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Prediction of *Hevea* Progeny Performance in the Presence of Genotype-environment Interaction

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ABSTRACT

Twenty two open-pollinated Hevea progenies *from different parental clones of the Asian origin were tested at five sites in the Northwestern São Paulo State Brazil to investigate the progeny girth growth, rubber yield, bark thickness and plant height. Except for the rubber yield, the analysis of variance indicated highly significant (p<0.01) genotype x environment interaction and heterogeneity of regressions among the progenies. However, the regression stability analysis identified only a few interacting progenies which had regression coefficients significantly different from the expected value of one. The linear regressions of the progeny mean performance at each test on an environmental index (mean of all the progenies in each test) showed the general stability and adaptability of most selected* Hevea *progenies over the test environments. The few progenies which were responsive and high yielding on different test sites could be used to maximize the rubber cultivars productivity and to obtain the best use of the genetically improved stock under different environmental conditions.*

Key words: *Hevea brasiliensis*, stability, adaptability, environmental index, linear regression

INTRODUCTION

Hevea breeder's concerned with genotype-environmental (G x E) interaction has led to a greater interest in the studies of genotypic stability across various environments. However, most stability studies in the rubber tree [*Hevea brasiliensis* (Willd. Adr. ex Juss.) Muell.-Arg.], have been done with only a few genotypes and those materials have been over a limited range of locations. The literature on the genotype-environment interaction in *Hevea* is not extensive. Its effects have been recognized in São Paulo State, Brazil by Gonçalves et al. (1990, 1992, 1998a, 1998b, 1999, 2003 and 2008) and Costa et al. (2000).

Breeders search for the genotypes that show a stable, high yield and good growth performance over the locations. In general, a genotype is considered stable when its performance across the environments does not deviate from the average performance of the group standard genotypes. Several measures have been devised to quantify the yield stability Lin et al. 1986 and Becker and Léon 1988. Searching for a superior genotype with respect to yield performance, a breeder selects among the offspring of the crosses between the promising parents (Dias et al. 2003). To be

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successful in the selection for the yield, the progeny of a cross should have a sufficient level and variation for both the components of the yield performance, i.e. yield level and yield stability. An important question related to this is whether the level and variation of progeny performance can be predicted on the basis of parent information. The question of heritability of the yield and its stability only addresses the level of yield performance and not the variation of the progeny with respect to both the components. For a breeder, both the level and variation of progeny performance are important.
As *Hevea* improvement programs became more intense in the Northwestern São Paulo State, and more improved *Hevea* progenies are produced, the adaptability and stability of selected *Hevea* progenies to a wide range of environmental conditions must be determined. A better understanding of the genotypic stability and adaptability of many selected progenies over various locations might increase the genetic gains by allowing the breeders to optimally deploy the progenies to sites. This paper reports the stability of 22 open-pollinated *Hevea* progenies at five locations in the Northwestern São Paulo State, Brazil.

MATERIAL AND METHODS

Plant material

The genetic material consisted of 22 half sib-progenies from the open-pollinated seeds, obtained from 22 parental clones phenotypically selected in an *H. brasiliensis* population of the Asian origin established at the Campinas Experimental Station (CES), Instituto Agronômico (IAC). The seeds were collected at the CES, placed in the polyethylene bags and germinated at each site of the progeny tests and taken to their definitive location when they showed two fluxes of the leaves.

Experimental locations

The progeny tests were grown in a total of five contrasting test environments in the plateau of São Paulo State (Table 1). These locations represented the most important continental climate non-traditional rubber production area. The experimental design at each test location was randomized complete blocks with three replications. Ten plants were used per progeny in each plot at all the locations the plants were spaced at 2.0 m x 2.0 m in single row. The progenies were assessed when they were three years old.

Measurements

The girth growth, yield of the rubber, bark thickness and plant height were measured at three years of age for each plant. The yield of rubber was determined by the Hamaker-Morris-Mann (HMM) test modified for three year-old seedlings (Tan and Subramanian, 1976) using the mean dry rubber yield from three-cycle test per plant. The tapping panel was opened 15cm from the soil, using the ½ S d/3 system, with a total of 35 tappings. The first five samples which corresponded to the “breaking in of the panel” stage, were discarded. The term ½ S corresponded to the half spiral cut and the term d/3 expressed the interval between the tappings, i.e. tapping each three days.
The virgin bark samples were removed from the stem as plugs at 20 cm height on the opposite side of the tapping panel. The bark thickness was measured using the sample for each progeny. The total number of latex vessel rings in the longitudinal and transverse sections of the bark sample was determined as described by Gonçalves et al. (1996). The girth was measured using a steel measuring tape at 0.50 m from the ground.

Statistical analysis

An analysis of variance was conducted on the family plot means by using the method of Freeman and Perkins (1971). Finlay and Wilkinson’s (1963) concept of the regression coefficient and progeny performance for the traits was used for estimating the stability and adaptability.
The progenies means from each test were regressed on the mean performance of all the genotypes at each location (environments index). All the analyses were performed using the GENES computer program, windows version, 2001 (Cruz 2001).

Table 1 - Details of experimental locations and planting dates from five different test locations where 22 *Hevea* progenies were evaluated in São Paulo State, Brazil.

Remarks	**Locations**				
	Mococa	**Pariquera-açu**	**Votuporanga**	**Jaú**	**Pindorama**
Spacing (m)	2.00 x 2.00	2.00 x 2.00	2.00 x 2.00	2.00 x 2.00	2.00 x 2.00
Planting density	1 rows x 10 plants 10 plants/plot	1 rows x 10 plants 10 plants/plot	1 rows x 10 plants 10 plants/plot	1 rows x 10 plants 10 plants/plot	1 rows x 10 plants 10 plants/plot
Design of experiment	RBD[1]	RBD	RBD	RBD	RBD
Number of replications	3	3	3	3	4
Total area (ha)	0.26	0.26	0.26	0.26	0.35
Elevation (m) (mean sea level)	665	25	450	580	560
Latitude (S)	21º28’	24º43’	20º25’	22º17’	21º13’
Longitude (EE)	47º01’	47º57’	49º50’	48º64’	48º56’
Temperature (annual mean)	24.5ºC	20.8ºC	22.3ºC	21.6ºC	21.0ºC
Annual rainfall (mm) (mean annual)	1500	1517	1480	1344	1390
Soil type	Eutrustox	Kandiudox	Paleudalf	Paleudalf	Paleudox
Terrain	Flat to undulating	Flat to undulating	Flat	Flat	Flat
Year of planting	2000	2000	2000	2000	2000

The regression coefficient (b) and the progeny means are presented in Figure 1 as a generalized method of interpretation for analyzing the stability and adaptability of the progenies. The position of particular genotype on the plot indicated the type of stability and performance over the test sites. The genotypes with b=1.0 had an average stability since their response to the environments was parallel to the mean response of all the genotypes in the tests. Genotypes with a high mean performance are well adapted to all environments (Okuyama et al. 2005). The genotypes with b>1.0 had low stability but were responsive to the improved environmental conditions the genotypes, with b<1.0 had high stability and were not sensitive to the changes in the environmental conditions. The ideal genotype was the one with maximum yield potential in all the environments (high mean performance) and maximum stability.

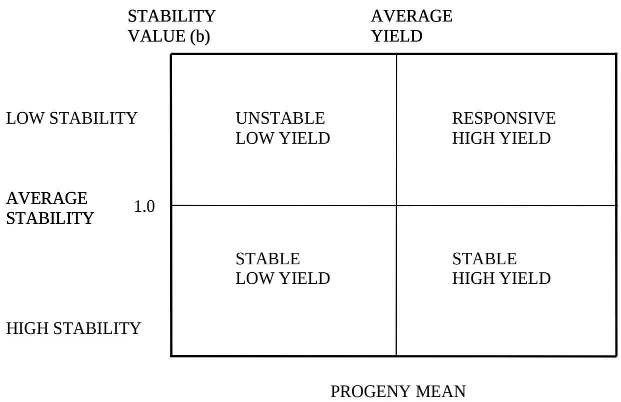

Figure 1 - A generalized interpretation of stability and adaptability for all genotypes by plotting regression coefficients (b) and family means over all tests.

RESULTS AND DISCUSSION

Except for the rubber yield, the effects of test location by the progeny interaction for the girth growth bark thickness and plant height were highly significant at the 1% level (Table 2). Significant linear effects partitioned from the interaction sum of squares suggested that G x E interaction was partially due to the heterogeneity of the progeny response over various environments. Also, a small but significant portion of the G x E interaction was nonlinear.

Table 2 - Analyses of variance for stability parameters for 22 *Hevea* progenies of three years girth growth, rubber yield, bark thickness and plant height tested at five sites in São Paulo State, Brazil.

Source of variation	DF	Mean squares			
		Girth (cm)	Yield (g)	Bark thickness (mm)	Height (m)
Locations	4	985.7419**	4.2382*	0.2950 n.s	32.4123**
Replications (locations)	10	448.3642**	0.2503n.s	0.1950 n.s	0.3374**
Progenies	21	91.8947**	0.6902n.s	2.2147**	1.7979**
Locations x Progenies	84	12.3775**	0.2196n.s	0.4881**	0.2448
Linear regressions	21	15.2364**	0.2429n.s	0.5815**	0.2262**
Deviation from regressions	63	13.5187**	0.3947n.s	0.3947**	0.2933**
Residual	210	6.2450	0.7090	0.1173	0.1386
General mean		20.8070	0.8155	3.7871	2.5779
Coef. Variation		12.01	32.65	9.04	8.10

*, ** significant at 5%, 1% respectively; n. s. = not significant.

The stability of a genotype across a range of the environments has been measured by its among-environment (Plaisted, 1960, Shukla, 1972), the regression of its mean to an environmental index (Finlay and Wilkinson, 1963, Perkins and Jinks, 1968), the residual mean square from the regression (Eberhart and Russell, 1966), or the combinations of these methods. Lin et al. (1986) examined nine stability statistics currently in use and concluded that the regression procedure was valid for providing information on the relative stability among the genotypes included in the experiment if the regression model fit the data. The use of the mean of all the genotypes as the environmental index for the regression has been criticized since it is biased by the genotypes under the consideration (Freeman and Perkins, 1971, Hardwick and Wood, 1972). The assumption of the linearity of the response was also questioned by Namkoong (1978). However, if the number of the genotypes and environments is reasonable large and the environmental range is sufficiently wide, the linear regression using the mean of all the genotypes should be biologically valid (Fripp and Caten, 1971, Fripp, 1972). In this study, the three test means represented 22 progenies per test and the test means ranged from 17.67 cm to 22.65 cm for the girth growth and 2.07 m to 3.07m for the plant height. The number of the progenies tested and the range in site quality and height growth were judged to be large enough to justify using the regression method. The coefficient of determination (R^2) for the regression was used in this study to determine how well the linear model fit the data. Essentially, the genotypic stability was measured as the deviation mean square from the regression as proposed by Eberhart and Russell (1966). A stable progeny is defined as one having $b=1.0$ and $R^2=1.0$.

For each *Hevea* progeny, the mean, regression coefficient (b) and standard error, and the coefficient of determination (R^2) are shown for the girth growth and rubber yield in Table 3 and bark thickness and plant height in Table 4. All (R^2) the values were highly significant, except for the progenies AVROS 49, Tjir 1 and Tjir 16 for the rubber yield. The b statistic interpreted as the genotypic response regression coefficients, ranged from 0.65 to 1.47 for the girth growth, 0.13 to 3.36 for the rubber yield, – 8.66 to 18.08 for the bark thickness, and 0.45 to 1.51 for the plant height and was used as a relative measure of the stability over the test sites since such a large part of the total variation was accounted for by the regression. The values for the height regression coefficients (b) were significantly different from 1.0 for relatively few progenies, for rubber yield (4 of 22), bark thickness (2 of 22) and for plant height (2 of 22) (Tables 3 and 4). The average stability of these *Hevea* progenies in this region was demonstrated by the majority of the selected progenies having the regression coefficients (b) not significantly different from one. The significant G x E interaction sums of the squares in the analysis of variance was contributed by only a few interacting progenies.

The different types of stabilities can be illustrated by plotting the means from three selected progenies against the test means for the girth growth (Fig 2). The progeny C 228 represented a genotype of average stability, as defined by b approximately 1.0, and average performance for the girth growth over all the tests. The changes in its performance across the test sites were

proportional to the changes in the test site averages and were essentially equal to the test average. The progeny C 259 represented a relatively stable genotype for the girth growth compared with other progenies in this study but was a poor performer for the girth over all the tests. The progeny PR 107 represented a relatively unstable genotype that was sensitive to the site changes and had greater adaptability to favorable and unfavorable sites.
The same patterns of differential reaction of the progenies to three environments for the plant height are shown in Figure 3. Three progenies were used to illustrate the application of the regression analysis in analyzing their relative stabilities and increment to the height in high and low yield hazard sites. There were differences in the plant height among the three progenies. The progeny PB 49 was a stable genotype (b = 0.83) over all the levels of the plant height while the progeny Tjir 1 was very instable (b = 1.51) and was very tall.

Table 3 - Progenies means for the girth growth and rubber yield, estimated, regression coefficients (b_i) and standard errors (in parenthesis), and the coefficients of determination (R^2) for the regression models, for 22 progenies grown at five sites in São Paulo State, Brazil.

Progenies	Girth growth (cm)				Rubber yield (g)			
	Means	b_1		R^2 %	Means	b_1		R^2 %
AVROS 1126	24.0850	0.8304	(0.133)	74.71	0.8306	1.5295	(0.129)	96.29
AVROS 1328	18.4605	1.1609	(0.070)	98.32	0.7678	1.4937	(0.136)	94.88
AVROS 255	23.0083	0.8687	(0.085)	96.83	0.9639	0.5868	(0.113)	40.62
AVROS 352	21.8288	0.8772	(0.055)	84.94	0.9294	1.4572	(0.102)	80.55
AVROS 363	22.4233	0.8919	(0.042)	99.89	1.0894	1.6730	(0.150)	81.08
AVROS 49	20.3261	0.6996	(0.048)	83.53	0.8539	0.4067	(0.164)	15.92
C 228	20.5778	0.9360	(0.064)	99.83	0.7300	0.6911	(0.224)	62.06
C 256	19.8750	1.0717	(0.039)	99.66	0.7011	0.5959	(0.137)	88.49
C 259	15.9400	0.7096	(0.094)	53.30	0.5644	0.5485	(0.252)	69.48
C 290	18.4400	0.9779	(0.116)	75.35	0.6161	0.3647	(0.201)	73.34
C 297	20.4788	1.4721	(0.172)	99.95	0.7288	1.6475	(0.132)	99.92
C 318	19.6844	1.2141	(0.107)	64.22	0.7767	0.1368**	(0.137)	57.96
GT 127	17.5283	0.8221	(0.077)	91.30	0.6917	0.2589	(0.107)	40.12
GT 711	22.0588	0.6738	(0.085)	62.66	0.8878	0.7404	(0.160)	52.96
PB 49	22.6883	0.7825	(0.150)	98.03	0.8511	1.5723	(0.248)	99.90
PB 563	18.6627	1.1138	(0.079)	99.94	0.5050	0.8244	(0.272)	76.14
PB 86	22.6583	1.2163	(0.071)	95.61	1.0600	2.0649**	(0.085)	82.59
PR 107	23.8277	1.3715	(0.089)	86.02	1.0722	0.9514	(0.194)	89.77
RRIM 513	21.5094	0.6500	(0.068)	81.20	1.0812	0.9423	(0.198)	96.74
RRIM 600	20.8156	1.2865	(0.055)	99.10	1.2444	3.3643**	(0.110)	71.73
Tjir 1	24.2972	1.2818	(0.127)	97.73	0.6517	0.1603*	(0.113)	10.68
Tjir 16	18.5788	1.0912	(0.134)	85.62	0.6139	0.2631	(0.297)	7.12

* and ** significant for p<0.05 and p<0.01, respectively.
t (5%, 315) = 1.96; t (1%, 315) = 2.58

Table 4 - Progeny means for bark thickness and plant height, estimated regression coefficients (b_i) and standard errors (in parenthesis), and the coefficients of determination (R^2) for the regression models, for 22 *Hevea* progenies grown at five sites in São Paulo State, Brazil.

Progenies	Bark thickness (mm)				Plant height			
	Means	b_1		R^2 %	Means	b_1		R^2 %
AVROS 1126	4.4894	0.3272	(0.035)	0.9711	2.9872	0.7970	(0.163)	80.20
AVROS 1328	4.1127	18.0862**	(0.098)	74.6264	2.4794	1.3483	(0.109)	95.01
AVROS 255	4.3078	-1.4619	(0.112)	99.5487	2.8533	0.7718	(0.127)	96.36
AVROS 352	3.8389	0.8795	(0.091)	93.5344	2.5717	0.7967	(0.158)	98.18
AVROS 363	3.9811	-1.7920	(0.069)	85.8558	2.6472	0.7813	(0.132)	64.70
AVROS 49	3.7800	2.0198	(0.109)	31.0749	2.7022	1.1602	(0.144)	96.29
C 228	3.8833	-0.0368	(0.069)	3.8869	2.6811	1.1140	(0.068)	98.81
C 256	3.6833	0.0118	(0.059)	0.0284	2.4483	1.1925	(0.053)	99.99
C 259	3.4844	-8.6601	(0.088)	61.1016	1.9056	0.8641	(0.103)	95.77
C 290	3.4356	4.3676	(0.127)	73.6834	2.2183	0.9965	(0.085)	94.26
C 297	3.6078	1.7808	(0.133)	40.4245	2.4138	1.2063	(0.103)	94.41
C 318	3.6389	5.1260*	(0.070)	36.2336	2.2372	1.1072	(0.053)	88.55
GT 127	3.1644	-0.8442	(0.085)	93.0381	2.0455	0.6740	(0.068)	89.07
GT 711	3.7650	0.3814	(0.055)	0.5759	2.9811	1.3178	(0.144)	94.63
PB 49	3.9956	-1.4232	(0.042)	45.6247	2.6278	0.8341	(0.132)	86.46
PB 5/63	3.2533	0.9809	(0.048)	34.0286	2.7644	1.1872	(0.158)	79.91
PB 86	4.2178	0.5882	(0.064)	1.3596	2.9267	1.1043	(0.127)	92.92
PR 107	3.8200	1.8369	(0.094)	54.0213	2.8211	0.9313	(0.109)	99.80
RRIM 513	3.9472	-1.2220	(0.073)	42.1003	2.4828	0.4481*	(0.163)	59.63
RRIM 600	3.7139	-0.5880	(0.164)	15.6100	2.8161	1.1324	(0.107)	85.48
Tjir 1	4.0356	-0.8558	(0.066)	7.1631	2.9650	1.5120*	(0.072)	99.99
Tjir 16	3.1656	2.4976	(0.116)	93.3244	2.1389	0.7231	(0.050)	91.76

* and ** significant for $p<0.05$ and $p<0.01$, respectively.
t (5%, 315) = 1.96; t (1%, 315) = 2.58

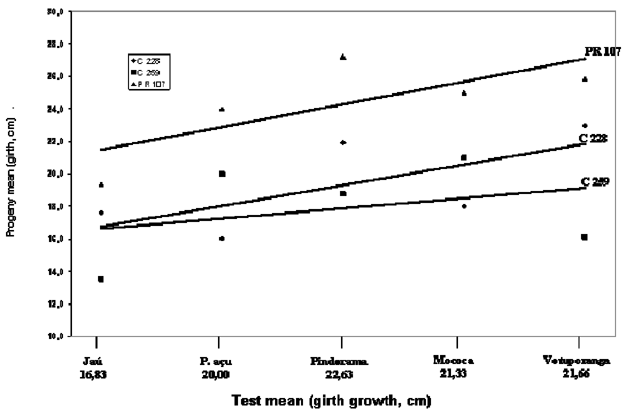

Figure 2 - The regression of three progeny means for girth growth on the environmental index (test means).

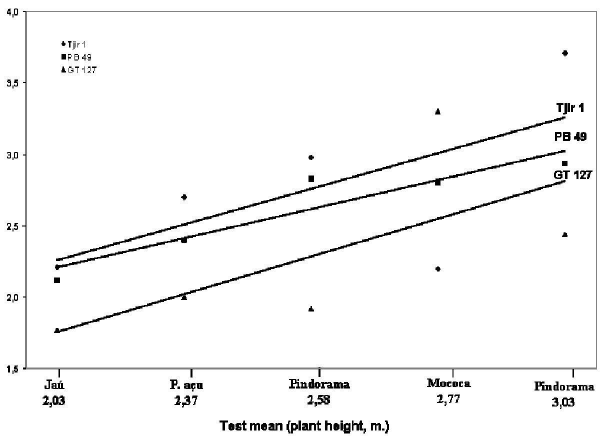

Figure 3 - The regression of the progeny means for plant height on the environmental index (test means).

To identify the genotypes with different levels of mean performances and stabilities in the study, the relationship between the regression coefficients and progeny means for the girth growth was plotted (Fig 4). High progeny mean performance over all the test environments indicated the general adaptability of the progenies. The regression coefficient further measured the stability of the genotype and indicated the kind of environmental condition to which the progeny was adapted. Most of the 22 selected *Hevea* progenies were classified as high stability genotypes because their linear response to the site averages was higher than b = 1.0 (Fig 2 and 4). The progeny C 228 was an example of an average stability genotype with b = 0.93 and average performance in the girth growth (Fig 4). There were some progenies such as PR 107 with b >1.0 and high mean performance (Fig 2 and 4), which were classified as the responsive high yield genotypes. These progenies were relatively unstable but performed relatively better on the favorable sites. They were also above average on the poor sites. Only a few progenies such as progeny C 259 were identified as stable low yield genotypes for the girth growth (Fig 4).

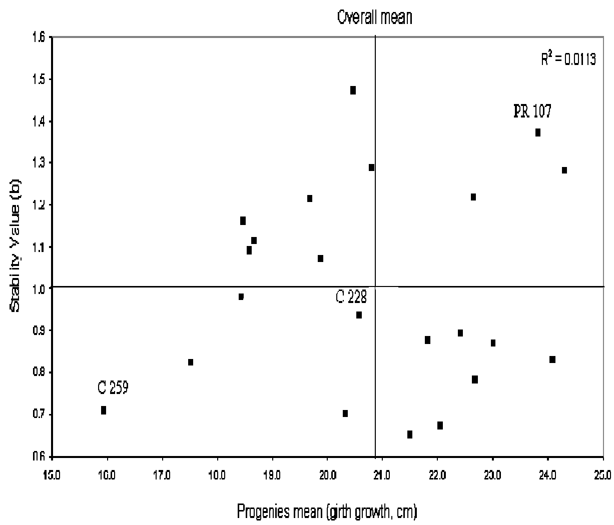

Figure 4 - The relationship of regression coefficients and mean performance for girth of *Hevea* progenies.

A significant positive relationship (r = 0.65) between the b parameters and the progeny mean performance for rubber yield was noted in this study. This kind of relation has been found in other crops (Finlay and Wilkinson, 1963, Gray, 1982) where the sites, were better. If there was genetic variation in the stability and performance among the progenies, *Hevea* breeders have the opportunity to select for different stabilities under different environmental conditions and determine the optimum genotypes and managements systems for each environmental condition. For example, the progenies in the responsive high yield group had higher specificity of adaptability to high quality environments and should respond well to the intensive management practices. Although there were few of these progenies found in this study it would be most valuable to use these progenies such as RRIM 600 on high site index lands to maximize the yield and to obtain the best use of genetically improved stock. If a *Hevea* plantation being established on less favorable sites on over large range of average sites, the progenies in responsive high yield group or in the average stability group with above average performance would be very productive genotypes. The average stability group has general stability and adaptability to all environments.

CONCLUSIONS

The strong trend in this study for selected *Hevea* progenies to have average stability and perform in a predictable manner over a range of sites was very valuable information for *Hevea* breeders. Significant G x E interaction in the analysis of variance was contributed by very few progenies for the plant height, bark thickness and girth growth. An important implication to the breeding program was that in progenies usually need not be tested over the environmental extremes to determine breeding values. It may be valuable to test over the environmental extremes to identify the few responsive high yield progenies which should be used to increase the rubber cultivars productivity on intensively managed sites.

RESUMO

Vinte e duas progênies de *Hevea* de polinização aberta obtidas de diferentes clones fenotipicamente selecionados de uma população de origem asiática *Hevea brasiliensis* (Willd. Adr. ex Juss.) Muell-Arg. durante três anos foram testadas em cinco locais. As variáveis perímetro do caule, produção de borracha, espessura da casca e a altura de planta foram determinadas em todos locais no Estado de São Paulo, Brasil. De acordo com as análises de variância, com exceção a produção de borracha, observou-se a existência de interações significativas entre genótipo x ambiente ($p<0.01$) e heterogeneidade de regressões entre as progênies. Porém, a análise de estabilidade de regressão identificou a interação de poucas progênies cujos coeficientes de regressão foram significativamente diferentes do valor esperado de um. Regressões lineares do desempenho médio das progênies para cada teste em um índice ambiental (média de todas as progênies em cada local) mostrou a estabilidade e adaptabilidade da grande maioria das progênies de *Hevea* nos diferentes locais. As poucas progênies que foram superiores e altamente produtivas nos diferentes testes de progênies podem ser utilizadas para maximizar a produtividade de cultivares de seringueira e determinar a melhor utilização do ganho genético dos grupos sob as diferentes condições ambientais de cultivo.

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