Universidade Federal Rural do Semi-Árido
Pró-Reitoria de Pesquisa e Pós-Graduação
https://periodicos.ufersa.edu.br/index.php/caatinga
ISSN 1983-2125 (online)

http://dx.doi.org/10.1590/1983-21252025v3812571rc

Scientific Article

Maturation cycle and fruit-to-bean conversion ratios in amazon robusta coffee cultivars

Ciclo de maturação e relações entre grãos processados e frutos de café robustas amazônicos

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ABSTRACT – This study aimed to characterize the outturn index, field outturn index, uniformity of maturity, and maturation cycle of fifteen *Coffea canephora* genotypes grown in different environments of the Western Amazon. Conducted in Amazonas (Itacoatiara and Manaus) and Rondônia (Porto Velho), the research evaluated the performance of ten cultivars and five promising genotypes from Embrapa. The genotype × environment interaction was significant, indicating different performance of clones across environments. Genotypic coefficients surpassed environmental ones, indicating a genetic influence on outturn indices and uniformity of maturity. The mean outturn index was 24.68%, and the field outturn index was 22.57%, with Itacoatiara having the highest mean values. The overall mean fruit uniformity of maturity was 63.02%, with Porto Velho achieving the highest mean uniformity value (71.78%). The cultivar BRS1216 exhibited the best performance for outturn indices and provided the highest gain from selection across environments, showing wide adaptability for the outturn index and adaptability to environments favorable for field outturn. Cultivars BRS3210 and BRS3220 achieved more than 82% uniformity of maturity across locations, with BRS3210 adapting to favorable environments and BRS3220 adapting to unfavorable ones. Additionally, BRS3220 had a high mean field outturn index, indicating wide adaptability and high phenotypic stability. The evaluated Amazon Robusta clones and cultivars displayed the expected maturation cycles.

Keywords: *Coffea canephora*. Uneven maturity. Genotype-environment interaction. Adaptability and stability. Selection gain.

RESUMO – O objetivo do trabalho foi caracterizar o índice de rendimento, o índice de rendimento de campo, a uniformidade e o ciclo de maturação de quinze genótipos de Coffea canephora cultivados em diferentes ambientes da Amazônia Ocidental. A pesquisa foi conduzida no Amazonas, em Itacoatiara e Manaus, e em Rondônia, em Porto Velho, Brasil. A interação entre genótipos x ambientes foi significativa, indicando que os clones apresentaram desempenho diferenciado entre os ambientes. A superioridade dos coeficientes genotípicos sobre aqueles de natureza ambiental sugere predominância dos efeitos genéticos na expressão dos índices de rendimento e da uniformidade de maturação. O índice de rendimento médio foi de 24,68% e o rendimento de campo de 22,57%, sendo o ambiente Itacoatiara com as maiores médias. A uniformidade de maturação de frutos teve uma média geral de 63,02%, com Porto Velho apresentando a maior uniformidade média (71,78%). A cultivar BRS1216 apresentou o melhor desempenho para os índices de rendimento e proporcionou maior ganho de seleção na média dos ambientes, apresentando adaptabilidade ampla para o índice de rendimento usual e adaptabilidade para ambientes favoráveis ao rendimento de campo. BRS3210 e BRS3220 se destacaram com mais 82% de uniformidade de maturação na média das localidades, porém a primeira com adaptabilidade para ambientes favoráveis e a segunda para ambiente desfavorável. BRS3220 também se destacou pela superioridade média para o rendimento de campo, exibindo ampla adaptabilidade e alta estabilidade fenotípica. Os clones avaliados apresentaram ciclos de maturação conforme o esperado.

Palavras-chave: *Coffea canephora*. Desuniformidade de maturação. Interação genótipos × ambientes. Adaptabilidade e estabilidade. Ganho de seleção.

Conflict of interest: The authors declare no conflict of interest related to the publication of this manuscript.

Received for publication in: March 19, 2024.
Accepted in: May 17, 2024.

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INTRODUCTION

Coffea canephora cultivation is gaining prominence in Brazil, particularly in Rondônia's technologically advanced coffee belt in the Amazon region. Other Western Amazon states are also expanding crop areas, boosting production (CONAB, 2024). Amazonas, for example, cultivates genotypes from Rondônia, known as "Amazon Robusta," including cultivars developed by Embrapa (TEIXEIRA et al., 2020; ROCHA et al., 2021).

Thriving in hot, humid climates (FERRÃO et al., 2007), *C. canephora* is diploid (2n = 2x = 22 chromosomes), and gametophytic self-incompatible, requiring cross-pollination for genetic variation. Breeding programs typically evaluate genetic variability and yield potential through progeny or clonal tests (FERRÃO et al., 2020; ROCHA et al., 2021). Clonal cultivars offer faster genetic gain at lower costs while reducing field heterogeneity (FERRÃO et al., 2020). Hybridization between 'Conilon' and 'Robusta' varieties can occur naturally or through directed breeding. Most *C. canephora* cultivars are propagated vegetatively, accelerating genetic gain and minimizing field heterogeneity (FERRÃO et al., 2020). These hybrids, combined with clonal propagation, can further enhance desired traits such as planting uniformity, earliness, and productivity.

While yield remains crucial in genotype selection (PARTELLI et al., 2021), yield components like the outturn index are gaining significance. This index reflects the ratio between mature fruit fresh weight and processed bean weight, indicating how much fruit material is converted into coffee beans. A higher index suggests a more efficient conversion, signifying superior quality and yield (FIALHO et al., 2022). This ratio directly impacts yield, as genotypes with similar yield potential may differ in husk and fruit moisture content (RAMALHO et al., 2014; LOURENÇO et al., 2022).

Green coffee yield depends on husk and bean weights, as well as fruit moisture content (FERRÃO et al., 2019). Uneven fruit maturity negatively affects yield, as harvesting unripe, ripe, overripe, and dry fruits together hinders processing (FERRÃO et al., 2019). Ideally, over 70-80% of fruits should be ripe at harvest, but achieving this uniformity is influenced by climate factors like temperature, humidity, and rainfall distribution (FERRÃO et al., 2007).

The outturn index, a measure of green coffee yield, also plays a role in determining coffee quality, which encompasses flavor, aroma, acidity, body, and overall sensory experience. The index impacts coffee quality by affecting quantitative aspects of yield, such as husk and bean weights, as well as fruit moisture (FERRÃO et al., 2019). Green coffee beans, with their higher moisture content, decrease farm profitability as their presence reduces coffee quality and the processed bean-to-fruit ratio (BORÉM, 2023).

Studies on *C. canephora* yield often rely on cherry fruit samples (GASPARI-PEZZOPANE et al., 2005; PARTELLI et al., 2021; FIALHO et al., 2022; LOURENÇO et al., 2022). However, these samples may not accurately represent the plant's condition at harvest. Therefore, considering fruit, husk, and bean weight ratios along with uniformity of maturity is a better production index. Achieving uniform flowering is challenging in adverse climates (SILVA et al., 2022), and *C. canephora* clones mature unevenly (TEIXEIRA et al., 2020). Consequently, field yield can differ significantly from yield based solely on ripe cherry fruits to processed coffee beans. However, limited literature exists on this topic.

The diverse Amazon environments, with varying soil and climate conditions (edaphic-climatic) and agricultural practices, necessitate a deeper understanding of genotype-by-environment interaction (G×E) on yield components. This interaction determines whether the effect of genotypes on a trait is simple (consistent across environments) or complex (varies across environments). It also reveals the adaptability type of clones (wide or specific to certain conditions) and their stability in the region. Only through detailed analysis can we select clones with optimal field performance. Lourenço et al. (2022) highlighted the complexity of environmental influence on coffee fruit weight reduction during drying, while weight reduction after pulping shows a simpler G×E interaction.

Considering these aspects, this study aimed to characterize the coffee outturn index, field outturn index, uniformity of maturity, and maturation cycle of fifteen pre-selected coffee genotypes in three Western Amazon environments. Therefore, we will analyze the genetic, environmental, and G×E effects on these trait expressions to identify superior clones for the region.

MATERIALS AND METHODS

Three *Coffea canephora* clone competition trials were established between December 2018 and March 2019 across three Western Amazonian locations. Two experiments were conducted in Amazonas State (AM), in the municipalities of Itacoatiara and Manaus, while the third took place in Rondônia State (RO), in the municipality of Porto Velho. The trials in Porto Velho (RO) and Itacoatiara (AM) were conducted under full sun with supplemental irrigation during the dry season. The trial in Manaus was carried out under dryland conditions.

A uniform planting density of 3,333 plants per hectare (3 x 1-meter spacing) was used in all locations. Standard management practices for *C. canephora* cultivation, including fertilization, soil amendments, and other cultural treatments, were followed as outlined by Ferrão et al. (2019). Evaluations were conducted during the second crop year. Tables 1 and 2 provide detailed descriptions of the locations and soil chemical properties from 0-20 cm and 20-40 cm depth layers for each environment.

A factorial arrangement of a randomized complete block design was used to quantify the effects of genotypes, environments, and genotype-by-environment interaction (G×E). The factors were genotypes and locations, with four replications of six plants per plot (18 m²). Fifteen genotypes were evaluated, including cultivars and clones selected for growth in the Western Amazon region, known as “Amazon Robusta.” Ten cultivars, identified by the prefix BRS – 1216, 2299, 2314, 2336, 2357, 3137, 3193, 3210, 3213, 3220, are grouped into three compatibility groups. The first number of the cultivar defines these groups, while the second number indicates maturation cycles: 1 – early, 2 – intermediate, and 3 – late (ESPINDULA et al., 2019; TEIXEIRA et al., 2020).

Table 1. Descriptions of the locations and soil and climate conditions (edaphic-climatic) for each environment.

Description	Environment		
	E1	E2	E3
Municipality	Itacoatiara, AM	Manaus, AM	Porto Velho, RO
Experimental area[@]	Sítio Jotapê	FAEXP/UFAM	FAEXP/Embrapa
Month/year of planting	March 2019	January 2019	December 2018
Geographic coordinates	3º04'15.2''S 58º28'2.1''W	2°39'09.0"S 60°03'15.9" W	8°48'05.5"S 63°51'02.7"W
Altitude (m)[#]	26.00	97.00	88.00
Irrigation type	Supplemental	Dryland	Supplemental
Soil classification	Clayey loam	Very clayey	Very clayey
Fertility level	Medium	Medium	Low
Topography	Flat	Flat	Flat
Annual rainfall (mm)[&]	3,046.6	2,733.5	2,216.0
Average temperature (ºC)[&]	27.3	27.1	26
Predominant climate[$]	Wet tropical climate (*Af*), without dry season (Köppen classification).		Wet tropical climate (*Am*), with dry winters (Köppen classification)

[#]Above sea level; [@] The experimental area in Itacoatiara (AM) is a commercial farm, while the trials in Manaus (AM) and Porto Velho (RO) were installed on experimental farms (FAEXP) of the *Universidade Federal do Amazonas* and Embrapa, respectively; [&]Climate data gathered from local automatic weather stations; [$]According to Alvares et al. (2013).

Table 2. Chemical properties in the 0-20 cm and 20-40 cm soil depth layers from the clonal competition trials in Itacoatiara, AM (E1); Manaus, AM (E2); and Porto Velho, RO (E3) - Brazil, during the 2021/2022 crop year.

Environment	Depth	pH[1]	P	K	Ca	Mg	Al+H	Al	O.M.[3]	V
	(cm)		mg dm^{-3}	------------------- cmolc dm^{-3} -------------------					g kg^{-1}	%
E1	0-20	5.74	26.54	0.23	2.77	0.32	3.05	0.00	28.6	52.00
	20-40	5.81	4.60	0.13	1.06	0.19	3.32	0.00	8.6	29.00
E2	0-20	5.30	18.9	3.57	1.90	0.60	2.70	0.13	n.a.[2]	48.00
	20-40	5.10	40.6	0.04	1.20	0.30	2.50	0.20	n.a.[2]	38.00
E3	0-20	5.40	2.00	0.09	1.48	1.02	13.53	0.87	51.0	16.00
	20-40	4.90	2.00	0.05	0.39	0.37	13.37	1.65	41.0	6.00

[1] pH in H_2O; [2] n.a.: not analyzed; [3] O.M.: Organic Matter.

Two others, RO-C125 and RO-C160, belong to the Conilon multiclonal cultivar BRS Ouro Preto (RAMALHO et al., 2014) and have an intermediate maturation cycle. The other three genotypes, Clone 09, Clone 12, and Clone 15, are not released on the market and are part of the breeding program of Embrapa-RO.

The outturn index was estimated by collecting only cherry fruits, respecting the maturation cycles of each genotype. Three 1-kg samples of washed cherry coffee were collected separately for each clone and dried naturally in raised drying beds for 10 to 15 days until reaching a moisture content near 12%, measured using a Gehaka® G610. After drying, the coffee samples (dry pods) were hulled using a manual Botini® coffee huller and then separated with Palinialves®. The outturn index was then estimated according to the following expression:

$$Outturn\ index\ (\%) = \left(\frac{m_{processed\ \ beans}}{m_{from\ \ field}}\right).F_{moist\ 12\%}.100$$

Where: $m_{processed\ beans}$ is the weight of beans after drying and hulling; $m_{fron\ field}$ is the weight of cherries when harvested in the field; $F_{moist\ 12\%}$ is the correction factor for 12% moisture, which is calculated as the ratio $\left(\frac{100 - M_{moist}}{100 - 12}\right)$, wherein M_{moist} represents the bean moisture content measured by the equipment; and 12 is the number used as reference moisture.

The uniformity of maturity ($U_{maturity}$) was calculated as the percentage difference between the total coffee sampled in the field and the unripe coffee, representing the proportion of ripe fruit. Samples consisted of 200 fruits collected randomly from the mixture of fruits on the harvesting cloth spread along the plant rows of each clone.

The field outturn index was calculated by weighting the outturn index by the uniformity of maturity ($U_{maturity}$) plus the outturn index for exclusively unripe fruit (*outturn index unripe*) multiplied by the proportion of unripe coffee harvested in the field (1 - $U_{maturity}$). This generates the following expression:

$$field\ outturn\ index\ (\%) = [outturn\ index\ .\ U_{maturity}] + [outturn\ index_{unripe}\ .(1 - U_{maturity})]$$

In this study, the outturn of unripe fruit adopted was 19% (GASPARI-PEZZOPANE et al., 2005). The number of days to maturity for each clone in the respective environments was quantified by the difference between the harvest day and the day of main flowering for the genotype.

After analyzing the homogeneity of variances in each environment, a combined analysis of variance was performed to test the significance of the effects of genotypes, environments, and G×E interaction. The effects of genotypes and environments were considered fixed. The Scott-Knott clustering test at a 5% significance level was used for comparing environments and clones in the decomposition of G×E. Additionally, the Pi criterion was employed to rank clones based on their proximity to the ideal genotype with the best performance across all evaluated environments, following Lin & Binns.

Upon detecting G×E, the analysis of adaptability and stability of the genotypes was quantified in different environments using the regression method proposed by Eberhart and Russell (1966). Adaptability was estimated by the linear regression coefficient (β_{1i}) for the i^{-th} genotype (i = 1, 2, ..., 15), while stability was evaluated by the regression deviations (sd_i^2) and complemented by the coefficient of determination (R_i^2) (CRUZ; REGAZZI; CARNEIRO, 2012). Locations were classified based on the environmental index (FINLAY; WILKINSON, 1963). Codified values were estimated for each location as the difference between the mean of the environment (j) and the overall mean of all environments; favorable environments had positive I_j values, and unfavorable ones had negative I_j values.

Genetic gains were predicted individually for each environment and combined, as described by Cruz, Regazzi and Carneiro (2012), aiming to increase the outturn and uniformity of maturity. The analyses were performed using the software Genes vs.1990.2023.61.

RESULTS AND DISCUSSION

Studies on genotype-by-environment interactions (G×E) investigate whether plant performance varies across distinct locations (CRUZ; REGAZZI; CARNEIRO, 2012). Significant G×E effects result in a non-additive relationship between genotype and environment, reflecting changes in plant performance based on the growing location (CRUZ; REGAZZI; CARNEIRO, 2012). In this study, the significant G×E effect indicated genotypes with differential performance across evaluated environments.

The environments examined showed greater differences in soil chemical characteristics than in climate conditions (Tables 1 and 2). These environments are classified as Am and Af climate types, both characterized by a tropical hot and humid climate, with low annual thermal amplitude and significant daily thermal amplitude from May to September (ALVARES et al., 2013). However, Porto Velho, RO, has lower base saturation, reflecting its lower fertility compared to other environments. Despite this, better plant performance in Porto Velho and Itacoatiara can be attributed to greater experience and familiarity with the crop (Tables 1, 2, and 3).

Additionally, differences in environmental quality among locations are associated with irrigation management, as Manaus used a dryland system, unlike the other locations (Table 1). Temperature and water deficits affect the physiological processes of coffee plants, restricting growth and development, causing leaf and fruit loss, poor fruit formation (DAMATTA et al., 2018), and consequently, reducing coffee bean yield.

The effects of genotypes, environments, and G×E were significant ($P < 0.01$) for the usual outturn index, the field outturn index, and the uniformity of maturity traits (Table 3). The significance observed in G×E effects indicates that *Coffea canephora* clones showed differentiated performance in the evaluated environments.

The three environments differed in terms of the outturn index and the uniformity of maturity. According to the Scott-Knott grouping, Itacoatiara - AM, and Porto Velho - RO were grouped, while Manaus - AM was separate for the field outturn index. Using the environmental quality index (FINLAY; WILKINSON, 1963), Itacoatiara and Porto Velho exceeded the environmental mean values for uniformity of maturity and field outturn index traits, classifying them as favorable environments, while Manaus was deemed unfavorable. Regarding the outturn index, only Itacoatiara was considered a favorable environment (Table 3). The greatest percentage differences among the mean values of the locations were 6.8% for the outturn index (between Manaus and Itacoatiara), 19.6% for uniformity of maturity (between Manaus and Porto Velho), and 7.4% for the field outturn index (between Manaus and Itacoatiara).

The residual coefficient of variation (CV_e), used to measure experimental accuracy, ranged from 3.15% for outturn traits to 12.88% for uniformity of maturity. For all three traits, the genetic coefficient of variation (CV_g) values exceeded those of CV_e, and the CV_g/CV_e ratios were all greater than 1. The genotypic coefficients of determination (H^2) were higher for the outturn indices (79% and 88%) than for uniformity of maturity (67%) (Table 3).

Fruit outturn and maturity characteristics showed good experimental accuracy, indicated by low CV_e values, compared to other studies (FERRÃO et al., 2022b; LOURENÇO et al., 2022). The CV_g values, along with the CV_g/CV_e ratio, indicated sufficient genetic variability to achieve gains from selection to increase coffee bean outturn and uniformity of maturity at harvest time (Table 3).

Table 3. Summary of analysis of variance, clustering of environments[$] , and estimated genetic parameters for outturn index (%), uniformity of maturity (%), and field outturn index (%) of Amazon Robusta coffee clones evaluated in the environments of Itacoatiara, AM (E1); Manaus, AM (E2); and Porto Velho, RO (E3), Brazil, during the 2022 harvest.

SV	DF	Outturn	uniformity of maturity	Field outturn
		F	F	F
Genotype (G)	9	8.80**	3.09**	4.88**
Environment (E)	2	65.69**	77.19**	85.81**
G x E Interaction	18	6.36**	6.73**	5.41**
Residue	60			
Total	89			
Overall mean		24.68	63.02	22.57
E1 mean		25.53a	63.86b	23.18 a
E2 mean		23.91c	53.41c	21.59b
E3 mean		24.58b	71.78a	22.93a
CV_e (%)		3.15	12.88	3.16
CV_g (%)		6.41	13.97	4.17
H^2		88.65	67.67	79.52
CV_g/Cv_e		2.03	1.08	1.32

**(P < 0.01) by the F-test; SV: sources of variation; DF: degrees of freedom; F: estimated F-statistic value; H^2: genotypic coefficient of determination; CV_e: experimental coefficient of variation; CV_g: genotypic coefficient of variation; [$]Averages followed by the same lowercase letters comprise homogeneous groups for the environments (E1, E2, and E3) by the Scott-Knott test (P < 0.05).

The genotypic coefficient of determination (H^2) represents the proportion of phenotypic variation due to genetic variations for a given trait, reflecting the difficulty of achieving selection gains based on genuine genetic variability in the population of interest (CRUZ; REGAZZI; CARNEIRO, 2012). The H^2 values indicated that uniformity of maturity was more affected by environmental factors than field outturn, despite high experimental accuracy. The outturn index is measured from samples composed solely of mature fruit, which is more uniform. The H^2 estimates demonstrated a predominant genetic contribution to the expression of the evaluated traits (Table 3). Values higher than 0.80 for outturn, as observed in other studies (FERRÃO et al., 2022b; LOURENÇO et al., 2022), highlight the importance of clone selection for gains in this yield component.

The ranking of clones by proximity to an ideal genotype of maximum performance (Pi) showed that clone BRS1216 had the highest outturns (27.96% and 24.24%) for the two indices, followed by clones RO-C125, BRS 3220, BRS3137, and Clone09, with varying order between the outturn indices considered in the study (Table 4).

Thus, the field outturn index is an important measure, more relevant to research than to everyday use by farmers. However, it influences productivity calculations, and when based only on ripe fruits, may not adequately represent reality (ROCHA et al., 2021; LOURENÇO et al., 2022).

The edaphoclimatic conditions of the Amazon region favor uneven maturation of coffee fruits, as fragmented breaks in water stress due to rainfall promote multiple flowering events (SILVA et al., 2022). Considering that the ideal harvest point starts at around 80% ripe beans (BORÉM et al., 2023), the clones with the highest uniformity in maturation were the BRS3210 and BRS3220 cultivars, each exhibiting 82% uniformity. They were followed by the BRS3193 cultivar with 75.75% and BRS3137 with 73.17% (Table 5).

On average, the field outturn index was 2.1% lower than the outturn index. The smallest difference between these indices occurred with clone BRS3210 in the favorable environment of Porto Velho (0.68%), while the greatest difference was with clone BRS1216 in the unfavorable environment of Manaus (6.24%).

The clustering of mean values grouped the genotypes into four groups for the outturn index, three to four groups for the field outturn index, and two to four groups for uniformity of fruit maturity. Genotype performances varied with environmental changes, indicating the complex nature of G×E for the three traits (Tables 4 and 5).

Due to G×E, genotype performance should be evaluated separately in each environment. The regression analysis method for investigating adaptability and phenotypic stability, proposed by Eberhart and Russell (1966), interprets the following estimates: i) the intercept ($ß0i$) as the mean of the i-th genotype; ii) the regression coefficient ($ß1i$) to determine if genotypes have wide ($ß1i = 1$) or specific adaptability to unfavorable or favorable environments ($ß1i > 1$); and iii) the variance component of the deviations from regression (s^2di) to identify genotypes with high phenotypic stability (predictability) ($s^2di = 0$) or low phenotypic stability ($s^2di > 0$). The coefficient of determination (R^2) also aids in selecting genotypes with low stability, where a high R^2 value indicates a good fit of the regression model in explaining trait variation as a function of environments (CRUZ; REGAZZI; CARNEIRO, 2012).

Despite the significant effects of G×E, slight changes are observed in the order of genotypes across different environments. Clone ranking could be interpreted using the stability index of Lin and Binns (Pi), which ordered the genotypes according to their performance in various environments (Tables 4 and 5). The cultivar BRS1216 had the highest mean outturn index at 27.96%, indicating that every 3.57 kg of fresh fruit harvested produced 1.00 kg of processed coffee beans. This means that a higher outturn index percentage indicates a lower fruit weight required to obtain processed coffee beans. The outturn index of Brazilian canephora coffee germplasm ranges from 17.04%, with a cherry coffee to processed coffee bean ratio of 5.87, to 31.25%, with a cherry coffee to processed bean ratio of 3.20 (PARTELLI et al., 2021; FERRÃO et al., 2022a; FERRÃO et al., 2022b).

Table 4. Performance of the Amazon Robusta coffee clones evaluated in the environments of Itacoatiara, AM (E1); Manaus, AM (E2); and Porto Velho, RO (E3), Brazil, in terms of outturn index and field outturn index. Averages were grouped according to the Scott-Knott test[&] at 5% probability.

Outturn (%)					
Cultivar	E1	E2	E3	Overall average	Pi
BRS1216	30.02Aa	27.89Ba	25.98Cb	27.96	1
BRS2299	24.88Ac	23.60Bc	23.48Bc	23.98	9
BRS2314	23.07Ad	21.97Ad	22.50Ad	22.51	15
BRS2336	24.00Ad	23.10Bd	22.63Bd	23.24	13
BRS2357	24.33Ad	22.70Bd	24.72Ac	23.91	10
BRS3137	27.37Ab	24.30Bc	24.07Bc	25.24	4
BRS3193	25.54Ac	24.04Bc	23.42Bc	24.33	7
BRS3210	24.94Ac	23.62Bc	22.85Bd	23.80	11
BRS3213	23.64Ad	22.22Bd	22.57Bd	22.81	14
BRS3220	26.10Ac	24.07Bc	25.55Ab	25.24	5
Clone09	27.39Ab	25.49Bb	28.03Aa	26.97	3
Clone12	23.42Bd	22.97Bd	25.63Ab	24.00	8
Clone15	23.79Ad	24.13Ac	23.45Ac	23.79	12
RO-C125	29.31Aa	25.84Cb	28.10Ba	27.75	2
RO-C160	25.19Ac	22.80Bd	25.73Ab	24.57	6
Field outturn (%)					
Cultivar	E1	E2	E3	Overall mean	Pi
BRS1216	26.60Aa	21.65Cb	24.48Ba	24.24	1
BRS2299	22.25Ac	21.55Ab	22.48Ab	22.09	9
BRS2314	21.20Ad	20.20Bc	21.75Ac	21.05	15
BRS2336	22.23Ac	20.15Bc	21.38Ac	21.25	14
BRS2357	21.65Bd	20.75Bc	22.63Ab	21.68	12
BRS3137	24.18Ab	23.18Ba	22.98Bb	23.44	4
BRS3193	23.65Ab	22.83Aa	22.50Ab	22.99	6
BRS3210	23.95Ab	22.75Ba	22.18Bc	22.96	7
BRS3213	22.48Ac	20.50Bc	21.80Ac	21.59	13
BRS3220	24.93Ab	23.25Ba	24.13Aa	24.10	2
Clone09	23.70Ab	21.13Bb	24.68Aa	23.17	5
Clone12	21.63Bd	20.28Cc	23.58Aa	21.83	10
Clone15	21.90Ad	21.73Ab	21.75Ac	21.79	11
RO-C125	24.53Ab	22.70Ba	24.55Aa	23.93	3
RO-C160	22.88Ac	21.35Bb	23.15Ab	22.46	8

[&]Averages followed by the same uppercase letters horizontally comprise statistically homogeneous groups. Averages followed by the same lowercase letters vertically comprise statistically homogeneous groups.

Table 5. Performance of the Amazon Robusta coffee clones evaluated in the environments of Itacoatiara, AM (E1); Manaus, AM (E2); and Porto Velho, RO (E3), Brazil, in terms of uniformity of maturity. Averages were grouped according to the Scott-Knott test[&] at 5% probability.

		Uniformity of maturity (%)			
Cultivar	E1	E2	E3	Overall mean	Pi
BRS1216	68.25Ab	30.25Bd	78.50Aa	59.00	7
BRS2299	55.50Bc	55.50Bc	77.00Aa	62.67	6
BRS2314	54.25Bc	40.25Cd	79.00Aa	57.83	8
BRS2336	65.00Ac	27.50Bd	66.00Ab	52.83	12
BRS2357	49.75Bc	47.25Bc	63.25Ab	53.42	14
BRS3137	61.75Bc	79.50Aa	78.25Aa	73.17	4
BRS3193	71.25Ab	76.75Aa	79.25Aa	75.75	3
BRS3210	83.75Aa	81.50Aa	83.00Aa	82.75	1
BRS3213	75.00Ab	47.00Bc	78.75Aa	66.92	5
BRS3220	83.75Aa	83.75Aa	78.75Aa	82.08	2
Clone09	56.50Ac	32.00Bd	63.00Ab	50.50	15
Clone12	58.00Ac	31.75Bd	68.5Ab	52.75	10
Clone15	60.50Ac	53.50Ac	61.75Ab	58.58	11
RO-C125	54.00Ac	54.00Ac	61.00Ab	56.33	13
RO-C160	60.75Ac	60.75Ab	60.75Ab	60.75	9

[&]Averages followed by the same uppercase letters horizontally comprise statistically homogeneous groups. Averages followed by the same lowercase letters vertically comprise statistically homogeneous groups. Pi: Clone ranking in terms of their proximity to an ideal genotype with the best performance for all the environments evaluated.

Other cultivars also stood out for their superior outturn (Table 4). The Amazon Robusta cultivar BRS3220, a full-sib of BRS1216, descends from a specific biparental cross between the Conilon and Robusta botanical varieties. Both are noted for their beverage quality, high yield potential, and resistance to orange rust (ESPINDULA et al., 2019; MORAES et al., 2020). The cultivar BRS3137, also with high yield potential, shows resistance to orange rust and nematodes, and tolerance to water stress (ESPINDULA et al., 2019). Clone RO C-125 is one of the highest-yielding genotypes of the multiclonal cultivar Conilon BRS Ouro Preto (RAMALHO et al., 2014) and is commonly used as a check variety in competition trials (MORAES et al., 2020).

Clone BRS3210 not only has greater uniformity of maturity across different environments (Table 5), but also stands out for yield potential, tolerance to water stress, disease resistance, and larger bean size (ESPINDULA et al., 2019; MORAES et al., 2020; TEIXEIRA et al., 2020). However, its lower outturn is associated with a higher percentage of husk compared to other Amazon Robusta cultivars (LOURENÇO et al., 2022).

For the outturn index, BRS1216 (with the best performance) and Clone 09 showed wide adaptability but low predictability of response (Table 6). The cultivar BRS3220, which also had a good outturn, demonstrated wide adaptability and high phenotypic stability. Genotypes BRS3137 and RO C-125 exhibited specific adaptability to the favorable environment (Itacoatiara), but RO C-125 had high predictability of response, whereas BRS3137 showed low predictability. However, BRS3137 should not be judged entirely undesirable in this aspect due to its high R^2 value (78.44%) (Table 6).

Regarding field outturn, clones BRS1216 and Clone 09, which had higher averages for this index, exhibited specific adaptability to the favorable environments of Itacoatiara and Porto Velho, but they had low stability. Nevertheless, they deserve attention as potential genotypes due to the high R^2 values obtained. The superior clones BRS3220 and RO C-125 are recommendable candidates, showing relative superiority, wide adaptability, and good predictability of response for field outturn (Table 6).

As for uniformity of maturity, cultivars BRS3220 and BRS3137 were recommended for the unfavorable environment of Manaus, while BRS3210 and BRS3193 exhibited specific adaptability to favorable environments (Itacoatiara and Porto Velho). However, only cultivar BRS3137 exhibited low predictability regarding uniformity of fruit maturity at harvest (Table 6).

The use of an outturn index in breeding programs to estimate yield in experimental plots is a desirable characteristic aimed at reducing costs and time in post-harvest evaluations (FIALHO et al., 2022). An outturn index that considers the fruit's maturity stage addresses the needs in equatorial regions where *C. canephora* growing areas frequently experience irregular crop maturation (BORÉM, 2023). In these regions, coffee is exposed to longer periods of light, allowing flower development nearly year-round (RAMÍREZ et al., 2013). Consequently, manual harvests and production costs increase significantly. On average, harvesting accounts for 30% of production costs and 40% of employed labor; therefore, greater harvest efficiency reduces operational costs.

Table 6. Estimates of adaptability, phenotypic stability of outturn, uniformity of maturity, and field outturn of Amazon Robusta coffee cultivars evaluated in Itacoatiara, AM; Manaus, AM; and Porto Velho, RO, Brazil.

Cultivar	Outturn				Uniformity of maturity				Field outturn			
	Mean	$ß_{1i}$	s^2d_i	R^2(%)	Mean	$ß_{1i}$	s^2d_i	R^2(%)	Mean	$ß_{1i}$	s^2d_i	R^2(%)
BRS1216	27.96	1.52^{NS}	4.97**	37.38	59.00	2.68**	0.11*	94.32	24.24	2.79**	0.91**	91.56
BRS2299	23.98	0.84^{NS}	0.12^{NS}	77.12	62.67	1.11^{NS}	0.12*	67.87	22.09	0.53^{NS}	-0.06^{NS}	86.05
BRS2314	22.51	0.67^{NS}	-0.15^{NS}	99.39	57.83	2.07**	0.01^{NS}	94.43	21.05	0.81^{NS}	0.16^{NS}	76.60
BRS2336	23.24	0.62^{NS}	0.31^{NS}	52.47	52.83	2.17**	0.01**	83.29	21.25	1.18^{NS}	0.03^{NS}	92.77
BRS2357	23.91	0.91^{NS}	1.06**	47.56	53.42	0.84^{NS}	0.13^{NS}	80.05	21.68	0.85^{NS}	0.59*	59.08
BRS3137	25.24	2.01**	1.32**	78.44	73.17	-0.15**	0.21**	2.02	23.44	0.37*	0.50*	24.24
BRS3193	24.33	1.02^{NS}	0.86*	57.76	75.75	0.10**	0.01^{NS}	5.01	22.99	0.27*	0.47*	14.69
BRS3210	23.80	0.91^{NS}	0.98**	49.54	82.75	0.09**	0.01^{NS}	66.65	22.96	0.36*	1.32**	11.63
BRS3213	22.81	0.90^{NS}	-0.11^{NS}	96.62	66.92	1.78*	0.01^{NS}	89.14	21.59	1.16^{NS}	-0.05^{NS}	96.23
BRS3220	25.24	1.21^{NS}	0.13^{NS}	87.17	82.08	-0.26**	0.01^{NS}	66.50	24.10	0.92^{NS}	0.04^{NS}	88.22
Clone09	26.97	1.05^{NS}	1.87**	41.75	50.50	1.72*	0.01^{NS}	94.25	23.17	1.97**	0.97**	83.64
Clone12	24.00	0.10**	3.88**	0.35	52.75	2.03**	0.01^{NS}	97.45	21.83	1.39^{NS}	2.57**	50.98
Clone15	23.79	-0.17**	0.04^{NS}	16.40	58.58	0.46^{NS}	0.01^{NS}	92.36	21.79	0.08**	-0.12^{NS}	51.85
RO-C125	27.75	2.08**	0.31^{NS}	92.59	56.33	0.36*	0.01^{NS}	67.15	23.93	1.23^{NS}	-0.07^{NS}	97.49
RO-C160	24.57	1.34^{NS}	2.34**	48.76	60.75	0.01**	0.01^{NS}	0.00	22.46	1.09^{NS}	0.03^{NS}	91.84

**(P < 0.01), *(P < 0.05), and ^{ns}(P > 0.05) by the *t*-test; $ß_{1i}$: regression coefficient for the response of the i-th genotype to environmental improvement, s^2d_i: mean squared deviation of regression for stability evaluation; R^2: coefficient of determination.

Complete stripping, the most common and inexpensive manual harvest practice, results in heterogeneous lots composed of unripe, ripe, overripe, and dry fruit (BORÉM, 2023). In some Amazon locations with restricted water access, supplemental irrigation management (SOLIMÕES et al., 2023) has been used to improve coffee maturity uniformity (FERNANDES et al., 2020).

Although characterizing outturn and maturity uniformity is the focus of some coffee plant studies (PARTELLI et al., 2021; FERRÃO et al., 2022a; FIALHO et al., 2022; LOURENÇO et al., 2022), few have evaluated these characteristics in different environments (FERRÃO et al., 2022b). Analyzing the adaptability and stability of clones helps understand their response and performance in specified locations, aiding the selection and recommendation of genotypes better adapted to outturn and fruit maturation (FERRÃO et al., 2022b).

The same clone exhibited different adaptability conditions for the two types of outturns (usual and field), as seen in cultivars BRS1216, BRS3137, and RO C-125 (Table 6). In contrast, cultivar BRS3220 stood out by exhibiting wide adaptability and good predictability of response for outturn and maturity uniformity. However, in Rondônia, clone BRS3220 showed specific adaptability to unfavorable environments (LOURENÇO et al., 2022).

Evaluating genetic progress or gain from selection (GS) predicts changes in the mean of the original population due to selecting the best genotype(s) according to the adopted selection procedure. Selecting cultivar BRS1216 for the outturn index and field outturn index resulted in mean increases of 11.82% and 5.82%, respectively, across all environments. The greatest genetic advances occurred in the Itacoatiara trial, with gains of 16.84% for outturn and 13.71% for field outturn (Table 7).

Regarding uniformity of maturity, selection based on the cultivar BRS3210 resulted in a mean gain from selection of 21.19% across all environments, with a notable genetic progress of 49.18% in the unfavorable environment of Manaus (Table 7). The presence of multiple flowerings in this coffee species leads to fruits at different maturation stages on a single plant simultaneously (MIRANDA; DRUMOND; RONCHI, 2020). This diversity complicates determining the optimal harvest time and affects the beverage quality (CAMPUZANO-DUQUE; BLAIR, 2022). The maturation of *C. canephora* beans involves complex morphological and biochemical changes, and proper maturation is crucial for high-quality coffee. Premature or delayed harvesting can compromise taste and quality.

In canephora coffee clones from the Amazon region, various characteristics exhibit significant genetic variability, creating opportunities to select superior genetic materials (SOUZA et al., 2017). Both the outturn trait and uniformity of maturity trait showed good possibilities for genetic progress, even considering genetic materials in advanced breeding stages (Table 7). Coffee bean yield in *C. canephora* has shown good gains from selection and a positive correlation with field performance. This has allowed a reduction in the size of the original parent plant population, saving time and resources during the breeding program phases (ROCHA et al., 2021).

Table 7. Estimated gains from selection for *Coffea canephora* cultivars with superior outturn, uniformity of maturity, and field outturn across three Western Amazonian environments: Itacoatiara, AM (E1); Manaus, AM (E2); and Porto Velho, RO (E3), Brazil, during the 2021/2022 crop year.

	Selection for superior outturn (BRS1216)		
Environment	GS	GS%	New mean
E1	4.30	16.84	30.02
E2	3.74	15.66	27.89
E3	1.36	5.53	25.98
All environments	2.92	11.82	27.96
	Selection for superior uniformity of maturity (BRS3210)		
Environment	GS	GS%	New mean
E1	17.25	27.00	83.75
E2	26.27	49.18	81.50
E3	10.21	14.23	83.00
All environments	13.35	21.19	82.75
	Selection for superior field outturn (BRS1216)		
Environment	GS	GS%	New mean
E1	3.18	13.71	26.60
E2	0.05	0.22	21.65
E3	1.42	6.17	24.48
All environments	1.33	5.89	24.24

GS: predicted genetic (in units of trait); GS%: predicted genetic (in percentage).

The coffee maturation cycle refers to the phenological interval between the main flowering of the clone and when the fruit is ready for harvest, aiming to harvest the maximum amount of ripe coffee. The experimental accuracy (CV_e%) of these evaluations in the three locations ranged from 0.17% (RO C-125) to 3.41% (BRS3137) – data not shown. The biggest difference in the maturation cycle between the earliest clone (BRS3193) and the latest clone (BRS2336) was 46 days in Itacoatiara (Table 8).

Table 8. Days to maturity from flowering to the harvest of Amazon Robusta coffee cultivars evaluated across environments in the states of Amazonas and Rondônia, Brazil.

	Number of days to maturity					
Clone	Itacoatiara (E1)	Manaus (E2)	Porto Velho (E3)	Mean#	Cycle	CV%
BRS1216	291	297	305	297.7b	intermediate	1.93
BRS2299	272	284	289	281.7c	early	2.53
BRS2314	297	299	309	301.7b	intermediate	1.74
BRS2336	311	309	325	315.0a	late	2.26
BRS2357	294	302	313	303.0a	late	2.57
BRS3137	275	288	299	287.3c	early	3.41
BRS3193	265	277	281	274.3c	early	2.48
BRS3210	279	297	299	291.7b	intermediate	3.08
BRS3213	297	297	301	298.3b	intermediate	0.63
BRS3220	272	271	280	274.3c	early	1.47
Clone09	297	297	293	295.7b	intermediate	0.64
Clone12	309	299	324	310.7a	late	3.31
Clone15	299	292	293	294.7b	intermediate	1.05
RO-C125	277	287	287	283.7c	early	1.66
RO-C160	282	281	282	281.7c	early	0.17
Mean	288	292	299	292.6		

#Averages followed by the same letter comprise a single group according to the Scott-Knott test at 5% probability; CV%: coefficient of variation (in percentage).

BRS2336 was the latest genotype in all environments, with a mean maturation cycle of 315 days, while BRS3193 was the earliest in Manaus and Porto Velho, with a mean cycle of 274 days. According to clustering, the genetic materials were divided into three maturity groups: the early group had a maturation period from 274 to 287 days, including BRS2299, BRS3137, BRS3193, BRS3220, RO-C125, and RO-C160; the intermediate group ranged from 291 to 301 days, including BRS2314, BRS3210, BRS3213, Clone09, and Clone15; and the late group ranged from 303 to 315 days, including BRS2336, BRS2357, and Clone12. Notably, although BRS2314 was classified in the intermediate group, its mean maturation cycle exceeded 300 days, with a period from flowering to harvest in Porto Velho lasting 309 days.

Length of fruit maturation is crucial in coffee growing as it affects coffee bean quality and harvest outturn. In the Western Amazon, early maturity genotypes are generally harvested in May, around 238 days (34 weeks). Intermediate cycle genotypes are typically harvested in June, reaching 287 days (41 weeks). Late-maturity clones are harvested in July, taking around 315 days (45 weeks) (SOUZA et al., 2015).

In this study, clones not classified in the expected maturity groups were clustered in the nearest class, and for some environments, they were classified as expected, such as clones BRS2299, BRS3220, and BRS2314 (Table 8). For instance, a clone previously understood as early was classified as intermediate rather than late, indicating a small deviation in the expected maturation cycle. Although the maturation cycle is not individualized for clones RO C-125 and RO C-160, they are categorized as having an intermediate cycle by the classification of the multiclonal cultivar Conilon BRS Ouro Preto they compose. In this study, they were understood to have an early cycle (RAMALHO et al., 2014).

Overall, the duration of each stage and, consequently, the time required for full fruit maturity depends not only on genetic material but also on factors such as altitude, temperature, water availability, and accumulated degree days, indicating a multifactorial effect (PETEK; SERA; FONSECA, 2009).

CONCLUSION

Genotype-by-environment interaction (G×E) significantly influences traits such as outturn and uniformity of maturity. The superiority of genotypic coefficients over environmental ones highlights a substantial breeding contribution, even in challenging environments.

There are clones with both wide and specific adaptability and good predictability of response for the outturn index, field outturn index, and uniformity of maturity. Improvements through selection are possible, achieving gains of 11.82% for outturn, 21.19% for uniformity of maturity, and 5.89% for field outturn indices.

The cultivar BRS1216 stands out for its high outturn, while cultivars BRS3210 and BRS3220 show uniformity of maturity higher than 80%. Overall, the clones exhibited maturation cycles within the expected range.

ACKNOWLEDGMENTS

The authors thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) and the Fundação de Amparo à Pesquisa do Estado do Amazonas (FAPEAM) for their support to the Graduate Program in Tropical Agronomy at UFAM. We also extend our gratitude to the Empresa Brasileira de Pesquisa Agropecuária (Embrapa) of Rondônia and Amazonas States. Finally, we thank the Experimental Farm of Manaus, AM, at FAEXP/UFAM and the farm Jotapê for their field support and provision of facilities for the study development.

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