Research Article

Analysis of Genotype-Environment Interaction and Yield Stability of Introduced Upland Rice in the Groundnut Basin Agroclimatic Zone of Senegal

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Identification of highly performing varieties under Senegalese environment is crucial to sustain rice production. Genotype-environment interaction and stability performance on the grain yield of ten upland rice genotypes were investigated across 11 environments in Senegal during the rainy seasons of 2016 and 2017 to identify adapted varieties. The experiment was conducted using a randomized complete block design with three replications at each environment. Data on grain yield were recorded and analyzed using the additive main effects and multiplicative interaction (AMMI) model. The combined analysis of variance revealed that the grain yield was significantly affected by environment (67.9%), followed by genotype × environment (G × E) interaction (23.6%) and genotype (8.5%). The first two principal component axes were highly significant with 37.5 and 26% of the total observed G × E interaction variation, respectively. GGE biplot grouped the environments into four potential mega-environments. Based on the yield stability index parameter and ranking GGE biplot, NERICA 8 and ART3-7-L9P8-1-B-B-1 were stable and high-yielding varieties compared to the local check NERICA 6. These varieties should be proposed for cultivation in order to sustain the rice production in the southern part of the groundnut basin of Senegal and used as parental lines in rice breeding program for grain yield improvement.

1. Introduction

Globally, rice is one of the most important cereals grown as staple food crop [1]. By 2035, it is estimated that supplementary 112 million metric tons of rice will be needed to fulfill human consumption [2]. In the Sahelian countries including Senegal, rice is the second most cultivated cereal after pearl millet. Despite the effort of Senegalese government for boosting local rice production, more than 1000 metric tons of rice were imported in 2018-2019, which was worth about $339 millions [3]. To meet the increasing rice demand, available agricultural practices, water management, and varietal opportunities should be exploited.

Rice is produced in various agroecologies and cropping systems including rain fed upland and lowland, irrigated, and mangrove [4]. Although upland rice represents a small amount (around 11%) of global rice production in the world, it plays a crucial role in local rice production in arid and semiarid countries [5]. Due to climate change effects, a

limitation of water resource for lowland rice cultivation has become a challenge. The upland rice appears as a promising sustainable crop that can contribute to cope with food security issue [6]. Development of new upland rice varieties has become a serious research interest for some Asian countries such as Vietnam [7], India [8], and China [9]. With regard to Africa, recent efforts were done by Africa Rice and their collaborators in order to develop upland rice varieties adapted to growing conditions in tropical regions. The successful exploitation of the varieties developed by Africa Rice required adaptability trials under local growing conditions. For this purpose, multienvironment trials are conducted.

Many plant breeding programs performed multi-environment trials in order to assess the response of plant material in several locations [10]. The key objective of plant breeders is to develop varieties with a wide adaptation to various environments. Multienvironment trial data have been revealed useful in identifying varieties with a high grain yield for diverse cereals such as maize [11, 12], sorghum [13], and irrigated [14] and upland rice [15]. Classical statistical models were developed to assess and provide useful information to exploit genotype by environment interactions. These models include analysis of variance, additive main effects and multiplicative interaction (AMMI), site regression (SREG), genotype regression (GREG), shifted multiplicative, completely multiplicative, and genotype by environment biplot (GGE). Among these models, AMMI and GGE have been widely adopted by plant breeders. The AMMI model combined analysis of variance and principal component analysis [16], while GGE biplot is based on genotype and environment scores. For the AMMI model, singular value decomposition is applied to the twice-centered two-way data, capturing genotype by environment only. In contrast, GGE captures Genotype and Genotype by Environment by applying singular value decomposition to environment-centered two-way data [17].

Previous studies highlighted the use of genotype by environment model in upland rice breeding for drought stress tolerance [18, 19], adaptability and yield stability assessment [20], optimum sowing date identification [21], and root morphology [22]. The aim of the present study was to identify high yielding and stable upland rice genotypes for cultivation in the groundnut basin agroecological zone of Senegal.

2. Materials and Methods

The experiments were carried out during the rainy seasons of 2016 and 2017 in 11 environments located in the groundnut basin agroecological zone (Table 1).

This agroecological zone, which covers over 30% of the land area of Senegal and 65% of the cultivated area, is characterized by a highly variable rainfall pattern which is monomodal with an annual mean of 600 mm. The rainy season usually begins in June-July, ends in October, and is followed by a long dry season, which begins in November and lasts till June. The soil texture in the 11 environments is clay or sandy loam.

Ten genotypes were used for the experiment (Table 2). These included nine genotypes selected based on farmers' preferences and agromorphologic performance and NERICA 6, the most popular variety cultivated in this region as a check. The experiments were laid out in a randomized complete block design with three replications. A plot consisted of 12 rows of five meters per plot. The spacing was 25 cm between rows and 20 cm between hills. All the recommended cultivation practices for upland rice cultivation were applied. The grain yield data per plot was recorded over the different environments.

An initial analysis of variance was performed for each of the 11 environments using Genstat software version 12.1 to determine the genotype effect. After this individual environment analysis of variance, the homogeneity between residual variances was determined, and a joint analysis of variance using Genstat software was performed to assess the genotype and environment effect and the magnitude of the $G \times E$ interaction. Additive main effect and multiplicative interaction (AMMI) model implemented in statistical software Genstat was used to adjust the main or additive genotype-environmental effects by analysis of variance, in addition to the adjustment of the multiplicative effects for the $G \times E$ interaction by principal component analysis. Assuming μ is the grand mean of upland rice genotypes yield, α_g is the genotype deviation of the grand mean, β_e is the environment deviation, λ_n is singular value for interaction principal component (IPC) n and λ_n^2 is the corresponding eigenvalue, γ_{gn} is the eigenvector for genotype g and component n, δ_{en} is the eigenvector for environment e, ρ_e is the residual, $\kappa_{r(e)}$ is the block effect for replication r within environment e and ε_{ger} is the error, the yield of genotype g in environment e for replication r (Y_{ger}) is expressed by Gauch's model [23]:

$$Y_{ger} = \mu + \alpha_g + \beta_e + \sum_n \lambda_n \gamma_{gn} \delta_{en} + \rho_e + \kappa_{r(e)} + \varepsilon_{ger},$$

(1)

Based on relative contributions of the IPC 1 and 2 axis scores to genotype by environment interaction effect, the AMMI stability value (ASV) was computed using the following formula described by Danquah et al. [24]:

$$ASV = \sqrt{\left[\frac{IPC1_{Sum\,of\,squares}}{IPC2_{Sum\,of\,squares}} \left(IPC1_{score} \right) \right]^2 + \left(IPC2_{score} \right)^2}.$$

(2)

Using yield-based genotype ranking and ranking based on the AMMI stability value, the yield stability index was calculated as follows:

$$yield\ stability\ index\ =\ ranking\ based\ on\ the\ AMMI\ stability\ value$$
$$+\ ranking\ based\ on\ yield.$$

(3)

Lower are AMMI stability value and yield-based ranking values, more stable and high yielding is the genotype [25].

Table 1: Environment, rainfall (mm), soil texture, longitude, and latitude at each experiment environment.

Environment	Code	Rainfall (mm)	Soil texture	Latitude	Longitude
Diama fara (2017)	DF17_.E1	723	Sandy loam	13°55′56.32″N	15°42′0.14″O
Medinatou salam (2016)	MeS16_.E2	668	Clay	13°49′16.35″N	15°28′0.43″O
Medinatou salam (2017)	MeS17_.E3	615	Clay	13°49′16.35″N	15°28′0.43″O
Maka sacoumba (2017)	MaS17_.E4	301	Clay	13°49′49.14″N	15°39′39.58″O
Nioro (2016)	N16_.E5	909	Sandy loam	13°45′30.64″N	15°47′17.50″O
Nioro (2017)	N17_.E6	702	Sandy loam	13°45′30.64″N	15°47′17.50″O
Ndama (2016)	Nd16_.E7	555	Clay	13°49′49.19″N	15°39′39.72″O
Bowou (2016)	B16_.E8	591	Sandy loam	13°40′57.96″N	15°41′35.19″
Medina ngueyene (2016)	MN_.E9	588	Clay	13°39′44.19″N	15°42′0.14″O
Medina ngueyene (2017)	MN_.E10	591	Clay	13°39′44.19″N	15°42′0.14″O
Keur babou penda (2017)	KBP17_.E11	492	Clay	13°45′23.12″N	16°19′35.69″O

Table 2: List of upland rice genotypes used in this study.

Genotype	Name	Origin
G1	ART16-13-13-2-2-B-1-B-1-B	Africa rice
G2	ART3-9-L6P2–B–B	Africa rice
G3	ART16-12-22-1-3-1-1-B-1-B	Africa rice
G4	CNAX 3031-78-2-1-7	Brazil
G5	ART16-17-7-18-1-B-1-B-1-B	Africa rice
G6	BRS CONAI	Brazil
G7	NERICA 8	Africa rice
G8	NERICA 14	Africa rice
G9	ART3-7-L9P8-1-B-B-1	Africa rice
G10	NERICA 6 (check)	Africa rice

Biplot graphs with the grain yield data were plotted using the package GGEBiplots following the GGE biplot model defined by Yan [17] in R 3.6.0 as follows:

$$y_{ij} = \sum_{n=1}^{r} \lambda_n \xi_{in} \eta_{jn}, \tag{4}$$

where r is the number of principal components required to approximate the original data, λ_n is the singular value of principal components, ξ_{in} and ξ_{jn} are the ith genotype score and the jth environment score for principal components, respectively, and y_{ij} is the response yield according the ith genotype in the jth environment.

3. Results

3.1. Significant Genotype by Environment Interaction.
Results of analysis of variance for yield data of upland rice genotypes using AMMI model are reported in Table 3.

All the sources of variation effects were significant ($P < 0.01$). The highest part of the total variation was attributable to environmental effects (68%), followed by genotype by environment interaction (24%) and genotype (8%). The initial first two IPCA were highly significant and contributed to 63.5% of the total genotype by environment variation.

The mean performance of all the ten upland rice genotypes across the 11 environments showed significant genetic variability for grain yield (Table 3). NERICA 14 had the highest grain yield (4764 kg ha^{-1}), while CNAX 3031-2-1-7 had the lowest grain yield (2751 kg ha^{-1}), followed by

the standard check NERICA 6 (3028 kg ha^{-1}) across all environments (Table 4).

3.2. Potential Mega-Environments.
We assessed the "which-won-where" pattern to identify the variety with the best performance in each megaenvironment. The biplot captured 68.96% of the variation in the data (Figure 1).

This suggests that the biplot provides a reliable visualization of the actual data. The 11 environments fell into four sectors with different wining varieties, suggesting that there was a crossover, and target environment could be divided into four different megaenvironments. G5 (ART16-17-7-18-1-B-1-B-1-B) and G9 (ART3-7-L9P8-1-B-B-1) were the highest yielding in the megaenvironment made up of E1, E6, E11, and E8. In the megaenvironment composed of E7, E4, E5, and E2, G8 (NERICA 14) was the winning variety in terms of grain yield. G3 (ART16-12-22-1-3-1-1-B-1-B) was the winning variety in the megaenvironment E3, while G4 (CNAX 3031-78-2-1-7) and G10 (NERICA 6) were the winning varieties in E9.

3.3. Stability and Mean Performance across Environments.
Additive main effect and multiplicative interaction stability value (ASV) and yield stability index (YSI) ranked the genotypes based on the least score (Table 4).

Low scores of ASV represent the most stable genotypes, while low score of YSI represent the most stable and high yielding genotypes. Based on the ASV, the most stable genotype for grain yield was BRS CONAI since it had the lower ASV value, followed by ART3-9-L6P2–B–B and NERICA 8. NERICA 14 had the highest yield across environments, but it was the least stable genotype because it had the highest ASV value. In terms of YSI, ART3-9-L6P2–B–B, followed by BRS CONAI, NERICA 8, and ART3-7-L9P8-1-B-B-1 were the best genotypes that combined high yield with stability. CNAX 3031-78-2-1-7, followed by ART16-12-22-1-3-1-1-B-1-B and NERICA 6, had the highest YSI and was considered as low yielding and unstable genotypes. Meanwhile, NERICA 14 and ART3-7-L9P8-1-B-B-1 exhibited earlier flowering status among the tested genotypes.

The patterns of mean performance and stability of the varieties across environments patterns were also graphically presented (Figure 2) using the GGE biplot model.

TABLE 3: Additive main effects and multiplicative interaction analysis of variance for grain yield (t ha^{-1}) of the genotypes across environments.

Source	df	SS	MS	Contribution to the SS (%)
Treatment	109	1332169710	12221740	
Genotypes (G)	9	112875818	12541758***	8.5
Environment (E)	10	904427485	90442749***	67.9
G × E	90	314866407	3498516***	23.6
IPCA1	18	117981244	6554514***	37.5
IPCA2	16	81898746	5118672***	26.0
IPCA3	14	40448548	2889182^{ns}	12.1
Residuals	30	39628719	1320957^{ns}	
Error	198	357980618	1807983^{ns}	

df: degree of freedom, SS: sum of squares, MS: mean square.

TABLE 4: Flowering and grain yield performance and stability parameters of the tested genotypes.

Genotypes	Flowering (DAS)	Grain yield (kg ha^{-1})	IPCAg1	IPCAg2	ASV	YSI
ART16-13-13-2-2-B-1-B-1-B	65	3889	3.75206	21.18663	21.9	9
ART3-9-L6P2–B–B	71	4102	−0.62371	16.49345	16.5	5
ART16-12-22-1-3-1-1-B-1-B	69	3341	38.53965	−22.01051	59.7	17
CNAX 3031-78-2-1-7	73	2751	36.89505	2.46959	53.2	18
ART16-17-7-18-1-B-1-B-1-B	68	3581	−34.81286	6.68594	50.6	13
BRS CONAI	65	3601	−6.87921	3.32973	10.5	7
NERICA 8	67	4038	−13.17107	−8.63944	20.8	7
NERICA 14	64	4764	−14.17198	−56.38124	60.0	11
ART3-7-L9P8-1-B-b-1	64	4404	−34.18457	14.92481	51.5	9
NERICA 6	71	3028	24.65662	21.94104	41.7	14

DAS: days after sowing, IPCAg1: component 1, IPCAg2: component 2, ASV: AMMI stability value, YSI: yield stability index.
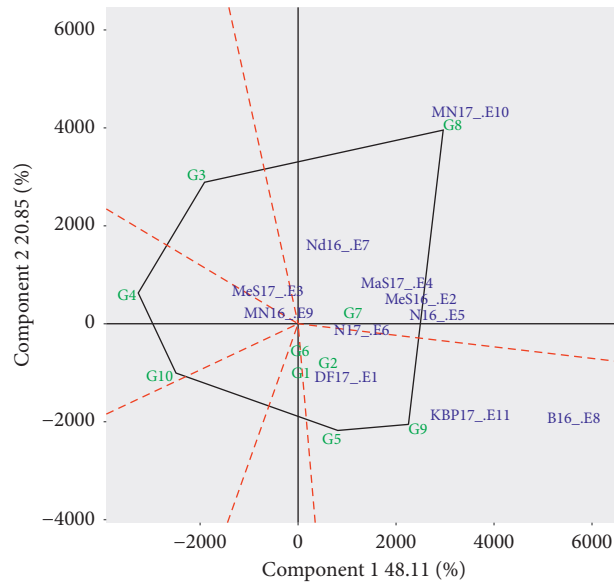

FIGURE 1: The which-won-where GGE biplot view depicting the performance of varieties in relation to potential megaenvironments (delineated in red dash lines) based on the genotype focused singular-value partitioning and environment-centered model. See Tables 1 and 2 for genotypes and environments code names, respectively.

The biplot explained 68.96% of the variation for grain yield. The principal components 1 and 2 accounted for 48.11 and 20.85% of the total variation, respectively. Based on the average-environment coordination (AEC), the genotypes NERICA 14 (8), ART3-7-L9P8-1-B-B-1 (9), and NERICA 8 (7) appeared as the highest yielding genotypes among which NERICA 8 and ART3-7-L9P8-1-B-B-1 were the most stable across environment. CNAX 3031-78-2-1-7, NERICA 6, and ART16-12-22-1-3-1-1-B-1-B were the lowest yielding genotypes.
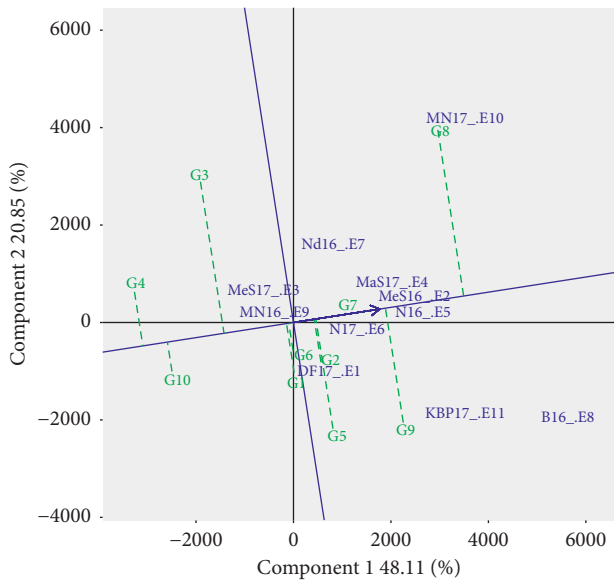
FIGURE 2: The average-environment coordination (AEC) view showing the performance and stability of varieties in the tested environments based on the genotype focused singular-value partitioning and environment-centered model. The x-axis blue single-arrowed line is oriented to the higher mean across the tested environments. The y-axis blue line depicts the stability (more closer to the center meaning more stable variety) of the mean. See Tables 1 and 2 for full genotypes and environments code names, respectively.

4. Discussion

The present study aimed at identifying high yielding and stable upland rice varieties for cultivation in the groundnut basin agroecological zone by evaluating a set of ten upland rice varieties in different environments. The results showed that the performance of the upland rice varieties was subjected to a strong influence of environments. Such variation may be due to differences in rainfall and soil texture across the different locations where the experimentations were established. Indeed, the rice grain yield in clay soil is known to be higher than that in sandy soil [26] and is closely correlated with total rainfall [27]. The significant effect of genotype by environment (GE) interaction reflected on the differential response of a given upland rice variety in various environments. This difference in response demonstrated that, in addition to the strong effect of the environments, the GE interaction had a remarkable effect on genotypic performance in different environments. The significant effect of GE has been previously noted in rice [28], pearl millet [29], and several other crops. The relative contributions of GE interaction effects for grain yield noted in this study were similar to Katsura et al. [30] results who evaluated 27 rice genotypes in four fields during three consecutive years in the Northern Region of Ghana. In contrast to the results of our study, Sharifi et al. [28] indicated that the GE interaction contributed for 40% of the total sum of squares of the rice grain yield of genotypes evaluated in Iran.

In our study, the NERICA 14 variety showed the highest grain yield, while the variety CNAX 3031-78-2-1-7 had the lowest grain yield. The grain performance of NERICA 14 was higher than the national average grain yield of the national released upland varieties. The high performance of this variety could be explained by its earliness compared to the other varieties which is an important aspect to consider because of the short rainfall season observed in this Sahelian zone. Farmers have even considered earliness as one of the most important criteria when selecting a variety to grow in this agro-ecological zone.

Identification of mega-environment requires consistency of the mega-environment' delineation and winning cultivars in each mega-environment over several years [17]. In our study, through the GGE biplot, the eleven environments were divided into four sectors each with its own winning cultivar. As a result, the target environments could be divided into four mega-environments. Subsequent evaluation of rice yield performance in the target environments can be done in four environments instead of 11 to save resources. Coupled with the high-yielding criteria, the yield stability is a crucial parameter allowing efficient implementation of released varieties for diverse environments. Our study identified ART3-9-L6P2–B–B, BRS CONAI, and NERICA 8 as the most stable varieties, indicating these materials are not only highly productive but also stable across environments. Consequently, a reliable benefit for Senegalese farmers can be expected no matter the growing location of these three varieties. Reliable identification and release of stable rice genotypes based on the yield stability index were successfully achieved regarding zinc-biofortified rice genotypes [19], productive mutant rice [31], and drought-tolerant rice breeding lines [25]. Considering the fragmented seed market in countries like Senegal [32], it is more profitable and practical for seed companies to produce seeds for varieties that are widely adopted and cultivated, which is the case of varieties that are stable with high performance across a wide agroecological zone. The dissemination of those identified varieties combining stability and productivity would increase rice production and reduce import bill in Senegal.

5. Conclusions

We evaluated a set of 10 rice varieties across 11 environments to assess their stability and productivity. We identified the most productive varieties (ART3-9-L6P2–B–B, BRS CONAI, and NERICA 8) within each environment and the most stable and productive varieties across environments. The varieties belonging to the latter category hold great potential to be introduced in varietal release pipeline to offer greater varietal choice for farmers. The use of these varieties could improve the overall rice production in Senegal and decrease rice import.

Data Availability

The data used to support the findings of this study are included within the supplementary information file.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

Supplementary Materials

Supplementary table: Yield data of the upland rice genotypes collected in the environments of study. (*Supplementary Materials*)

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