Stability and adaptability for wood volume in the selection of *Eucalyptus saligna* in three environments

Thiago Wendling Gonçalves de Oliveira[1], Rinaldo Cesar de Paula[2], Mario Luiz Teixeira de Moraes[3], Clayton Alcarde Alvares[4], Aline Cristina Miranda[5] and Paulo Henrique Muller da Silva[6]

[1]Universidade Federal do Paraná, Departamento de Ciências Florestais, Avenida Prefeito Lothário Meissner, nº 900, CEP 80210-170 Curitiba, PR, Brazil. E-mail: thiagowendling@yahoo.com.br [2]Universidade Estadual Paulista (Unesp), Faculdade de Ciências Agrárias e Veterinárias, Campus Jaboticabal, Via de Acesso Prof. Paulo Donato Castellane, s/nº, CEP 14884-900 Jaboticabal, SP, Brazil. E-mail: rcpaula@fcav.unesp.br [3]Universidade Estadual Paulista (Unesp), Faculdade de Engenharia, Campus de Ilha Solteira, Avenida Brasil Sul, nº 56, Centro, CEP 15385-000 Ilha Solteira, SP, Brazil. E-mail: teixeira@agr.feis.unesp.br [4]Suzano Papel e Celulose, Avenida Dr. José Lembo, nº 2.215, Jardim Bela Vista, CEP 18207-780 Itapetininga, SP, Brazil. E-mail: caalvares@yahoo.com.br [5]Suzano Papel e Celulose, Unidade Mucuri, BR 101, Km 945,5, Caixa Postal 63, CEP 45930-000 Mucuri, BA, Brazil. E-mail: miranda.acf@gmail.com [6]Instituto de Pesquisa e Estudos Florestais, Via Comendador Pedro Morganti, nº 3.500, Monte Alegre, CEP 13415-000 Piracicaba, SP, Brazil. E-mail: paulohenrique@ipef.br

Abstract – The objective of this work was to evaluate the genotype x environment (GxE) interaction in open-pollinated *Eucalyptus saligna* progenies for simultaneous selection for greater stability and adaptability for wood volume, as well as to compare the selection strategies through combined and individual analyses in three environments. Three experiments were conducted in a randomized complete block design, with four replicates and six plants per plot, with 102 to 122 progenies. Three years after planting, survival rate and wood volume were evaluated. The genetic parameters were estimated by the maximum restricted likelihood and best linear unbiased prediction (REML/Blup) methods, and the stability and adaptability analysis was conducted using the harmonic mean of the relative performance of genetic values (HMRPGV). The highest survival rate (82%) was observed in Sabinópolis and the highest volume (120 m^3 ha^{-1}) in Lençóis Paulista. The mean heritability of progenies for the two analyzed variables was considered high, and the genetic correlations between survival rate and volume were weak for all sites. The G×E interaction was significant and of the complex type, with genotype correlation between sites of 47%, indicating that the ranking of the best progenies differed in each studied environment. The analysis of stability and adaptability indicated the possibility of selecting progenies with good performance in the three environments; however, to improve the quality of the evaluated characteristics, it is necessary to select specific progenies for each environment.

Index terms: forest breeding, genetic selection, genotype × environment interaction, REML/Blup.

Estabilidade e adaptabilidade para volume de madeira na seleção de *Eucalyptus saligna* em três ambientes

Resumo – O objetivo deste trabalho foi avaliar a interação genótipo x ambiente (GxA) em progênies de polinização aberta de *Eucalyptus saligna*, para seleção simultânea para maior estabilidade e adaptabilidade para volume de madeira, bem como comparar as estratégias de seleção por análises conjunta e individuais em três ambientes. Foram instalados três experimentos, em delineamento de blocos ao acaso, com quatro repetições e parcelas de seis plantas, com 102 a 122 progênies. Três anos após o plantio, foram avaliados a taxa de sobrevivência e o volume de madeira. Os parâmetros genéticos foram estimados pelos métodos da máxima verossimilhança restrita e melhor predição linear não viciada (REML/Blup), e a análise de estabilidade e adaptabilidade foi realizada pela média harmônica do desempenho relativo dos valores genéticos (MHPRVG). A maior taxa de sobrevivência (82%) foi observada em Sabinópolis e o maior volume (120 m^3 ha^{-1}) em Lençóis Paulista. As herdabilidades médias das progênies para as duas variáveis avaliadas foram consideradas altas, e as correlações genéticas entre taxa de sobrevivência e volume foram baixas para todos os locais. A interação GxA foi significativa e do tipo complexa, com correlação genotípica entre ambientes de 47%, o que indica que o ordenamento das melhores progênies foi diferente para cada local estudado. A análise de estabilidade e adaptabilidade indicou a possibilidade de selecionar progênies com comportamento plástico nos três ambientes; contudo, para melhoria da qualidade das características avaliadas, é necessária a seleção de progênies específicas para cada ambiente.

Termos para indexação: melhoramento florestal, seleção genética, interação genótipo x ambiente, REML/Blup.

Introduction

Eucalyptus saligna Sm. is a species of Australian origin, where it is known by the name Sydney blue gum. It is found in regions of subtropical and temperate climates, at altitudes of up to 1,100 m, and is often confused with *Eucalyptus grandis* W.Hill (Flores et al., 2016). However, its wood has a higher and more uniform density than the basic genetic material of *E. grandis* (Alzate et al., 2005), being more suitable for wood structures than several other species of eucalyptus (Anjos & Fonte, 2017). *Eucalyptus saligna* is also more suitable than *E. grandis* for regions subject to frost, enduring temperatures of up to -10°C (Paludzyszyn Filho et al., 2006).

In Brazil, the species has been of great importance; however, due to its demand for good soil conditions, it has become less interesting than *Eucalyptus urophylla* S.T.Blake and *E. grandis* (Ferreira, 2016), despite the good climatic suitability for the species in the Southern and Southeastern regions of Brazil (Flores et al., 2016).

The productivity of *E. saligna* varies significantly in different environments. A study on 36-month-old progenies of this species in the Brazilian states of São Paulo, Minas Gerais, and Rio Grande do Sul showed a mean annual increment (MAI) ranging from 24 to 31 m^3 ha^{-1} per year in General Câmara, in the state of Rio Grande do Sul; from 30 to 33 m^3 ha^{-1} per year in Brotas, in the state of São Paulo; and from 27 to 32 m^3 ha^{-1} per year in Bom Despacho, in the state of Minas Gerais (Mori et al., 1986).

Different provenances of *E. saligna* at 78 months of age, in five sites of the state of São Paulo, showed volumes ranging from 184 to 396 m^3 ha^{-1}, that is, a MAI of 28 to 61 m^3 ha^{-1} per year (Santana et al., 1999). In Vale do Jequitinhonha, in the state of Minas Gerais, the MAI varied from 4 to 21 m^3 ha^{-1} per year at 30 months (Barros et al., 1984) due to the effect of fertilizer use; this shows the importance of the management and nutritional requirements of this species.

The environment may affect the responses of the genotypes as to adaptability and stability due to the genotype × environment (G×E) interaction, generating a reduction in genetic gain when selection is carried out simultaneously in different environments (Santos et al., 2016; Teodoro et al., 2016). This shows that the knowledge of the environmental effect is critical to the selection of productive genetic material for *E. saligna*.

The analysis of G×E interactions allows evaluating the performance of genetic material in several environments, which may aid in selection, requiring special attention (Pupin et al., 2015; Castro et al., 2016). Therefore, when the G×E interaction is significant, changes in the studied environments have different effects on the genetic materials tested. It should be noted that, if the interaction is of the complex type, the stratification of environments is necessary for selection; this is done by dividing the environment into regions in order to obtain gains with selection (Dvorak et al., 2008).

Using genotypes with wide adaptability and stability can mitigate the effect of G×E interactions; however, it is necessary to adopt a methodology that allows the simultaneous selection for stability and adaptability, such as the harmonic mean of the relative performance of genetic values – HMRPGV (Resende 2002a, 2002b). The HMRPGV is a useful tool to ensure that the highest percentage of genetic gain is achieved among the forest production environments, prioritizing more productive, stable, and adapted genetic materials (Santos et al., 2013; Pagliarini et al., 2016).

One advantage of the HMRPGV method is that it allows working with unbalanced data, i.e., the lack of treatments in one of the experiments does not require it to be excluded from the combined analysis, which is not possible with other G×E interaction study methods, such as the additive main effects and multiplicative interaction (AMMI) (Malosetti et al., 2013).

The objective of this work was to evaluate the genotype x environment (GxE) interaction in open-pollinated *E. saligna* progenies for simultaneous selection for greater stability and adaptability for wood volume, as well as to compare the selection strategies through combined and individual analyses in three environments.

Materials and Methods

Three experiments were installed using open-pollinated progenies of *E. saligna* in the municipalities of Belo Oriente and Sabinópolis, both in the state of Minas Gerais, and of Lençóis Paulista, in the state of São Paulo, Brazil (Figure 1 and Table 1).

The design used was a randomized complete block with four replicates of each treatment. The plots consisted of six plants in the same planting row. The progenies

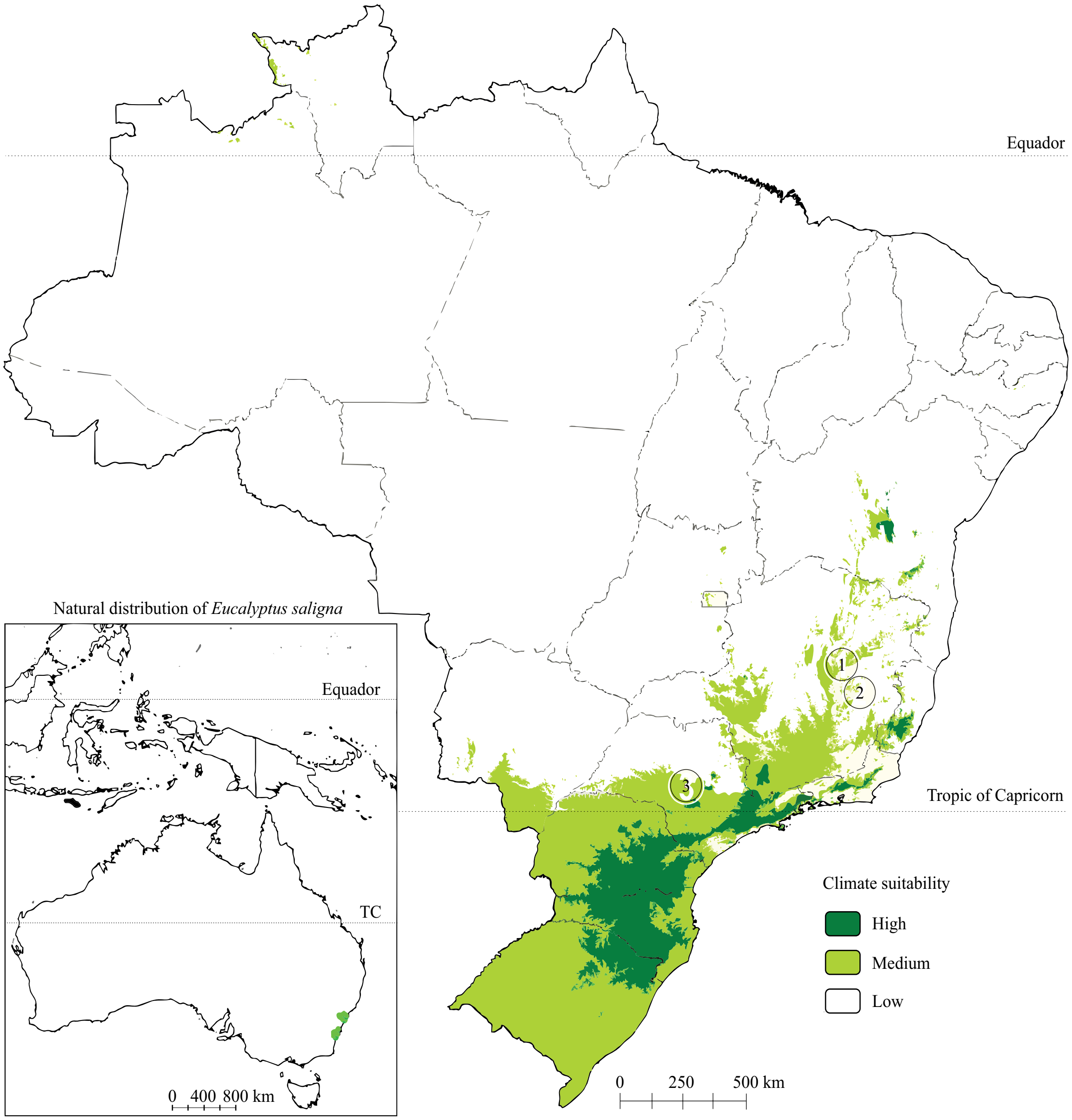

Figure 1. Experimental sites and climate suitability for *Eucalyptus saligna* in Brazil. 1, Sabinópolis, in the state of Minas Gerais; 2, Belo Oriente, in the state of Minas Gerais; and 3, Lençóis Paulista, in the state of São Paulo. Source: Flores et al. (2016).

Table 1. Characterization of the experimental sites in Brazil where the *Eucalyptus saligna* progenies were tested(1).

Site	Latitude (S)	Longitude (W)	Altitude (m)	Köppen's classification	AAT (°C)	Rainfall (mm)	Number of progenies
Sabinópolis, MG	18°66'	43°07'	700	Cwa	20.5	1,474	119
Belo Oriente, MG	19°33'	42°29'	300	Aw	23.7	1,165	102
Lençóis Paulista, SP	23°13'	48°34'	827	Cwa	19.7	1,370	122

(1)MG, state of Minas Gerais; SP, state of São Paulo; AAT, annual average temperature (°C); Cwa, humid temperate climate with dry winters and hot summers; and Aw, tropical climate with dry season in winter. Source: Alvares et al. (2013).

of *E. saligna* belonged to the cooperative program for forest enhancement of Instituto de Pesquisas e Estudos Florestais and were provided by the companies Fibria, Suzano Papel e Celulose, Duratex, Aperam, Cenibra, and Conpacel (currently Suzano Papel e Celulose), and also by Estação Experimental de Ciências Florestais de Itatinga of Escola Superior de Agricultura Luiz de Queiroz of Universidade de São Paulo.

Assessments were performed at three years of age, and the following characters were evaluated: survival rate, diameter at breast height (DBH) taken at 1.30 m from the ground, and full height (H). After obtaining DBH and H, timber volume (VOL) was calculated with the equation $VOL = \pi \times (DBH/2)^2 \times H \times FF$, using a form factor (FF) of 0.5. To obtain the MAI ($MAI = (\Sigma VOL)/S \times EA$), the surface (S) of the experiment and evaluation age (EA) were used.

The analyses of deviance for survival rate and wood volume were conducted using the maximum likelihood ratio test (LRT), in order to evaluate the significance of the model effects. Estimates of variance components were obtained by restricted maximum likelihood (REML) and best linear unbiased prediction (Blup). The analyses related to stability and adaptability were carried out using the HMRPGV according to Resende (2002b).

A mixed linear model was used: $y = Xr + Zg + Wp + Ti + e$, for which the effect of replicate (r) was considered fixed; and of genotype (g), plots (p), G×E interaction (i), and residue (e) were considered random. The matrices of incidence effects were represented by X, Z, W, and T. For the analysis, the Selegen software was used (Resende, 2016).

Results and Discussion

Among progenies, the survival rate varied from 25 to 100% in Sabinópolis, from 8 to 96% in Belo Oriente, and from 20 to 100% in Lençóis Paulista (Figure 2). The average survival rate among progenies was 82, 69, and 77% for Sabinópolis, Belo Oriente, and Lençóis Paulista, respectively, and 76% considering the three environments. Van den Berg et al. (2017) obtained a higher average survival rate of 88%, while studying progenies of *E. grandis* in three environments in South Africa.

The MAI in wood volume was 29.7, 30.1, and 39.7 m³ ha^{-1} per year in Sabinópolis, Belo Oriente, and Lençóis Paulista, respectively. It should be highlighted that the differences observed for survival rate and productivity in each site are due to the different environmental conditions of the study areas, such as drought periods, humidity, and soil drainage, which affect plant development (Gonçalves et al., 2013, 2017; Silva et al., 2016).

Both experiments carried out in Minas Gerais showed a productivity 25% below the average of 40 m³ ha^{-1} per year reported for eucalyptus plantations in Brazil. However, this average was obtained for plantations mainly composed of clonal materials (Gonçalves et

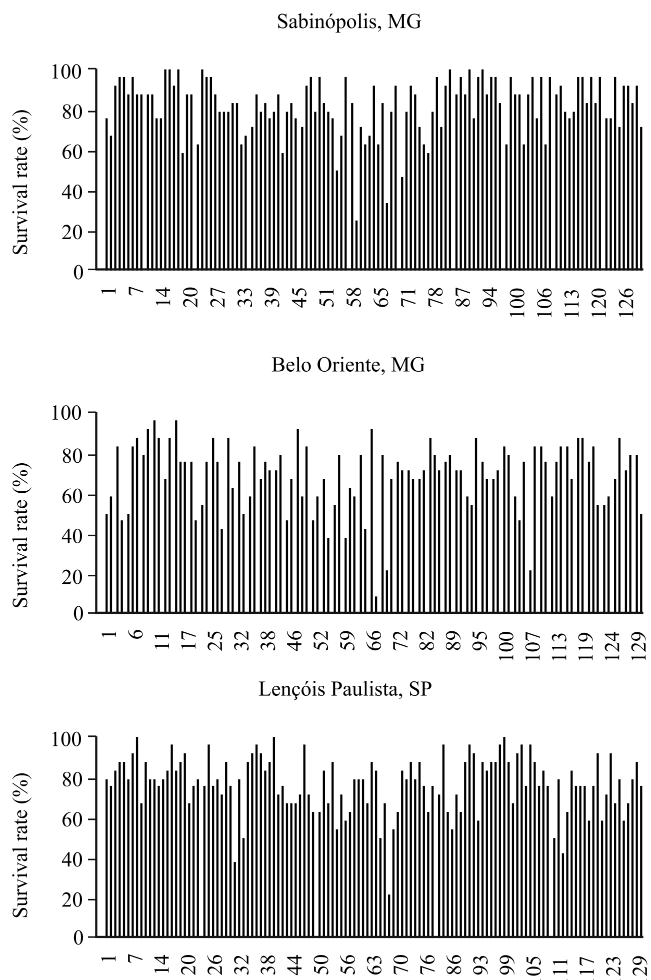

Figure 2. Survival rates of three-year-old *Eucalyptus saligna* progenies in three experimental sites in Brazil. MG, state of Minas Gerais; and SP, state of São Paulo.

al., 2013; Silva et al., 2013), i.e., genotypes with a high selection intensity, different from the seminal material evaluated in the present study.

Variations in survival rate and productivity among study sites are commonly observed in experiments with this type of material, such as progenies and provenances. Hodge & Dvorak (2015) analyzed different provenances of *E. urophylla* at three years of age, and found MAI ranging from 11 to 20 m^3 ha^{-1} per year in Brazil, Venezuela, Colombia, Mexico, and South Africa; these values are similar to those obtained in the present study with *E. saligna.*

Even the lowest productivities found in both experiments in Minas Gerais were higher than the ones obtained by Barros et al. (1984) in Vale do Jequitinhonha, in the same state, in the 1980s. This could be explained by the fact that the experiments of the present study were carried out in regions of average and low climate suitability (Figure 1) and using a higher technological level than that available in the 1980s.

The LRT among progenies was significant for the two studied characters in all experimental sites, indicating the existence of genetic differences among progenies (Table 2), which is a key requirement for genetic selection. In a study with *Eucalyptus camaldulensis* Dehnh. (Santos et al., 2008) and *Eucalyptus resinifera* Sm. (Sato et al., 2007), genetic variability was detected among progenies for wood volume, evidencing the possibility of genetic gains in breeding.

For the assessed characters, the coefficient of experimental variation between plots (c_p^2) was considered low (<10%) in all sites (Pimentel-Gomes, 2009). This indicates that the quality of the evaluations and the way the experiments were conducted were appropriate, and that the dispersion of data was low and did not affect the estimates of the model parameters.

The individual additive genetic coefficient of variation (CV_{gi}) showed the existence of genetic variability among individuals of the studied population with potential for breeding, which can aid in the selection of superior individuals.

The estimates of individual additive heritability in the narrow sense (h_a^2) ranged from medium (0.15 to 0.50) to high (>0.50) according to Resende (1995). The obtained values indicate potential for genetic gain through the selection of the best individuals in the experiment.

The coefficient of average progeny heritability (h_m^2) was high for the two characters in all sites, indicating good genetic control and selection gain for individuals from the families of *E. saligna* in each site. High values of h_m^2 for DBH were also found for progenies of *E. urophylla* in the Southeastern and Midwestern

Table 2. Maximum likelihood ratio test (LRT), additive genetic variance (α_a^2), environmental variance between plots (α_p^2), environmental + nonadditive residual variance (α_e^2), phenotypic variance (α_f^2), coefficient of determination of plot effects (c_p^2), individual additive genetic coefficient of variation (CV_{gi}), individual additive heritability (h_a^2), average progeny heritability (h_m^2), additive heritability within the plot (h_d^2), and general average for survival rate and wood volume of *Eucalyptus saligna* progenies in different experimental sites in Brazil[(1)].

Parameter	Survival rate (%)			Wood volume (m^3)		
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
LRT	61.25**	52.76**	43.82**	74.47**	44.19**	48.14**
α_a^2	0.0522	0.0742	0.0468	0.0005	0.0010	0.0023
α_p^2	0.0047	0.0057	0.0039	0.00004	0.00005	0.00004
α_e^2	0.0911	0.1347	0.1285	0.0005	0.0015	0.0063
α_f^2	0.1480	0.2147	0.1794	0.0011	0.0026	0.0086
c_p^2	0.03	0.03	0.02	0.04	0.02	0.01
CV_{gi}	27.28	39.62	28.24	35.47	40.38	36.16
h_a^2	0.35±0.06	0.35±0.06	0.26±0.05	0.50±0.08	0.40±0.08	0.26±0.06
h_m^2	0.66	0.66	0.60	0.74	0.70	0.62
h_d^2	0.30	0.29	0.21	0.45	0.34	0.22
General average	0.81	0.68	0.76	0.07	0.08	0.13

[(1)]Site 1, Sabinópolis, in the state of Minas Gerais; Site 2, Belo Oriente, in the state of Minas Gerais; and Site 3, Lençóis Paulista, in the state of São Paulo. **Significant by the chi-square test with one degree of freedom at 1%:6.63.

regions of Brazil (Pupin et al., 2015), evidencing the possibility of higher selection gains among progenies. Lower values of h_m^2 were obtained for wood volume in Lençóis Paulista (0.62), compared with the other sites, showing the great effect of the environment on the genetic control of the variable, as reported by Canuto et al. (2016).

The genetic correlations between survival rate and wood volume were not significant (Table 3), indicating there is no relationship between the two characters. Therefore, indirect selection is not possible because it is only feasible with high-magnitude genetic correlations (Vencovsky & Barriga, 1992).

Table 3. Individual additive genetic correlations (r_{aa}) between survival rate and wood volume (m³) for *Eucalyptus saligna* progenies in three experimental sites in Brazil.

Site(1)	r_{aa} (survival rate × volume)
Sabinópolis, MG	0.40
Belo Oriente, MG	0.15
Lençóis Paulista, SP	0.10

(1)MG, state of Minas Gerais; and SP, state of São Paulo.

For the analysis of the G×E interaction, the LRT values were significant for both characters, except for survival rate between Sabinópolis (site 1) and Belo Oriente (site 2). Lençóis Paulista (site 3) was the most divergent of the three sites regarding survival rate and wood volume (Table 4), showing that progenies with greater survival and higher productivity varied among sites.

In contrast with the present study, Mori et al. (1986) found that the G×E interaction was not significant for progenies of *E. saligna* evaluated in the states of Rio Grande do Sul, São Paulo, and Minas Gerais. According to these authors, despite the different climatic conditions of the sites, the obtained results showed that the breeding program could be conducted in only one of them, i.e., the assessed progenies had a stable performance across environments.

This difference in results between studies might be related to the assessed genetic basis, as discussed by Silva et al. (2015). This is due to the origin of the material and diversity within the population, which are factors that affect growth and lead to varying responses to different environments, as observed in the present study.

Table 4. Maximum likelihood ratio test (LRT), additive genetic variance (α_a^2), environmental variance between plots (α_p^2), variance of genotype × environment interaction (α^2), residual variance (α_e^2), phenotypic variance (α_f^2), individual additive heritability (h_a^2), average progeny heritability (h_m^2), additive heritability within the plot (h_d^2), coefficient of determination of plot effects (c_p^2), coefficient of determination of the genotype × environment interaction (c_i^2), genotypic correlation between the performance of the progenies in different environments (r^2_{gloc}), and general average for survival rate and wood volume of *Eucalyptus saligna* progenies considering the sites (1, 2, and 3) in Brazil combined two-by-two and their combined analysis(1).

Parameter	Survival rate (%)			All sites	Wood volume (m³)			All sites
	1 × 2	1 × 3	2 × 3		1 × 2	1 × 3	2 × 3	
LRT	0.99 ns	34.7**	25.6**	35.2**	20.9**	39.8**	7.33**	46.4**
α_a^2	0.0559	0.0167	0.0255	0.0316	0.0004	0.0004	0.0012	0.0006
α_p^2	0.0051	0.0043	0.0048	0.0048	0.00004	0.00002	0.00003	0.00002
α^2	0.0014	0.0082	0.0084	0.0062	0.00008	0.0003	0.0001	0.0002
α_e^2	0.1161	0.1347	0.1568	0.1363	0.0011	0.0041	0.0047	0.0033
α_f^2	0.1785	0.1639	0.1954	0.1789	0.0017	0.0048	0.0060	0.0042
h_a^2	0.31±0.04	0.10±0.02	0.13±0.03	0.18±0.02	0.26±0.05	0.09±0.03	0.20±0.04	0.15±0.03
h_m^2	0.75	0.35	0.42	0.62	0.59	0.32	0.60	0.57
h_d^2	0.27	0.08	0.11	0.15	0.23	0.07	0.16	0.12
c_p^2	0.03	0.03	0.02	0.03	0.03	0.004	0.005	0.005
c_i^2	0.01	0.05	0.04	0.03	0.05	0.05	0.02	0.04
r^2_{gloc}	0.91	0.34	0.43	0.56	0.58	0.30	0.68	0.47
General average	0.75	0.79	0.72	0.76	0.072	0.099	0.106	0.093

(1)Site 1, Sabinópolis, in the state of Minas Gerais; Site 2, Belo Oriente, in the state of Minas Gerais; and Site 3, Lençóis Paulista, in the state of São Paulo. **Significant by the chi-square test with one degree of freedom at 1%:6.63. nsNonsignificant by the chi-square test with one degree of freedom at 1%:6.63.

The coefficient of determination of the G×E interaction (c_i^2) varied from 1 to 5% in the combined analysis and between pairs of sites, which, according to Resende (2002a), indicates that the interaction was of the complex type. The ranking of the best progenies changed from one site to another, and selection could not be performed in a single environment. A similar result was obtained for survival rate of *Corymbia citriodora* (Hook.) K.D.Hill & L.A.S.Johnson progenies in three environments in the state of São Paulo (Morais et al., 2010).

However, a significant simple-type interaction was reported for DBH in progenies of *E. urophylla* (Pupin et al., 2015) and *E. grandis* (Miranda et al., 2015), as well as of *Pinus taeda* L. (Martinez et al., 2012). In this case, the interaction between genotypes and environments did not change the ranking the evaluated materials. These contrasting results highlight the importance of considering the different interactions between genotype and environment for the establishment of commercial plantations of forest species, such as *E. saligna*.

The h_m^2 in the combined analysis of the pairs of sites was lower than that estimated for each individual site (Tables 2 and 3), as also found in another study with *E. saligna* (Mori et al., 1986). This occurred because of the higher number of environments in the combined analysis, generating greater environmental variation, which indicates lower prediction of genetic gain with a greater number of environments.

Six progenies showed stability and adaptability in the three study sites (Table 5), and were among the top 20 in all environments. These progenies may be recommended for orchards for the production of improved seeds in all three experimental sites, due to the simple-type G×E interaction, including the attributes stability and adaptability, as also reported in an work with *Eucalyptus macarthurii* H.Deane & Maiden (Engel et al., 2016).

Studies using the HMRPGV are important because they allow for the simultaneous selection of adapted and stable genotypes across environments (Maia et al., 2009). However, the need to conduct selection for each individual site becomes evident due to the difference in the ranking of the progenies in each environment as a result of a G×E interaction of a predominantly complex nature.

Table 5. Selection of the 20 best progenies of *Eucalyptus saligna* based on the stability and adaptability analysis for wood volume(1).

Family	Stability and adaptability	Adaptability	Stability	Sabinópolis	Belo Oriente	Lençóis Paulista
3	1	1	4	1	4	1
112	2	3	5	3	3	13
11	3	2	8	32	1	2
83	4	4	6	4	9	7
44	5	5	11	21	6	3
9	6	6	7	12	2	17
89	7	7	9	6	7	18
8	8	8	12	2	12	10
7	9	9	10	8	5	24
47	10	10	14	30	10	5
36	11	11	13	25	8	8
25	12	12	15	5	33	9
96	13	14	20	17	31	14
17	14	13	16	10	15	52
31	15	17	18	16	18	46
12	16	16	21	9	40	25
85	17	15	17	7	17	68
120	18	18	23	14	38	20
43	19	19	25	40	19	16
116	20	22	27	38	23	15

(1)Underlined progenies are not among the top 20 in the selection based on the harmonic mean of the relative performance of genetic values (HMRPGV).

Conclusions

1. The genotype x environment interaction is significant and of the complex type, indicating that the ranking of the best *Eucalyptus saligna* progenies differed between sites.

2. It is only possible to select a few progenies with adaptability and stability simultaneously in the three studied sites, indicating the need to select specific progenies for each environment in order to improve the quality of the evaluated characters survival rate and wood volume.

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