GGE Biplot Analysis of Forage Yield Performance and Stability Assessment of Tall Fescue Experimental Populations Selected Under Grazing Pressure in a Stress Environment

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Abstract
Integrating the yield and stability of genotypes selected under grazing pressure is an important objective in breeding forage crops. Genotype × environment (G x E) interaction is a major source of inconsistency in crop performance across locations. As a result, a genotype is considered stable if it has a low contribution to the G x E interaction. This study explores the effects of G x E interaction on yield and stability of 10 tall fescue experimental populations selected for persistence under grazing pressure outside the area of adaptation of the species (stress environment). Six standard checks were included. The populations were tested in a randomized complete block design with 5 replications in 9 environments. The pooled analysis of variance (ANOVA) revealed highly significant ($p < 0.01$) variations between populations, locations, years, and G × E interaction. The first two principal components generated by the GGE biplot accounted for 46.78% and 28.45% variation in GGE for yield. The locations (Athens and Blairsville) were found to be the most significant causes of yield variation. The GGE biplot revealed three winning populations GALA1301 (ga1), GALA1302 (ga2), and GALA1306 (ga6) in terms of yield across environments. These populations performed better than all the checks. GALA1502T (g2t) was the most stable and GALA1502A(g2a), GALA1301(ga1), and GALA1303(ga3) are both comparatively stable and high yield performers. Comparison of the two populations g2t and g2a that were selected from the same base population but in different environments (g2t selected for persistence at Tifton under grazing pressure and g2a selected for yield without grazing in Athens) showed that g2t was the most stable across environments but lower in yield than g2a. Our results suggest that selection under grazing pressure in stress environments could result in improved stability across environments while yield performance will still depend on the genetic background of the germplasm.

Introduction
Tall fescue (*Lolium arundinaceum* Schreb) is a temperate cool season, C3 perennial, outcrossing, and allohexaploid grass species used in pastures and turf. It is highly plastic and produces a high yield even in stressful environmental and soil conditions (Vega et al., 2021). This deep-rooted bunchgrass is adapted to cool and humid environments and soils with a pH of 5 to 7 (USDA NRCS 2022). Various studies successfully utilized the genotype and genotype-by-environment interaction (GGE) biplot method to evaluate yield and stability. Saeidnia et al. (2022) evaluated drought tolerance in 24 tall fescue genotypes including 17 Iranian native landraces and seven foreign accessions using both GGE biplot and the additive main effects and multiplicative interactions (AMMI) method for yield and stability analysis. They observed highly consistent results from the two methods and also found that the GGE biplot method was more efficient compared to AMMI. Georgieva et al. (2022) utilized the GGE biplot method as one of several tools to simultaneously evaluate yield and stability among eight species of meadow grasses including three highest-yielding species *Festuca arundinacea* Schreb., *Agrostis alba* L. and *Festuca rubra* L., two lowest-yielding species *Briza maxima* L. and *Lolium perenne* L., and the remaining three species *Dactylis glomerata* L., *Arrhenatherum elatius* P.B., and *Trisetum flavescens* L. AMMI model was used by Dehghani et al. (2016) to evaluate 72 tall fescue genotypes including 24 parental genotypes, 24 early flowering polycross progeny, and 24 late flowering polycross progeny for G x E interaction, drought adaptation, and yield stability under drought-stressed environments. The stability of yield of a genotype across diverse environments may indicate potential adaptation of the genotype in abiotic or biotic stress as the resistance or tolerance mechanism of the plant is responsible for the trait stability (Duvick 1996). The selected genotypes for tall fescue improvement should have higher yield and stability for multiple years even under grazing pressure. This study explored G x E interaction on yield and stability of 16 tall fescue populations using the GGE biplot method. The objectives were to evaluate: (1) the performance of different populations in nine testing environments, (2) which-won-where, mean performance, and stability of the populations, (3) ranking populations relative to the ideal

population and the representativeness and discriminating ability of the environments, and (4) ranking environments and correlation.

Methods

The experiment was carried out in two locations Athens and Blairsville in Georgia from 2017 through 2021 with Blairsville trials starting in 2018. The trials in Athens and Blairsville were established on November 28, 2016, and March 9, 2017, respectively. The fields were prepared in both sites by conventional tillage. The average annual maximum and minimum temperatures in Athens were 72.4ºF and 50.6 ºF, respectively while in Blairsville were 68.0ºF and 43ºF, respectively. The total precipitations in Athens and Blairsville were 48.93 in and 55.41 in, respectively. The averages were based on the data from 1949 to 2016 for Athens (33.948 ºN, 83.328 ºW, 239 m elevation) and 1932 to 2016 for Blairsville (34.854 ºN, 83.944 ºW, 594 m elevation) (http://www.georgiaweather.net/). The soil types in Athens and Blairsville were Cecil sandy loam and Bradson loam, respectively. Nitrogen (N) Fertilizer was applied in both sites at the rate of 56 Kg/ha and the weed management was done using Quinclorac, Dicamba, and Pendamenthalin. Soil pH above 6 was maintained in both sites using lime. The trials were grown as rainfed. A combination of a location and a year was treated as an environment and thus we created nine test environments (AT17 through 21 and BL18 through 21 where AT and BL refer to Athens and Blairsville, respectively and the last two digits refer to the year) for evaluating 16 populations including 10 experimental populations [GALA1301(ga1), GALA1302(ga2), GALA1303(ga3), GALA1304(ga4), GALA1306(ga6), GALA1502A(g2a), GALA1503A(g3a), GALA07101T(g1t), GALA1502T(g2t), and GALA1503T(g3t)] and six checks [Barianne(brn), BarOptima(bop), Cajun(cjn), KY31(k31), MaxQ(mxq), and Texoma(tma)]. The experimental populations included the selections developed both with or without grazing stress. The experimental design used was a randomized complete block design with five replications in each of the two locations. Analysis of variance (ANOVA) of yield was carried out using JMP pro 2016 (JMP, 2016). The GGE biplot analysis was carried out using the GGEBiplotGUI package in R with the procedure described by Frutos et al. (2014).

Results and Discussion

Location and year had significant effects on yield performance of tall fescue. In Athens, there were significant differences ($P < 0.05$) among populations for all years except 2017 and 2021. In Blairsville, there were yield differences among populations in each of the years. The GGE variation explained by the first two principal components (PC1 and PC2) was 46.78% and 28.45%, respectively.

The Performance of Different Populations in Nine Test Environments

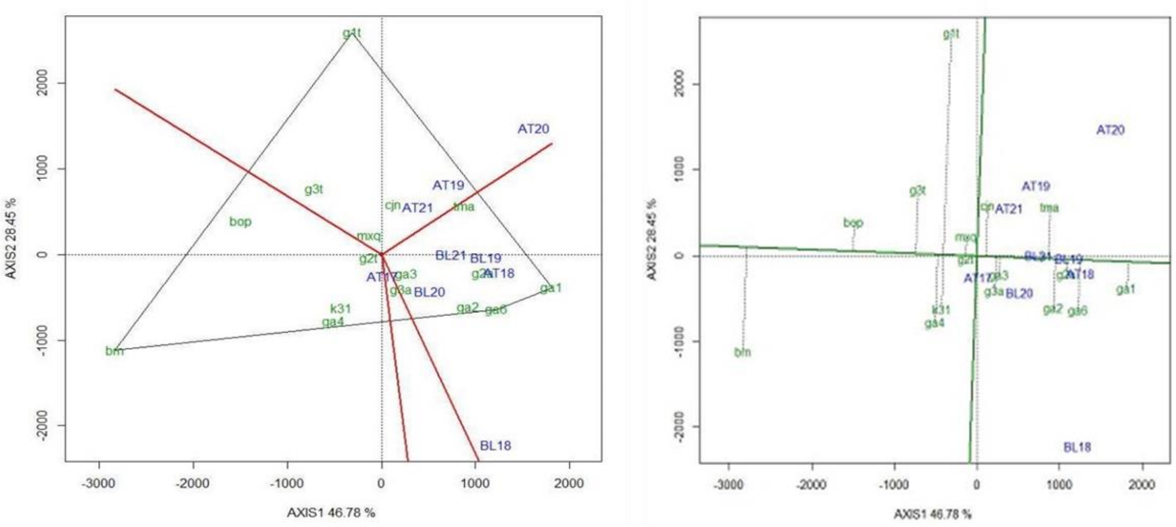
In each of the nine testing environments, different sets of populations showed above-average performance (Table 1). We used GGE biplot to compare a few pairs of populations. In one of the pairwise comparisons, GALA1502T(g2t) performed better in both Athens and Blairsville compared to GALA1502A(g2a) in general. Similarly, in another pairwise comparison, GALA1503T(g3t) performed better in Athens while ALA1503A(g3a) performed better in Blairsville.

Table 1. Above-average performers in different environments

Year	Above average performers	
	Athens	Blairsville
2017	brn, ga4, ga6, ga2, k31, ga1, g3a, g2a, ga3, and g2t	
2018	ga1, ga6, ga2, g2a, tma, ga3, and g3a	ga1, ga6, ga2, g2a, ga3, ga4, k31, and ga3
2019	g1t, tma, ga1, g2a, cjn, ga6, ga2, mxq, and g3t	ga1, ga6, g2a, ga2, tma, ga3, g3a, and cjn
2020	g1t, ga1, tma, g2a, cjn, ga6, ga2, mxq, and ga3	ga1, gaga6, ga2, g2a, g3a, ga3, tma, ga4, and k31
2021	g1t, tma, ga1, cjn, g2a, g3t, ga6, mxq, and ga2	ga1, ga6, g2a, ga2, tma, ga3, g3a, and cjn

Which-Won-Where, Mean Performance and Stability of the Populations

As indicated in Fig. 1 (a), GALA07101T(g1t) was the best experimental population for Athens while GALA1301(ga1) and GALA1306(ga6) were the best populations for Blairsville. The populations GALA07101T(g1t), GALA1503T(g3t), Cajun(cjn), and MaxQ(mxq) can be recommended for Athens while the populations GALA1301(ga1), GALA1302(ga2), GALA1303(ga3), GALA1306(ga6), GALA1502A(g2a), and GALA1503A(g3a) can be recommended for Blairsville. The check Texoma(tma) showed similar performance in both Athens and Blairsville. Fig. 1 (b) showed that GALA1301(ga1) had the highest mean yield as shown by the highest distance from the biplot origin on average-environment coordination (AEC) abscissa (the single-arrowed line) followed by GALA1306(ga6), GALA1502A(g2a), GALA1302(ga2), Texoma(tma), GALA1303(ga3), GALA1503A(g3a), and Cajun(cjn), whereas Barianne (brn) had the lowest mean yield. GALA07101T(g1t) had the highest variability (poorer stability) as shown by the longest perpendicular distance to AEC abscissa while GALA1502T(g2t) was the most stable. The experimental populations GALA1502A(g2a), GALA1301(ga1), and GALA1303(ga3) are comparatively both stable and high yield performers.

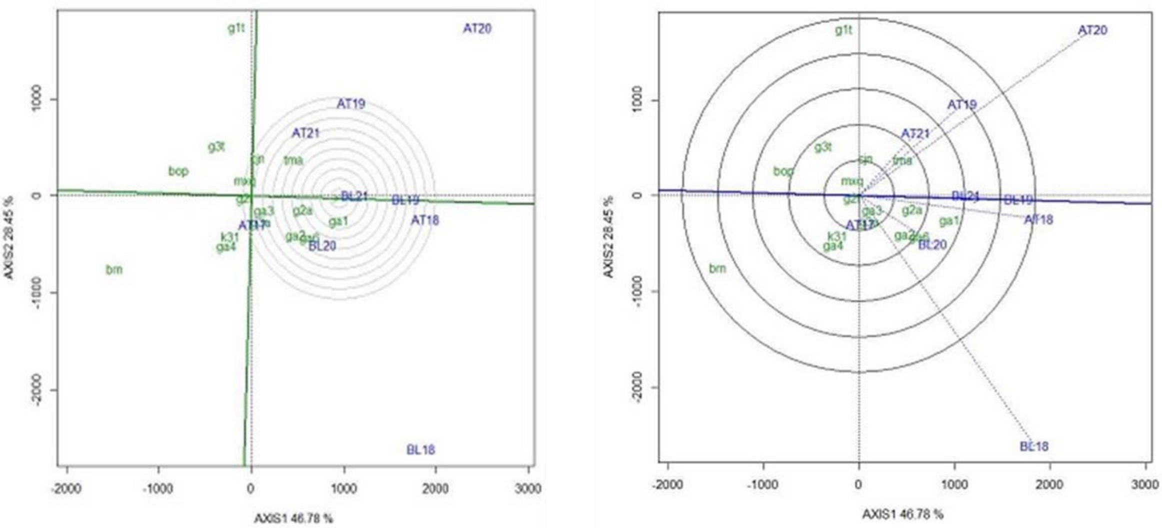


(a) **(b)**

Figure 1. The which-won-where view of the GGE biplot (a) and mean performance and stability of the populations (b) for tall fescue yield performance and stability data. [i]

Ranking Populations Relative to the Ideal Population and the Representativeness and Discriminating Ability of the Environments

The most ideal population was GALA1301(ga1) and the populations closer to it were more desirable. Therefore, GALA1301(ga1), GALA1502A(g2a), GALA1306(ga6), GALA1302(ga2), Texoma(tma), GALA1303(ga3), GALA1503A(g3a) and Cajun(cjn) were desirable populations [Fig. 2 (a)]. As shown in Fig. 2 (b), among the nine environments, AT20 and BL18 were more discriminating (informative) as shown by their long vector distances from the biplot origin, and AT17 least discriminating. BL19 was the most representative of the other environments while AT20 and BL18 were less representative. Therefore, if multiple locations are not available, Blairsville can be selected as the representative location.



(a) **(b)**

Figure 2. GGE biplots showing ranking populations relative to the ideal population (a) and the representativeness and discriminating ability of the environments (b).[i]

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[i] *The population is represented using a combination of three smallcase letters or a combination of two smallcase letters and a number in green color while the environment is represented using a combination of two capitalcase letters and two numerals in blue color. AT represents location 'Athens' while BL represents location 'Blairsville'. The last two numerals in blue color indicate the year of field trial.*

Ranking Environments and Correlation

The ideal environment should be both the most discriminating (informative) and most representative of other environments. Therefore, BL19 was the most ideal environment. Biplot can also be used to check the correlation among the environments and the information can be used to choose the number of environments to be included in the experiment for the performance evaluation of breeding materials. Correlation among locations can help in the economic and optimum planning of multiple environment variety trials. In our study among nine test environments, AT19, AT20, and AT21 were correlated in Athens, and all environments BL18, BL19, BL20, and BL21 were correlated in Blairsville. AT17 and AT18 were comparatively more correlated with Blairsville environments.

Table 2. Total annual yield (Kg ha^{-1}) of different experimental populations in Athens and Blairsville from 2017 through 2021

	Athens						Blairsville				
Populations	2017	2018	2019	2020	2021	5-Yr Avg	2018	2019	2020	2021	4-Yr Avg
GALA1301(ga1)	1714	6229	3196	9016	3761	4783	8681	4518	5041	3927	5542
GALA1306(ga6)	1336	6059	3372	8044	3479	4458	8310	4729	5589	3917	5636
GALA1502A(g2a)	1136	6214	3392	8364	3385	4498	7991	4335	5431	3663	5355
GALA1302(ga2)	1320	6436	3105	7905	3550	4463	8141	4329	5224	3763	5365
Texoma(tma)	1604	5393	3425	9164	3676	4652	7648	3986	5221	3562	5105
GALA1303(ga3)	1561	4865	3321	7874	3217	4168	7737	4683	5161	4058	5410
Cajun(cjn)	1527	5799	3584	8413	3729	4610	7310	3358	4602	3305	4644
GALA1503A(g3a)	1391	6127	3138	8053	3142	4370	8000	3575	4795	3045	4854
GALA1502T(g2t)	1333	4767	2964	8179	3336	4116	7639	3870	5206	3607	5080
MaxQ(mxq)	1598	4643	3010	8265	3067	4117	7339	4423	4918	3626	5076
KY31(k31)	1459	5536	2688	7010	3517	4042	7451	4643	5232	3034	5090
GALA07101T(g1t)	971	5622	3773	8751	3860	4596	5063	4080	4691	3440	4318
GALA1304(ga4)	1678	4903	2847	7496	2987	3982	7963	3706	5172	3448	5072
GALA1503T(g3t)	1507	4432	3061	8428	3523	4190	6940	3574	4713	3085	4578
BarOptima(bop)	1520	4873	2773	7237	3331	3947	6457	3520	4643	3244	4466
Barianne(brn)	1401	4606	2094	5810	2883	3359	7156	2600	4602	2713	4268
Grand Mean	1441	5406	3109	8001	3403	4272	7469	3959	4960	3474	4965
LSD $_{\alpha=0.05}$	NS	1452	763	1419	NS		1745	921	765	548	

^{NS}Not significant yield differences among the populations

The cooler temperature and comparatively more rainfall have been reflected in the higher yield performance of the populations in Blairsville (Table 2). High yield, stability across locations and years, and the good survival of the plant stands for several years after establishment are desirable attributes of tall fescue.

Conclusions

Using the GGE biplot method, we explored the effects of G x E interaction on yield and stability of experimental populations and standard checks. Different sets of populations were adapted to different environments, a few populations showed only stability, while some other populations showed both high yield and stability. Our study indicated that the stability of the populations can be improved by selection under stress environments such as grazing pressure while the intrinsic yield potential is controlled by the genotype of the plant itself.

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