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Estimating Elephant-Grass Adaptability and Stability for Energy-Biomass Production by Regression Models

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Abstract

In Brazil, elephant grass has been researched for energy generation, as it represents an alternative energy source by virtue of its biomass production. The present study was developed to examine the adaptability and energy-biomass production stability of 73 elephant-grass genotypes under a biannual-harvest regime, using the methodologies proposed by Eberhart and Russell and Cruz. The experiment was carried out at the northern region of Rio de Janeiro State, Brazil. Nine harvests and subsequent evaluations were performed at six-month intervals. Each harvest was considered an environment of genotype evaluation. After the plants were harvested, their dry matter yield (DMY) was estimated in t ha^{-1} harvest. Combined analysis of variance revealed highly significant effects of genotypes, harvests, and genotype × harvest interaction, by the F test. In five of the nine evaluated harvests, the genotypes had an average dry matter yield greater than the overall mean. The method of Eberhart and Russel was effective in identifying highly adaptable elephant-grass genotypes with high dry matter production stability throughout the nine harvests. When the method of Cruz was used, no genotypes were found comprising high yielding ability, adaptability to unfavorable environments, responsiveness to environmental improvement, and high stability altogether.

Keywords: bisegmented regression, genotype × environment interaction, *Pennisetum purpureum*

1. Introduction

The world's energy mix is majorly constituted by finite sources—fossil fuels, mainly—which are responsible for the emission of a large amount of pollutant gases. These gasses aggravate the greenhouse effect, posing a threat to the earth's climate balance (Morais et al., 2009). Considering this reality and given the large demand for energy in the next years, there has been an increased awareness about a possible energy crisis in the future. Therefore, alternative energy sources, especially those which are renewable and environmentally sustainable, have been sought to reduce dependence on fossil fuels (Silva et al., 2018a; Freitas et al., 2018; Magalhões et al., 2017; Oliveira et al., 2017).

In this scenario, the exploitation of plant biomass emerges as an excellent alternative, because in addition to being a renewable energy source, this material carries economic and environmental advantages compared with the use of fossil fuels (Ibrahim et al., 2014). Within this context, elephant grass (*Pennisetum purpureum* Schum.), a plant of the family Poaceae, has caught the interest of researchers mainly because of its high efficiency in fixating atmospheric CO2 during the photosynthesis process. Further, the species has a high dry matter yield and a short cycle, coupled with biomass-quality characteristics such as elevated fiber contents. More specifically, it contains high levels of high-carbon components with high calorific value such as cellulose and lignin, as well as a high carbon/nitrogen (C/N) ratio (Paterlini et al., 2013; Mohammed et al., 2015).

In spite of all of these favorable characteristics, research focusing on the breeding of elephant grass for energy generation can be considered still incipient, especially when compared with that of many commodities. In this regard, the State University of Northern Rio de Janeiro (UENF) develops an elephant-grass breeding program aimed at the assessment of the viability of use of plant biomass and at the selection of high-yielding genotypes with appropriate biomass quality to be used in the generation of energy (Silva et al., 2017, 2018a, 2018b; Daher et al., 2014; Menezes et al., 2016; Sousa et al., 2016, 2017; Araújo et al., 2017).

In forage-plant breeding programs, in which plants are harvested several times during evaluations, a trait to be taken into account is the productive stability of genotypes. Breeders should select those that best adapt to different environmental conditions. In this way, materials with greater mean yield at different harvests and with smaller decreases in production during the periods of environmental stress should be identified and selected for the continuity of the breeding program (Sobrinho et al., 2005). Nevertheless, this selection may often be undermined by the presence of genotype × environment (G × E) interactions, which result in genotypes showing different responses across distinct environments (Cunha et al., 2013).

Despite its importance, a simple analysis of the G × E interaction does not provide complete and precise information about the behavior of each genotype under various environmental conditions. Evaluations of phenotypic adaptability and stability should be undertaken to identify genotypes with a predictable behavior and which are responsive to environmental changes under specific or broad conditions (Cruz et al., 2014). There are several methods for the estimate of stability; *e.g.*, regression analysis. Among these, the simple linear (Eberhart & Russel, 1996) and two-segment (Cruz et al., 1989) regression methods stand out. In this case, the means and coefficients of regression and deviation in relation to the adjusted line are used as estimates of adaptability and stability of the studied genetic material (Cruz et al., 2012). However, there are no studies of regression applied to elephant grass for energy production in various environments.

On these bases, the present study proposes to evaluate the adaptability and energy-biomass production stability of 73 elephant-grass genotypes under a biannual-harvest regime, using the methodologies proposed by Eberhart and Russell (1996) and Cruz et al. (1989).

2. Method

The experiment was developed at the State Center for Research on Agro-energy and Waste Utilization (PESAGRO-RIO/CEPAAR), located in Campos dos Goytacazes, northern region of Rio de Janeiro State, Brazil (21°44′47″S and 41°18′24″W, and an average altitude of 11 m). The climate of the region is anAw type, according to the Köppen (1948) classification, and the soil is characterized as a dystrophic Argisol (EMBRAPA, 2006).

Seventy-three genotypes of elephant grass that compose the Active Germplasm Bank of the State University of Northern Rio de Janeiro (BAG-UENF) were evaluated (Table 1). Considering the expected genetic variability of these elephant grass genotypes, due to their cultivation on different continents, genetic divergences were characterized and estimated using RAPD and ISSR markers (Lima et al., 2011), as well as discrete morphological, quantitative and qualitative characteristics (Oliveira et al., 2014). The experiment was implemented in February 2011, using three-bud cuttings aligned with the base of a cutting touching the apex of another, which were planted into 10-cm-deep furrows. Upon planting, the area was fertilized with 100 kg ha^{-1} P_2O_5 (single superphosphate). Ten months after planting, all genotypes were cut near the soil level (uniformity cut) and the area was top-dressed using 25 kg ha^{-1} ammonium sulfate and 25 kg ha^{-1} potassium chloride.

Table 1. List of the 73 genotypes from the Active Germplasm Bank of elephant grass of UENF

Id.	Genotype	Id.	Genotype	Id.	Genotype
1	Elefante Colômbia	26	Mole de Volta Grande	51	Cameroon
2	BAGCE 2	27	Porto Rico	52	BAGCE 69
3	Três Rios	28	Napier	53	Guaçu
4	Napier Volta Grande	29	Mercker Comum	54	Napierzinho
5	Mercker Santa Rita	30	Teresopólis	55	IJ 7125 cv EMPASC 308
6	Pusa Napier Nº 2	31	Taiwan A-46	56	IJ 7136 cv EMPASC 307
7	Gigante de Pinda	32	Duro de Volta Grande	57	IJ 7139
8	Napier Goiano	33	Mercker Comum Pinda	58	Goiano
9	Mercker S. E. A	34	Turrialba	59	CAC 262
10	Taiwan A-148	35	Taiwan A-146	60	Ibitinema
11	Porto Rico 534-B	36	Taiwan A-121	61	Australiano
12	Taiwan A-25	37	Vrukwona	62	13 AD
13	Albano	38	P 241 Piracicaba	63	10 AD IRI
14	Pusa Gigante Napier	39	BAGCE 51	64	07 AD IRI
	Elefante Híbrido 534-A	40	Elefante Cach.Itapemirim	65	Pasto Panamá
16	Costa Rica	41	Capim Cana D'África	66	BAGCE 92
17	Cubano Pinda	42	Gramafante	67	05 AD IRI
18	Mercker Pinda	43	Roxo	68	13 AD IRI
19	Mercker Pinda México	44	Guaçu/I.Z.2	69	03 AD IRI
20	Mercker 86 México	45	Cuba-115	70	02 AD IRI
21	Napier S.E.A.	46	Cuba-116	71	08 AD IRI
22	Taiwan A-143	47	King Grass	72	BAG 86
23	Pusa Napier Nº 1	48	Roxo Botucatu	73	BAG 87
24	Elefante de Pinda	49	Mineirão IPEACO		
25	Mineiro	50	Vruckwona Africano		

The experiment was set up as a randomized block design with two replicates. Each experimental unit was represented by a genotype planted in 5.5-m rows spaced 2 m apart, totaling 11 m^2. The usable area was the 2-m^2 central part of the plot. Nine harvests, followed by evaluations, were performed at six-month intervals from June 2012 to December 2016. Each harvest was considered an assessment environment. After harvest, the plant's dry matter yield (DMY) was estimated in t/ha.harvest as the product of the fresh matter weight of whole plants (kg) from each usable area (2 m^2), obtained using a digital crane scale, and the dry matter percentage (%DM), obtained by sampling those plants.

To estimate the %DM, two tillers were collected at random, cut into pieces of 2 to 3 cm, placed in a paper bag, weighed and taken to a forced ventilation oven at 65 °C for 72 hours. Then the samples were weighed again to obtain the air-dried sample (ADS), according to the methodology described by Silva and Queiroz (2002). Subsequently, the dry samples were ground in a Willey mill with a 1 mm sieve and packed in plastic bags for the determination of the kiln dried sample (KDS). The ASE was then obtained using 2 g of each ground sample, which were kept in an oven at 105 °C for 12 hours and then weighed. Thus, %DM was estimated from the multiplication of ADS and KDS.

After the homogeneity of residual variances was tested by Hartley's test, a combined analysis of variance of the data was undertaken. The joint ANOVA was performed using the following statistical model, as proposed by Ramalho et al. (2005):

$$Y_{IJK} = m + G_i + B_j + \mathcal{E}_a + C_k + \mathcal{E}_b + GC_{ik} + \mathcal{E}_c \quad (1)$$

where, Y_{IJK}: observed value pertaining to genotype i in block j, at harvest k; m: overall constant of the trial; G_i: effect of genotype i; B_j: effect of block j; $\mathcal{E}_a$: 'a' error associated with genotype i in block j; C_k: effect of harvest k; $\mathcal{E}_b$: 'b' error associated with block j at harvest k; GC_{ik}: effect of the interaction between genotype i and harvest k; and $\mathcal{E}_c$: 'c' error associated with genotype i in block j, at harvest k.

The methods of Eberhart and Russell (1996) and Cruz et al. (1989) were used to evaluate the adaptability and stability of genotypes. The method of Eberhart and Russell (1996) is based on the following linear regression model:

$$Y_{ij} = \hat{\beta}_{0i} + \hat{\beta}_{1i} I_j + \delta_{ij} + \varepsilon_{ij} \quad (2)$$

where, Y_{ij}: mean of genotype i in environment j; $\hat{\beta}_{0i}$: overall mean of genotype i; $\hat{\beta}_{1i}$: linear regression coefficient that measures the response of genotype i to the environmental variation; I_j: coded environmental index; δ_{ij}: deviation from regression of genotype i in environment i; and ε_{ij}: mean experimental error associated with observation Y_{ij}.

The estimates of adaptability and stability parameters are the genotype mean ($\hat{\beta}_{0i}$) and the linear regression coefficient ($\hat{\beta}_{1i}$). According to this methodology, genotypes with $\hat{\beta}_{1i} = 1$ have general or wide adaptability; genotypes with $\hat{\beta}_{1i} > 1$ have adaptability specific to favorable environments; and those with $\hat{\beta}_{1i} > 1$ have adaptability specific to unfavorable environments. The H_0: $\hat{\beta}_{1i} = 1$ hypothesis was evaluated by the t test. The stability parameter ($\hat{\sigma}^2_{di}$) was estimated by the method of analysis of variance, based on the mean squared deviation from regression of each genotype (MSDi) and the residual mean square (RMS), where, $\hat{\sigma}^2_{di}$ = (MSDi - RMS)/r. Genotypes with non-significant deviations from regression are considered stable, whereas those with significant deviations are considered unstable. The F = MSDi/RMS statistics was applied to test the H_0: $\hat{\sigma}^2_{di} = 0$ hypothesis. As an auxiliary measure in the evaluation of genotype stability, the coefficient of determination (R^2) was employed.

The method proposed by Cruz et al. (1989) is based on the two-segment regression model, where the mean ($\hat{\beta}_{0i}$), the linear response to unfavorable environments ($\hat{\beta}_{1i}$), and the linear response to favorable environments ($\hat{\beta}_{1i} + \hat{\beta}_{2i}$) are employed as adaptability parameters. Stability is evaluated based on the deviations from regression ($\hat{\sigma}^2_{di}$) of each material, as a function of environmental variations. The following model was adopted:

$$Y_{ij} = \hat{\beta}_{0i} + \hat{\beta}_{1i} I_j + \hat{\beta}_{2i} T(I_j) + \delta_{ij} + e_{ij} \quad (3)$$

where, Y_{ij}: average yield of genotype i in environment j; $\hat{\beta}_{0i}$: average yield of genotype i across all environments (means of the genotypes were grouped using Scott and Knott's clustering); $\hat{\beta}_{1i}$: linear regression coefficient that gives the response of genotype i to the variation in the unfavorable environments; β_{2i}: linear regression coefficient that informs about the response differential of genotype i to the variation in the favorable environments; I_j: coded environmental index ($\sum_j^i = 0$), where, $I_i = Y_{.i} - Y_{..}$; $T(I_i) = 0$ if $I_i < 0$; and $T(I_i) = I_i - I_+$ if $I_i > 0$, in which I_+: mean of positive I_j indices; δ_{ij}: deviation from regression of genotype i in environment j; and e_{ij}: mean experimental error associated with observation Y_{ij}. Statistical significances relative to the parameters were obtained by the t test through the following hypotheses: H_{01}: $\hat{\beta}_{1i} = 1$; H_{02}: $\hat{\beta}_{2i} = 0$; and H_{03}: $\hat{\beta}_{1i} + \hat{\beta}_{2i} = 1$. As in the method of Eberhart and Russell (1996), the coefficient of determination (R^2) was used as an auxiliary measure in the evaluation of stability.

All statistical analyses were performed using the computer resources of Genes Software (Cruz, 2013).

3. Results and Discussion

Joint analysis of variance revealed a highly significant effect ($P < 0.01$) of genotypes (G), harvests (H), and genotype × harvest interaction (G × H) by the F test (Table 2). Thus, the significance found for the source of variation genotypes demonstrates the existence of genetic variability across the genotypes involved in this research, which is essential for the continuity of the process of selection of superior genotypes.

Table 2. Summary of the joint analysis of variance for the dry matter yield trait, in t ha^{-1} harvest, evaluated in nine biannual harvests of 73 genotypes of elephant grass for energy generation

SV	DF	DMY
		Mean square
Block	1	263.45
Genotypes (G)	72	183.04**
A error	72	56.19
Harvests (H)	8	3868.06**
B error	8	77.15
G × H	576	48.74**
C error	576	34.67
Overall mean	17.56	
CV (%)	33.53	
RMS+/RMS-	6.54	

Note. SV = source of variation; DF = degrees of freedom; CV = coefficient of variation (%); ** significant at the level of 1% of probability by F test.

The significance of the G × H interaction demonstrates that the relative performance of the genotypes was not consistent throughout the successive harvests. Significant G × H interactions in the evaluation of elephant grass for energy generation over several harvests were also reported by Rocha et al. (2015), Araújo et al. (2017), and Silva et al. (2018b).

In this regard, it is of paramount importance to identify genotypes whose productive behavior is superior to that of another, and which have smaller fluctuations in dry matter yield across the harvests performed over the years. Thus, evaluations of phenotypic adaptability and stability should be carried out so that it is possible to identify the genotypes most stable and responsive to environmental variations.

It should be emphasized that the joint analysis of variance was evaluated using Hartley's test (Table 2), given as the ratio between the highest and lowest residual mean square (RMS), which was 6.54. According to Pimentel-Gomes and Garcia (2002), combined analysis of variance can be performed when this ratio is smaller than seven, which was the case in the current experiment. The present result also agrees with Araújo et al. (2017), who evaluated 83 elephant-grass genotypes for energy production at four harvests and obtained a ratio between highest and lowest RMS of 6.57.

Experimental precision, which can be measured based on the coefficient of variation (CV), was 33.53%. This value is considered acceptable for DMY, which is a quantitative trait whose genetic control involves several genes, making it highly influenced by the environment (Table 2). This CV value is in line with those typically reported in studies with this crop, also in field conditions (Pimentel-Gomes & Garcia, 2002; Rossi et al., 2014; Rocha et al., 2015; Araújo et al., 2017).

In four (1st, 3rd, 7th, and 8th) of the nine evaluated harvests, the genotypes achieved an average dry matter yield greater than the overall mean. These environments were thus classified as favorable to the development of the evaluated genotypes; *i.e.*, they could take advantage of the environmental conditions and express their genes for that trait, displaying good average performance, as confirmed by the positive environmental indices (Table 3). However, the other harvests (2nd, 4th, 5th, 6th, and 9th) had mean dry matter yields smaller than the overall mean and, consequently, a negative environmental index, which caused them to be classified as environments unfavorable to the development of the genotypes. This result was probably due to the smaller precipitation occurring in those periods, which did not benefit the expression of the genes for yield.

Table 3. Mean dry matter yield (t ha^{-1}·harvest), environmental indices, and precipitation per harvest in 73 genotypes of elephant grass for energy generation in Campos dos Goytacazes, RJ, Brazil

Harvest	Mean (t ha^{-1} harvest)	Environmental index (I_j)	Precipitation** (mm)
1	22.89	5.33	537.2
2	10.82	-6.73	223.9
3	18.36	0.80	677.8
4	16.85	-0.70	325.3
5	16.37	-1.18	313.4
6	11.89	-5.66	167.2
7	25.57	8.01	551.6
8	22.05	4.49	512.6
9	13.19	-4.36	309.2
Overall mean	17.56		

Note. ** Precipitation corresponds to the sum of the daily amount of rainfall occurring throughout the genotypes' growing period, at each harvest.

Source: Evapotranspiration Station—Irrigation and Agrometeorology Section of PESAGRO-RIO/CEPAAR.

Overall, the large fluctuation in average yield of the genotypes throughout the harvests contributed to the genotype × harvest interaction. Therefore, investigating the interaction through methodologies of adaptability and stability shall contribute to a more in-depth analysis of the genotypes' performance. Silva et al. (2018b) evaluated elephant grass at annual harvests, and joint analysis of variance showed significant effects of the genotype × harvest interaction on dry matter yield, indicating that the genotypes showed different production performances at each harvest.

The genotypes were separated into two groups for mean dry matter yield ($\hat{\beta}_{0i}$). The overall mean for this trait was 17.56 t ha^{-1}·harvest (Table 4). Of the 73 evaluated genotypes, 39 had a yield greater than the overall mean, characterizing them as those of best adaptability (Vencovsky & Barriga, 1992).

Most genotypes, however, exhibited wide adaptability, since their regression coefficients did not present significant differences from unity ($\hat{\beta}_{1i} = 1$), indicating that these genotypes showed wide or general adaptability in the different environmental conditions found across the harvests (Table 4). This result suggests that these genotypes maintain their yield around the overall mean in both favorable and unfavorable environmental conditions.

In terms of performance stability, which is defined by the estimate of deviations from regression ($\hat{\sigma}^2_{di}$), among the most adaptable genotypes ($\hat{\beta}_{0i}$ > overall mean), only the clones Australiano, Pusa Napier N°1, Mole de Volta Grande, Cubando Pinda, Pusa Napier Gigante, 10 AD IRI, Mercker Santa Rita, Porto Rico 534-B, Elefante C. Itapemirim, and IJ 7139 showed a $\hat{\sigma}^2_{di}$ significantly different from zero, coupled with low coefficients of determination (R^2). This means that these genotypes showed low performance predictability; *i.e.*, their average yield varied largely throughout the harvests (Table 4).

According to Eberhart and Russell (1996), the ideal genotype is that which has high yields ($\hat{\beta}_{0i}$ > overall mean), a regression coefficient equal to unity ($\hat{\beta}_{1i} = 1$) (general adaptability), and zero deviation from regression ($\hat{\sigma}^2_{di} = 0$) (high stability). Therefore, the 24 genotypes fit those three criteria. Among those, the five best-ranking for DYM are Gramafante, Taiwan A-46, Gigante de Pinda, Três Rios, and Guaçu/I.Z.2.

The ideal genotype defined by Cruz et al. (1989) is that which encompasses high yielding ability (high $\hat{\beta}_{0i}$), adaptability to unfavorable environments ($\hat{\beta}_{1i} < 1$), responsiveness to environmental improvements ($\hat{\beta}_{1i} + \hat{\beta}_{2i} > 1$), and high stability (MSdev = zero). However, no such genotype was found in our study (Table 5). Under specific environmental conditions (favorable or unfavorable), however, some genotypes exhibited satisfactory performance in one or another condition (Table 5).

Table 4. Overall means ($\hat{\beta}_{0i}$) and estimates of regression coefficients ($\hat{\beta}_{1i}$), deviations from regressions ($\hat{\sigma}^2_{di}$), and coefficient of determination (R^2) according to the method of Eberhart and Russell, for the dry matter yield (t ha^{-1}·harvest) of 73 genotypes of elephant grass under a biannual nine-harvest regime

Genotype	$\hat{\beta}_{0i}$ (1)	$\hat{\beta}_{1i}$ (2)	$\hat{\sigma}^2_{di}$ (3)	R^2 (%)
King Grass	25.78 a	1.87**	-12.10^{ns}	95.28
Pasto Panamá	23.32 a	1.87**	-3.42^{ns}	88.40
Gramafante	23.24 a	1.13^{ns}	-2.61^{ns}	72.29
Taiwan A-46	23.03 a	0.62^{ns}	2.21^{ns}	37.25
Australiano	22.61 a	1.24^{ns}	33.84**	47.62
Gigante de Pinda	21.54 a	0.98^{ns}	-3.40^{ns}	67.89
Três Rios	21.52 a	0.96^{ns}	-3.40^{ns}	66.77
Guaçu/I.Z.2	21.38 a	1.09^{ns}	-9.83^{ns}	82.94
Pusa Napier Nº 1	21.14 a	1.88**	22.26*	72.92
Taiwan A-121	21.10 a	1.54^{ns}	5.75^{ns}	75.57
IJ 7125 cv EMP. 308	20.61 a	1.12^{ns}	-6.38^{ns}	77.51
Vruckwona africano	20.60 a	0.93^{ns}	4.99^{ns}	54.10
Duro de Volta Grande	20.49 a	1.20^{ns}	-11.79^{ns}	88.68
Mole de Volta Grande	20.32 a	0.71^{ns}	33.76**	22.80
03 AD IRI	20.30 a	1.14^{ns}	4.37^{ns}	64.48
Napierzinho	20.27 a	1.36^{ns}	-8.08^{ns}	85.73
Taiwan A-148	20.24 a	0.76^{ns}	16.9^{ns}	34.03
P 241 Piracicaba	19.63 a	0.96^{ns}	0.69^{ns}	60.68
Albano	19.40 a	1.68*	7.77^{ns}	77.22
Cubano Pinda	19.32 a	0.88^{ns}	27.05*	34.36
Cuba-115	19.26 a	1.56*	4.09^{ns}	77.42
Elefante da Colômbia	19.10 a	0.73^{ns}	17.52^{ns}	31.89
Pusa Gigante Napier	19.10 a	1.14^{ns}	31.06**	44.68
10 AD IRI	19.09 a	1.95**	40.89**	66.49
Guaçu	19.08 a	1.04^{ns}	27.74^{ns}	42.02
Taiwan A-25	19.06 a	1.58*	-4.07^{ns}	85.08
Mercker Santa Rita	18.96 a	1.04^{ns}	58.02**	30.21
Mineiro	18.96 a	0.59^{ns}	-9.07^{ns}	55.88
Porto Rico 534-B	18.92 a	0.53^{ns}	26.09*	16.26
Elefante C. Itapemirim	18.86 a	1.10^{ns}	25.13*	46.49
Mineirão IPEACO	18.75 a	0.90^{ns}	-13.18^{ns}	85.44
Vrukwona	18.68 a	1.25^{ns}	5.39^{ns}	67.54
IJ 7139	18.61 a	1.83**	39.42**	64.19
Ibitinema	18.41 a	0.91^{ns}	-4.50^{ns}	65.99
CAC 262	18.31 a	1.23^{ns}	-5.98^{ns}	80.13
Cuba-116	18.16 a	1.06^{ns}	11.26^{ns}	54.39
Mercker Pinda México	18.05 a	0.87^{ns}	-2.63^{ns}	61.12
Mercker Pinda	17.95 a	1.45^{ns}	7.40^{ns}	72.75
BAGCE 69	17.70 a	1.29^{ns}	8.23^{ns}	66.45
05 AD IRI	17.50 b	0.54^{ns}	7.19^{ns}	26.53
Cameroon	17.36 b	0.99^{ns}	12.79^{ns}	49.52
07 AD IRI	17.23 b	1.17^{ns}	-3.34^{ns}	74.81
02 AD IRI	16.74 b	1.12^{ns}	-2.28^{ns}	71.67
BAGCE2	16.74 b	1.23^{ns}	-7.09^{ns}	81.77
IJ7136 cv EMP. 307	16.46 b	0.75^{ns}	-3.28^{ns}	54.82
13 AD	16.20 b	0.80^{ns}	-1.10^{ns}	54.28
Napier Volta Grande	16.10 b	1.30^{ns}	107.07**	29.28
BAGCE 92	15.99 b	0.82^{ns}	-9.72^{ns}	72.87
Mercker S. E. A	15.80 b	1.01^{ns}	1.41^{ns}	62.34
Mercker Comum	15.79 b	0.56^{ns}	-13.87^{ns}	73.30
Mercker 86 México	15.76 b	1.24^{ns}	11.86^{ns}	61.49
Costa Rica	15.71 b	0.80^{ns}	-1.38^{ns}	54.79

Teresopólis	15.57 b	0.63^{ns}	-13.62^{ns}	76.38
Taiwan A-143	15.50 b	1.13^{ns}	-7.11^{ns}	79.17
Turrialba	15.46 b	0.98^{ns}	1.76^{ns}	60.52
Napier S.E.A.	15.29 b	0.73^{ns}	13.89^{ns}	34.35
Elefante Híbrido 534-A	15.21 b	0.72^{ns}	1.29^{ns}	45.60
BAGCE 51	14.73 b	0.45^{ns}	-5.81^{ns}	35.14
BAG 87	14.44 b	0.43*	2.14^{ns}	22.20
Roxo Botucatu	14.43 b	0.66^{ns}	-9.42^{ns}	62.59
Goiano	14.23 b	0.54^{ns}	-8.04^{ns}	48.65
Taiwan A-146	14.17 b	0.62^{ns}	30.36**	19.65
BAG 86	13.98 b	0.66^{ns}	-2.91^{ns}	47.65
Capim Cana D'África	13.48 b	0.62^{ns}	-7.01^{ns}	53.22
Mercker Comum	13.37 b	0.93^{ns}	-8.63^{ns}	74.98
Napier Goiano	13.23 b	0.85^{ns}	7.82^{ns}	46.71
Pusa Napier Nº 2	12.97 b	0.98^{ns}	-8.95^{ns}	77.48
Napier	12.73 b	0.55^{ns}	-3.85^{ns}	40.44
08 AD IRI	12.70 b	0.73^{ns}	-3.94^{ns}	54.57
Porto Rico	12.40 b	0.55^{ns}	-2.09^{ns}	37.51
13 AD IRI	11.92 b	1.03^{ns}	2.07^{ns}	62.40
Elefante de Pinda	11.02 b	0.59^{ns}	-6.13^{ns}	48.86
Roxo	10.76 b	0.27*	-10.43^{ns}	24.42
Overall mean	17.56			

Note. (1) Values within columns followed by the same letter do not differ by Scott-Knott's test at 5% probability; **, *, ns = significant ($p < 0.01$), significant ($p < 0.05$), and not significant, respectively; (2), (3) significance by the t test and by the F test, respectively.

Table 5. Adaptability and stability parameters according to the method of Cruz for dry matter yield ($t \cdot ha^{-1} \cdot$harvest) of 73 elephant-grass genotypes from nine biannual harvests

Genotype	$\hat{\beta}_{0i}^{(1)}$	MU	MF	$\hat{\beta}_{1i}^{(2)}$	$\hat{\beta}_{1i} + \hat{\beta}_{2i}^{(3)}$	MSdev.	R^2 (%)
King Grass	25.78 a	18.28	35.16	1.98**	1.11^{ns}	6.34^{ns}	97.55
Pasto Panamá	23.32 a	16.64	31.67	1.75*	2.69*	25.75^{ns}	90.80
Gramafante	23.24 a	18.90	28.66	1.11^{ns}	1.23^{ns}	34.23^{ns}	72.38
Taiwan A-46	23.03 a	21.59	24.84	0.61^{ns}	0.71^{ns}	45.52^{ns}	37.36
Australiano	22.61 a	18.86	27.31	1.31^{ns}	0.77^{ns}	117.16**	48.61
Gigante de Pinda	21.54 a	17.04	27.15	1.14^{ns}	-0.11^{ns}	20.33^{ns}	79.92
Três Rios	21.52 a	18.18	25.71	1.01^{ns}	0.61^{ns}	31.28^{ns}	68.04
Guaçu/I,Z,2	21.38 a	17.77	25.90	1.11^{ns}	1.03^{ns}	17.47^{ns}	82.98
Pusa Napier Nº 1	21.14 a	14.29	29.70	2.01**	0.97^{ns}	84.02*	75.38
Taiwan A-121	21.10 a	16.09	27.36	1.38^{ns}	2.59*	42.53^{ns}	80.71
IJ 7125 cv EMP. 308	20.61 a	16.28	26.03	1.14^{ns}	0.93^{ns}	25.21^{ns}	77.83
Vruckwona africano	20.60 a	17.89	24.00	0.75^{ns}	2.19^{ns}	36.12^{ns}	68.18
Duro de Volta Grande	20.49 a	16.30	25.73	1.20^{ns}	1.16^{ns}	12.93^{ns}	88.69
Mole de Volta Grande	20.32 a	17.20	24.21	0.82^{ns}	-0.09^{ns}	112.84**	26.95
03 AD IRI	20.30 a	17.42	23.89	1.08^{ns}	1.60^{ns}	48.54^{ns}	65.96
Napierzinho	20.27 a	15.16	26.65	1.34^{ns}	1.45^{ns}	21.52^{ns}	85.79
Taiwan A-148	20.24 a	17.03	24.25	0.77^{ns}	0.71^{ns}	79.85*	34.05
P 241 Piracicaba	19.63 a	15.28	25.08	1.10^{ns}	-0.02^{ns}	32.33^{ns}	69.78
Albano	19.40 a	12.21	28.39	1.65*	1.87^{ns}	58.19^{ns}	77.37
Cubano Pinda	19.32 a	15.56	24.02	0.79^{ns}	1.49^{ns}	99.79**	36.76
Cuba-115	19.26 a	13.74	26.15	1.48^{ns}	2.12^{ns}	46.83^{ns}	78.86
Elefante da Colômbia	19.10 a	16.60	22.23	0.76^{ns}	0.55^{ns}	81.00*	32.18
Pusa Gigante Napier	19.10 a	13.85	25.67	1.35^{ns}	-0.36^{ns}	90.11*	55.86
10 AD IRI	19.09 a	12.80	26.96	1.59*	4.47**	71.48^{ns}	82.37
Guaçu	19.08 a	15.70	23.31	0.91^{ns}	1.94^{ns}	96.99*	46.53
Taiwan A-25	19.06 a	13.81	25.62	1.45^{ns}	2.47^{ns}	22.88^{ns}	88.97

Mercker Santa Rita	18.96 a	17.10	21.29	1.04^{ns}	1.00^{ns}	175.82**	30.21
Mineiro	18.96 a	16.88	21.57	0.63^{ns}	0.30^{ns}	18.46^{ns}	57.78
Porto Rico 534-B	18.92 a	17.18	21.10	0.55^{ns}	0.34^{ns}	100.98**	16.54
Elefante C. Itapemirim	18.86 a	15.35	23.24	0.91^{ns}	2.43^{ns}	81.18*	56.17
Mineirão IPEACO	18.75 a	15.97	22.24	0.84^{ns}	1.31^{ns}	7.94^{ns}	88.07
Vrukwona	18.68 a	14.60	23.79	1.14^{ns}	2.00^{ns}	47.32^{ns}	71.04
IJ 7139	18.61 a	12.10	26.75	1.50^{ns}	4.16**	77.69*	79.00
Ibitinema	18.41 a	15.44	22.13	0.91^{ns}	0.86^{ns}	29.92^{ns}	66.01
CAC 262	18.31 a	13.11	24.81	1.26^{ns}	1.00^{ns}	25.94^{ns}	80.54
Cuba-116	18.16 a	14.12	23.21	1.11^{ns}	0.74^{ns}	65.67^{ns}	55.11
Mercker Pinda México	18.05 a	14.66	22.29	0.96^{ns}	0.27^{ns}	30.66^{ns}	65.27
Mercker Pinda	17.95 a	13.01	24.11	1.36^{ns}	2.31^{ns}	50.71^{ns}	76.07
BAGCE 69	17.70 a	12.34	24.40	1.28^{ns}	1.36^{ns}	59.62^{ns}	66.47
05 AD IRI	17.50 b	16.10	19.24	0.67^{ns}	-0.37^{ns}	48.74^{ns}	37.42
Cameroon	17.36 b	13.15	22.63	1.07^{ns}	0.41^{ns}	66.96^{ns}	51.92
07 AD IRI	17.23 b	12.76	22.82	1.28^{ns}	0.44^{ns}	27.21^{ns}	79.02
02 AD IRI	16.74 b	11.27	23.59	1.21^{ns}	0.48^{ns}	30.90^{ns}	75.08
BAGCE2	16.74 b	11.86	22.84	1.16^{ns}	1.70^{ns}	21.66^{ns}	83.50
IJ7136 cv EMP. 307	16.46 b	13.88	19.68	0.74^{ns}	0.85^{ns}	32.70^{ns}	54.96
13 AD	16.20 b	13.55	19.51	0.61^{ns}	2.11^{ns}	20.31^{ns}	75.50
Napier Volta Grande	16.10 b	10.61	22.97	1.30^{ns}	1.36^{ns}	290.26**	29.29
BAGCE 92	15.99 b	13.57	19.01	0.74^{ns}	1.36^{ns}	14.82^{ns}	77.37
Mercker S. E. A	15.80 b	13.00	19.30	0.93^{ns}	1.57^{ns}	40.61^{ns}	65.05
Mercker Comum	15.79 b	13.33	18.86	0.60^{ns}	0.28^{ns}	7.27^{ns}	76.01
Mercker 86 México	15.76 b	9.77	23.26	1.46^{ns}	-0.30^{ns}	44.02^{ns}	75.12
Costa Rica	15.71 b	12.51	19.71	0.80^{ns}	0.80^{ns}	37.24^{ns}	54.79
Teresopólis	15.57 b	13.42	18.25	0.61^{ns}	0.74^{ns}	8.55^{ns}	76.69
Taiwan A-143	15.50 b	11.23	20.84	1.21^{ns}	0.59^{ns}	20.86^{ns}	81.79
Turrialba	15.46 b	11.17	20.83	1.08^{ns}	0.28^{ns}	39.54^{ns}	64.96
Napier S.E.A.	15.29 b	12.46	18.84	0.65^{ns}	1.33^{ns}	69.29^{ns}	37.57
Elefante Híbrido 534-A	15.21 b	11.92	19.33	0.78^{ns}	0.26^{ns}	41.36^{ns}	48.26
BAGCE 51	14.73 b	13.13	16.73	0.53^{ns}	-0.08^{ns}	24.06^{ns}	42.00
BAG 87	14.44 b	11.94	17.57	0.59^{ns}	-0.73*	31.93^{ns}	45.33
Roxo Botucatu	14.43 b	12.52	16.82	0.59^{ns}	1.14^{ns}	16.14^{ns}	67.30
Goiano	14.23 b	12.10	16.89	0.50^{ns}	0.79^{ns}	21.07^{ns}	50.12
Taiwan A-146	14.17 b	10.70	18.51	0.63^{ns}	0.53^{ns}	111.20**	19.72
BAG 86	13.98 b	11.21	17.45	0.69^{ns}	0.42^{ns}	33.08^{ns}	48.54
Capim Cana D'África	13.48 b	11.34	16.16	0.65^{ns}	0.45^{ns}	23.81^{ns}	53.79
Mercker Comum	13.37 b	10.37	17.12	0.86^{ns}	1.37^{ns}	18.30^{ns}	77.46
Napier Goiano	13.23 b	9.60	17.76	0.83^{ns}	1.02^{ns}	58.42^{ns}	46.97
Pusa Napier Nº 2	12.97 b	9.84	16.88	0.96^{ns}	1.12^{ns}	19.35^{ns}	77.73
Napier	12.73 b	10.92	15.00	0.61^{ns}	0.11^{ns}	29.47^{ns}	44.23
08 AD IRI	12.70 b	8.79	17.60	0.86^{ns}	-0.16^{ns}	23.19^{ns}	66.30
Porto Rico	12.40 b	9.86	15.57	0.60^{ns}	0.23^{ns}	34.54^{ns}	39.33
13 AD IRI	11.92 b	6.95	18.12	1.12^{ns}	0.38^{ns}	40.98^{ns}	65.96
Elefante de Pinda	11.02 b	8.13	14.62	0.65^{ns}	0.19^{ns}	24.48^{ns}	52.13
Roxo	10.76 b	10.30	11.34	0.29*	0.18^{ns}	16.01^{ns}	24.86
Overall mean	17.56	13.83	22.22				

Note. MU = mean of unfavorable environments; MF = mean of favorable environments; (1) Values within columns followed by the same letter do not differ by Scott-Knott's test at 5% probability; (2) $H_0 = \hat{\beta}_{1i} = 1$; (3) $H_0 = \hat{\beta}_{1i} + \hat{\beta}_{2i} = 1$; **, *, ns = significant ($p < 0.01$), significant ($p < 0.05$), and insignificant, respectively, by the t test.

Genotypes Pasto Panamá, 10 AD IRI, and IJ 7139 showed regression coefficients ($\hat{\beta}_{1i} + \hat{\beta}_{2i}$) of 2.69, 4.47, and 4.16, respectively, by the method of Cruz et al. (1989) (Table 5). These values were statistically greater than unity, and their magnitude was greater than the respective regression coefficients of 1.87, 1.95, and 1.83 as estimated by the method of Eberhart and Russell (1996). This finding demonstrates that the method of Cruz et al. (1989) is more refined for the recommendation of genotypes for specific environmental conditions—favorable, unfavorable, or both—when compared with the method of Eberhart and Russell (1996).

The estimates of $\hat{\beta}_{1i}$, which evaluates the performance of genotypes in unfavorable conditions, were significant and greater than one for the clones King Grass, Pasto Panamá, Pusa Napier N°1, Albano, and 10 AD IRI, indicating that they are highly sensitive to unfavorable environmental conditions. This result can be verified by the means of those genotypes, since they are among the most productive in the environments considered favorable, with their yield reduced by approximately 50% in unfavorable environments (Table 5).

As regards the linear response to the favorable environments ($\hat{\beta}_{1i}$ + $\hat{\beta}_{2i}$), genotypes Pasto Panamá, Taiwan A-121, 10 AD IRI, and IJ 7139 showed results significantly greater than one. Further, all have dry matter yields greater than the overall mean ($\hat{\beta}_{0i}$ > overall mean). In this way, these genotypes were considered adapted to favorable environments and responsive to environmental improvements.

The analyses of stability and adaptability based on the methods of Eberhart and Russel (1996) and Cruz et al. (1989) present more-simplified applications. They allow for statistical tests to more accurately identify the most stable genotypes and the group of environments to which they are best adapted (Oliveira et al., 2006).

4. Conclusions

The method of Eberhart and Russel was effective in the identification of elephant grass genotypes with wide adaptability and high dry matter production stability throughout the nine harvests.

When the method of Cruz was used, no genotypes were found comprising high yielding ability, adaptability to unfavorable environments, responsiveness to environmental improvement, and high stability altogether.

Genotypes Gramafante, Taiwan A-46, Gigante de Pinda, Três Rios, Guaçu/I.Z.2, Taiwan A-121, IJ7125 cv EMP. 308, Vruckwona Africano, Duro de Volta Grande, 03 AD IRI, and Napierzinho stood out for displaying high yielding ability, wide adaptability, and production stability simultaneously. Therefore, these genotypes are potential candidates for use in breeding programs aiming at energy generation.

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