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Full Length Research Paper

Use of the AMMI model to analyse cultivar-environment interaction in cotton under irrigation in South Africa

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Upland cotton (*Gossypiumhirsutum* L.) is considered to be the most important textile fiber crop in the world. Unpredictable weather patterns caused a need for the identification of stable genotypes that have specific adaptation to specific environments. The objective of this study was to evaluate yield performance of different cotton cultivars under irrigation in South Africa by using the AMMI model. Five genotypes were evaluated over three seasons (2003 to 2006) at six locations. The additive main effects and multiplicative interaction (AMMI) statistical model was used to investigate the cultivar x environment interaction (GEI), yield stability and adaptation to environments. AMMI analysis indicated that cotton yield showed highly significant differences ($p<0.01$) affected by Environments (E), genotypes (G) and genotype x environment interaction (GEI). 84.0 % of the total sum of squares was attributed to environmental fluctuations showing that the environments were diverse, with large differences among environmental means accounting for most of the variation in cotton yield. Results showed that NuOPAL was the best performing cultivar in 15 out of 18 observations in fibre yields.

Key words: AMMI model, cotton, cultivar x environment interaction.

INTRODUCTION

Cotton fibre is the world's most important natural textile fibre (Stiff and Haigler, 2012). Chaudry and Guitchounts (2003) stated that cotton is unique among agricultural crops, because it provides food and fiber. They further stated that cotton also provides an edible oil and seed by-products for livestock feed and employment, and income for hundreds of millions of people. Cotton requires specific climatic conditions to produce good yields and quality fibre (Dippenaar, 1988).The Lower Orange River, Northern Cape, North West (Vryburgand Rustenburg), Limpopo Valley, Loskop (Springbok Flats), Mpumalanga and KwaZulu-Natal have been identified by Ehlers and van Heerden (1976) as the most suitable cotton production areas in South Africa. While Mpumalanga and areas further north are usually warm enough in early spring to ensure good emergence and stands, early season temperatures in the Northern Cape are usually too low for rapid growth of cotton. Most of the cotton producing areas in South Africa are known for their unpredictable weather patterns. Thus, multi-location trials should always be conducted to select the best adapted cultivars for specific environments. The Agricultural Research Council, Institute for Industrial Crops at Rustenburg(ARC-IIC) has been conducting national cotton cultivar evaluation trials for the past six decades in order to recommend specific cultivars for the different production areas in South Africa. The best way to analyze such data is via the well-known Additive Main effects and Multiplicative Interaction (AMMI) technique. AMMI is primarily used for exploring cultivar x environment data as this technique combines the additive main effects for the ANOVA and the multiplicative model for the principal component analysis (PCA). The PCA model is fitted to the residuals from the ANOVA and the resulting scores are called the (I) (for interaction) PCA scores.

The IPCA scores are calculated for both the cultivars and the environments. Graphs are produced of the first IPCA scores versus the cultivar and environment

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means, from which the stability of both can be seen (scores closest to zero are more stable), as well as which are similar in yield (Smith and Smith, 1992).

AMMI has been used successfully by researchers on crops such as barley (Gebremedhin *et al*., 2014), bread wheat (Purchase *et al*., 2000),coconut (Odewale *et al*., 2012) cotton (Campbell and Jones, 2005), durum wheat (Mohammadi and Amri, 2011), field pea (Fikere *et al.*, 2010), lucern (Smith and Smith, 1992), maize (Ma'ali, 2008), potatoes (Steyn *et al.*, 1993) rice (Nassir and Ariyo, 2011) and tobacco (Sadeghi *et al.*, 2011). The graphical version (biplot) of the cultivar means and the first interaction (PCA)principle component analysis scores eases interpretation and identification of high yielding cultivars. Principal component analysis is a variable reduction procedure and is the most frequently used multivariate method (Crossa, 1990; Purchase, 1997). Its aim is to transform the data from one set of coordinate axes to another, which preserves, as much as possible, the original configuration of the set of points and concentrates most of the data structure in the first principal component axis.The objective of the study was to analyze and interpret cultivar environment interactions for cotton yield and quality in South Africa by means of the AMMI statistical model.

MATERIALS AND METHODS

Data obtained from the (ARC-IIC) national cotton evaluation trials during the 2003/04 to 2005/06 seasons were used in this study. Five cultivars, namely Delta OPAL, NuOPAL, Delta OPALRR, SZ9314 and LS9219 (Table 1), were evaluate dat six different cotton producing areas. Loskop, Makhathini, Rustenburg, Upington, Vaalharts and Weipe were selected as target areas for the study. Treatments, represented by cultivars, were arranged in a randomized block design with four replications. Plots were 4 m x 9 m in size and consisted four rows. The planting space between and within rows were 1 m and 0.15m, respectively. Due to different planting dates, soil types, agronomic practices and weather conditions, the eighteen trials (6 localities x 3 seasons) were considered to represent eighteen environments. Fertilizer was applied according to the soil analysis of each site. Irrigation was applied at all the trials according to the crop's requirements. Table 2 indicates the sites at which the trials were conducted (with codes as used in the biplotgraph) as well as soil forms, fertilization and annual rainfall. Variables measured were fibre percentage (%), fibre yield (kg ha^{-1}), lint length (mm), lint strength (g tex^{-1}) and micronaire.

First, an analysis of variance (ANOVA) was done to check for normality and constant variances and then AMMI analysis was performed using the AMMI procedure in GenStat®(Payne *et al.*, 2009). The AMMI statistical model is explained by Gauch (1992). It combines ANOVA and Principal Component Analysis (PCA) into a single analysis. The GEI (Genotype x Environment Interaction) is partitioned into a number of interaction (IPCA) components and a residual. The IPCA scores assist in understanding GEI, improving accuracy of yield estimates and increasing the probability of successfully selecting cultivars with the highest yields. AMMI stability values (ASV) were then calculated in order to rank cultivars in terms of stability. Purchase(1997) explained ASV in detail and summarized ASV as the distance from the coordinate point to the origin in a two dimensional scatter gram of IPCA1 scores against IPCA2 scores.

$$AMMIstabilityvalue(ASV) = \sqrt{[\frac{SSIPCA1}{SSIPCA2}(IPCA1score)]^2 + [IPCAscore]^2}$$

Where: SS = Sum of squares; IPCA1 = interaction principal component analysis axis 1; IPCA2 = interaction principal component analysis axis 2; $\frac{SSIPCA1}{SSIPCA2}$ = the weightgiven to the PCA1-value by dividing the PCA1 sum of square by the PCA2 sum of square.Large IPCA scores (negative/positive), shows specific adaptation of a cultivar to a certain environment. Small IPCA scores show more stable cultivars over all environnent.

RESULTS

Yield Performance

The AMMI analyses of the yield variables are presented in Table 3. In all cases, the first two IPCA components were selected (P<0.001), thus known as AMMI 2.All AMMI analyses indicated highly significant differences (P<0.001) for cultivar and environment main effects and GEI. The environment SS (Sum of Squares) relative to the total SS explained most of the variation in the data (52% and 84% for fibre % and fibre yield, respectively), as can be expected in diverse cotton production areas. SS was calculated as the square of the sum of differences between each measure and the average.

The mean fibre percentage was 40.4%. SZ9314 gave the highest mean fibre percentage of 41.7%.SZ9314 (IPCA1=0.1) and Delta OPALRR (0.2) were adapted to most environments. Delta OPAL (1.5) and NuOPAL (1.1) were slightly sensitive cultivars adapted to higher yielding environments, while LS9219 (-2.9) was more sensitive and was adapted to lower potential environments, resulting in below average fibre percentages of 37.8%.The ASV showed both SZ9314 (1.5) and Delta OPALRR (1.5) to be the most stable cultivars. Mean fibre yield was 1750, with NuOPAL producing the highest fibre yield of 2032 kg ha^{-1}. The IPCA1 score of the cultivar Delta OPALRR (4.5)indicates that it was a relatively stable cultivar, adapted to most environments, as was LS9219 (-5.0). DeltaOPAL (-6.0) is less stable and NuOPAL

Table 1. Five cotton cultivars evaluated for fibre yield and quality under irrigation at Loskop, Makhathini, Rustenburg, Upington, Vaalharts and Weipe South Africa in 2003/04 to 2005/06 growing seasons.

Cultivar	Description	Year of release	Company
DeltaOPAL	A conventional cultivar	1997	Delta Pine, South Africa
NuOPAL	A cultivar containing the Bollgard™ gene for protection against Lepidoptera.	2002	Delta Pine, South Africa
DeltaOPALRR	A cultivar containing the Roundup Ready™ gene	2003	Delta Pine, South Africa
LS9219	A long staple, hairy cultivar	2001	Quton Cotton, Zimbabwe
SZ9314	A medium staple, hairy cultivar (28.5 – 29.4 mm)	2002	Quton Cotton, Zimbabwe

Table 2. Location, soil form, fertilization and annual rainfall (mm) of cotton cultivar evaluation trials irrigation at Loskop, Makhathini, Rustenburg, Upington, Vaalharts and Weipe South Africa in 2003/04 to 2005/06 growing seasons.

Locality	Season	Code	Soil form	Fertilization (kg ha^{-1})			Rainfall
				N	P	K	(mm)
Loskop	2003/2004	L1	Hutton	140	70	40	134.7
	2004/2005	L2	Hutton	140	70	40	315.8
	2005/2006	L3	Hutton	140	70	40	436.1
Makhathini	2003/2004	M1	Hutton	150	40	80	275.2
	2004/2005	M2	Hutton	150	40	80	585.2
	2005/2006	M3	Hutton	150	40	80	401.8
Rustenburg	2003/2004	R1	Arcadia	140	30	80	710.8
	2004/2005	R2	Arcadia	170	30	80	513.4
	2005/2006	R3	Arcadia	150	30	80	636.3
Upington	2003/2004	U1	Hutton	150	30	40	303.1
	2004/2005	U2	Hutton	150	30	40	196.1
	2005/2006	U3	Hutton	150	30	40	356.8
Vaalharts	2003/2004	V1	Hutton	220	50	70	334.8
	2004/2005	V2	Hutton	220	50	70	295.7
	2005/2006	V3	Hutton	260	50	70	212.3
Weipe	2003/2004	W1	Hutton	70	0	0	295.4
	2004/2005	W2	Hutton	70	0	0	165.9
	2005/2006	W3	Hutton	70	0	0	93.1

Table 3. AMMI analysis of the cotton cultivar evaluation trials (yield variables) under irrigation at Loskop, Makhathini, Rustenburg, Upington, Vaalharts and Weipe South Africa in 2003/04 to 2005/06 growing seasons.

	Fibre percentage (%)				Fibre yield (kg ha^{-1})		
Source	DF	SS	SS%	Prob	SS	SS%	Prob
Environment	17	1408.5	52	***	149676773	84	***
Block	36	80.0		***	4010206		
Cultivar	4	485.9	17.8	***	9915737	5.6	***
Interaction	68	589.1	21.6	***	8476395	4.8	***
IPCA1	20	429.2		***	3910975		***
IPCA2	18	96.6		***	2675161		***
Residual	30	63.3			1890259		
Error	138	173.4			6260389		
Total	269	2737.0			178339500		

DF = Degrees of freedom, SS = Sum of squares,
*** Indicates probability of significant differences at 0.001 alpha-level.
Block indicates blocks within environments
SS% is the proportion of the effect SS to the total SS

Table 4. AMMI model best three cultivar selections for fibre yield (kg ha^{-1}) of five cotton cultivars evaluated under irrigation at Loskop, Makhathini, Rustenburg, Upington, Vaalharts and Weipe South Africa in 2003/04 to 2005/06 growing seasons.

Environment	Mean fibre yield (kg ha^{-1})	Three best cultivars and their mean fiber yield (kgha^{-1})					
Loskop 2004	1246	NuOPAL	1516	DeltaOPAL	1416	DeltaOPAL RR	1240
Loskop 2005	1301	NuOPAL	1506	DeltaOPAL	1427	SZ9314	1344
Loskop 2006	1163	NuOPAL	1380	DeltaOPAL	1241	DeltaOPAL RR	1103
Makhathini 2004	1438	NuOPAL	1982	DeltaOPAL	1705	DeltaOPAL RR	1415
Makhathini 2005	1218	NuOPAL	1557	DeltaOPAL	1358	DeltaOPAL RR	1160
Makhathini 2006	976	NuOPAL	1226	DeltaOPAL	1114	DeltaOPAL RR	970
Rustenburg 2004	1466	NuOPAL	1641	DeltaOPAL	1525	DeltaOPAL RR	1406
Rustenburg 2005	1359	NuOPAL	1613	DeltaOPAL	1505	DeltaOPAL RR	1360
Rustenburg 2006	821	NuOPAL	940	DeltaOPAL	860	SZ9314	827
Upington 2004	3215	SZ9314	3421	NuOPAL	3409	DeltaOPAL	3398
Upington 2005	3565	LS9219	3773	NuOPAL	3620	DeltaOPAL	3517
Upington 2006	2287	NuOPAL	2560	DeltaOPAL	2418	DeltaOPAL RR	2258
Vaalharts 2004	2338	NuOPAL	2793	DeltaOPAL	2525	DeltaOPAL RR	2268
Vaalharts 2005	2134	NuOPAL	2818	DeltaOPAL	2383	LS9219	2006
Vaalharts 2006	956	NuOPAL	1487	DeltaOPAL	1221	DeltaOPAL RR	939
Weipe 2004	2079	NuOPAL	2431	DeltaOPAL	2308	DeltaOPAL RR	2124
Weipe 2005	2146	SZ9314	2457	DeltaOPAL	2213	DeltaOPAL RR	2153
Weipe 2006	1518	NuOPAL	1722	DeltaOPAL	1636	SZ9314	1543

Table 5. AMMI analyses of the cultivar evaluation trials (quality variables) of five cotton cultivars evaluated under irrigation at Loskop, Makhathini, Rustenburg, Upington, Vaalharts and Weipe South Africa in 2003/04 to 2005/06 growing seasons.

	Fibre length (mm)				Fibre strength (g tex^{-1})			Micronaire		
Source	**DF**	**SS**	**SS%**	**Prob**	**SS**	**SS%**	**Prob**	**SS**	**SS%**	**Prob**
Environment	17	147.5	18	***	433.8	22	***	34.26	16	***
Block	36	32.5			87.4			2.34		
Cultivar	4	437.4	54	***	240.3	17	***	2.77	5	***
Interaction	68	117.1	14	***	318.2	22	***	8.95	16	***
IPCA1	20	72.4		***	87.2		***	5.57		***
Residual	30	11.3			131.0			3.38		
Error	141	81.6			339.4			9.45		
Total	269	816.1			1419.1			57.77		

DF = Degrees of freedom, SS = Sum of squares,
*** Indicates probability of significant differences at 0.001 alpha-level.

(-19.6) was a sensitive cultivar showing specific adaptation to higher yielding environments. SZ9314 (26.0) is specifically adapted to lower potential environments and gave a below average fibre yield of 1451 kg ha^{-1}.

According to the ASV, DeltaOPAL RR (8.7) followed by DeltaOPAL (12.6) were the most stable cultivars, but they did not result in the highest fibre yields. Table 4 summarizes the AMMI model's best three cultivar selections for fibre yield (kg ha^{-1}).

Quality Performance

Norms for the different fibre qualities are as follows: Length > 27.4 mm, Strength > 28 g/tex, and micronaire 3.5 - 4.9. All quality traits evaluated at the eighteen environments were within the acceptable range. The AMMI analyses of the quality variables are presented in Table 5. The mean micronaire obtained was 4.2. According to the IPCA1 values, DeltaOPAL (0.2) as well as DeltaOPALRR (-0.4) were adapted to most environments. NuOPAL (-0.6) and LS9219 (0.8) were slightly sensitive cultivars adapted to lower yielding environments, while SZ9314 (0.4) was a slightly sensitive cultivar adapted to higher yielding environments.

LS9219 gave the longest fibres of 34.5 and 32.4 mm, respectively at Weipe and Vaalharts during 2005/06.

LS9219 gave above average strengths of 34.5 g tex^{-1} and its IPCA1 score (-2.1) proved it to be a sensitive cultivar adapted to higher yielding environments. SZ9314 (-0.1) and NuOPAL (0.5) were adapted to most environments. DeltaOPAL (1.0)and Delta OPALRR (1.1) were adapted to lower yielding environments.

DISCUSSION

Environment, cultivars and the cultivar x environment interaction had a highly significant effect (P<0.001) on fibre yield. Variance components of the sum of squares ranged from 6.0 % for cultivars to 83.1 % for environments. This indicates the overwhelming influence of the environment on fibre yield produced by cotton cultivars in South Africa. Regarding quality, cultivar LS9219 outperformed NuOPAL in fibre length and strength, but was second to NuOPAL in respect of seed cotton and fibre yields. For fibre length, the IPCA1 score of SZ9314 (0.3), indicated that it was adapted to most environments. LS9219 (1.8) was a sensitive cultivar specifically adapted to higher yielding environments. Delta OPAL (-0.6), NuOPAL (-0.8) and Delta OPALRR (-0.7) were less sensitive cultivars specifically adapted to lower yielding environments. Length, strength and micronaire are the three most important properties of fiber qualities.

Micronaire measurements are a combination of fibre fineness and maturity. Cotton lint with micronaire below 3.5 is usually considered immature and weak (Chaudhry and Cuitchounts, 2003). Micronaire values higher than 4.9 are less desirable as the fibre becomes too coarse for spinning. Micronaire was influenced more by environments than cultivars but all values was in the acceptable range. DeltaOPAL had the lowest IPCA1 value of -0.2 showing that it is adapted to most environments. The best performing cultivar regarding seed cotton and fibre yield (NuOPAL) gave the highest fibre yield (kg ha^{-1}) in fifteen out of the eighteen environments. Mean fibre yield for NuOPAL was 2032 kg ha-1. However, NuOPAL showed higher sensitivity to environmental differences. DeltaOPALRR followed by DeltaOPAL were the most stable cultivars with regard to fibre yield, butthey did not produce the highest fibre yields. Geng *et al.* (1987) also found a positive correlation between yield and stability in cotton and this association suggests that cotton cultivars producing higher yields are, in general, less stable across production environments. Rustenburg had very low yields (821 kg ha^{-1}) in the 2005/06 season compared to high yields at Upington (3565 kg ha^{-1}) in the 2004/05 season. Upington has high day time temperatures with cooler nights. Warmer environments usually haverapid heat loss during the night (less clouds, lower relative humidity) which results in lower night temperatures. This contributes to higher yields, i.e. less carbohydrate loss from respiration. Since no cultivar matched the performance of NuOPAL in respect of seed cotton or fibre yield, NuOPAL is recommended for planting in all of the different cotton-production areas of South Africa.

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