estimator θ_i (%) (ascending order) and the average (descending order) were the most indicated, presenting itself as more stable and productive. Thus, the best varieties in order of increasing magnitude were EMCAPA 8121, 8131, 8151, and 8111 (Table 5).

Table 5. Estimates of the stability parameter obtained by Kuang (1988) methodology, based on the θ_i scoring of Plaisted and Peterson (1959) methodology and the average grain yield for four *Coffea canephora* varieties assessed in five harvests in areas of high altitude in the Rio de Janeiro State, Brazil.

Varieties	θ_i (%)	Ranking θ_i	Average	Ranking of the average productivity	Sum of Kuang (1988) Ranking
Emcapa 8111	35.25	4	24.19	4	8
Emcapa 8121	17.01	1	37.30	2	3
Emcapa 8131	27.85	3	49.92	1	4
Emcapa 8151	19.86	2	33.94	3	5

The ranking obtained with the Kuang (1988) method showed similarity with that obtained by the Lin and Binns (1988) method, changing the positions of varieties EMCAPA 8131 and EMCAPA 8121. Vilhegas et al. (2001) observed that the Lin and Binns (1988) and Kuang (1988) methods pointed to the same maize genotype, while Daher et al. (2003) observed that the methods pointed to different genotypes of *P. purpureum*. This may be due to the number of genotypes, since the latter authors worked with a larger number of genotypes.

With the Eberhart and Russell (1966) method, the ideal cultivar was the one with high productivity, high adaptability ($\beta1_i = 1$) and good stability ($\sigma^2 di = 0$). In this study, cultivars with specific adaptability to favorable ($\beta1_i > 1$) or unfavorable ($\beta1_i < 1$) environments were not recommended, since the varieties showed no overall adaptability (Bl$_i$ was highly significant for all varieties). Thus, EMCAPA 8131 and 8151 varieties showed specific adaptation to favorable environments, with EMCAPA 8131 showing the highest value and EMCAPA 8111 and 8121 varieties displaying specific adaptations to unfavorable environments and EMCAPA 8111 showing the lowest value (Table 6). Regarding stability, the varieties did not show good stability with highly significant deviations, which was probably related to coffee biannuality.

Table 6. Estimates of adaptability and stability parameters obtained by Eberhart and Russell (1966) methodology for grain yield (bags of 60 kg/ha), assessed in four *Coffea canephora* varieties in five harvests in areas of high altitude in the Rio de Janeiro State, Brazil.

Variety	B_{li}	$\hat{\sigma}^2_{di}$	R^2_i (%)
Emcapa 8111	0.74**	46.084**	93.20
Emcapa 8121	0.95**	21.8339**	97.94
Emcapa 8131	1.23**	20.4498**	98.82
Emcapa 8151	1.07**	33.7045**	97.48

* and **Significant at 1 and 5% probability respectively by the *t*-test (Ho: $\beta1i = 1.0$) and F test (Ho: $\hat{\sigma}^2_{di} = 0$).

The Annicchiarico (1992) method estimates the confidence index, i.e., the probability of success or failure of a variety, associated with a significance level (α). Thus, the EMCAPA 8131 and 8121 varieties showed the highest potential yield, with a 75% confidence level, where they were respectively capable of a yield of 41.13 and 1.14% higher than the environmental average. On the other hand, EMCAPA 8111 and 8151 showed, with a 75% confidence level, the lowest potential yield, where they were only capable of a yield of 41.85 and 21.95% lower than the environmental average, respectively, and therefore not recommended for planting according to this method (Table 7). Botelho et al. (2010) observed the highest confidence index in the most productive arabica coffee genotypes in three regions of Minas Gerais State, Brazil.

Table 7. Estimation of the confidence index parameter obtained by Annicchiarico (1992) methodology, for grain yield (bags of 60 kg/ha) assessed in four *Coffea canephora* varieties in five harvests in the Rio de Janeiro State, Brazil.

Varieties	Average (%)	Deviation (%)	Wi
Emcapa 8111	63.96	20.03	58.482579
Emcapa 8121	103.95	10.30	101.137621
Emcapa 8131	148.08	25.42	141.129007
Emcapa 8151	84.01	21.77	78.055077

Significance level = 0.25.

There was consistency between the methods of Lin and Binns (1988), based on non-parametric statistics, and Annicchiarico (1992), based on the analyses of variance, in the classification of the best genotypes (EMCAPA 8131 and 8121) for both the adaptability and stability parameters and best average grain yield (Table 8). The EMCAPA 8131 variety was selected as the best among all, in three of the five methods studied, showing a CI of 60%, followed by EMCAPA 8121, which showed a CI of 40% for both the first and second position in the ranking. The EMCAPA 8111 variety showed the worst performance in all methods with a CI of 100% in the last position in the ranking.

Table 8. Ranking of four *Coffea canephora* varieties for grain yield (bags of 60 kg/ha) in areas of high altitude in the Rio de Janeiro State, Brazil, by different statistical methods and coincidence index (CI) for the highest frequency (parentheses value) of the position in the ranking.

Varieties	Lin Binns (1988)	Plaisted and Peterson (1959)	Kuang (1988)	Eberhart and Russel (1966)	Annicchiarico (1992)	CI%
Emcapa 8111	4	4	4	4	4	100 (4)
Emcapa 8121	2	1	1	3	2	40 (1, 2)
Emcapa 8131	1	3	2	1	1	60 (1)
Emcapa 8151	3	2	3	2	3	60 (3)

Under low-temperature conditions, clone 02 (early ripening) of the EMCAPA 8111 variety was less tolerant compared to clone 153 (late ripening) of the EMCAPA 8131 variety in relation to photosynthetic rate, chlorophyll fluorescence and zeaxanthin cycle (Partelli et al., 2009). Clone 02 was more efficient in the lipid classes and fatty acid composition (Scotti-Campos et al., 2014). This fact confirms the trend found in this study, where the late ripening clone group was often more productive under low temperature conditions, compared to early ripening clones. It is also noteworthy that *C. arabica* was better than *C. canephora* in practically all physiological and biochemical characteristics when subjected to low temperatures (Partelli et al., 2009; Scotti-Campos et al., 2014, Ramalho et al., 2014).

According to Cargnelutti Filho et al. (2007), genotypes with high productivity and associated with high instability and adapted to favorable environments are indicated by the Lin and Binns (1988) method modified by Carneiro (1998) and Annicchiarico (1992). Corrêa et al. (2006) also observed that these two methods pointed to the same Icatú genotypes cultivated in two regions in Minas Gerais. The Kuang (1987) method showed a tendency towards this same behavior. On the other hand, Eberhart and Russell (1966) and Plaisted and Peterson (1959) methods showed similarities in classifying the most productive genotypes in less stable varieties (Table 8).

The Eberhart and Russell (1966) and Lin and Binns (1988) methods were poorly correlated, and the use of these have involved only additional information with different approaches to the stability and adaptability studies (Silva and Duarte, 2006).

The Lins and Binns method has the advantage of classifying more stable and more productive varieties, since this method combines stability with the ability of varieties to show the smallest deviation in relation to maximum, in all study environments (Melo et al., 2007).

It is worth mentioning that the different performance between varieties probably involves genetic factors, which can influence the defense/adaptation mechanisms, since there is divergence between the clones (Fonseca et al., 2006). These factors, interacting with the environment are also related to ripening time.

Regarding ripening time, Partelli et al. (2009) observed in *C. canephora* clones a higher CO_2 assimilation rate and increased respiratory activity and starch accumulation in late ripening (clone 153) compared with early ripening (clone 02), when subjected to low temperatures.

Stored carbohydrates are important sources of energy and metabolic compounds that are used during plant development, especially in times that require rapid vegetative and reproductive growth (Silva et al., 2004a). Thus, *C. canephora* clones that have higher amounts of stored starches and respiratory enzyme activity may have a better ability to sustain the flowering process, after the harvest period, since it is a process that requires a lot of energy (Chaves Filho and Oliveira, 2008), and probably result in higher grain yield. In the study area of this research, the temperature in the winter period (prior to flowering), is still below that considered optimal for this species (Partelli et al., 2013), which could help to understand the factors that contributed to the better performance of the EMCAPA 8131 variety, late ripening, compared to medium and early ripening clones.

Regarding variety recommendation, the EMCAPA 8131 variety had average productivity close to *C. arabica* planted more in the region, designated Catuaí Vermelho144 (52 bags/ha), in research done in the same region of this study, with spacing of 2.5 x 1.0 m (Andrade et al., 2014). Moreover, in areas of higher altitudes, it is observed that coffee takes longer to complete its cycle which may contribute to increased quality of the grains (Silva et al., 2004b). Nevertheless, it is noteworthy that other studies related to management with the application of pruning and applying optimal densities, among other characteristics must be performed to reduce the biannual effect and thereby improve stability across harvests and regions to ensure the viability of this promising variety in high-altitude areas.

CONCLUSIONS

The EMCAPA 8131 variety showed the best stability and adaptability parameters of performance of grain yield over years, thus being promising for cultivation in areas of high altitude.

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