

Genotype x environment interaction, adaptability and stability of 'Piel de Sapo' melon hybrids through mixed models

Edicleide Macedo da Silva¹, Elaine Welk Lopes Pereira Nunes¹, José Maria da Costa¹, Anânkia de Oliveira Ricarte¹, Glauber Henrique de Sousa Nunes¹ and Fernando Antonio Souza de Aragão^{2*}

Abstract: *The aim of this study was to evaluate the genotypic performance of twelve Piel de Sapo melon hybrids in the Mossoró-Assú agricultural region, state of Rio Grande do Norte, Brazil, using mixed models. Adaptability and stability of the predicted genotypic values were studied by the Harmonic Mean of the Relative Performance of Genotypic Values (HMRPGV) procedure. The traits evaluated were yield ($Mg\ ha^{-1}$) and soluble solids content ($^{\circ}Brix$). The genotype x environment interaction was significant for the two variables in all the hybrid groups evaluated, with predominance of the complex part of the interaction, and this makes the selection process more difficult. Considering the genotypic values predicted, the HMRPGV method allowed identification of hybrids with greater genotypic adaptability and stability. The experimental hybrids HP-09 and HP-06 were more promising for growing in the Mossoró-Assú agricultural region since they have high stability and adaptability, as well as high yield and soluble solids.*

Keywords: *Cucumis melo, BLUP, HMRPGV, yield, soluble solids.*

INTRODUCTION


Melon is among the main types of fruit produced and exported by Brazil; it is in the first place in volume and second in export value (Kist et al. 2018). The Northeast region of Brazil is responsible for more than 95% of production and all exports of Brazilian melon (IBGE 2019). The states of Ceará and Rio Grande do Norte are not only the main producer states, but are also responsible for more than 99% of Brazilian melon exports (MDIC 2019). The main reasons for the prominence of the semiarid Northeast region in melon production are favorable edaphic and climatic conditions, allowing up to three melon crop seasons per year (Oliveira et al. 2017a).

Most of the fruit produced in the Mossoró-Assú agricultural region is of the yellow type (Canary melon/yellow melon). However, in recent years, companies have given greater attention to diversifying the product offering, growing other types of fruit, among them, the Piel de Sapo type melon (Aragão et al. 2019). This type of melon is characterized by its dark green skin, white-colored flesh, and, above all, high soluble solids content ($> 11\%$). The Piel de Sapo melon is mainly exported to Spain, which is the main consumer of this type of fruit.

Crop Breeding and Applied Biotechnology
19(4), 402-411, 2019
Brazilian Society of Plant Breeding.
Printed in Brazil
<http://dx.doi.org/10.1590/1984-70332019v19n4a57>

***Corresponding author:**

E-mail: fernando.aragao@embrapa.br

 ORCID: 0000-0002-4041-7375

Received: 20 December 2018

Accepted: 01 August 2019

¹ Universidade Federal Rural do Semi-Árido, Departamento de Ciências Agronômicas e Florestais, 59.625-900, Mossoró, RN, Brazil

² Embrapa Agroindústria Tropical, 60.511-110, Fortaleza, CE, Brazil

Due to the growth of the production sector, companies have invested in studies to develop melon cultivars of the Piel de Sapo type. However, before the new cultivar is released, it must be tested in different years and locations, because only that way will there be greater reliability in recommending a possible hybrid for the diverse growing conditions of this vegetable crop in the Northeast semiarid region (Gurgel et al. 2005). Furthermore, due to the different environmental conditions in which melon hybrids are evaluated in Rio Grande do Norte, an accentuated genotype x environment (G x E) interaction is expected, and this plays an important role in phenotype manifestation. In plant breeding programs, evaluation of the G x E interaction is indispensable.

When this interaction occurs, the best genotype in one environment may not be the best in another, and this creates difficulties in the selection process (Oliveira et al. 2017b). The G x E interaction arises from the differentiated response of genotypes in what are considered to be contrasting environments. Thus, the breeder seeks genotypes with greater genotypic value in relation to the values of the environment and of the G x E interaction (Pereira et al. 2016). When an interaction is detected, measures must be adopted to attenuate its effect. One of the most common alternatives is the use of genotypes with high phenotypic stability and adaptability, for it is possible to identify genotypes with predictable performance that are able to respond in a consistent way to environmental variations (Cruz et al. 2014). They can be selected for broad or specific conditions (Carvalho et al. 2016).

Studies on the G x E interaction are necessary because they allow identification of high yielding genotypes that are highly adaptable and stable, which will guide the researcher in recommendation of the most adequate genotypes for a determined region. There are many methods used in studies of adaptability and stability of cultivars. However, more recently, methods that consider the effect of genotypes to be random based on mixed models (REML/BLUP – Restricted Maximum Likelihood/Best Linear Unbiased Prediction) have been suggested. These methods provide important information regarding parameters indispensable for selection (Freitas et al. 2013), and this is a trend in plant breeding (Pimentel et al. 2014). Currently, the REML/BLUP mixed model developed by Henderson (1950, 1953, 1975) is the most adequate procedure for genetic evaluation in breeding, and it has become necessary for understanding the G x E interaction (Pires et al. 2011). This methodology allows consideration of correlated errors within locations, taking adaptability and stability into consideration as a criterion for selection of superior genotypes (Santos et al. 2016). The Harmonic Mean of the Relative Performance of Genotypic Values (HMRPGV) method, idealized by Resende (2004), has been applicable to different crops, both perennial and annual, for the purpose of stability and adaptability studies. However, there are no reports of the use of this method on the melon crop.

The HMRPGV method presents adaptability, stability, and yield simultaneously in a single measure in the scale of the trait assessed (Resende 2004, Rosado et al. 2012). This model is responsible for determining the effects of environments and blocks within environments considered as fixed effects, thus taking into account all the degrees of freedom available in the sources of variation in reference to environments and blocks within environments. That way, when predicted genotypic values are obtained for a given genotype in each environment, the data from all the environments are used simultaneously. Therefore, the random effects are predicted with greater precision, allowing greater reliability since the entire dataset is used (Resende 2004).

Some studies are reported in the literature in which the G x E interaction was analyzed in melon (Nunes et al. 2011a, Nunes et al. 2011b, Silva et al. 2011, Aragão et al. 2015, Guimarães et al. 2016). However, none of these studies were performed with the Piel de Sapo melon using the method described above. Another question is that few studies have been performed concerning adaptability and stability in cucurbits, in spite of the importance of these vegetable crops (Restrepo et al. 2013). Within this context, the aim of the present study was to evaluate the genotypic performance of Piel de Sapo melon hybrids in the Mossoró-Assú agricultural region in the state of Rio Grande do Norte, Brazil, using mixed models.

MATERIAL AND METHODS

Genotypes

Ten experimental hybrids and two commercial hybrid F_1 , 'Sancho' (Syngenta[®]) and 'Grand Prix' (Sakata[®]), were evaluated. All the hybrids are of the Piel de Sapo type, have a white-colored mesocarp, and have andromonoecious

sexual expression. All the hybrids are derived from the melon breeding program of the Universidade Federal Rural do Semi-Árido (UFERSA).

Experiments

The trials were conducted from September to November 2016 in the municipalities of Mossoró (lat 5° 11' S, long 37° 21' W, alt 18 m asl, t_{min} 22.7 °C and t_{max} 35 °C, Ferralsol), Baraúna (lat 05° 05' S, long 37° 38' W, alt 94 m asl, t_{min} 23.3 °C and t_{max} 31.2 °C, Haplic Lixisol), Assú (lat 5° 34' S, long 36° 54' W, alt 27 m asl, t_{min} 22.1 °C and t_{max} 33.3 °C, Fluvisol), and Ipanguassu (lat 5° 05' S, long 37° 38' W, alt 94 m asl, t_{min} 21.9 °C and t_{max} 32.9 °C, Fluvisol), all within the Mossoró-Assú agricultural region, in different crop seasons. There was no rainfall during the experiments.

Experiments were conducted in randomized complete blocks with three replications. Each plot was composed of one 6.0 m length row, with rows spaced at 2.0 m. The space between plant holes was 0.3 m, with one plant per hole. Each plot had 20 plants and the plants at the ends of the plot formed the border area. The 8 center plants in the row were used for data collection.

Seeds were sown in 200-cell polystyrene trays on September 5, 2016, in a greenhouse in order to obtain seedlings. The cells were filled with a commercial substrate with a coconut husk fiber base. The trays were irrigated twice a day using inverted sprinklers until reaching fifteen days after sowing (DAS), the time frame adequate for transplanting seedlings in the experimental field. Seedlings were transplanted on September 20, 21, and 22 of 2016 in the municipalities of Mossoró, Baraúna, and Assú/Ipanguassu, respectively. In all the trials, the soil was tilled using a disk plow to a depth of 20 cm and then a pass with a leveling disk. Soon after, ridges were raised with a between row distance of 2.0 m and a height of 20 cm. A drip irrigation system was then set up; emitters were spaced at 0.30 m, with a diameter of 16 mm and discharge rate of 1.7 L h⁻¹.

Crop management practices, such as agricultural chemical applications and weeding, were performed according to crop needs, following the recommendations for the crop and the standard crop practices for melon in the state of Rio Grande do Norte (Nunes et al. 2011a, Nunes et al. 2011b). The fruit was harvested manually, removed from the plants with use of a pocketknife, identified with marker pens, and placed in raffia bags for transport for post-harvest analyses.

The commercial yield and soluble solids of the fruit were evaluated; these traits were considered the most important for the crop from the commercial perspective according to the producers themselves. Commercial yield was obtained by weighing all the commercial fruit gathered from the plot. Commercial fruit was considered that which had adequate size for the Piel de Sapo type melon (> 2.0 kg). Total soluble solids content was measured by removing a sample of approximately 2/3 the thickness of the flesh in the equatorial region of the fruit in the direction of the fruit cavity. The sample was manually pressed until part of the juice was deposited in a digital refractometer (Digital Refractometer Palette 100), in which soluble solids content was determined. Eight melons per plot were sampled for measurement of soluble solids content.

Statistical analyses

Statistical analysis was performed according to statistical model 54 of the software SELEGEN-REML/BLUP (Resende 2007). This model corresponds to $y = X_b + Z_g + W_c + e$, where y , b , g , c , and e correspond to the vectors of data, of fixed effects (means of blocks through the environments), of genotype effects (random), of effects of the G x E interaction (random), and of random errors, respectively. X , Z , and W are the incidence matrixes for b , g , and c , respectively.

The distributions and structures of means (E) and variances (Var) adopted were:

$$E \begin{bmatrix} y \\ g \\ c \\ e \end{bmatrix} = \begin{bmatrix} Xb \\ 0 \\ 0 \\ 0 \end{bmatrix}; \text{Var} \begin{bmatrix} g \\ c \\ e \end{bmatrix} = \begin{bmatrix} 1\sigma_g^2 & 0 & 0 \\ 0 & 1\sigma_c^2 & 0 \\ 0 & 0 & 1\sigma_e^2 \end{bmatrix}$$

The model was fitted from the following mixed model equations:

$$\begin{bmatrix} X'X & X'Z & X'W \\ Z'X & Z'Z + \lambda_1 & Z'W \\ W'X & W'Z & Z'Z + \lambda_2 \end{bmatrix} \times \begin{bmatrix} \hat{b} \\ \hat{g} \\ \hat{c} \end{bmatrix} = \begin{bmatrix} X'y \\ Z'y \\ W'y \end{bmatrix}$$

where $\lambda_1 = \frac{\sigma_e^2}{\sigma_g^2} = \frac{1 - h_g^2 - c^2}{h_g^2}$; in which $h_g^2 = \frac{\sigma_g^2}{\sigma_g^2 + \sigma_c^2 + \sigma_e^2}$ corresponds to the individual heritability (considering the average plot) in the broad sense in the block; $c^2 = \frac{\sigma_c^2}{\sigma_g^2 + \sigma_c^2 + \sigma_e^2}$ corresponds to the coefficient of determination of the effects of the G x E interaction; σ_g^2 is the genotypic variance among hybrids (genotypes) of melon; σ_c^2 is the variance of the G x E interaction; σ_e^2 is the residual variance among plots; and $r_{gloc} = \frac{\sigma_c^2}{\sigma_g^2 + \sigma_c^2} = \frac{h_c^2}{h_g^2 + c^2}$ corresponds to the genotypic correlation of the genotypes, through the environments.

The iterative estimators of the variance components by REML through the algorithm EM are: $\hat{\sigma}_e^2 = \frac{[y'y - \hat{b}'X'y - \hat{g}'Z'y - \hat{c}'W'y]}{[N-r(x)]}$;
 $\hat{\sigma}_g^2 = \frac{[\hat{g}'g + \hat{\sigma}_e^2 tr C^{22}]}{s}$; $\hat{\sigma}_c^2 = \frac{[\hat{c}'c + \hat{\sigma}_e^2 tr C^{33}]}{s}$; where C^{22} and C^{33} come from $C^{-1} = \begin{bmatrix} C_{11} & C_{21} & C_{31} \\ C_{21} & C_{22} & C_{32} \\ C_{31} & C_{23} & C_{33} \end{bmatrix}^{-1} = \begin{bmatrix} C^{11} & C^{21} & C^{31} \\ C^{21} & C^{22} & C^{32} \\ C^{31} & C^{23} & C^{33} \end{bmatrix}$, in which

C is the matrix of coefficients of the mixed model equations; tr is the trace matrix operator; r(x) is the matrix rank X; and N, q, and s are the total number of data, number of genotypes, and number of G x E combinations, respectively.

The empirical BLUP predictors of the free genotypic values of the interaction were obtained by means of this model, given by $\hat{\mu} + \hat{g}$, where $\hat{\mu}$ is the mean of all the environments and \hat{g} is the genotypic effect free of the GxE interaction. For each environment j, the genotypic values are predicted by $\hat{\mu}_j + \hat{g}_1 + \hat{g}e_{ij}$, where $\hat{\mu}_j$ is the mean of the environment j, \hat{g}_1 is the genotypic effect, and $\hat{g}e_{ij}$ is the G x E interaction concerning genotype i.

Combined selection, simultaneously considering the trait in question, stability, and the adaptability of the melon genotypes (hybrids) is given by the statistic: Harmonic Mean of the Relative Performance of Genotypic Values $HMRPGV_1 = \frac{n}{\sum_{j=1}^n \frac{1}{Vg_{ij}}}$, where n is the number of locations where genotype i was evaluated and Vg_{ij} is the genotypic

value of genotype i in environment j, expressed as a proportion of the mean of this environment.

Considering multiple traits, the sum of the standardized HMRPGV of yield and soluble solids was used for greater stability and adaptability in recommendation of genotypes. The standardization was done by dividing each HMRPGV by the standard deviation of the trait.

RESULTS AND DISCUSSION

In the final step of breeding programs, genotypes with potential for becoming new cultivars should be evaluated. Consequently, experiments must be carefully conducted to reduce experimental error since the lower the estimate of experimental error, the greater the possibility of detecting differences among the materials evaluated. The coefficient of variation (CV) is still the measure most used to compare experimental accuracy. In the present study, the estimates of the CVs for the two traits evaluated are within the range observed for the crop in other cultivar evaluation studies performed in the Mossoró-Assú agricultural region (Gurgel et al. 2005). Considering an initial classification proposed by Lima et al. (2004) for melon, the values found for yield can be classified as low for the trials in Mossoró and Assú, and medium for the trials in Baraúna and Ipanguassu. For soluble solids, the values were considered low in all the trials, except for the trial in Assú, which was considered medium (Table 1).

In recent years, the use of selective accuracy has become popular to check the quality of an experiment. This parameter simultaneously considers the experimental coefficient of variation, the number of replications, and the genotypic coefficient of variation. This accuracy shows high precision in inferences of the genotypic means because it has the property of indicating the correct ordering of the cultivars for purposes of selection (Resende 2002). According to the classification presented by Resende and Duarte (2007), the accuracy for yield was very high ($0.90 \leq A_{c_g} \leq 0.99$)

Table 1. Components of variances, accuracy, genotypic and residual coefficient of variation obtained through REML of yield and soluble solids evaluated in Piel de Sapo melon hybrids grown in four environments in the municipalities of the Mossoró-Assú agricultural region

Effect	Yield (Mg ha ⁻¹)			
	Environment ¹			
	MOS	BAR	ASS	IPA
Complete model	154.32	151.61	138.69	164.10
Genotypes (G)	171.26 (16.94 ^{**})	151.62 (0.01)	158.27 (19.58 ^{**})	175.99 (11.89 ^{**})
$\hat{\sigma}_g^2$	36.92	0.41	26.25	37.01
$\hat{\sigma}_e^2$	15.73	28.64	9.27	23.77
$\hat{\sigma}_p^2$	52.65	29.04	35.52	60.78
h_{mg}^2	0.87	0.04	0.89	0.82
Ac_g	0.93	0.20	0.94	0.91
CV_g	20.31	2.01	16.59	19.50
CV_e	13.26	16.95	9.86	15.62
Mean	29.91	31.56	30.88	31.20

Effect	Soluble solids (%)			
	Environment			
	MOS	BARz	ASS	IPA
Complete model	39.74	36.08	59.41	24.36
Genotypes (G)	52.59 (12.85 ^{**})	73.26 (37.18 ^{**})	61.39 (1.98)	47.29 (22.93 [†])
$\hat{\sigma}_g^2$	0.91	2.40	0.48	0.96
$\hat{\sigma}_e^2$	0.54	0.30	1.40	0.27
$\hat{\sigma}_p^2$	1.44	2.70	1.89	1.23
h_{mg}^2	0.84	0.96	0.51	0.91
Ac_g	0.91	0.98	0.71	0.95
CV_g	8.34	12.48	5.50	7.77
CV_e	6.40	4.40	9.34	4.13
Mean	11.43	12.42	12.67	12.60

¹ LRT: Maximum likelihood ratio test; **, *: significant by the Chi-square test at (p<0.01) and (p<0.05), respectively; $\hat{\sigma}_g^2$: genetic variance; $\hat{\sigma}_e^2$: environmental variance; $\hat{\sigma}_p^2$: phenotypic variance; h_{mg}^2 : mean heritability; Ac_g : selective accuracy; CV_g : genetic coefficient of variation, CV_e : environmental coefficient of variation. ² MOS-Mossoró; BAR- Baraúna; ASS-Assú; IPA- Ipanguassu.

for the trials in Mossoró, Assú, and Ipanguassu. In the trial in Baraúna, accuracy was low ($0.10 \leq Ac_g \leq 0.40$). For soluble solids, the accuracies were very high in Mossoró, Baraúna, and Ipanguassu and high in Assú ($0.70 \leq Ac_g \leq 0.85$). Thus, the accuracy estimates confirm that the trials were conducted with high accuracy, except for yield in Baraúna (Table 1). This lower accuracy may be explained by the occurrence of greater intensity of leaf miner flies (*Liriomyza* spp.). In certain plots, even with the use of insecticide control measures, there was greater yield variation in the plots of the same genotype, that is, higher experimental error.

In individual analyses, an effect of genotypes was observed for the two traits in three (Mossoró, Assú, and Ipanguassu) of the four trials, showing the genetic heterogeneity among the hybrids evaluated. The only exception was the trial conducted in Baraúna. This result ratifies the estimates observed for accuracy and the coefficient of variation observed in each trial (Table 1), indicating that the lower the experimental accuracy, the lower the possibility of detecting differences among the treatments by reducing the power of the test (rejecting the null hypothesis H_0 when it is false) and, consequently, committing type II error (accepting the null hypothesis H_0 when it is false). In assessment trials of Canary/yellow honeydew melon (Gurgel et al. 2005), Galia melon (Nunes et al. 2011a), and Cantaloupe melon (Nunes et al. 2011b) performed in the Mossoró-Assú agricultural region, differences were observed among genotypes for yield and soluble solids.

As trials were conducted in different municipalities, combined analysis was performed aiming to study the G x E interaction. Thus, as in most of the trials, an effect of genotypes was found for the two traits, confirming heterogeneity

among the hybrids. An effect of the G x E interaction was also found for the two variables. The presence of the interaction shows the differentiated response of the hybrids in the different municipalities.

The c^2 component measures how much the interaction affected phenotypic variance. A greater effect of the interaction was found on soluble solids (43%) than on commercial yield (30%). In general, the interaction has had a greater effect on soluble solids, confirming the estimates of the present study. The G x E interaction in melon has been observed in studies for assessment of melon hybrids in the Brazilian semiarid region (Gurgel et al. 2005, Nunes et al. 2011a, Nunes et al. 2011b), as well as in trials for assessment of families (Silva et al. 2011, Aragão et al. 2015, Guimarães et al. 2016).

Two components compose the G x E interaction. The first, called the simple part in the interaction, occurs due to the magnitudes of the differences in variability among the genotypes, and the second, called complex, depends on the genetic correlation of the genotypes in the environments (Cruz and Castoldi 1991). Mean genotypic correlation of hybrid performance, through environments (r_{loc}), provides the reliability of how constant the ordering of the hybrids is, and, indirectly, it indicates the participation of the complex part in the interaction. Considering the performance of environments two by two, Mossoró and Barauna had the highest correlation for yield, and Mossoró and Assu for soluble solids (Figure 1). The estimate of r_{loc} was found to be greater for commercial yield compared to soluble solids, corroborating the estimates of the c^2 component. For the two traits, nearly absolute predominance was found for the complex part in the interaction for the two traits evaluated, making the selection process more difficult (Table 2). Previous studies in the Mossoró-Assu agricultural region indicated the predominance of the complex part in the interaction for yield and soluble solids (Silva et al. 2011, Aragão et al. 2015, Guimarães et al. 2016). Only Nunes et al. (2011a) found predominance of the simple part in the interaction, upon measuring soluble solids in Galia melon hybrids evaluated in nine environments of the same agricultural area.

The G x E interaction plays a fundamental role in the selection process. One of the implications of the effect of the interaction can be observed in the estimates of the component of genetic variance. That is because in evaluations in only one location or environment, the estimate of genetic variance is overestimated by the component of the G x E interaction that cannot be estimated. In contrast, in evaluations in more than one environment, the component of the interaction can be estimated and separated from the genetic effect. This result was ratified for the two traits upon observing the estimates of the components of variance of the individual and combined analyses (Tables 2 and 3). The G

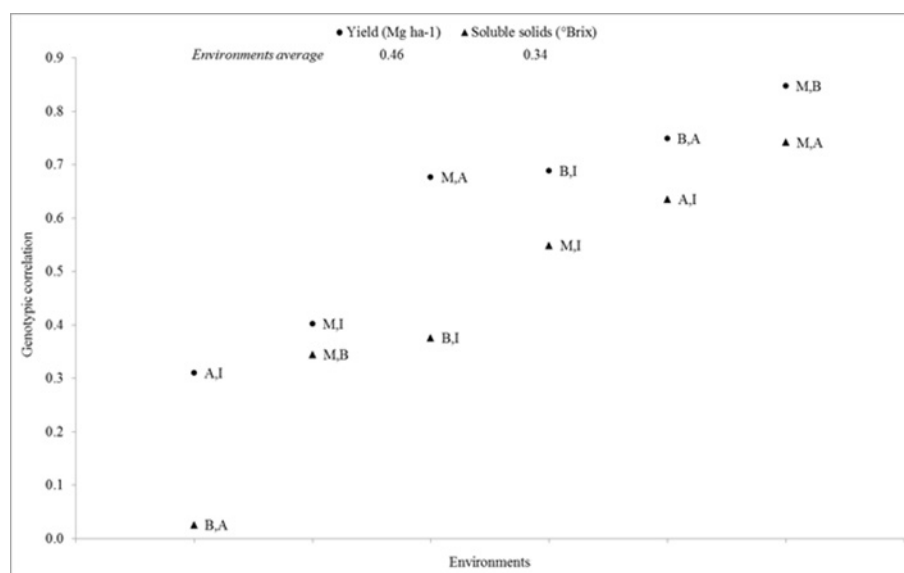


Figure 1. Scatter plot of the genotypic correlation coefficients obtained from yield (Mg ha⁻¹) and soluble solids (°Brix) of the 12 Piel de Sapo melon hybrids, evaluated in the municipalities of Assu (A), Barauna (B), Mossoró (M), and Ipanguassu (I).

Table 2. Analysis of deviance, variance components, accuracy, genotypic and residual coefficient of variation obtained through individual REML, considering combined analysis of Piel de Sapo melon hybrids evaluated in four municipalities of the Mossoró-Assú agricultural region

Effect	Yield (Mg ha ⁻¹)			Soluble solids (°Brix)		
	Deviance	LRT	σ ²	Deviance	LRT	σ ²
Complete model	616.32			179.39		
Genotypes (G)	623.07	6.75**	11.43	183.76	4.37*	0.40
G x E (environment)	633.87	17.55**	13.65	213.33	33.94**	0.79
Residual			19.42			0.63
Phenotypical			44.50			1.82
h ² _{mg}			0.69			0.62
Ac _g			0.83			0.79
c ²			0.30			0.43
r _{gloc}			0.46			0.34
CV _g			10.94			5.17
CV _e			14.27			6.45
Mean			30.89			12.28

¹ LRT: Maximum likelihood ratio test; σ²: Variance component. ***: significant by the Chi-square test at (p<0.01) and (p<0.05), respectively. h²_{mg}: mean heritability; Ac_g: selective accuracy; c²: coefficient of determination of the effects of the GxE interaction; r_{gloc}: correlation among the environments; CV_g: genetic coefficient of variation; CV_e: environmental coefficient of variation.

Table 3. Stability of genotypic values (HMGV), adaptability of genotypic values (RPGV) and stability and adaptability of genotypic values (HMRPGV) of Piel de Sapo melon hybrids conducted in four environments of the Mossoró-Assú agricultural region

Hybrid	Traits			
	Yield (Mg ha ⁻¹)		Soluble solids (°Brix)	
	HMGV ¹	RPGV	HMGV	RPGV
HP-01	27.48	0.91	12.41	1.01
HP-02	31.25	1.03	12.69	1.04
HP-03	35.29	1.15	10.94	0.89
HP-04	29.23	0.98	12.80	1.05
HP-05	25.16	0.82	11.52	0.94
HP-06	34.72	1.13	12.62	1.03
HP-07	29.02	0.94	12.39	1.01
HP-08	30.63	0.99	11.57	0.95
HP-09	32.99	1.07	13.79	1.13
HP-10	32.19	1.04	11.65	0.98
Grand Prix	35.50	1.15	12.54	1.02
Sancho	24.44	0.79	11.71	0.96
	HMRPGV (HMRPGV*OM)			
	Yield (Mg ha ⁻¹)	Soluble solids (°Brix)		Sum
HP-01	0.89 (27.55)	1.01 (12.42)		25.04
HP-02	1.01 (31.20)	1.04 (12.71)		26.70
HP-03	1.14 (35.27)	0.89 (10.98)		25.54
HP-04	0.95 (29.26)	1.04 (12.83)		26.11
HP-05	0.82 (25.17)	0.94 (11.55)		23.22
HP-06	1.12 (34.73)	1.03 (12.65)		27.61
HP-07	0.94 (29.06)	1.01 (12.42)		25.53
HP-08	0.99 (30.63)	0.95 (11.61)		25.05
HP-09	1.07 (33.02)	1.12 (13.80)		28.58
HP-10	1.04 (32.18)	0.95 (11.66)		25.53
Grand Prix	1.15 (35.51)	1.02 (12.55)		27.74
Sancho	0.96 (24.46)	0.95 (11.71)		24.75

¹ HMGV - harmonic mean of genotypic values; RPGV - relative performance of genotypic values; HMRPGV - harmonic mean of relative performance of genotypic values; and OM - overall mean.

x E interaction is directly related to gain from selection. The consequence of this fact is that the estimates of gain from selection are overestimated, disguising the real gains obtained in the selection process.

One of the ways of attenuating the G x E interaction is identifying those productive materials with greater stability and adaptability in the group evaluated. Resende (2004, 2007) developed the HMRPGV-BLUP method, which uses genotypic data that incorporate stability, adaptability, and the mean of the trait of interest in a single statistic.

The HMGV (harmonic mean of genotypic values) allows selection based on stability and yield. The HMGV are the very values of yield or soluble solids, penalized by instability, which facilitates selection of higher yielding hybrids with better fruit quality that are, at the same time, more stable. The HMGV penalizes instability when genotypes are evaluated in diverse environments, resulting in a new mean adjusted by this penalization. Thus, for yield, the experimental hybrids HP-03, HP-06, and HP-09, as well as the control 'Grand Prix', were the genotypes that most stood out. For soluble solids content, only the experimental hybrid HP-09 was one of greater expression (Table 3).

Melon growing requires application of high production technology with modern techniques of irrigation and intense application of fertilizers and agricultural chemicals. Within this context, melon breeders seek not only stability but also new cultivars with high adaptability. To identify this trait, appropriate methods must be used and among those available is relative performance of genotypic values (RPGV), which capitalizes on the ability of each genotype to respond to improvement of the environment. Thus, for yield, the experimental hybrids HP-03, HP-06, and HP-09 once more stood out, as well as the control 'Grand Prix'; whereas for soluble solids content, the hybrid HP-09 stood out (Table 3).

Table 4. Estimates of genetic means of Piel de Sapo melon hybrids evaluated in four municipalities of the Mossoró-Assú agricultural region

Hybrid	Yield (Mg ha ⁻¹)				
	$\mu + \hat{g} + \hat{g}_e/\text{Environment}^1$				\hat{g}
	MOS	BAR	ASS	IPA	
HP-01	22.02	28.49	30.10	31.41	28.67
HP-02	36.20	31.39	33.93	25.61	31.58
HP-03	37.49	36.00	33.51	34.41	34.33
HP-04	28.59	30.54	23.26	38.26	30.33
HP-05	23.88	26.72	28.16	22.65	26.62
HP-06	33.07	34.54	36.76	34.70	33.88
HP-07	26.43	31.70	29.10	29.35	29.55
HP-08	31.56	31.53	29.35	30.19	30.71
HP-09	30.11	32.74	32.91	36.88	32.64
HP-10	32.84	32.43	32.19	31.33	31.89
Grand Prix	33.78	35.40	36.98	35.98	34.47
Sancho	22.97	27.24	24.28	23.65	26.00
Soluble solids (^o Brix)					
HP-01	11.61	12.98	11.95	13.23	12.44
HP-02	11.86	13.07	12.94	12.98	12.71
HP-03	9.65	11.49	11.43	11.45	11.00
HP-04	11.67	12.98	13.11	13.60	12.84
HP-05	10.38	11.88	12.04	11.95	11.56
HP-06	11.54	12.91	13.38	12.81	12.66
HP-07	11.22	12.69	12.77	13.04	12.43
HP-08	10.37	12.10	12.02	12.01	11.62
HP-09	13.02	14.49	14.07	13.66	13.81
HP-10	12.05	9.02	13.97	12.85	11.97
Grand Prix	11.89	13.18	12.23	12.93	12.56
Sancho	11.91	12.28	12.09	10.71	11.75

¹MOS: Mossoró; BAR: Baraúnas; ASS: Assú; IPA: Ipinguassu.

The harmonic mean of relative performance of genotypic values (HMRPGV) method, based on genotypic values predicted through mixed models, combines stability, adaptability, and yield in a single statistic (Resende 2002). A HMRPGV*OM provides the genotypic values of each genotype penalized by instability and capitalized by adaptability. For this criterion, the hybrids that stood out for yield were HP-03, HP-06, and HP-09, plus the cultivar 'Grand Prix'; whereas for soluble solids content, the hybrid HP-09 stood out (Table 3).

In order to recommend genotypes, considering multiple traits, the sum of the standardized HMRPGV for the two traits studied was used. Thus, the best experimental hybrids were HP-09 and HP-06 (Table 3), which had performance similar to the 'Grand Prix' commercial control.

Producers agree that melon hybrids need to produce at least 25.0 Mg ha⁻¹ to be profitable. Combined analysis shows that all the hybrids met this requirement. All of them surpassed the control 'Sancho'. This hybrid was used as a control because it was the genetic material of the Piel de Sapó type most planted in the past decade in the Mossoró-Assú agricultural region. This fact indicates that the new hybrids obtained in the breeding programs, such as the experimental hybrids, as well as the hybrid 'Grand Prix' recently released, are superior to the cultivar 'Sancho'. This shows that the work of researchers in increasing the yield of the most recent hybrids has been successful. In relation to soluble solids, it should be noted that the minimum value for trade in Europe, especially in the Spanish market, of the Piel de Sapó melon is 11%. All the hybrids had values that meet this level of quality (Table 4).

CONCLUSIONS

The harmonic mean of relative performance of genotypic values (HMRPGV), based on genotypic values predicted through mixed models, allows identification of Piel de Sapó melon hybrids with genotypic adaptability and stability.

The experimental hybrids HP-09 and HP-06 were most promising for growing in the Mossoró-Assú agricultural region as they have high genotypic stability and adaptability, as well as high yield and soluble solids.

ACKNOWLEDGMENTS

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brazil (CAPES), that granted graduate study scholarships to student Edicleide Macedo da Silva, and by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for research scholarships to Glauber Henrique de Sousa Nunes (309882/2017-6) and to Fernando Antonio Souza de Aragão (Process 312139/2017-9).

REFERENCES

- Aragão FAS, Celin EF, Silva JCV, Nunes GHS and Queiróz MA (2019) Melhoramento genético e biotecnologia no meloeiro. In Guimarães MA and Aragão FAS (eds) **Produção de melão**. Editora UFV, Viçosa, p. 63-82.
- Aragão FAS, Nunes GHS and Queiróz MA (2015) Genotype x environment interaction of melon families based on fruit quality traits. **Crop Breeding and Applied Biotechnology** 15: 79-86.
- Carvalho LPDE, Farias FJC, Morello CDEL and Teodoro PE (2016) Uso da metodologia REML/BLUP para seleção de genótipos de algodoeiro com maior adaptabilidade e estabilidade produtiva. **Bragantia** 75: 1-8.
- Cruz CD and Castoldi FL (1991) Decomposição da interação genótipos x ambientes em partes simples e complexas. **Revista Ceres** 38: 422-430.
- Cruz CD, Carneiro PCS and Regazzi AJ (2014) **Modelos biométricos aplicados ao melhoramento genético**. UFV, Viçosa, 668p.
- Freitas ILJ, Amaral Junior AT, Viana AP, Pena GF, Cabral PDAS, Vittorazzi C and Silva TRDAC (2013) Ganho genético avaliado com índices de seleção e com REML/Blup em milho-pipoca. **Pesquisa Agropecuária Brasileira** 48: 1-8.
- Guimarães IP, Dovale JC, Antônio RP, Aragão FAS and Nunes GHS (2016) Interference of genotype-by-environment interaction in the selection of inbred lines of yellow melon in an agricultural center in Mossoró-Assu, Brazil. **Acta Scientiarum Agronomy** 38: 1-9.
- Gurgel FL, Krause W, Schmildt ER and Sena CN (2005) Indicação de híbridos de melão para o Rio Grande do Norte. **Revista Ceres** 52: 115-123.
- Henderson CR (1950) Estimation of genetics parameters. **Annals of Mathematical Statistics** 21: 309-310.
- Henderson CR (1953) Estimation of variance and covariance components. **Biometrics** 9: 226-252.
- Henderson CR (1975) Best linear unbiased estimation and prediction under a selection model. **Biometrics** 31: 423-447.
- IBGE – Instituto Brasileiro de Geografia e Estatística (2019) Sistema IBGE de recuperação automática – SIDRA. Available at: <<http://www.sidra.ibge.gov.br>>. Accessed on May 3, 2019.

Genotype x environment interaction, adaptability and stability of 'Piel de Sapo' melon hybrids through mixed models

- Kist BB, Carvalho C, Treichel M and Santos CE (2018) **Brazilian fruit yearbook**. Editora Gazeta, Santa Cruz do Sul, 88p.
- Lima LL, Nunes GHS and Bezerra Neto F (2004) Coeficientes de variação de algumas características do meloeiro: uma proposta de classificação. **Horticultura Brasileira** **22**: 14-17.
- MDIC – Ministério do Desenvolvimento, Indústria e Comércio Exterior (2019) Available at: <<http://comexstat.mdic.gov.br/>>. Accessed on April 30, 2019.
- Nunes GHS, Andrade Neto RC, Costa Filho JHDA and Melo SBDE (2011b) Influência de variáveis ambientais sobre a interação genótipos x ambientes em meloeiro. **Revista Brasileira de Fruticultura** **33**: 1194-1199.
- Nunes GHS, Santos Júnior H, Grangeiro LC, Bezerra Neto F, Dias CTS and Dantas MSM (2011a) Phenotypic stability of hybrids of Gália melon. **Anais da Academia Brasileira de Ciências** **83**: 1421-1433.
- Oliveira FIC, Nunes AC, Silva FD and Silva GTMA (2017a) A cultura do melão. In Figueirêdo MCB, Gondim RS and Aragão FAS (eds) **Produção de melão e mudanças climáticas: sistemas conservacionistas de cultivo para redução das pegadas de carbono e hídrica**. Embrapa, Brasília, p. 17-31.
- Oliveira IJDE, Atroch AL, Dias MC, Guimarães LJ and Guimarães PEDEO (2017b) Seleção de cultivares de milho quanto à produtividade, estabilidade e adaptabilidade no Amazonas. **Pesquisa Agropecuária Brasileira** **52**: 455-463.
- Pereira TCV, Schmit R, Haveroth EJ, Melo RCDE, Coimbra JLM, Guidolin A F and Backes RL (2016) Reflexo da interação genótipo x ambiente sobre o melhoramento genético de feijão. **Ciência Rural** **46**: 411-417.
- Pimentel AJB, Guimarães JFR, Moacil ADES, Resende MDV, Moura LM, Carvalho JRASDE and Ribeiro G (2014) Estimação de parâmetros genéticos e predição de valor genético aditivo de trigo utilizando modelos mistos. **Pesquisa Agropecuária Brasileira** **49**: 882-890.
- Pires IE, Resende MDV, Silva RL and Resende Júnior MFR (2011) **Genética florestal**. UFV, Viçosa, 317p.
- Resende MDV (2002) **Genética biométrica e estatística no melhoramento de plantas perenes**. Embrapa Informação tecnológica, Brasília, 975p.
- Resende MDV (2004) **Métodos estatísticos ótimos na análise de experimentos de campo**. Embrapa Florestas, Colombo, 57p.
- Resende MDV (2007) **Matemática e estatística na análise de experimentos e no melhoramento genético**. Embrapa Florestas, Colombo, 362p.
- Resende MDV and Duarte JB (2007) Precisão e controle de qualidade em experimentos de avaliação de cultivares. **Pesquisa Agropecuária Tropical** **37**: 182-194.
- Restrepo MPV, Grisales SO, Cabrera FAV and Garcia DB (2013) Phenotypic stability of traits associated with fruit quality in butternut squash. **Agronomía Colombiana** **31**: 147-152.
- Rosado AM, Rosado TB, Alves AA, Laviola B and G and Bhering LL (2012) Seleção simultânea de clones de eucalipto de acordo com produtividade, estabilidade e adaptabilidade. **Pesquisa Agropecuária Brasileira** **47**: 1-8.
- Santos ADOS, Ceccon G, Teodoro PE, Correa AM, Alvarez RDEC, Silva JFDA and Alves VB (2016) Adaptabilidade e estabilidade de genótipos de feijão caupi ereta via REML/BLUP e GGE Biplot. **Bragantia** **75**: 299-306.
- Silva JM, Nunes GHS, Costa GG, Aragão FAS and Maia LKR (2011) Implicações da interação genótipos x ambientes sobre ganhos com a seleção em meloeiro. **Ciência Rural** **41**: 51-56.